Foundations of Science for Sustainable Future

Principles and Innovations

TÜBA

Türkiye Bilimler Akademisi

Turkish Academy of Sciences

Foundations of Science for Sustainable Future: *Principles and Innovations*

TÜBA
TÜRKİYE BİLİMLER AKADEMİSİ
TURKISH ACADEMY OF SCIENCES

Foundations of Science for Sustainable Future:
Principles and Innovations

ISBN: 978-625-6110-22-9

DOI: 10.53478/TUBA.978-625-6110-22-9

Editors
Prof. Muzaffer Şeker
Dr. Zeynep Aysan Şahintaş
Dr. Gülben Avşar

Graphic Designer
Mustafa Altıntepe

Publication Place and Date:
ANKARA

Pcs.: 750

Turkish Academy of Sciences
Vedat Dalokay Cad. No: 112 06670 Çankaya - Ankara Tel: +90 312 442 29 03 www.tuba.gov.tr

Foundations of Science for Sustainable Future: Principles and Innovations / ed. Muzaffer Şeker, Zeynep Aysan Şahintaş ve Gülben Avşar. -- Ankara : Turkish Academy of Sciences, 2024.
444 pages : res., fig.; 24 cm. -- (Science and Thought Series: 59)
Includes bibliographical references.

ISBN 978-625-6110-22-9
1.Sürdürülebilirlik. 2.Sustainability. 3. Bilim. 4. Science. 5. Bilim -- Türkiye – Tarih. 6.Science—
Türkiye—History.

Q127.T9 F68 2024
303.483

TABLE OF CONTENTS

FOREWORD

It is with great pride and enthusiasm that I present this work, *Foundations of Science for a Sustainable Future: Principles and Innovations*, a testament to the critical role basic sciences play in fostering sustainable development and addressing the pressing challenges of our time. This publication stands as a collective effort by distinguished scholars, dedicated to exploring the transformative potential of scientific research and innovation in shaping a more sustainable, equitable, and prosperous world.

Turkish Academy of Sciences has long upheld the vision of advancing scientific excellence and fostering collaboration among national and international scientific communities. This volume emerges at a pivotal moment, as global challenges such as climate change, resource depletion, and socio-economic inequalities demand bold, interdisciplinary approaches rooted in the principles of sustainability. The International Year of Basic Sciences for Sustainable Development, celebrated under UNESCO's auspices, highlighted the indispensable contribution of basic sciences to achieving these goals. It is within this context that this book takes its place as a valuable resource and a call to action.

This work encapsulates a wealth of knowledge across diverse disciplines, from the chemical and physical sciences to biology, medicine, and the humanities. It emphasizes the interconnectedness of these fields in addressing sustainability challenges and underscores the critical need for capacity building, technological innovation, and the integration of scientific insights into policy and practice. Moreover, it reflects on Turkish Academy of Sciences' commitment to fostering an environment where science can thrive, benefiting humanity and the planet alike.

I extend my heartfelt gratitude to the esteemed contributors who have dedicated their expertise and insights to this endeavor. Their work exemplifies the values of curiosity, integrity, and responsibility that drive scientific progress.

As you explore the chapters that follow, I invite you to reflect on the profound impact that basic sciences can have in shaping sustainable futures. May this book inspire researchers, policymakers, and global citizens to recognize the transformative potential of science and to commit to collaborative efforts toward achieving the United Nations Sustainable Development Goals.

I hope this publication provides valuable insights and practical knowledge to support efforts toward creating a more sustainable and equitable future through science.

Prof. Muzaffer Şeker
Turkish Academy of Sciences, President
ORCID: 0000-0002-7829-3937

PREFACE

The 21st century is a defining era for humanity, marked by unprecedented challenges such as climate change, environmental degradation, resource scarcity, and socio-economic inequalities. These global issues demand innovative solutions rooted in the synergy between scientific knowledge and sustainable practices. It is within this context that we proudly present Foundations of Science for a Sustainable Future: Principles and Innovations, a comprehensive exploration of the transformative role of basic sciences in addressing the complexities of sustainable development.

This book emerges as a collaborative endeavor to highlight the pivotal contributions of fundamental research in science and technology to the advancement of sustainability. Drawing upon diverse fields, it bridges the realms of physical, chemical, biological, and social sciences to present interdisciplinary approaches for fostering a resilient and sustainable future. The contributions in this volume underscore the importance of integrating scientific insights into practical applications and policy frameworks to address urgent global concerns effectively.

Our inspiration for this book stems from the global recognition of the International Year of Basic Sciences for Sustainable Development, as declared by UNESCO. This initiative reinforced the indispensable role of basic sciences in improving the quality of life and achieving the United Nations Sustainable Development Goals (SDGs). With this foundation, we sought to compile a work that not only illuminates the transformative power of science but also serves as a resource for researchers, educators, and policymakers committed to building a sustainable future.

Each chapter in this book represents a deep commitment to exploring critical scientific advances, innovations, and their implications for society and the environment. From the role of green chemistry in reducing environmental impact to the application of digital technologies in medicine and agriculture, the authors provide insights into how science can lead the way in tackling pressing challenges.

We extend our deepest gratitude to Turkish Academy of Sciences for their unwavering support and to the contributors who enriched this work with their expertise and dedication. Their collective efforts reflect a shared vision of harnessing science for the benefit of humanity and the planet.

As editors, it is our hope that this book serves not only as an academic reference but also as a source of inspiration for those striving to make a difference. We invite readers to engage with the ideas and solutions presented here, to innovate, and to collaborate across disciplines and borders. Together, we can advance the cause of sustainability and ensure that the legacy of scientific discovery continues to enrich lives for generations to come.

Editors

ADVANCING SUSTAINABILITY IN THE CHEMICAL SECTOR: THE ROLE OF GREEN AND SUSTAINABLE CHEMISTRY INITIATIVES

Bekir Salih

Mehmet Atakay

10.53478/TUBA.978-625-6110-22-9.ch01

Advancing Sustainability in the Chemical Sector: The Role of Green and Sustainable Chemistry Initiatives

Bekir Salih
Hacettepe University

Mehmet Atakay
Hacettepe University

Abstract

Chemicals are essential for contemporary existence, and the advancement of the chemical industry has contributed to improving the quality of life, which serves as a measure of a country's level of industrialisation. The concept of green chemistry is defined as the application of a specific set of principles aimed at minimizing or eliminating the use and production of harmful compounds in the design, production, and use of chemical products. The purpose is to be more environmentally friendly, and the principles of green chemistry are to be utilized as a method to achieve this goal. The advancements made in reducing the environmental impact of the chemical industry have mostly focused on critical aspects related to chemical production and sustainability. These aspects include sustainable energy and resources, the implementation of a circular economy, the evaluation of cleaner manufacturing methods and sustainable processes, and the promotion of innovation in chemical products. In this article, the green and sustainable chemistry initiatives in the chemical industry are briefly discussed, considering the stakeholders in the field and mentioning the relevant initiatives in the chemical industry in Türkiye.

Keywords
Chemical industry, green chemistry, sustainability, environmentally friendly

Introduction

Chemists are professionals who design and construct molecules. They create molecules that serve as the foundation for materials and products that fulfill human requirements and desires. A sustainable civilization relies on chemical goods and processes that are intentionally created to be "favorable to life" and do not provide a possible risk to the well-being of humans and ecosystems in the short and long term (Zimmerman et al., 2020).

Considering climate change, energy crises, resource shortages, and the possibility of a global pandemic, it is reasonable to assert that modern existence is indeed unfavorable (Flerlage & Slootweg, 2023). Considering the escalating environmental contamination caused by hazardous chemicals and their wide-ranging effects, including ozone depletion and the decline of biodiversity, it may be argued that contemporary chemistry is essentially worthless (Steffen et al., 2015). The chemical manufacturing processes and technical advancements have generated significant amounts of chemical waste, both during and after production. This has led to various human health issues and environmental catastrophes at different levels (Persson et al., 2022). Over the last 25 years, the ideas of green chemistry have prompted the development of chemical products and procedures in both academic and industrial settings that reduce or eliminate the usage of dangerous compounds and waste (Anastas & Warner, 2000; Krasnodębski, 2022). The concepts of green and sustainable chemistry have garnered considerable global attention due to their capacity to foster innovation and propel chemistry towards the attainment of global sustainable development goals and targets.

Green chemistry is defined by scientific principles that prioritize innovation in chemistry. However, sustainable chemistry proposes a more comprehensive approach that considers economic, environmental, and social aspects (Blum et al., 2017; Kümmerer, 2017). Sustainable chemistry encompasses a wider range of subjects by acknowledging the interconnectedness of nested systems, such as the economy inside society within the environment. These encompass several aspects such as sophisticated manufacturing, ensuring safe working conditions, promoting the well-being of local communities and upholding human rights, analyzing consumption and disposal trends, considering the ethical responsibilities of citizens, and exploring innovative business and service models (Blum et al., 2017).

The rapid and occasionally uncontrolled growth of human activities has led to unforeseen and dynamic interconnections among the increasing population, food consumption, industrial progress, and environmental harm (Meadows, 1972). The manufacturing, distribution, use, and discharge of chemicals in increasingly huge quantities inside a confined area have caused significant environmental and health issues (Catling & Zahnle, 2009). The concept of sustainable chemistry was promoted by the OECD during the late 1990s and early 2000s. The OECD has defined sustainable chemistry as a scientific approach that aims to enhance the efficiency of utilizing natural resources to fulfill human requirements for chemical goods and services. From this standpoint, sustainable chemistry involves the deliberate creation, production, and utilization of chemical products and processes that are highly efficient, effective, safe, and have minimal negative impact on the environment. The primary objective is to foster innovation in many industries by developing and exploring novel chemicals, production methods, and product management strategies that offer improved performance and added value. This is done while ensuring the protection and enhancement of human health and the environment. The scope of sustainability has expanded throughout time to include various new areas such as full life-cycle assessment, resource conservation, promotion of reuse and recycling, implementation of corporate social responsibility, and consideration of downstream users like consumers (Bazzanella et al., 2017).

Green Chemistry

The green chemistry concept promotes ongoing advancements in innovation to safeguard human health and the environment, utilizing the 12 Principles as a practical guide (Table 1) (Anastas & Warner, 2000). It has established a versatile structure for dedicating oneself to acts and a process of acquiring knowledge through these dedications. The utilization and adherence to the 12 principles serve as a powerful incentive for both chemistry researchers and chemical firms, as they generate prospects for recognition and benefits. The strategy of encouragement and flexibility is a crucial aspect contributing to the worldwide success of the green chemistry concept. The green chemistry market is projected to reach almost 100 billion US dollars by 2020 (Anastas, 2011; Betts, 2015). The profound influence of green chemistry has been evident in the extensive research conducted, resulting in the publication of numerous articles on the subject and the establishment of research networks worldwide. This has elevated green chemistry to a valuable asset for aspiring scientists (Betts, 2015).

Table 1.

The 12 principles of green chemistry (Anastas & Warner, 2000).

1	***Prevention.*** It is better to prevent waste than to treat or clean up waste after it has been created.
2	***Atom Economy.*** Synthetic methods should be designed to maximize incorporation of all materials used in the process into the final product.
3	***Less Hazardous Chemical Syntheses.*** Wherever practicable, synthetic methods should be designed to use and generate substances that possess little or no toxicity to human health and the environment.
4	***Designing Safer Chemicals.*** Chemical products should be designed to preserve efficacy of function while reducing toxicity.
5	***Safer Solvents and Auxiliaries.*** The use of auxiliary substances (e.g., solvents, separation agents, etc.) should be made unnecessary wherever possible and, innocuous when used.
6	***Design for Energy Efficiency*.** Energy requirements should be recognized for their environmental and economic impacts and should be minimized. Synthetic methods should be conducted at ambient temperature and pressure.
7	***Use of Renewable Feedstocks.*** A raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable.
8	***Reduce Derivatives.*** Unnecessary derivatization (use of blocking groups, protection/deprotection, temporary modification of physical/chemical processes) should be minimized or avoided if possible, because such steps require additional reagents and can generate waste.
9	***Catalysis.*** Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.
10	***Design for Degradation.*** Chemical products should be designed so that at the end of their function they break down into innocuous degradation products and do not persist in the environment.
11	***Real-time analysis for Pollution Prevention.*** Analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances.
12	***Inherently Safer Chemistry for Accident Prevention.*** Substances and the form of a substance used in a chemical process should be chosen to minimize the potential for chemical accidents, including releases, explosions, and fires.

Research aligned with the concepts of green chemistry has facilitated several advancements in various domains, such as the creation of less harmful chemicals and formulations, the development of bio-based chemicals and renewable resources, the use of safer and less toxic solvents and reagents, and the production of environmentally friendly polymers and other materials (Anastas & Warner, 2000; Philp et al., 2013). The following examples of achievements in green chemistry demonstrate the significant influence of green chemistry across several industries, ranging from pharmaceuticals to household appliances, and provide a means to achieve a more favorable global environment. The production of computer chips necessitates the utilization of numerous chemicals, substantial quantities of water, and electricity. A case study in green chemistry where supercritical carbon dioxide is used during chip fabrication, reducing the required quantities of chemicals, energy, and water for production (Rubin et al., 1998). The feathers' protein, keratin, was utilized to create a fiber structure that possesses both low weight and sufficient durability to endure mechanical and thermal strains. The outcome is a printed circuit board made from feathers that operates at a pace that is twice as fast as conventional circuit boards (Frazer, 2004). The pharmaceutical sector is consistently striving to provide medications with reduced adverse effects and employing methods that generate less toxic waste. The green production of sitagliptin molecule the main active ingredient in a medication designed for the treatment of type 2 diabetes. The development of an enzymatic production method that effectively reduces waste, enhances yield and safety, and obviates the necessity for a metal catalyst (Hansen et al., 2009). Simvastatin, a pharmaceutical agent, is commonly prescribed for the management of hypercholesterolemia. The conventional multistep process for manufacturing this medication entails the use of substantial quantities of chemicals and generates a significant quantity of harmful byproducts during its synthesis. An environmentally friendly production of simvastatin was documented, employing a genetically modified enzyme and an inexpensive raw material (Xie & Tang, 2007). Many companies have been engaged in the pursuit of producing plastics derived from renewable and biodegradable sources. Food containers were produced using polylactic acid as the polymer (Vink & Davies, 2015). A novel technique has been identified wherein microorganisms facilitate the conversion of cornstarch into a resin with comparable strength to the stiff petroleum-based plastic presently employed in the production of food containers. A biodegradable polyester film was developed for the production of bags that are completely biodegradable. These bags are created using a combination of this film, cassava starch, and calcium carbonate. The bags, which have obtained certification from the Biodegradable Products Institute, undergo total disintegration into water, carbon dioxide, and biomass within industrial composting systems. The substitution of traditional plastic bags with these bags facilitates the rapid degradation of kitchen and yard waste within municipal composting systems (Siegenthaler et al., 2012). Alkyd paints, which are based on oil, emit significant quantities of volatile organic compounds (VOCs). The volatile compounds undergo evaporation from the paint throughout the process of drying and curing, and a significant number of them exhibit one or more environmental consequences. A blend of soya oil and sugar serves as a substitute for paint resins and solvents derived from fossil fuels, effectively reducing dangerous volatiles by fifty percent. The formulas of biobased oils as a substitute for petroleum-based solvents, resulting in a paint that is characterized by enhanced safety and reduced generation of toxic waste. The water-based acrylic alkyd paints with minimal volatile organic compounds (VOCs) were developed and can be produced using recycled soda bottle plastic (PET), acrylics, and soybean oil. These paints integrate the functional advantages of alkyds with the minimal volatile organic compound (VOC) content of acrylics.

Green Engineering

Green engineering also encompasses the strategic development, marketing, and utilization of various processes and products with the aim of mitigating pollution, fostering sustainability, and minimizing potential hazards to both human health and the environment, all while maintaining economic feasibility and operational effectiveness. The field of green engineering covers the notion that making decisions aimed at safeguarding human health and the environment can yield the most significant outcomes and cost-efficiency when implemented within the initial stages of process or product design and development. The green engineering principles delineate the criteria for creating a more environmentally friendly chemical process or product (Table 2) (Anastas & Zimmerman, 2003).

Table 2.

The 12 principles of green engineering (Anastas & Zimmerman, 2003).

1	***Inherent Rather Than Circumstantial.*** Designers need to strive to ensure that all materials and energy inputs and outputs are as inherently nonhazardous as possible.
2	***Prevention Instead of Treatment.*** It is better to prevent waste than to treat or clean up waste after it is formed.
3	***Design for Separation.*** Separation and purification operations should be designed to minimize energy consumption and materials use.
4	***Maximize Efficiency*.** Products, processes and systems should be designed to maximize mass, energy, space, and time efficiency.
5	***Output-Pulled Versus Input-Pushed.*** Products, processes, and systems should be "output pulled" rather than "input pushed" through the use of energy and materials.
6	***Conserve Complexity.*** Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse, or beneficial disposition.
7	***Durability Rather Than Immortality.***Targeted durability, not immortality, should be a design goal.
8	***Meet Need, Minimize Excess.*** Design for unnecessary capacity or capability (e.g., "one size fits all") solutions should be considered a design flaw.
9	***Minimize Material Diversity.*** Material diversity in multicomponent products should be minimized to promote disassembly and value retention.
10	***Integrate Material and Energy Flows.*** Design of products, processes, and systems must include integration and interconnectivity with available energy and materials flows.
11	***Design for Commercial "Afterlife".*** Products, processes, and systems should be designed for performance in a commercial "afterlife."
12	***Renewable Rather than Depleting.*** Material and energy inputs should be renewable rather than depleting.

The chemical processing industry is integrating green engineering practices to reduce risk, minimize waste, and enhance the economic viability of chemical manufacture. The application of green engineering principles to industrial processes can be exemplified through the utilization of various case studies. As an example of case study, the reactive distillation method offer several advantages over older methods, particularly in the manufacture of methyl acetate. These advantages include improved selectivity, reduced energy consumption, ability to handle challenging separations, and enhanced overall rates (Doherty & Malone, 1999). Another case study was on the UltraLight Steel Auto Body-Advanced Vehicle Concepts (ULSAB-AVC). The study examined the impact of utilizing lightweight steel in car construction on reducing automobile emissions and enhancing fuel efficiency (Thorpe &

Adam, 2002). One other case study pertains to the reduction of hazardous chemical usage within the paper industry. Closed-mill bleaching technique utilizes a novel delignification agent, known as a polyoxometalate (POM), to reduce the need for and potential exposure to dangerous chemicals during the bleaching process (Weinstock et al., 1996). Inhalation of mist emitted by machining fluids can lead to severe health complications, including as cancer, respiratory diseases, and allergic responses. The impact of incorporating polymers into water-based and straight-oil machining fluids was examined in order to reduce the risk of inhaling this mist. The automotive sector has extensively adopted a cost-effective approach for reducing mist formation from oil-based fluids, serving as a prominent case study (Smolinski et al., 1996).

Policy Recommendations and Strategies

There is a notable global increase in the demand for products that are both safer and more sustainable. In light of mounting scientific data and growing activism, governmental bodies are implementing substantial policy reforms at several levels, including national, state, and local, with the aim of mandating transparency on product ingredients, gradually eliminating chemicals of concern, and embracing safer alternatives. Efficiently formulated regulatory rules can exert a significant impact on fostering innovation and reducing the adverse effects of chemicals (Golden et al., 2021). According to the European Commission's Roadmap to a Resource Efficient Europe (2011), it is imperative to ensure the appropriate and effective utilization of resources, while also taking into account the principles of sustainable production and consumption (Lozano et al., 2018). The European Union Ecodesign Directive establishes criteria for energy-related products and evaluates the benefits and drawbacks of implementing the directive, while also offering suggestions for future measures (Dalhammar, 2014). The primary emphasis of the European Ecodesign Directive lies in prioritizing energy considerations over resource efficiency (Bundgaard et al., 2017).

The growing prominence of green chemistry and sustainable chemistry indicates that the pollution control and disposal system, which has guided environmental policy since the 1970s, has proven ineffective in preventing widespread chemical pollution (Thornton, 2001). This necessitates a deeper comprehension of how the redirection and acceleration of technical advancements can facilitate the creation, advancement, and implementation of more environmentally friendly products and processes that can effectively manage resource consumption and prevent the generation of hazardous waste (Falcone & Hiete, 2019). Changes in traditional policy frameworks play a crucial role in facilitating the transition towards sustainability by directly supporting emergent businesses and disrupting existing regimes (Turnheim & Geels, 2013).

The industry has a crucial role in attaining sustainable development and enhancing the quality of life for the global population, as it serves as the primary source of raw materials for the creation of most manufactured goods (Tickner et al., 2022). Nevertheless, it is imperative to realize that it plays a significant role in exacerbating the climate, hazardous pollution, and plastic waste crises, hence posing potential risks to both human and planetary health. A significant industrial change of this magnitude necessitates the implementation of well-defined strategies. It is crucial to establish a well-defined vision for the chemical industry that is well-suited for the future. This vision should include specific goals that are time-bound and aligned with the United Nations' Decade of Action, which aims to expedite sustainable solutions. By doing so, objectives can be clarified and metrics can be identified to assess progress (United Nations, Decade of Action, 2024). In order to comply with the European Green Deal, the chemical industry that has undergone transformation must also achieve the objectives of "dematerialization" (establishing a circular economy) and "detoxification" (creating a non-toxic environment) (Jackson, 1993). To do this, it is necessary to find a balance between meeting the chemical and downstream material requirements of modern society and achieving the United Nations Sustainable Development Goals (SDGs) that protect present and future generations (WCED, 1987).

The regulation on the registration, evaluation, authorisation and restriction of chemicals (REACH) is the primary legislation of the European Union (EU) aimed at safeguarding human health and the environment against the potential hazards associated with chemicals. This is achieved by enhanced and timely recognition of the inherent characteristics of chemical compounds, as well as through the implementation of strategies such as the gradual elimination or limitation of substances that pose significant risks. REACH also aims to augment innovation and enhance the competitiveness of the European Union's chemicals industry. REACH imposes the obligation on the industry to effectively handle the hazards associated with chemicals and to produce safety data regarding these substances. In order to achieve this objective, it is mandatory for manufacturers and importers to collect data regarding the characteristics of their chemical compounds and thereafter record this information in a single database maintained by the European Chemicals Agency (ECHA). The agency manages the databases required for system operation, supervises the comprehensive assessment of chemical information, and operates a public database that provides risk information to consumers and professionals (Reach Regulation EU, n.d.).

REACH is applicable to all chemical substances, encompassing not just those utilized in industrial operations but also those found in our daily routines, such as cleaning products, paints, and other products like clothing, furniture, and electrical equipment. The regulation also affects the majority of enterprises throughout the EU. REACH imposes the responsibility of providing evidence on companies. In order to adhere to the regulation, enterprises are required to identify and effectively handle the hazards associated with the substances they produce and promote in the EU. They are required to exhibit to ECHA the safe utilization of the substance and effectively convey the risk mitigation strategies to the users. If risks cannot be effectively reduced, authorities have the ability to impose certain restrictions on the utilization of chemicals. Over time, it is advisable to replace the most hazardous chemicals with less hazardous alternatives (Reach Regulation EU, n.d.).

The REACH Regulation (EC 1907/2006) was implemented in June 2007 and has been adapted to incorporate the progress made in understanding different chemicals and their characteristics (Regulation (EC) No 1907/2006 concerning the Registration: Evaluation, authorisation and restriction of chemicals.). The "Chemicals Strategy for Sustainability" was published by the EU Commission in 2020 with the aim of enhancing the REACH regulations. It is also targeting non-toxic material cycles. Key components of this improved approach, such as the implementation of the "one substance—one assessment" principle, the incorporation of a mixture assessment factor, the facilitation of group rules, and the shift towards intrinsically safe chemicals, will play a crucial role in advancing sustainable chemicals management (Steinhäuser et al., 2022). The implementation of green and sustainable chemistry innovation is crucial in promoting the progress of a circular economy. It promotes the creation of molecules, materials, and products that are more readily recyclable compared to those presently available in the market. One way to accomplish this is by removing harmful substances from items that currently hinder the process of recovery and recycling.

The European Union (EU) generates almost 2.2 billion tonnes of waste yearly. It is presently revising its waste management laws to encourage a transition towards a more sustainable approach called the circular economy. The circular economy is a conceptual framework that encompasses many modes of production and consumption, employing strategies such as sharing, leasing, reusing, repairing, refurbishing, and recycling to extend the lifespan of resources and products. Practically, it entails minimizing waste to the greatest extent possible. Recycling ensures that the materials of a product are retained within the economy wherever feasible after it reaches the end of its lifespan. These can be repeatedly utilized in a productive manner, therefore generating additional value. The circular economy represents a departing from the traditional, linear economic model, which relies on a pattern of taking, producing, consuming, and disposing.

The practice of reusing and recycling products has the potential to slow down the depletion of natural resources, reduce landscape and habitat disturbances, and contribute to the mitigation of biodiversity loss. Developing efficient and sustainable products would reduce energy and resource consumption. This is particularly significant given that the design phase is responsible for determining over 80% of a product's environmental effect. Adopting a transition towards more reliable products that are capable of being reused, updated, and restored would effectively lower the quantity of waste. The global population is increasing, leading to a corresponding rise in the demand for essential supplies. Nevertheless, the availability of essential raw resources is constrained. Recycling raw materials helps to reduce the risks related to supply, such as fluctuations in prices, limited availability, and reliance on imports. This is particularly relevant in the context of critical raw materials required for the manufacturing of products that play a pivotal role in attaining climate objectives, such as batteries and electric engines. The adoption of a circular economy has the potential to enhance competitiveness, foster innovation, encourage economic growth, and generate employment opportunities. The implementation of circular design principles in materials and products has the potential to stimulate innovation across several sectors of the economy.

Green and Sustainable Chemistry Innovation

Green and sustainable chemistry innovation can be utilized to design molecules and materials that quickly break down in the environment while still maintaining their intended functions. This is particularly relevant for products that are intentionally released into the environment and have open-environmental applications, such as pesticides, cosmetics, biocides, or pharmaceuticals (Kümmerer et al., 2020).

Chemistry has a vital role in various end markets that are crucial for influencing the future of development and sustainable development. Some examples encompass the transportation sector, the building sector, the food and packaging industry, and waste management. It is crucial to include green and sustainable chemical principles in pertinent innovations.

The implementation of green and sustainable chemical innovation holds the capacity to propel sustainability in crucial sectors of the economy. Due to the significance of the energy sector in combating climate change, this sector is briefly discussed to demonstrate the relevance and impact of green and sustainable chemistry in facilitating a sustainable transition at the sectoral level.

One of the principles of green chemistry emphasizes the importance of acknowledging the environmental and economic consequences of energy demand and striving to decrease them. Whenever feasible, synthetic procedures should be carried out under conditions of standard temperature and pressure (Anastas & Warner, 2000). Although the chemical industry has made notable progress in conserving energy during chemical production, achieving additional substantial improvements through process efficiency measures is difficult. This highlights the necessity for technological disruption, specifically through the adoption of green chemistry reactions that require less energy. Researchers are studying disruptive concepts, such as electrochemical synthesis and other new catalytic techniques, to replace thermochemical methods with less energetically demanding processes. Emerging sustainable technical technologies that enable the simultaneous production of energy and chemical products are on the horizon. To successfully promote these breakthroughs and establish an energy-efficient, secure, and robust chemical sector, it is imperative to continue providing incentives and investing in the development of these technologies.

The primary objective of the green and sustainable chemical endeavor is to create materials that exhibit superior performance while also guaranteeing their non-toxicity and recyclability. Hence, it is imperative to subject "green materials" that are touted for their energy-saving capabilities to a rigorous evaluation based on green and sustainability chemical standards prior to deeming them as more sustainable.

Solar fuels encompass methods that use sunlight to generate valuable chemicals, such as hydrogen and methanol, through the conversion of water and carbon dioxide. This technique is unique in that it utilizes solar energy directly to synthesize well-established and extensively utilized compounds from water and carbon dioxide. The notion encompasses the use of fuels for transportation and energy generation, as well as chemical raw materials used to make petrochemicals, fertilizers, polymers, and pharmaceuticals.

Batteries possess the capacity to furnish society with a reliable and uninterrupted stream of energy derived from sustainable sources. Lithium, which is crucial for the growth of electric vehicles and grid applications, faces potential supply constraints and difficulties in recycling and disposal. Chemical advancements hold the capacity to enhance the safety, dependability, longevity, and recyclability of batteries. Innovation issues encompass several areas, such as the development of novel materials for lithium-ion batteries, redox flow batteries, metal-air batteries, organic batteries, and materials for high-capacity thermo-solar and heat energy storage (Larcher & Tarascon, 2015).

The pharmaceutical sector has also emerged as a prominent area within the chemical industry. The production of pharmaceutical raw materials is possible through main lines, synthetic chemistry and biotechnology. In the world, the number of products produced by synthetic chemistry is decreasing while biotechnology is increasing; on the other hand, increased R&D investment is gaining weight in the field of biopharmaceuticals. Biopharmaceuticals are unique products due to high R&D and investment costs, advanced technology and special requirements, purification difficulties, preservation, stability, and dosing challenges.

For almost a century, the chemical industry has relied on fossil fuels, predominantly oil, coal, and gas, to manufacture fundamental chemicals like ammonia, methanol, ethylene, and propylene. These compounds serve as the foundation for a diverse array of other chemicals, materials, and products throughout the chemical industry value chain. Due to the exhaustion and eventual scarcity of fossil resources, their role in emitting greenhouse gases, and uncertainties in global supply chains, efforts are underway to investigate the utilization of novel bio-based sources for the production of chemical feedstocks. Biomass is the organic matter obtained from living organisms, typically plants. Biorefinery technologies can generate a variety of fundamental chemicals that are typically manufactured using energy-intensive and environmentally harmful petrochemical refinery processes (Kohli et al., 2019). Biomass has the potential to serve as the fundamental basis for a variety of products and uses, encompassing food, energy, materials, and pharmaceuticals.

There are multiple ways to effectively utilize carbon dioxide, which is a powerful greenhouse gas, as a valuable resource. These encompass the transformation of carbon dioxide into fuels, the utilization of carbon dioxide as a raw material for the chemical industry, and other applications of carbon dioxide that do not involve conversion. These technologies possess the capacity to sequester carbon dioxide from the atmosphere, aiding in the alleviation of climate change. Nevertheless, due to the substantial energy demands, the utilization of renewable energy is imperative in order to fulfill sustainability standards.

The stakeholders of chemistry innovations

Facilitating cooperative efforts and promoting action, such as supporting start-up enterprises, is crucial for advancing research and innovation in green and sustainable chemistry. National research and technology institutes, economic development agencies, and trade promotion programmes have the potential to assist in both domestic and international collaborative endeavors.

Historically, universities have mostly concentrated on imparting knowledge and conducting fundamental research. However, due to the growing demand for practical and goal-oriented research, they are now becoming more involved in entrepreneurial and corporate endeavors (Etzkowitz et al., 2008). This implies that individuals not only assume the roles of problem-solvers, inventors, and entrepreneurs (EC and OECD 2012) but also possess significant influence as stakeholders in the realm of green and sustainable chemistry innovation. Relevant university activities encompass the process of patenting or licensing ideas, as well as the creation of start-up support networks, such as the formation of spin-off ventures (Klofsten & Jones-Evans, 2000). Developing young researchers is crucial to guarantee the long-term viability of start-ups. Creating connections between research groups, curriculum, and the industry is crucial for fostering the growth of green and sustainable chemistry-oriented initiatives. This helps to overcome limitations in educational programs and creates an environment that supports the establishment of new firms (Ocampo-López et al., 2019).

Chemical firms engage in substantial research and development that require significant investment and engineering expertise. Due to the exorbitant expenses associated with research and innovation, there is a growing trend towards a strong partnership between industry and academia. In recent years, significant advancements in chemistry have emerged through collaborative efforts, including the development of heterogeneous catalysis, the synthesis of monomers for small-molecule medicinal chemistry, organometallic chemistry, electrochemistry, and energy storage (Whitesides, 2015). The commercial sector's direct funding for universities is highly valuable. It may encompass several elements, such as research funding, collaborative training agreements, and technical service contracts (Malairaja & Zawdie, 2008).

Governments have a crucial role in facilitating chemistry innovation by addressing market deficiencies that hinder innovation, as stated by the United Nations Economic Commission for Europe. Governments can offer several forms of support, such as monetary incentives, funding for infrastructure, or direct financing for innovative initiatives (da Silva et al., 2012). Additionally, they can ensure the elimination of obstacles that impede creativity. The government also has a crucial role in facilitating collaboration across important sectors and stakeholders to promote the public interest.

Governments can promote the advancement of green and sustainable chemistry innovation by implementing national industrial policies or programs. These programs align with the government's responsibility to establish facilitative mechanisms and favorable circumstances rather than making specific decisions.

The Global Chemical Sector and Chemical Sector in Türkiye

The chemical sector, one of the top three industries in the industrialized countries, is a development indicator. In industrialized countries, the locomotive sector is positioned because of the high value-added products it provides in areas such as energy, agriculture, health, transportation, food, construction, electronics, and textiles (The Eleventh Development Plan of Türkiye, Chemical Industry). The chemical industry supplies raw materials to many sectors and plays an important role in both production and foreign trade. There are very few products from the chemical industry that are produced without the use of raw materials. In this context, it provides final and intermediate products to many industries, such as mineral fuels/oils, organic/inorganic chemicals, pharmaceuticals, fertilizers, dyes, varnishes, cosmetics, soaps, thermoplastics, explosives, plastics, and products from rubber (Chemical Sector Report, 2023).

The primary problem of the chemical sector, which has made a significant contribution to the economy of countries and other sectors, is the inadequacy of domestic production in the field. The chemical sector is heavily dependent on imports, both raw materials and technology. The development of the sector requires new and modern technology and capital-intensive production and, thus, large-scale investments.

The chemical industry in Türkiye consists mainly of plants, where various raw chemical materials and consumer products such as petrochemicals, soaps, detergents, fertilizers, medicines, paints, synthetic fibers, and soda are produced. Companies operating in the sector vary in scale and capital resources. While a significant proportion of the companies operating in the sector are small and medium-sized enterprises, large firms and multinationals also operate (Chemical Sector Report, 2023).

Research and development (R&D) activities are an important indicator of the value-added sector's ability to produce and export high-value products. The high R&D expenditure of the world's top exports in the chemical sector supports this view. The climate of encouragement and exemption in Türkiye has created a good climate in the country for R&D activities. This and similar mechanisms can be co-operated with other institutions and institutions of the state, which will further advance R&D and innovation firms. The priorities in license applications and the reduction of waiting times for R&D commercial products made in Türkiye strengthen stakeholders' confidence in innovation activities. Priorities to address the requirements that may arise during the conversion of projects supported by The Scientific and Research Council of Türkiye (TÜBİTAK) or EU funds to investment and production can be examples. The presence of representatives of the relevant professional groups in the management of universities or research institutes is important in order to communicate the needs of the sectors first and foremost. Thus, different incentive mechanisms could be developed for cooperation projects.

Through R&D and innovation, the chemical industry in Türkiye has a sustainable competitive position in international markets. It increases the value of the country's exports per kilogram by developing high-value products. To achieve a sustainable competitive position in international markets, a high level of knowledge and technology, R&D and an innovation-based economic model is required. The increase in R&D and innovation is also known to be directly linked to the increase in exports.

Effective action plans should be developed to enhance industrial research, commercialise intellectual property rights, promote entrepreneurship, raise the innovation index, encourage postgraduate students to participate in industrial research and promote cooperation between industry and universities. Appropriate models should be developed to meet R&D needs, using the infrastructure of research laboratories at the universities without investing in R&D infrastructure. In this way, at a lower cost for the economy, universities can conduct R&D to meet the needs of industry and contribute to the implementation of research projects. To achieve these goals, however, the coordination of university-industry cooperation needs to be more effective and efficient. To encourage the training of qualified staff and increase the number of researchers with doctoral degrees in industry, grant opportunities for postgraduate students can improve the research performances at university research laboratories.

The responsibilities of producers, consumers, civil society organizations, business organizations and governments in the fight against climate change are increasing. One of the most important concrete steps being taken is the Paris Agreement, which aims to limit global warming to 1.5 °C, if possible. The European Union (EU), which plays a leading role in the fight against climate change, announced the European Green Deal in 2019. With this regulation, the EU aims to reduce greenhouse gas emissions both within its borders and globally. The Green Deal Action Plan of Türkiye was announced in July 2021. The overall framework of the action plan consists of nine main headings: carbon regulation at the border, green and circular economy, green financing, clean, economical and safe energy, sustainable agriculture, smart, sustainable transport, combating climate change, diplomacy and awareness-raising activities. Within the framework of this plan, Türkiye aims to adapt to the green transformation process by raising awareness and motivating consumers and producers. The Türkiye Green Industry Project will be implemented by the Republic of Türkiye Ministry of Industry and Technology, TÜBITAK, and the Small and Medium Enterprises Development Organization (KOSGEB), with the support of the World Bank to support the sustainable and efficient green transformation of industry in Türkiye in connection with the provisions of the Green Deal Action Plan of Türkiye *(Information note by TÜBİTAK "Türkiye Green Industry Project" to be implemented with the support of World Bank: Supporting Green Innovation Activities of Industry).*

Republic of Türkiye Ministry of Environment, Urbanization and Climate Change has been conducting work for many years to determine the compliance and requirements of the energy, iron-steel, aluminum, chemical, mineral, automotive, textile, food, fertilizer, glass, paper, leather, cement and waste management sectors with energy and resource-efficient clean production technologies. In Türkiye, the "Green Transformation of Turkish Industry" document will enable them to benefit from funds for environmental investment and to compete on equal terms in exports while also documenting their environmental approach during their activities. The Green Transformation in Industry, which is continuing to accelerate with the documentation process aimed at starting in 2023, and the air, water, and soil quality is being preserved; the objective is to take important steps towards achieving green development with progressive industry producing clean, in line with zero pollution targets for 2053 year. In the framework of the Türkiye Green Deal Action Plan, "Zero Pollution for Air, Water and Soil", an action plan is planned to be prepared that covers the transition calendar and national policies for all environmental environments, with the best techniques and technologies for green transformation in industry aimed at clean production.

Conclusion

Recent advancements in the chemical sector have often prioritized the utilization of renewable resources and minimized waste during production. However, these advancements have not consistently taken into account the environmental impact throughout their whole life cycle and overall environmental consequences. In order to minimize resource and energy consumption, chemical strategies should be optimized for their intended purpose. The chemical products should be designed to be safe for both human health and the natural environment. This prevents the creation of harmful substances that are poisonous to ecosystems, can accumulate in living organisms, persist in the environment, and easily move around. Additionally, it aims to minimize or eliminate the usage and production of hazardous materials during the manufacturing process. The circular approach aims to replicate natural cycles and create closed-loop systems that enable the retrieval and reuse of valuable goods and all forms of waste. The ultimate objective should be to achieve zero waste and zero pollution by redesigning processes, chemicals, and products in order to maintain materials within secure and efficient closed loops, all while satisfying our requirements. There are prominent corporations in the chemical industry that are beginning to practice green chemistry. However, the persistence of outmoded and deeply ingrained industry processes has hampered the adoption of green chemistry in the industrial sector. In order to implement green chemistry in industry, it is necessary to adopt a new approach that emphasizes collaboration among a wide range of stakeholders. This approach should involve technology forcing through customer and market awareness, industry compromise to change the current situation, and improved education for both consumers and industry. In order to achieve a sustainable future, we must establish the necessary physical foundation. This entails incorporating functionality, efficiency, safety, and circularity into the innovation process from the outset and maintaining these principles throughout the whole life cycle. Governments can foster the progress of green and sustainable chemistry innovation through the implementation of industrial policies or programs. Türkiye is experiencing a significant increase in chemical industry capacity, and with this increase, many supportive initiatives, deals, plans and projects focusing on green and sustainable advances are being implemented.

References

Anastas, P. (2011). Twenty years of green chemistry. *Chemical & Engineering News*, 89(26), 62-63. ISO 690

Anastas, P. T., & Warner, J. C. (2000). *Green chemistry: theory and practice*. Oxford university press.

Anastas, P. T., & Zimmerman, J. B. (2003). Peer reviewed: design through the 12 principles of green engineering. In: ACS Publications.

Bazzanella, A., Friege, H., & Zeschmar-Lahl, B. (2017). Identification of priority topics in the field of sustainable chemistry. *Dessau-Roßlau: Umweltbundesamt*.

Betts, K. (2015). How industrial applications in green chemistry are changing our world. In: American Chemical Society Washington, DC.

Blum, C., Bunke, D., Hungsberg, M., Roelofs, E., Joas, A., Joas, R., Blepp, M., & Stolzenberg, H.-C. (2017). The concept of sustainable chemistry: Key drivers for the transition towards sustainable development. *Sustainable Chemistry and Pharmacy*, *5*, 94-104.

Bundgaard, A. M., Mosgaard, M. A., & Remmen, A. (2017). From energy efficiency towards resource efficiency within the Ecodesign Directive. *Journal of Cleaner Production*, *144*, 358-374.

Catling, D. C., & Zahnle, K. J. (2009). The planetary air leak. *Scientific American*, *300*(5), 36-43.

da Silva, C. E. L., Narcizo, R. B., & Cardoso, R. (2012). The proximity between Academy, Industry and Government: towards a more sustainable development of a Brazilian oil region. *Procedia-Social and Behavioral Sciences*, *52*, 100-109.

Dalhammar, C. (2014). *Addressing resource efficiency through the Ecodesign Directive*. Nordic Council Of Ministe.

Doherty, M., & Malone, M. (1999). Recent Advances in Reactive Distillation. *AICHE Annual Meting, Dallas, paper203c*.

Etzkowitz, H., Ranga, M., Benner, M., Guaranys, L., Maculan, A. M., & Kneller, R. (2008). Pathways to the entrepreneurial university: towards a global convergence. *Science and Public Policy*, *35*(9), 681-695.

Falcone, P. M., & Hiete, M. (2019). Exploring green and sustainable chemistry in the context of sustainability transition: The role of visions and policy. *Current Opinion in Green and Sustainable Chemistry*, *19*, 66-75.

Flerlage, H., & Slootweg, J. C. (2023). Modern chemistry is rubbish. *Nature Reviews Chemistry*, *7*(9), 593-594.

Frazer, L. (2004). Chicken electronics: a technology plucked from waste. In: National Institue of Environmental Health Sciences.

Golden, J., Handfield, R., Daystar, J., Kronthal–Sacco, R., & Tickner, J. (2021). Green Chemistry A Strong Driver of Innovation, Growth, and Business Opportunity. *Industrial Biotechnology*, *17*(6), 311-315.

Hansen, K. B., Hsiao, Y., Xu, F., Rivera, N., Clausen, A., Kubryk, M., Krska, S., Rosner, T., Simmons, B., & Balsells, J. (2009). Highly efficient asymmetric synthesis of sitagliptin. *Journal of the American Chemical Society*, *131*(25), 8798-8804.

Jackson, T. (1993). *Clean production strategies developing preventive environmental management in the industrial economy*. CRC Press.

Klofsten, M., & Jones-Evans, D. (2000). Comparing academic entrepreneurship in Europe–the case of Sweden and Ireland. *Small business economics*, *14*, 299-309.

Kohli, K., Prajapati, R., & Sharma, B. K. (2019). Bio-based chemicals from renewable biomass for integrated biorefineries. *Energies*, *12*(2), 233.

Krasnodębski, M. (2022). Lost Green Chemistries: History of Forgotten Environmental Trajectories. *Centaurus*, *64*(2), 509-536.

Kümmerer, K. (2017). Sustainable chemistry: a future guiding principle. In (Vol. 56, pp. 16420-16421): Wiley Online Library.

Kümmerer, K., Clark, J. H., & Zuin, V. G. (2020). Rethinking chemistry for a circular economy. *science*, *367*(6476), 369-370.

Larcher, D., & Tarascon, J.-M. (2015). Towards greener and more sustainable batteries for electrical energy storage. *Nature chemistry*, *7*(1), 19-29.

Lozano, F. J., Lozano, R., Freire, P., Jiménez-Gonzalez, C., Sakao, T., Ortiz, M. G., Trianni, A., Carpenter, A., & Viveros, T. (2018). New perspectives for green and sustainable chemistry and engineering: Approaches from sustainable resource and energy use, management, and transformation. *Journal of Cleaner Production*, *172*, 227-232.

Malairaja, C., & Zawdie, G. (2008). Science parks and university–industry collaboration in Malaysia. *Technology Analysis & Strategic Management*, *20*(6), 727-739.

Meadows D., Meadows D. Randers, L. Behrens, W. W. (1972). *The Limits to Growth.* Universe Book.

Ocampo-López, C., Ramírez-Carmona, M., Rendón-Castrillón, L., & Vélez-Salazar, Y. (2019). Applied research in biotechnology as a source of opportunities for green chemistry start-ups. *Sustainable Chemistry and Pharmacy*, *11*, 41-45.

Persson, L., Carney Almroth, B. M., Collins, C. D., Cornell, S., De Wit, C. A., Diamond, M. L., Fantke, P., Hassellöv, M., MacLeod, M., & Ryberg, M. W. (2022). Outside the safe operating space of the planetary boundary for novel entities. *Environmental science & technology*, *56*(3), 1510-1521.

Philp, J. C., Ritchie, R. J., & Allan, J. E. (2013). Biobased chemicals: the convergence of green chemistry with industrial biotechnology. *Trends in biotechnology*, *31*(4), 219-222.

REACH Regulation EU (Access Date March 2024). https://environment.ec.europa.eu/topics/chemicals/reach-regulation_en

Regulation (EC) No 1907/2006 concerning the Registration: Evaluation, authorisation and restriction of chemicals. (Access Date March 2024). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02006R1907-20221217

Rubin, J., Davenhall, L., Taylor, V., Sivils, L., Pierce, T., & Tiefert, K. (1998). *CO2-Based Supercritical Fluids as Replacements for Photoresist-Stripping Solvents*.

Siegenthaler, K., Künkel, A., Skupin, G., & Yamamoto, M. (2012). Ecoflex® and Ecovio®: biodegradable, performance-enabling plastics. *Synthetic biodegradable polymers*, 91-136.

Smolinski, J. M., Gulari, E., & Manke, C. W. (1996). Atomization of dilute polyisobutylene/mineral oil solutions. *AiChE journal*, *42*(5), 1201-1212.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., De Vries, W., & De Wit, C. A. (2015). Planetary boundaries: Guiding human development on a changing planet. *science*, *347*(6223), 1259855.

Steinhäuser, K. G., Von Gleich, A., Große Ophoff, M., & Körner, W. (2022). The necessity of a global binding framework for sustainable management of chemicals and materials—interactions with climate and biodiversity. *Sustainable Chemistry*, *3*(2), 205-237.

Thornton, J. (2001). Implementing green chemistry. An environmental policy for sustainability. *Pure and Applied Chemistry*, *73*(8), 1231-1236.

Thorpe, M. D., & Adam, H. (2002). ULSAB-AVC-Overview and Design.

Tickner, J. A., Geiser, K., & Baima, S. (2022). Transitioning the chemical industry: elements of a roadmap toward sustainable chemicals and materials. *Environment: Science and Policy for Sustainable Development*, *64*(2), 22-36.

Turnheim, B., & Geels, F. W. (2013). The destabilisation of existing regimes: Confronting a multi-dimensional framework with a case study of the British coal industry (1913–1967). *Research Policy*, *42*(10), 1749-1767.

Understanding REACH_ECHA_EU (Access Date March 2024). https://echa.europa.eu/regulations/reach/understanding-reach

United Nations, Decade of Action (Access Date March 2024). https://www.un.org/sustainabledevelopment/decade-of-action/

Vink, E. T., & Davies, S. (2015). Life cycle inventory and impact assessment data for 2014 Ingeo™ polylactide production. *Industrial Biotechnology*, *11*(3), 167-180.

WCED, S. W. S. (1987). World commission on environment and development. *Our common future*, *17*(1), 1-91.

Weinstock, A., Atalla, R. H., Reiner, R. S., Moen, M. A., Hammel, K. E., Houtman, C. J., & Hill, C. L. (1996). A new environmentally benign technology and approach to bleaching kraft pulp. Polyoxometalates for selective delignification and waste mineralization. *New Journal of Chemistry*, *20*(2), 269.

Whitesides, G. M. (2015). Reinventing chemistry. *Angewandte Chemie International Edition*.

Xie, X., & Tang, Y. (2007). Efficient synthesis of simvastatin by use of whole-cell biocatalysis. *Applied and environmental microbiology*, *73*(7), 2054-2060.

Zimmerman, J. B., Anastas, P. T., Erythropel, H. C., & Leitner, W. (2020). Designing for a green chemistry future. *science*, *367*(6476), 397-400.

About Authors

Prof. Bekir SALIH | Hacettepe University | bekir[at]hacettepe.edu.tr | ORCID: 0000-0002-8542-6531

Bekir Salih, PhD is currently a full Professor in the Physical Chemistry Divison at the Department of Chemistry, Hacettepe University Ankara-TÜRKİYE. He received his PhD from Hacettepe University in 1990. He was the Dean of the Faculty of Science in 2013-2016 at Hacettepe University. He was the scientific head of the Turkish Doping Control Center between 2013 and 2016, and during that period, the centre was re-accredited by WADA in 2016. He is currently a full member of the Turkish Academy of Sciences (TÜBA), and he is a member of the council of TÜBA. Professor Salih has supervised 18 PhD and 34 MSc students, and he is an author of over 250 peer-reviewed articles with citations of over 8000, edited two books and is the author of 8 book chapters on mainly mass spectrometry and sample preparation. Research areas of Bekir Salih cover mass spectrometry and atomic spectroscopy, including chromatographic and electrophoretic separation techniques. He was focused on preconcentration techniques, new sol-gel materials for purifications, post-translational modifications, proteomics, metabolomics, ion mobility, noncovalent interactions, and polymer characterization using mass spectrometric techniques. He has also done intensive work on the development of various industrial products. He has several patents on some chemical and biological testing kits.

Assoc. Prof. Mehmet ATAKAY | Hacettepe University | mehmetatakay[at]hacettepe.edu.tr | ORCID: 0000-0002-7102-2974

Mehmet Atakay, PhD is currently an Assoc. Professor in the Physical Chemistry Divison at the Department of Chemistry, Hacettepe University Ankara-TÜRKİYE. He received his PhD from Hacettepe University in 2016. As a scholar, he spent a year between 2013 and 2014 at the University of Akron Department of Chemistry Mass Spectrometry Center as part of his PhD studies. He is a member of the governing board of the Turkish Proteomics Association as of 2023. Mehmet Atakay's research area covers the development of bioanalytical methods using mass spectrometry techniques, including Omics approaches, the characterization of biopharmaceuticals, food and agriculture products, noncovalent interactions, and polymers.

INTERTWINED DEPENDENCE OF PHARMACEUTICAL RESEARCH AND BASIC SCIENCES

İlkay Erdoğan Orhan

10.53478/TUBA.978-625-6110-22-9.ch02

Intertwined Dependence of Pharmaceutical Research and Basic Sciences

İlkay Erdoğan Orhan
Lokman Hekim University

Abstract

Drug discovery and development is a complex and lengthy procedure, which may take at least 10 to 12 years. Besides, it is an extremely expensive process, which may cost up to billions of dollars to discover a new molecular or biological entity. Although pharmaceutical sciences are considered a branch of applied sciences, the procedure consists of pre-clinical and clinical stages from start to marketing, where basic sciences play a critical role, particularly in the pre-clinical stage. In fact, designing a bioactive molecule to become a lead or hit compound as a possible drug candidate, needs an extensive knowledge and background in chemical and biological sciences. Consequently, biological targets such as genes and proteins (enzymes, receptors, structural proteins) are among the most important ones to elucidate and explain the molecular mechanism of pharmacological action of any drug candidate. A comprehensive understanding of diseases threatening human health requires input from basic sciences at the molecular level since pharmaceutical research relies on the data acquired from basic research. Therefore, the role of basic sciences in pharmaceutical research cannot be ignored at all. In this sense, the discovery of antibiotics can be presented as the best and one of the first examples in the 1900s. Since not only pharmacotherapy and pharmacobiotechnology but also other therapeutic applications such as gene therapy are quite intertwined with basic sciences. In this chapter, the essential role of chemical and biological sciences, as well as basic medical sciences, will be highlighted in drug discovery supported by examples.

Keywords
Basic sciences, pharmaceutical sciences, drug research, drug discovery

Introduction

Drug discovery and development is a time-consuming, expensive, multistage, and complex process that involves a wide range of scientific disciplines and technologies. To develop a new drug may take up to 10-15 years (Drews, 2000). The first step in drug discovery is the identification of a potential drug target, which is typically a specific protein, enzyme or other biological molecule that is involved in the development or progression of a disease (Sams-Dodd, 2005; Swinney & Anthony, 2011). Once a target is identified, researchers begin to screen large libraries of chemical compounds to identify molecules that have the potential to bind to and modify the target in a way that will treat or prevent the disease (Overington et al., 2006).

The screening process typically involves a combination of high-throughput screening (HTS) techniques, computer modeling, and other methods to identify molecules that are most likely to be effective and safe (Wu et al., 2023). Once a promising compound is identified, it undergoes further testing and optimization to improve its safety, efficacy, and other properties (Wu et al., 2019).

The next stage of drug discovery involves preclinical testing, which includes testing the safety and efficacy of the drug in animal models (Kaitin, 2010). Preclinical testing helps to identify any potential safety issues and determine the appropriate dosage and administration methods for the drug (Paul et al., 2010). If the preclinical testing is successful, the drug can then proceed to clinical trials, which involve testing the drug in humans to define its safety and efficacy (Moffat et al., 2017). Clinical trials typically involve three phases of testing, with each phase designed to test different aspects of the drug's safety and efficacy (Arrowsmith & Miller, 2013). If a drug successfully completes clinical trials, it can then be submitted to regulatory agencies for official approval. Once approved, the drug can be marketed and made available to patients, who need it. The clinically available drug is also followed after approval as phase 4 monitoring.

Overall, as aforementioned, drug discovery is a complex and challenging process that requires a significant investment of time, resources, and expertise. However, the development of new drugs can have a significant impact on the treatment and prevention of diseases, improving the health and well-being of millions of people around the world. During drug research, basic sciences play a crucial role as they provide a strong foundation for the discovery, development, and testing of new drugs (Bhogal & Balls, 2008; Mohs & Greig, 2017). Here are some of the ways in which basic sciences contribute to drug research:

- Identification of drug targets: Basic sciences help identify and understand the biological processes that are involved in the development and progression of diseases. By studying the underlying mechanisms of diseases, researchers can identify potential targets for drug development.
- Drug design: Basic sciences provide the knowledge and tools necessary to design potential drugs that target specific molecular pathways or biological processes. For example, researchers may use computer modeling and simulation to design drugs that bind to specific enzymes or receptors in the body.
- Preclinical testing: Basic sciences provide the foundation for preclinical testing of drugs, which involves testing the safety and efficacy of new drugs in animal models before they are tested in humans. This testing helps researchers determine the appropriate dosage, safety, and potential side effects of a drug.
- Clinical trials: Basic sciences also play a role in clinical trials, which are the final stage of drug development. Clinical trials involve testing drugs in humans to determine their safety and efficacy. Basic sciences provide the knowledge necessary to design clinical trials, develop appropriate measures of efficacy and safety, and interpret the results.

Results and Discussion

Basic science has a critical function in medicine, as it provides the fundamental knowledge and understanding of how biological systems work at the molecular, cellular, and organismal levels (Mello & Brennan, 2011). Basic scientific research is focused on identifying the underlying mechanisms of diseases, developing new diagnostic tools as well as discovering new treatments and therapies (Patani & LaVoie, 1996). For example, research relevant to basic sciences has been instrumental in the discovery of new drug targets and the development of new drugs and therapies for various diseases.

Scientists use basic science research to understand the molecular pathways involved in diseases and to identify new targets for drug development. By understanding the mechanisms of disease, researchers can develop new drugs and therapies that target specific molecular pathways and help prevent or treat diseases.

- For instance; molecular biology owns a crucial role in drug targeting as it allows researchers to identify specific molecular targets in the body that are involved in disease processes. After identifying these targets by basic science researchers, pharmaceutical researchers can design drug candidates that specifically interact with and modulate the activity of these targets.
- The points associated with molecular biology contributes to drug targeting can be presented as below:
- Identification of drug targets: Molecular biology techniques such as gene expression analysis and protein profiling can help identify specific molecular targets that are involved in disease processes (Gross & Piwnica-Worms, 2006). These targets can then be used to design drugs that specifically interact with and modulate the activity of these targets (Al-Lazikani et al., 2012).
- Understanding drug mechanisms: Molecular biology techniques can also be used to understand how drugs interact with their targets and how this interaction affects cellular and molecular pathways in the body. This understanding is critical for optimizing drug design and developing new drugs with improved efficacy and fewer side effects.
- Personalized medicine: Molecular biology techniques can be used to identify genetic variants that influence drug response in individual patients (Savoia et al., 2017). This information can be used to develop personalized medicine approaches that consider individual genetic differences and tailor drug treatments to individual patients.
- Drug resistance: Drug resistance is a major challenge in the field of medicine, particularly in the treatment of infectious diseases and cancer. Basic sciences play a critical role in understanding the underlying mechanisms of drug resistance and developing strategies to overcome it (Gottesman et al., 2002; Davis & Davis, 2010). Molecular biology techniques can be used to study drug resistance

mechanisms and identify ways to overcome drug resistance. For example, by identifying the specific genetic mutations that lead to drug resistance, researchers can design drugs that are less susceptible to these mutations or develop combination therapies that target multiple pathways to prevent drug resistance.

Overall, molecular biology plays a critical role in drug targeting by providing a deeper understanding of disease mechanisms, identifying specific drug targets, and optimizing drug design and development.

On the other hand, chemistry has been an essential part of in drug discovery process by enabling the design, synthesis, and optimization of molecules with the desired therapeutic properties (Lipinski et al., 2001). The importance of chemistry in drug discovery, including the development of methods to predict drug solubility and permeability, the use of novel chemical reactions for drug design, and the optimization of drug candidates based on their structure-activity relationships is very clear. Chemical sciences possess a vital position in drug development, including the identification of druggable targets, the design and optimization of drug candidates based on their physical and chemical properties, the use of computational methods to predict drug-target interactions, and the targeting of multiple binding sites on proteins for improved efficacy and selectivity. In addition, the findings emphasize the need for interdisciplinary collaboration and integration of multiple disciplines, such as biology, chemistry, and computational sciences, to achieve successful drug development (Lipinski, 2004; Chen & Shoichet, 2009). Thus, pharmaceutical sciences and chemistry are inseparable parts of each other.

Virtual screening is a computational technique used in drug research to identify potential drug candidates from a large database of compounds. It should also be noted that virtual screening has great potential in drug research as well as the challenges and limitations of this approach (Lavecchia, 2013). Virtual screening can be a useful tool in identifying potential drug candidates, particularly in cases, where experimental screening is not feasible or practical (Kitchen et al., 2004; McGaughey et al., 2007). However, the accuracy of virtual screening results depends on the quality of the input data, the choice of screening method, and the selection of appropriate evaluation criteria. In addition, the success of virtual screening in drug discovery often requires a combination of different computational and experimental approaches.

Relevantly, bioinformatics is an essential part of drug discovery from the initial identification of potential drug targets to the optimization of drug candidates (Jorgensen, 2004). Bioinformatics tools can be used to identify for assorted purposes including potential drug targets, predict drug-target interactions, and optimize drug candidates. In addition, bioinformatics methods can be employed to analyze large datasets generated in drug discovery research, such as genomic and proteomic data, to gain insights into disease mechanisms, and to identify potential drug targets (Li et al., 2017). The use of bioinformatics in drug discovery has greatly facilitated the process of drug development and helped to accelerate the discovery of new drugs.

Molecular biology owns a central role in all stages of the drug discovery and development process, from target identification and validation to lead optimization, preclinical testing, and clinical translation (Lazo, 2010; Vamathevan et al., 2019). Molecular biology techniques are used to identify and validate molecular targets implicated in diseases as well as translational biomedicine (Zou et al., 2013). This involves studying the genetic, biochemical, and signaling pathways associated with diseases to identify proteins, nucleic acids, or other molecules that could serve as potential drug targets. Advances in molecular biology continue to drive innovation in drug discovery, leading to the development of novel therapeutics for a wide range of diseases. Molecular biology techniques underpin the development of gene therapies and personalized medicine approaches (Belfield & Delaney, 2015). Molecular biology assays are used in high-throughput screening campaigns to identify potential drug candidates from large compound libraries (Patel, 2013). These assays measure the activity of compounds against specific targets or biological pathways, allowing researchers to identify lead compounds with desired pharmacological properties (Eder & Herrling, 2016). Gene editing technologies such as CRISPR-Cas9 enable precise modification of the genome to correct disease-causing mutations or modulate gene expression, while molecular diagnostics enable the molecular profiling of patients to guide treatment decisions (Robert et al., 2017). It also enables the discovery of biomarkers—molecular signatures associated with disease diagnosis, prognosis, and treatment response. Biomarkers help stratify patient populations, monitor disease progression, and evaluate the efficacy and safety of drug candidates in clinical trials. On the other hand, molecular modeling and computational biology techniques are used in rational drug design to predict the interactions between drugs and their targets at the atomic level (Nero et al., 2018; Brogi, 2019). This approach facilitates the design of novel drug candidates with improved potency, selectivity, and pharmacokinetic properties. These techniques help characterize drug targets at the molecular level, including their structure, function, expression patterns, and subcellular localization. This information is essential for understanding how drugs interact with their targets and for optimizing drug efficacy and selectivity.

Genomic and proteomic approaches enable the comprehensive analysis of genes, proteins, and their interactions in health and disease (Finan et al., 2017; Heilbron et al., 2021). Genome-wide association studies (GWAS) and next-generation sequencing (NGS) technologies identify genetic variations associated with diseases, while proteomics techniques such as mass spectrometry identify and quantify proteins involved in disease pathways (Wu et al., 2019; Andrews et al., 2020).

It should also be mentioned that systems biology is an interdisciplinary field that aims to understand complex biological systems by analyzing their components and interactions at a holistic level. It combines experimental and computational approaches to study how biological molecules and networks function together to regulate cellular processes and maintain homeostasis (Berg, 2014). In the context of drug research, systems biology offers valuable insights into the mechanisms of disease and drug action, facilitating the identification of novel drug targets, optimization of therapeutic strategies, and prediction of drug responses (Butcher et al., 2004). Systems biology approaches enable the comprehensive analysis of molecular pathways and networks underlying diseases, such as cancer, neurodegenerative disorders, and metabolic diseases. By integrating omics data (genomics, transcriptomics, proteomics, and metabolomics) and computational modeling, researchers can identify key molecular drivers of disease progression and potential therapeutic targets (Russell et al., 2013). It facilitates the discovery of novel drug targets by providing insights into the complex interactions between biological molecules and pathways involved in disease pathogenesis. Network-based analyses and computational modeling can prioritize candidate targets based on their centrality, connectivity, and relevance to disease modules (Pujol et al., 2010). Besides, systems biology approaches are valuable for identifying new therapeutic indications for existing drugs through drug repurposing. By analyzing drug-gene interaction networks and molecular signatures associated with different diseases, researchers can uncover unexpected connections between drugs and diseases, leading to the discovery of novel therapeutic uses for approved drugs. Systems biology contributes to the development of personalized medicine approaches by integrating multi-omics data with clinical information to characterize individual variability in drug responses (Azmi, 2014). By identifying biomarkers and molecular signatures associated with drug efficacy and adverse reactions, personalized treatment strategies can be tailored to individual patients, maximizing therapeutic benefits and minimizing side effects. Overall, systems biology plays a pivotal role in drug research by providing a comprehensive understanding of disease mechanisms, facilitating target identification and validation, enabling drug repurposing, supporting personalized medicine approaches, and accelerating the drug development process through predictive modeling and simulation (Pearlstein et al., 2017). By harnessing the power of systems biology, researchers can advance our understanding of complex diseases and develop more effective and personalized therapies.

Conclusion

In summary, basic sciences are essential to drug research, providing the foundation for drug discovery, design, testing, and development. Without a solid understanding of the biological processes involved in diseases and the mechanisms of drug action, it would be difficult to develop safe and effective drugs.

Overall, basic science research is essential for improving our understanding of diseases and for developing new and more effective treatments and diagnostic tools. Without basic science research, many of the advances in pharmaceutical sciences that we have today would not be possible.

References

Andrews, S.J., Fulton-Howard, B., & Goate, A. (2020). Interpretation of risk loci from genome-wide association studies of Alzheimer's disease. *Lancet Neurology*, *19*(4), 326-335. doi: 10.1016/S1474-4422(19)30435-1.

Al-Lazikani, B., Banerji, U., & Workman, P. (2012). Combinatorial drug therapy for cancer in the post-genomic era. *Nature Biotechnology*, *30*(7), 679-692. doi: 10.1038/nbt.2284.

Arrowsmith, J., & Miller, P. (2013). Trial watch: phase II and phase III attrition rates 2011-2012. *Nature Reviews Drug Discovery, 12*(8), 569. doi: 10.1038/nrd4090.

Azmi, A. S. (2014). Systems and network biology in pharmaceutical drug discovery. *Current Pharmaceutical Design, 20*(1), 2-3. doi: 10.2174/138161282001140113122054.

Belfield, G. P., & Delaney, S. J. (2006). The impact of molecular biology on drug discovery. *Biochemical Society Transactions, 34*(Pt 2), 313-316. doi: 10.1042/BST20060313.

Berg, E. L. (2014). Systems biology in drug discovery and development. *Drug Discovery Today, 19*(2), 113-125. doi: 10.1016/j.drudis.2013.10.003.

Bhogal, N., & Balls, M. (2008). Translation of new technologies: from basic research to drug discovery and development. *Current Drug Discovery and Technology, 5(*3), 250-262. doi: 10.2174/157016308785739839.

Brogi, S. (2019). Computational approaches for drug discovery. *Molecules, 24*(17), 3061. doi: 10.3390/molecules24173061.

Butcher, E. C., Berg, E. L., & Kunkel, E. J. (2004). Systems biology in drug discovery. *Nature Biotechnology, 22*(10), 1253-1259.

Chen, Y., & Shoichet, B. K. (2009). Molecular docking and ligand specificity in fragment-based inhibitor discovery. *Nature Chemical Biology, 5*(5), 358-364. doi: 10.1038/nchembio.155.

Collins, F. S., & Varmus, H. (2015). A new initiative on precision medicine. *New England Journal of Medicine, 372*(9), 793-795. doi: 10.1056/NEJMp1500523.

Davies, J., & Davies, D. (2010). Origins and evolution of antibiotic resistance. *Microbiology and Molecular Biology Reviews, 74*(3), 417-433. doi: 10.1128/MMBR.00016-10.

Drews, J. (2000). Drug discovery: a historical perspective. *Science, 287*(5460), 1960-1964. doi: 10.1126/science.287.5460.1960.

Eder, J., & Herrling, P. L. (2016). Trends in modern drug discovery. *Handbook of Experimental Pharmacology*, 232, 3-22. doi: 10.1007/164_2015_20.

Finan, C., Gaulton, A., Kruger, F. A., Lumbers, R. T., Shah, T., Engmann, J., Galver, L., Kelley, R., Karlsson, A., Santos, R., Overington, J. P., Hingorani, A. D., & Casas, J. P. (2017). The druggable genome and support for target identification and validation in drug development. *Science Translational Medicine, 9*(383), eaag1166. doi: 10.1126/scitranslmed.aag1166.

Gottesman, M. M., Fojo, T., & Bates, S. E. (2002). Multidrug resistance in cancer: role of ATP-dependent transporters. *Nature Reviews Cancer, 2*(1), 48-58. doi: 10.1038/nrc706.

Gross, S., & Piwnica-Worms, D. (2006). Molecular imaging strategies for drug discovery and development. *Current Opinion in Chemical Biology, 10*(4), 334-342. doi: 10.1016/j.cbpa.2006.06.028.

Heilbron, K., Mozaffari, S. V., Vacic, V., Yue, P., Wang, W., Shi, J., Jubb, A. M., Pitts, S. J., & Wang, X. (2021). Advancing drug discovery using the power of the human genome. *Journal of Pathology, 254*(4), 418-429. doi: 10.1002/path.5664.

Jorgensen, W. L. (2004). The many roles of computation in drug discovery. *Science, 303*(5665), 1813-1818. doi: 10.1126/science.1096361.

Kaitin, K. I. (2010). Deconstructing the drug development process: the new face of innovation. *Clinical Pharmacology & Therapeutics, 87*(3), 356-361. doi: 10.1038/clpt.2009.293.

Kitchen, D. B., Decornez, H., Furr, J. R., et al. (2004). Docking and scoring in virtual screening for drug discovery: methods and applications. *Nature Reviews Drug Discovery, 3*(11), 935-949. doi: 10.1038/nrd1549.

Lavecchia, A. (2013). Virtual screening strategies in drug discovery: a critical review. *Current Medicinal Chemistry, 20*(23), 2839-2860. doi: 10.2174/09298673113209990001.

Lazo, J. S. (2010). Molecular biology and anticancer drug discovery. *Progress in Molecular Biology and Translational Science,* 95, 9-29.

Li, Z., Han, P., You, Z. H., Li, X., Zhang, Y., Yu, H., Nie, R., & Chen, X. (2017). In silico prediction of drug-target interaction networks based on drug chemical structure and protein sequences. *Scientific Reports, 7*(1), 11174. doi: 10.1038/s41598-017-10724-0.

Lipinski, C. A. (2004). Lead- and drug-like compounds: the rule-of-five revolution. *Drug Discovery Today and Technology, 1*(4), 337-341. doi: 10.1016/j.ddtec.2004.11.007.

Lipinski, C. A., Lombardo, F., Dominy, B. W., Feeney, P. J. (2001). Experimental and computational approaches to estimate solubility and permeability in drug discovery and development settings. *Advance Drug Delivery Reviews, 46*(1-3), 3-26. doi: 10.1016/s0169-409x(00)00129-0.

McGaughey, G. B., Sheridan, R. P., Bayly, C. I., Culberson, J. C., Kreatsoulas, C., Lindsley, S., Maiorov, V., Truchon, J. F., & Cornell, W. D. (2007). Comparison of topological, shape, and docking methods in virtual screening. *Journal of Chemical Information and Modeling, 47*(4), 1504-1519. doi: 10.1021/ci700052x.

Moffat, J. G., Vincent, F., Lee, J. A., Eder, J., & Prunotto, M. (2017). Opportunities and challenges in phenotypic drug discovery: an industry perspective. *Nature Reviews: Drug Discovery, 16*(8), 531-543. doi: 10.1038/nrd.2017.111.

Mohs, R. C., Greig, N. H. (2017). Drug discovery and development: role of basic biological research. *Alzheimers Dementia (N Y), 3*(4), 651-657. doi: 10.1016/j.trci.2017.10.005.

Nero, T. L., Parker, M. W., & Morton, C. J. (2018). Protein structure and computational drug discovery. *Biochemical Society Transactions, 46*(5), 1367-1379. doi: 10.1042/BST20180202.

Overington, J. P., Al-Lazikani, B., & Hopkins, A. L. (2006). How many drug targets are there? *Nature Reviews Drug Discovery, 5*(12), 993-996. doi: 10.1038/nrd2199.

Patani, G. A., & LaVoie, E. J. (1996). Bioisosterism: a rational approach in drug design. *Chemical Reviews, 96*(8), 3147-3176. doi: 10.1021/cr950066q.

Patel, A. C. (2013). Clinical relevance of target identity and biology: implications for drug discovery and development. *Journal of Biomolecular Screening, 18*(10), 1164-85. doi: 10.1177/1087057113505906.

Paul, S. M., Mytelka, D. S., Dunwiddie, C. T., Persinger, C. C., Munos, B. H., Lindborg, S. R., & Schacht, A. L. (2010). How to improve R&D productivity: the pharmaceutical industry's grand challenge. *Nature Reviews Drug Discovery, 9*(3), 203-214. doi: 10.1038/nrd3078. doi: 10.1038/nrd3078.

Pearlstein, R. A., McKay, D. J. J., Hornak, V., Dickson, C., Golosov, A., Harrison, T., Velez-Vega, C., & Duca, J. (2017). Building new bridges between in vitro and in vivo in early drug discovery: where molecular modeling meets systems biology. *Current Topics in Medicinal Chemistry, 17*(23), 2642-2662. doi: 10.2174/1568026617666170414152311.

Pujol, A., Mosca, R., Farrés, J., & Aloy, P. (2010). Unveiling the role of network and systems biology in drug discovery. *Trends in Pharmacological Sciences, 31*(3), 115-123. doi: 10.1016/j.tips.2009.11.006.

Robert, F., Huang, S., & Pelletier, J. (2017). CRISPR/Cas9 editing to facilitate and expand drug discovery. *Current Gene Therapy, 17*(4), 275-285. doi: 10.2174/1566523217666171121164615.

Russell, C., Rahman, A., & Mohammed, A. R. (2013). Application of genomics, proteomics and metabolomics in drug discovery, development and clinic. *Therapeutic Delivery, 4*(3), 395-413. doi: 10.4155/tde.13.4.

Sams-Dodd, F. (2005). Target-based drug discovery: is something wrong? *Drug Discovery Today, 10*(2), 139-147. doi: 10.1016/S1359-6446(04)03316-1.

Savoia, C., Volpe, M., Grassi, G., Borghi, C., Agabiti Rosei, E., & Touyz, R. M. (2017). Personalized medicine-a modern approach for the diagnosis and management of hypertension. *Clinical Sciences (London), 131*(22), 2671-2685. doi: 10.1042/CS20160407.

Swinney, D. C., & Anthony, J. (2011). How were new medicines discovered? *Nature Reviews Drug Discovery, 10*(7), 507-519. doi: 10.1038/nrd3480.

Vamathevan, J., Clark, D., Czodrowski, P., Dunham, I., Ferran, E., Lee, G., Li, B., Madabhushi, A., Shah, P., Spitzer, M., & Zhao, S. (2019). Applications of machine learning in drug discovery and development. *Nature Reviews Drug Discovery, 18*(6), 463-477. doi: 10.1038/s41573-019-0024-5.

Wu, Y., Byrne, E. M., Zheng, Z., Kemper, K. E., Yengo, L., Mallett, A. J., Yang, J., Visscher, P. M., & Wray N. R. (2019). Genome-wide association study of medication-use and associated disease in the UK Biobank. *Nature Communications, 10*(1), 1891. doi: 10.1038/s41467-019-09572-5.

Wu, K., Karapetyan, E., Schloss, J., Vadgama, J., & Wu, Y. (2023). Advancements in small molecule drug design: a structural perspective. *Drug Discovery Today, 28*(10), 103730. doi: 10.1016/j.drudis.2023.103730.

Zou, J., Zheng, M. W., Li, G., & Su, Z. G. (2013). Advanced systems biology methods in drug discovery and translational biomedicine. *Biomed Research International,* 2013, 742835. doi: 10.1155/2013/742835.

About Author

Prof. İlkay ERDOĞAN ORHAN | Lokman Hekim University | ilkayerdoganorhan[at]gmail.com | ORCID: 0000-0002-7379-5436

Prof. Dr. Ilkay Erdogan Orhan holds a Pharmacist degree (1993) from Gazi University (Ankara, Türkiye), 1st M.Sc. degree from the Department of Pharmacognosy at the same Faculty (1996) with a scholarship provided by the Scientific and Technological Research Council of Türkiye (TUBITAK). She was awarded her second M.Sc. degree in marine natural product chemistry (1998) at the University of the Ryukyus in Japan with a Monbusho scholarship. She earned a Ph.D. in Pharmacognosy at Gazi University (2002). She was a post-doc at the Department of Chemistry at the University of Winnipeg (Canada) in 2003 *via* the NATO-TUBITAK fellowship program. She was promoted to Assoc. Prof. position in 2004 and became a full professor in 2009. Dr. Orhan was appointed as Dean of the Faculty of Pharmacy at Eastern Mediterranean University in Northern Cyprus (2011-2014) and the Faculty of Pharmacy at Gazi University (2016-2024). She is vice president of the International Scientific Board of the Austrian Drug Screening Institute (ADSI), the principal member of the Turkish Academy of Sciences (TÜBA), and the Islamic World Academy of Science. Dr. Orhan was granted a number of science and patent awards, including the Science Award in 2024, presented by The World Academy of Sciences (TWAS). She published over 300 scientific papers in SCI-E journals and owned 4 patents. Her h index is 56 (WoS) and 61 (SCOPUS) with over 14500 citations. Currently, Prof. Orhan is Dean of the Faculty of Pharmacy at Lokman Hekim University.

SUSTAINABILITY AND SUSTAINABLE WATER MANAGEMENT

Mehmet Emin Aydın

Senar Aydın

10.53478/TUBA.978-625-6110-22-9.ch03

Sustainability and Sustainable Water Management

Mehmet Emin Aydın
Necmettin Erbakan University

Senar Aydın
Necmettin Erbakan University

Abstract

In this study, sustainability and sustainable development concepts are briefly introduced. After giving some information on sustainable water management concept relating to sustainable development, information about important issues of water management such as hydrological cycle, human intervention on hydrological cycle, water treatment, wastewater collection and treatment are given. Virtual water and water foot print concept is important about indirect use, import or export of water. If in water scarce locations main income depends on export of high water demanding agricultural or industrial products, it will make water shortages even more pronounced and that is not sustainable in terms of water management as well as in terms of development. Therefore integrated water and wastewater management, demand side management approach should be adopted. Water resources protection and investment on water resources structures are important for clean and good quality water supply instead of only investing water treatment plants and processes. Waste water collection and treatment parts are also important; however before treatment water should be used multiple times for varying purposes. In this work it is also emphasized that investigations about wastewater treatment methods, water, materials and energy recoveries should be carried out in order to improve physical, chemical and biological processes involved.

Keywords
Sustainability, water management, hydrological cycle, water treatment, basic sciences

Introduction

The terms “sustainability” and “sustainable development” are widely used. Sustainability means development in a way that humanity can continue to exist within the boundaries of the earth, the only livable planet. Sustainable development is the process of achieving development within ecological boundaries. There are many different definitions of sustainable development. Sustainability can simply be defined as meeting today's needs without reducing the ability to meet the needs of future generations.

Solow (1991) defined sustainability as while meeting our own needs, it is our duty to ensure that the options or capacities of future generations to meet their needs are as good as our own, or not to weaken them. This definition brings moral responsibility for all of us to use the Earth's resources wisely and fairly. New definitions are being made regarding the concept of sustainability as the relationships between economic development and the environment are understood. Therefore, the need to define sustainability becomes important as environmental crises increase (Gray, 2015).

Sustainable development is about preventing the problems that arise, including climate change and accompanying problems, affecting the environment, humanity and ecosystem, water quality, nutritional quality, and chemical and microorganism pollution. Sustainability should take into account issues such as increasing water scarcity, problems with food production, protection of plant and animal biodiversity and habitat diversity. While economic growth increases the rate of production and consumption of goods and services, it leads to increased use of resources and an increase in the production of waste and a wide variety of pollutants. Therefore, if economic growth mechanisms are not changed, the physical, chemical and biological properties of the environment will deteriorate as a result of excessive consumption of natural resources, exceeding the ability of natural systems to assimilate waste.

Sustainability has ecological, economic and social dimensions that are interrelated with each other. All three dimensions need to be addressed to find sustainable solutions. Environmental Sustainability, which focuses on the continuity and protection of natural resources, ecological resources that is often referred to as ecosystem services. Economic Sustainability focuses on the natural resources that provide physical input to the production process of goods and services. Social Sustainability, which addresses poverty and human development, is social sustainability that ensures the continuity of ecological systems, social, cultural needs and welfare.

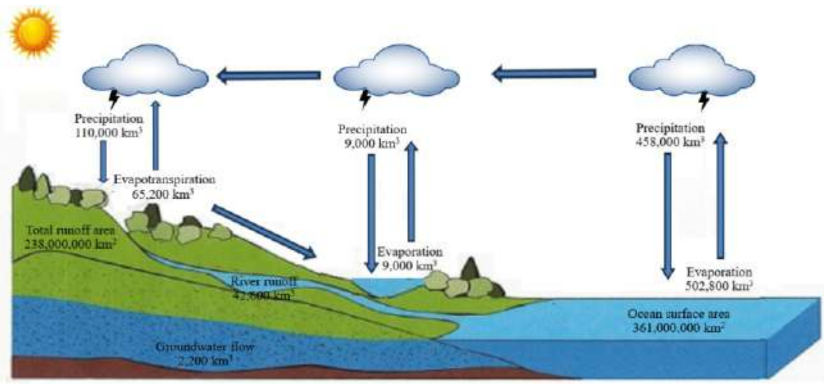
Socio-economic interactions should be fair, economy-environment relations should be livable, and environment-social relations should be acceptable. Sustainability is considered a balance in which ecological, economic and social dimensions are of equal importance. However, in practice, the economic dimension dominates through continuous growth, while environmental resources are rapidly being depleted. Since the environment and its resources cannot be expanded, society must develop within the environmental boundaries and the economy must meet the needs of society within these limits. Therefore, for a sustainable society, the environmental dimension should be more important and protected. When the economy-ecology-social balance is considered today, it is seen that the economy and social demands exceed the ecological capacity of the Earth. Therefore, it must be accepted by society that the economy must remain within the limits set by society to reflect values such as justice. This situation requires the most economical use of available water in water supply and prevention of overuse, known as demand side management, instead of supply side management, where the increase in water demand must be met with a limited volume of usable water. Increasing needs must be met by protecting and better managing water resources rather than using them more.

Sustainability is generally viewed as fundamental to all future development goals, thus seeking to ensure equal development opportunities for future generations. Sustainability underpins the UN 2030 Agenda for Sustainable Development, which sets out 17 Sustainable Development Goals (SDGs). Adopted by all UN Member States in 2015, the SDGs are a global plan for a sustainable planet where all people can live in peace and prosperity. Goal 6 of the Sustainable Development is about ensuring the availability and sustainable management of water and sanitation for all (UN, 2015; 2021). The three headings of Goal 6 are access to water supply and sanitation, sustainable use and development of water resources, and improved water quality and wastewater management. An EU Sustainable Development Strategy including the Sustainable Development Goals (EC, 2021) was adopted in 2021. Sustainable development requires finding appropriate solutions using a range of existing and emerging sustainable technologies that may vary according to local conditions and culture. These technologies must be both reliable and effective and of minimal cost, as long as they do not harm the quantity or quality of resources, including biodiversity (van der Vleuten-Balkema, 2003).

Sustainable Water Management

Water is in constant motion due to solar energy and gravity. The sun causes water to evaporate from oceans, lakes, streams, lands and plants. The evaporated water forms clouds, which move in the atmosphere and form precipitation. About 80 percent of precipitation returns to the oceans, while the rest falls on land. This cycle is called the hydrological cycle that renews soil moisture and groundwater, feeds rivers and lakes, and provides the water needed by plants, animals and humans on land and in fresh water (Figure 1).

Figure 1.
Hydrological cycle



While the total volume of water on Earth remains constant, its quality and availability at any given location constantly changes. 97.5% of the huge amount of water on the planet is found in the oceans as salt water (Table 1). This means that only 2.5% of the available water is fresh water and 75% is stored in glaciers (Figure 2). The volume of glaciers is decreasing due to climate change. The other 24% is stored in aquifers as groundwater. It can be said that less than 1% of the total fresh water on the planet is found in surface waters such as rivers and lakes and in soil. Thus, with 0.01% of the world's water budget available in surface water and another 0.01% as soil moisture, there is a very limited amount of freshwater available for use by an ever-increasing human population. The availability and distribution of water depends on many factors, such as seasons and quality, and is not uniform. Water is absent or limited in many parts of the planet, where the population and therefore the demand is highest, water resources are often insufficient.

Table 1.

Water sources on the earth (Shiklomanov, 1993)

Water sources	Volume of water (10^6 km^3)	Percent of total water
Oceans, seas, bays	1338	96.54
Ice caps, glaciers, permanent snow	24.0	1.732
Groundwater	23.4	1.69
Lakes	0.176	0.013
Streams and rivers	0.002	0.0001
Soil moisture	0.016	0.0012
Atmosphere	0.012	0.0008
Biological water	0.001	0.0001
Swamp water	0.011	0.0008
Ground ice, permafrost	0.3	0.022

The hydrological cycle is continuous, therefore it makes water a renewable resource. Essentially, the more it rains, the greater the flow in rivers and the higher the water table rises as aquifers fill with water that percolates down through the soil and seeps into the permeable rocks below. Since water resources ultimately depend on rain, when the amount of rain decreases, the amount of water also decreases, and serious droughts occur. Therefore, resources need to be carefully managed to provide adequate amounts of water all year round. When precipitation falls in a basin, the path followed by water can be evaluated in three parts:

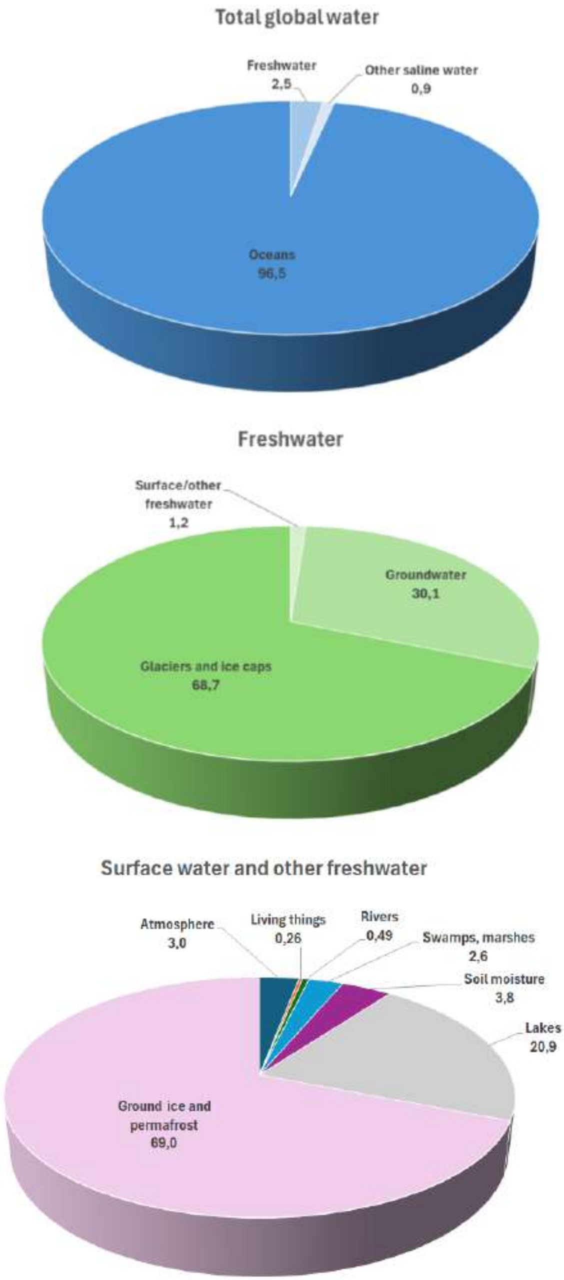
1- It can remain on the ground as surface moisture and eventually return to the atmosphere through evaporation. If precipitation is in the form of snow, it can be stored as snow on the surface until it melts. Snow is an important source of drinking water in some areas.

2- Precipitation flows from the surface and reaches streams and lakes. Ultimately the water returns to the sea as surface flow from rivers.

3- Precipitation infiltrates and percolates into the soil and forms groundwater, which is stored in porous media and rocks. Groundwater can persist in these porous environments for periods ranging from a few days in Karst systems to possibly thousands of years in deep confined aquifers. Eventually groundwater continues to flow through a number of natural and artificial means. These include natural capillary flow towards the soil surface, plant uptake, groundwater flowing into surface rivers and lakes or directly to the sea, or pumping out from wells.

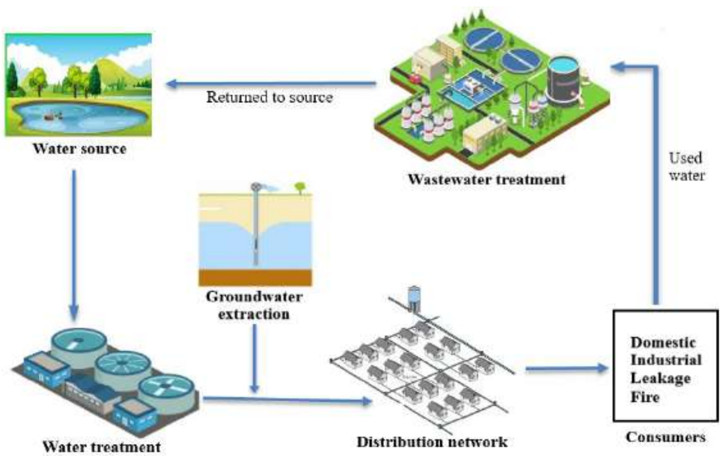
Water in oceans, glaciers and groundwater is very old and is a depository for both minerals and pollutants. All pollutants discharged as gases, liquids or solids eventually enter the hydrological cycle and reach groundwater or the seas. As rain falls from the atmosphere to the ground, it dissolves gases such as CO_2, NOx and SOx and becomes slightly acidic. In some areas, precipitation can be quite acidic. As water flows across and through the Earth's surface through the hydrological cycle, it constantly dissolves minerals and other substances. The substances dissolved from the soil and main rock create the properties of water. Therefore, the quality of water has natural variability, largely depending on its source. Surface waters such as rivers and lakes are often vulnerable to pollution caused by anthropogenic inorganic and organic pollutants such as nutrients, metals, pesticides, pharmaceuticals and endocrine disrupting compounds, which have a negative impact on water quality.

Figure 2.
Water distribution on Earth (Shiklomanov, 1993)



Water management is important in order to provide sufficient water for industry, agriculture and domestic use. Management of surface water and groundwater resources requires the supply, treatment, distribution of water and the collection of wastewater, treatment and recycling of wastewater (Figure 3). Water is taken from the hydrological cycle, used and returned to the hydrological cycle after being treated. The quality of the returned water should be close to the level of the abstracted water. The hydrological cycle is increasingly affected by climate change as rising temperatures increase evaporation. Climate change causes some areas to become wetter and some areas to become drier, increasing the incidence of drought. In higher latitudes, changes in snowfall patterns lead to spring flooding; Sea levels are rising as the proportion of water stored as snow and ice in the cycle begins to decrease.

Figure 3.
Human intervention in the water cycle



Global water problems

The world is experiencing the worst water problems ever seen. More than two billion people worldwide are constantly exposed to severe water stress (UN, 2018) and four billion people suffer from severe water scarcity for at least one month per year (Mekonnen & Hoekstra, 2016). In particular, it is estimated that by 2030, 700 million people worldwide will migrate from arid and semi-arid regions due to intense water scarcity (FAO, 2020). 2.4 billion people are exposed to epidemic diseases due to inadequate water supply and sanitation. Two million children die every year from preventable waterborne diseases. It is predicted that by 2040, one in four children under the age of 18 in the world will live in areas with extremely high water stress (Gray, 2022).

Globally, almost half of the population currently lives in areas with potential water scarcity for at least one month per year. By 2050, this figure is predicted to increase to approximately 4.8 to 5.7 billion. Water stress is an indicator used to measure progress in achieving Goal 6 of the Sustainable Development Goals.

Over abstraction and pollution of water resources affect not only humans but also aquatic species that depend on. In addition to the increasing demands on water resources due to the increasing population, a significant stress occurs in aquatic ecosystems due to changing precipitation patterns, increasing wastewater discharges, and temperature increases due to the effect of climate change. It is not just surface water at risk, it is estimated that one-third of the world's largest groundwater systems are at risk of critical overexploitation (Richey et al., 2015).

Water footprints

Water footprint is used to calculate the total amount of water consumed by a person, a business or a country and is the total volume of water used directly and indirectly. Direct water use at the business level is total water use, which can be easily measured with a water meter. Measuring indirect water use is rather complex and life cycle analysis needed for estimates. Indirect water is often called as the virtual water content of a product, i.e. m^3 of water per unit of a product produced, and also divided into Internal, water used for products produced within the country, and external, water used for the production of exported products (Table 2). It is not sustainable big amount export of virtual water from water scarce regions because it will make water scarcity much worse in that region. Virtual water import and export values of Mediterranean Sea Countries are given in Table 3 and Figure 4.

Table 2.

Six largest agricultural virtual water importers and exporters (Gm^3/yr) (Gray, 2022).

Net virtual importers of water				**Net virtual exporter of water**			
Country	Export	Import	Net import	Country	Export	Import	Net export
Brazil	91	199	108	US	298	137	161
Mexico	19	103	84	Australia	71	10	61
Japan	4	86	82	Argentina	58	4	54
China	55	133	78	Canada	70	27	43
Italy	38	88	50	Thailand	52	9	43
UK	15	55	40	India	66	24	42

Water use, like carbon emissions, is linked to consumption and consumer preferences, as large amounts of water are used in the production of goods and the provision of services (Gray, 2015). The water amount used in the production of unit volumes or weights of some household goods is given in Table 4. The water footprint can be examined in more detail in terms of the source and volume of water contaminated during production. There are three categories:

Blue water: The amount of used surface or ground water.

Green water: The amount of used rainwater.

Gray water: The amount of polluted freshwater.

Table 3.

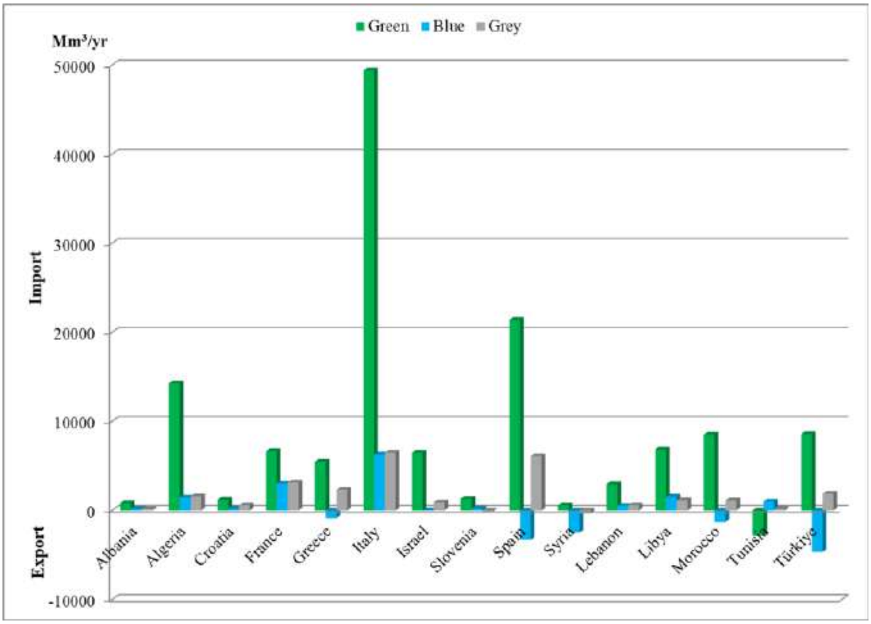
The virtual water import and export values of Mediterranean Sea Countries (Mm^3/yr) (Mekonnen and Hoekstra, 2011)

Country	Import			Export			Net virtual water import		
	Green	Blue	Grey	Green	Blue	Grey	Green	Blue	Grey
Albania	1148.4	217.4	199.6	313.3	42.7	44.8	835.1	174.7	154.8
Algeria	14505.8	1551.2	1979.0	235.9	92.7	396.4	14269.8	1458.5	1582.6
Croatia	2411.1	389.0	896.4	1207.5	189.5	326.1	1203.6	199.5	570.3
France	52707.1	10467.7	15133.5	46049.2	7438.4	11998.6	6658.0	3029.4	3134.9
Greece	9007.6	1960.6	2791.7	3549.0	2830.8	477.7	5458.7	-870.2	2314.0
Italy	72465.9	13383.5	15567.0	23077.6	7105.2	9077.1	49388.4	6278.3	6490.0
Israel	7107.3	820.6	1712.4	618.5	808.9	801.1	6488.7	11.7	911.3
Slovenia	1922.4	428.8	768.3	613.7	226.7	864.2	1308.7	202.1	-95.8
Spain	40910.0	5753.7	9582.9	19523.9	9048.8	3471.1	21386.1	-3295.1	6111.8
Syria	3240.0	802.4	542.6	2664.8	3297.0	890.1	575.2	-2494.5	-347.5
Lebanon	3367.7	647.8	626.2	401.8	130.8	52.0	2965.9	517.0	574.3
Libya	6890.7	1597.6	1285.4	44.2	44.5	125.6	6846.5	1553.1	1159.8
Morocco	10082.9	1165.9	1394.3	1569.8	2647.3	269.5	8513.1	-1301.4	1124.8
Tunisia	5754.4	1450.8	893.4	8584.4	455.4	725.1	-2829.9	995.5	168.2
Türkiye	17511.2	6718.7	5229.0	8934.0	11376.8	3362.2	8577.2	-4658.1	1866.8

Spain, Syria, Morocco and Türkiye are net virtual blue water exporting countries (Figure 4). Water scarcity is already an important issue in Mediterranean Countries. Climate change estimates unanimously suggest that the water scarcity problem will be increased in Mediterranean basin. It could also be suggested that exporting virtual blue water will further increase already existing water scarcity problem.

Figure 4.

Net virtual water import export situation of Mediterranean Sea Countries



The agricultural water use accounts for approximately 92% of annual global freshwater consumption. Because crops need water, water footprints are increasingly used to compare and optimize production methods. The best-case scenario is when crops are grown using only rainwater, although growing a lot of crops, including vegetables, requires ground or surface water (blue water) for irrigation. The most sustainable situation is the practices that use the most rainwater (green water) and cause the least pollution (grey water).

Table 4.

The water amount needed in the production of common household goods per unit volume or weight (Gray, 2022).

	Used water (L)
(Per liter)	
Water	1
Bottled water	4
Milk	1000
(Per cups or glass)	
Tea	120
Orange juice	850
Coffee	1120
(Meat per kg)	
Lamb	6100
Beef	15000-70000
Eggs	3300
(Main foodstuffs per kg)	
Bread	1300
Rice	3400
Tea	9200
Roasted coffee	21000
House items (each)	
Pair jeans	10850
Cotton shirt	4500
Cotton sheet (1 kg)	11000
Disposable nappy	810
The average car	400000

Sustainability in Wastewater Treatment

Wastewater management includes wastewater generation, sewage systems that collect wastewater, and facilities where wastewater treatment is carried out. Wastewater treatment should include the recovery and reuse of byproducts, including water, nutrients (nitrogen and phosphorus), and sludge. Sustainability in wastewater treatment depends on the location, size of the facilities, amounts of pollutants, wastewater characteristics, amount of investment, easy accessibility of technology and expertise, and sensitivity of the receiving environments. Sustainable wastewater treatment systems are particularly well-suited for small and medium-sized facilities in hot regions.

The goals of sustainable wastewater treatment can be multiple, for example minimizing costs, energy use, greenhouse gas (GHG) emissions, land area required, nutrient loss and waste production, while increasing the amount of material recovered, such as water, biogas, biomass, fertilizers, compost etc. (Balkema et al., 2002). Within these goals, the selection of treatment technologies may not always be easy under certain cultural and climatic conditions. In order to overcome the problems related to the design and operation of wastewater treatment, it is necessary to select the most suitable technologies and management systems at the planning stage and operate them in accordance with the planning, and to make sustainability-related assessments to eliminate the problems. Sustainability assessments are provided by sustainability-related indicators that measure parameters that affect the operation and effectiveness of the wastewater treatment plant.

In the past, economic indicators have been the determining criteria in the selection of treatment technologies. These normally consist of investment costs consisting of land and construction costs, and operation and maintenance costs. An important factor that should not be overlooked is the lifespan of the infrastructure. Environmental indicators are evaluated in terms of wastewater quality, energy and other inputs used, and the overall impact on the environment and public health. Wastewater quality is measured in terms of removal rates of organic substances, suspended solids, nutrients, metals and other pollutants, and must be linked to environmental quality objectives, taking into account the impact on receiving waters that have limited assimilation capacity for some components of wastewater. Energy consumption is often used as a measure of carbon footprint, which depends on the electricity generation mix supplied to the facility. However, due to the potential for the release of other greenhouse gases, the total greenhouse gas emission value in terms of carbon dioxide equivalent must be calculated for the facility. Recovery and reuse of components in wastewater is an important indicator of sustainability. This enables the reuse of both water and solids in wastewater, namely biosolids or sludge content. Biosolids production is also an important indicator that determines reuse value, both positive and negative environmental impacts, in terms of volume and contaminant levels. The land requirement depends on the hydraulic loading and the technology chosen. In high-income countries, intensive high-energy systems are extremely efficient in terms of both organic and hydraulic loading, making the treatment plants very compact. In contrast, low-energy types of systems, especially in middle- to low-income countries, require large areas of land, making direct comparisons difficult, especially with respect to the price of land. The reliability of treatment systems is related to the robustness of the technology and the complexity of its operation and maintenance. System failures are included in the environmental dimension, as they often result in pollution due to inadequate treatment of discharges. Social indicators indicate wastewater treatment, biosolids disposal, and public acceptance of the physical facility. Social indicators should be considered at the social acceptance in planning stage, including post-construction indicators such as visual impact, odor and noise, among other dimensions. Smaller treatment plants and those using natural treatment systems, particularly in low- and middle-income countries, are taking a broader approach that includes local involvement with an emphasis on public health and reuse.

The main objectives of all sustainability efforts, including water management, of which wastewater treatment is an important component, are: (i) gradual reduction of waste and pollution through innovative design, (ii) continuous recovery and recycling of products and materials, limited and scarce use of resources and (iii) improving the interface between an activity and nature, preserving and regenerating ecosystems and processes.

It is divided into three basic processes (optimization, reuse, and renewal) to optimize water quality and volume within the hydrological cycle. Optimization refers to the need to maintain adequate volumes of flow in rivers and aquifers to protect and enhance water resources and ecosystems, including biodiversity. Within the hydrological cycle, water changes its chemical composition as it passes over and through soil and permeable rocks and interacts with both flora and fauna.

As it passes through soil or flows downstream in rivers, it undergoes a process of self-purification by microorganisms and plants. In order for water to be renewed by completing the natural cycle, evaporation, infiltration or flow into streams, rivers and ultimately the seas must be as clean as possible.

The most important problems affecting natural waters globally include excessive water withdrawal, especially for agricultural irrigation, and discharge of wastewater and pollutants. Excessive water extraction and discharge of pollutants damage rivers, lakes and groundwater, making their management unsustainable. The main mechanisms are based on demand-side management techniques, such as preventing excess water use through better production planning and reducing water use through improvement in efficiency, savings and management. There is huge potential for reusing water both in industry and in houses. This potential creates closed loops where water is used multiple times during production and can be reused before being treated on site. Finally, the water can be restored to its former quality and used to replenish the watershed.

For the water industry, this means viewing wastewater as a resource rather than waste, while also tackling key global challenges such as energy use, water scarcity, and nutrient release into receiving waters. With the need to overcome these problems, the industry has been undergoing major changes in recent years, particularly through the use of various management and technological solutions, largely in response to stricter environmental legislation. Water demand management practices such as education, reducing losses and leakages, using conservation measures such as measurement, using efficient water use tools such as low-volume toilet flushes, low-water-using household appliances, and water efficiency labeling in some regions ensure the effective use of water. Prevention of discharge of pollutants to wastewater collection facilities, removal of biological nutrients, better operational management and control, for example, especially the need for ventilation and prevention of NOx and CH_4 formation, advanced anaerobic treatment (AAD) using pre-treatment steps such as thermal and enzymatic hydrolysis, increase the reliability of biogas production and It enables the control of pollutants. Therefore, many of the tools needed to achieve circularity in the waste industry largely already exist. The development of long-term, viable and coherent policy and a strong regulatory environment is necessary. The International Water Association (IWA, 2016) proposes a circular economy related to the water sector, evolving the concept of wastewater treatment plants from simple purification systems to fully integrated resource recovery facilities by separating the flow of water, materials and energy into three integrated pathways. Energy and a wide variety of chemicals are used in water treatment, and chemical and energy needs can be reduced by investing in the natural infrastructure in water resources. The cleaner the water taken from the source, the fewer treatment steps are required, thus reducing both investment and operating costs.

Investing in natural infrastructure as well as water treatment facilities is important because this improves aquatic ecosystems and also protects biodiversity.

Traditionally, rainwater has been widely used for seasonal irrigation of gardens. Rainwater from domestic and commercial roofs in urban areas can be used through harvesting and storage, in addition to landscape irrigation, for some household functions such as toilet flushing, and for laundry with varying levels of on-site treatment. In this way, the capacity of rainwater collection and removal facilities in urban areas is not exceeded.

Key outcomes have been investigated in an EU project called Smart-Plant (2021). In this project, the main outputs are listed and the efficient use of resources is emphasized to ensure that less raw materials and energy are used in water and wastewater treatment, and thus minimize material losses, as well as in saving water for a sustainable management. It can be reduced by eliminating or minimizing pollutants at the source of production, replacing pollutants with more sustainable products, and encouraging minimizing waste flows directly from homes, businesses and industry through better management.

The water industry uses huge amounts of energy, and one of the key factors in achieving sustainability and "net zero" emissions is to reduce this dependence by increasing the use of renewable energy, seeking low-energy alternatives to reduce fossil fuel consumption. The largest use of energy in houses after space heating, is for laundry, food preparation, and heating water for beverages. The use of low-water appliances, such as washing machines and dishwashers, and water-saving measures at home, such as water-saving showers and taps, can be encouraged, which forms the basis of water efficiency labeling. There are many opportunities to save energy as well as produce energy within the energy route. Where pressures and flows are high in water distribution networks, microturbines can be installed to generate electricity. Heat recovery is possible in the sewer system, for example from laundry and other hot wastewater streams. Wastewater can be up to ten degrees warmer than ambient temperature in winter. The high carbon content allows Biosolids to be used as an ideal fuel after processing. These processes include biogas production, gasification, pyrolysis, or simple biomass combustion after dewatering and drying. The remaining solids and ash are rich in nutrients and trace elements and can be used as fertilizer or further processed to recover certain materials such as metals. Water and wastewater treatment plants are often located in large areas, such as water resources. In recent years, these sites have been increasingly used for renewable energy production using wind turbines or solar panels. By combining biogas production with renewable energy production, wastewater treatment plants can be turned into green power plants that become self-sufficient in energy use and even produce more electricity than they need.

Emerging Technologies

Emerging technologies in wastewater treatment are almost exclusively associated with the enhancement of traditional biological and/or physicochemical processes (USEPA, 2013), but algal technologies have become widely accepted as low-cost, sustainable, and effective alternatives for the treatment of emerging contaminants (Shah et al., 2020). Natural treatment systems have not been fully exploited or sufficient research and investment has not been made. However, it is still a sustainable "net zero" wastewater treatment alternative. An important element of the circular economy is the recovery and reuse of wastewater components. Current processes used and developed also include energy recovery: Biogas as biofuel, on-site wind and solar power generation, combustion of biosolids, heat pumps, microalgae, wastewater hydroelectric power and bioelectric systems. Nutrient reuse: Application of biosolids to agricultural lands, use of wastewater in irrigation of agricultural and landscape areas, struvite production. Water reuse includes options such as use as irrigation water, indirect potable water reuse, industrial reuse and domestic reuse, direct potable water reuse.

Fertilizers are largely produced by the chemical fixation from atmospheric nitrogen to ammonia. This extra nitrogen, in the form of ammonia or oxidized nitrogen, enters the hydrological cycle due to overuse in agricultural areas and triggers eutrophication. Discharges from wastewater treatment plants play an important role in transporting nitrogen to surface waters. Initially, to prevent toxicity to fish, it was thought sufficient to oxidize the ammonia and convert it to nitrate, which could be safely discharged into surface waters with sufficient dilution. However, as the population increased, the need to remove nitrate and phosphorus became imperative to prevent eutrophication, often resulting in solutions with high energy needs.

Basic Sciences and Water Management

Chemical Experiments allow us to understand how our environment works and how to identify potential problems to the environment and human health. The scientific community has attempted to define and identify environmental problems for long time since environmental awareness. Processes in the Biosphere is like a reactor, which can be assumed as a closed system in which reactions take place, atoms and molecules are not created or destroyed.

Atoms and molecules are always present in our environment, combining into various compounds, existing in different physical states, being transported or accumulated in organisms. Air and water are used as moving and stabilizing medium for Biotic and abiotic chemical transformations in nature. All chemical reactions that occur in the environment and related to the natural cycles and transformation of elements on Earth are defined in Chemistry. The transformations or chemical interactions and processes of substances, natural compounds or living organisms released into the environment as a result of human activities are also considered within environmental chemistry and ecology. In the natural cycles of elements and molecules, biochemical and chemical transformations have been recycling substances and enabling ecosystems and organisms to coexist for thousands of years.

With rapid population growth, ever-changing and expanding demands for activities, products and services, humankind has increased the use of raw materials and thus environmental pollution. A lot of the contaminants are natural compounds but at higher concentrations. Therefore, the natural chemical cycles have been altered by releasing into environmental mediums large amounts of compounds that cannot be assimilated, transported, or transformed at the same rate as before human influence. This has led to adverse effects on the environment and health due to high concentrations of natural compounds and elements in a particular environmental medium, region or organism. High concentrations may exceed the toxicity levels of organisms or cause overgrowth of one organism relative to others. This changes reproductive rates, food chains, energy and mass balances in ecosystems. In addition to natural elements and molecules, man-made synthetic compounds have been produced that are beneficial to humanity and they are usually not natural substances. Pesticides are intentionally released into the environment while others have been discharged into the environment accidentally or as waste, partly due to a lack of awareness of their potential detrimental environmental impacts in the long or even short term. Pollutants released into the environment can undergo abiotic or biotic transformations and turn into harmless compounds that do not pose a health hazard. However, most xenobiotic compounds are toxic and can undergo partial transformations into even more toxic derivatives. Parent compounds or their derivatives are transported in the biosphere and then partially degraded in the environment by waste decomposition reactions. It is important to understand the chemistry of abiotic and metabolic processes and the biochemistry mechanisms of xenobiotic compounds and natural compounds in biotic processes. It helps to determine which chemicals do not pose a hazard to the environment and human health, which may be beneficial for human, and which chemicals are dangerous to use and carry a high risk for humanity.

Water plays an important role in the transport of elements in global biogeochemical cycles. Water acts as a reagent in the chemical transformations and as a medium in the transport of dissolved and solid compounds to different sources. The water cycle consists of the movement of approximately 600,000 km^3 of water through the cycle per year. Water is separated from its solutes through the processes of evaporation or freezing, mixing and reacting again with other compounds in its stream as it moves and condenses as rain or snow. Water flows on and under the ground until it reaches the oceans. Considering the water cycle, it is understood that it is almost impossible to find pure water in nature.

After addressing the problems, determining the degree of risk in the worldwide ecology-health system becomes a priority issue. The standards and regulations regarding the levels of environmental pollutants in application today are mostly guidelines. In every region of the world, in every country, the priorities of pollutants need to be evaluated according to their risk levels to human health. In terms of human health, exposure to pollutants mainly occurs in four ways: drinking water, air, soil and food.

Analyzing and cleaning or preventing the disposal of all priority pollutants that have a negative impact on human health in a region can be followed, but this entails incredibly high costs. At the beginning of the twentieth century, it was realized that we were on the verge of a global ecological crisis that threatened the existence of humanity. Industrial production still remains at the top of the sectors that produce high waste. For this reason, the concepts of sustainable development and circular economy have developed, an understanding that focuses on preserving ecological balance, trying to combine social, economic and ecological systems. When talking about drinking water quality, first of all the quality of drinking water supply sources should be considered and protected. The solution to existing problems regarding the protection of ecosystems from pollution and damage caused by humanity should aim to find new technical solutions and not only overcome the problems, but also prevent the causes that lead to negative ecological consequences.

Processes Affecting Water Composition

The composition of water in each region depends on its geological environment as well as the dissolution and chemical reactions of solids, liquids, and gases during the water cycle. Therefore, no generalization can be made for the composition of natural waters as there are many interdependent variables. Various processes cause the mixing of different compounds that affect the properties of natural waters.

Many pollutants can be broken down by certain microorganisms, that is, biodegradable, while others are very difficult or impossible to break down or assimilate through metabolism. Types of substances that degrade very slowly are called non-biodegradable or persistent substances. Although transformations of organic compounds can occur in the environment, such processes rarely completely transform organic compounds into inorganic substances. These processes usually occur through oxidation, hydrolysis or photolysis reactions. Biological processes can partially transform organic pollutants at discharge sites or during transportation. Biological transformation is largely carried out by microorganisms and causes changes in the structure and toxicological properties of pollutants. In order for microorganisms to continue their activities, they need organic or inorganic carbon sources, nitrogen, phosphorus, sulfur, some trace minerals, water and an energy source. Various conditions must exist for biodegradation to occur. The organism must be present in the environment and it must have the necessary enzymes, and the target substance must be within the physical reach of the degrading organism.

The abundance of microorganisms in an environment is related to physical and chemical factors such as the presence of carbon, oxygen and nutrients, temperature, pH and salinity. Biodegradation enables the transformation of organic compounds into inorganic substances, called mineralization. Microorganisms are important for biodegradation processes in contaminated soil, water and sediments because they mineralize anthropogenic organic compounds. Microorganisms cause biodegradation in many different environments. Wastewater treatment systems, soils, chemical waste disposal, groundwater, surface waters, oceans, sediments and estuaries are places where pollutants are eliminated by microorganisms. Microorganisms can degrade and mineralize different types of natural and synthetic organic pollutants.

Conclusions

Increasing population, increasing economic and industrial developments bring about increased use of natural resources. The waste generated for these reasons and the excessive use of resources create intense pressure on natural resources, biodiversity and ecosystems. It is important that economic and industrial developments occur in a sustainable manner, within the boundaries of ecosystems and without pushing the boundaries. Sustainable development and environmental protection can be possible through approaches such as effective use and reuse of resources, recovery of waste generated, and reuse of as much of it as possible. It is very important to improve and develop the physical, chemical and biological processes that are effective in these processes for the sustainability of energy and clean water resources, the treatment of wastewater and the recovery and reuse of the energy, organic substances and nutrients it contains. Developments and research in basic sciences are important.

References

Balkema, A.J., Preisig, H.A., Otterpohl, R., & Lambert, F.J.D. (2002). Indicators for the sustainability assessment of wastewater treatment systems. *Urban Water*, 4, 153–161. https://doi.org/10.1016/S1462-0758(02)00014-6

EC. (2021) *The 2030 agenda for sustainable development and the SDGs*. European Commission, Brussels. https://ec.europa.eu/environment/sustainable-development/SDGs/index_en.htm

EU Smart-Plant. (2021). *Scale-up of low-carbon footprint material recovery techniques for upgrading existing wastewater treatment plants*. EU Smart-Plant Project. https://www.smart-plant.eu/

FAO. (2020). *The state of food and agriculture: overcoming water challenges in agriculture*. Food and Agricultural Organization of the United Nations, Rome. www.fao.org/documents/card/en/c/cb1447en/

Gray, N.F. (2015). *Facing Up to Global Warming: What is going on and how you can make a difference?* Springer, Cham, Switzerland.

Gray, N.F. (2022). *Natural Wastewater Treatment Systems and Sustainability*, World Scientific, 2022. Printed in Singapore.

IWA. (2016). *Water utility pathways in a circular economy*. International Water Association, London. https://iwa-network.org/wp content/uploads/2016/07/IWA_Circular_Economy_screen-1.pdf

Mekonnen, M.M. and Hoekstra, A.Y. (2011) Four billion people facing severe water scarcity. *Science Advances*, 2(2), 1500323. https://advances.sciencemag.org/content/2/2/e1500323

Mekonnen, M.M. and Hoekstra, A.Y. (2011) National water footprint accounts: The green, blue and grey water footprint of production and consumption, volume 2, Appendices value of water research report, Series no: 50, UNESCO, Delft, The Netherlands. https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1077&context=wffdocs

Richey, A.S., Thomas, B.F., Lo, M-H., Reager, J.T., Famiglietti, J.S., Voss, K., Swenson, S. and Modell, M. (2015) Quantifying renewable groundwater stress with GRACE. *Water Resources Research*, 51(7), 5217–5238. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2015WR017349

Shah, A.I., Din Dar, M.J., Bhant, R.A., Singh, J.P., Singh, K. and Bhat, S.A. (2020) Prospectives and challenges of wastewater treatment Technologies to combat contaminants of emerging concerns. *Ecological Engineering*, 152, 105882. https://doi.org/10.1016/j.ecoleng.2020.105882

Shiklomanov, I.A. (1993). World freshwater resources, Water in Crisis: A Guide to the World's Fresh Water Resources, Peter H. Gleick (editor), Oxford University Press, New York.

Solow, R. (1991). *Sustainability: An economist's perspective*. The 18th Edward J. Seward Johnson Lecture to the Marine Policy Center Woods Hole Oceanographic Institution, Woods Hole Massachusetts. http://cda.morris.umn.edu/~kildegac/Courses/Enviro/3008/Readings/Solow.pdf

UN. (2015). *Transforming our world: The 2030 agenda for sustainable development*. A/RES/70/1. United Nations, New York. https://sustainabledevelopment.un.org/content/documents/21252030 Agenda for Sustainable Development web.pdf

UN. (2018). *SDG 6 Synthesis Report 2018 on water and sanitation. United Nations*, New York. https://www.unwater.org/publication_categories/sdg-6-synthesis-report-2018-on-water-and-sanitation/

UN. (2021). *Sustainable Development Goals. United Nations*, New York. https://www.unenvironment.org/explore-topics/sustainable-developmentgoals/about-sustainable-development-goals

USEPA. (2013). *Emerging technologies for wastewater treatment and in plant wet weather management*. EPA 832-R-12-11. US Environmental Protection Agency, Washington, DC.

van der Vleuten-Balkema, A.J. (2003). *Sustainable wastewater treatment, developing a methodology and selecting promising systems*. Proefschrift, Technische Univesiteit Eindhoven, Eindhoven.

About Authors

Prof. Mehmet Emin AYDIN | Necmettin Erbakan University | meaydin[at]erbakan.edu.tr | ORCID: 0000-0001-6665-198X

Mehmet Emin Aydın studied Civil engineering at Selçuk University in Konya, Türkiye (1980-1985) and received his PhD in 1993 in the field of drinking water treatment at Civil Engineering Department of Loughborough University of Technology in England. He is appointed as Assoc. Prof. Dr. in Environmental Engineering of Selçuk University in 1997. Since 2003, he is full Professor in Environmental Engineering initially at Selçuk University and then since 2012 in Necmettin Erbakan University in Konya, Türkiye. He is working as full Professor in Civil Engineering of Necmettin Erbakan University since 2018. His teaching and research cover water supply, wastewater disposal, water pollution, water and wastewater treatment, ecotoxicology, PAHs, PCBs, pesticides, pharmaceuticals and illicit drugs in environment. Prof. Dr. Aydın published 232 papers in international peer-reviewed journals and proceedings volumes; 82 presentations in National symposiums; 21 international book chapters, 10 book editorships and co-editorships.

Prof. Senar AYDIN | Necmettin Erbakan University | sozcan[at]erbakan.edu.tr | ORCID: 0000-0002-0960-480X

Senar Aydin studied in Environmental engineering department at Selçuk University in Konya (1995-1999) and received her Doctorate in 2007 in the field of Analyses of micro pollutants such as pesticides, PAHs and PCBs in Environment at Environmental Engineering Department of Selçuk University. Senar Aydın was appointed as Assistant Prof. Dr. in Environmental Engineering Department of Selçuk University in 2010 and then as Associate Prof. Dr. in 2012. Since 2017 she is full Professor in Environmental Engineering Department of Necmettin Erbakan University in Konya, Türkiye. Her teaching and research cover unit processes, laboratory application of unit processes, water pollution, water and wastewater treatment, ecotoxicology, PAHs, PCBs, pesticides, pharmaceuticals and illicit drugs in environment. She has been the head of the Department of Environmental Engineering since 2011. She was awarded as excellency in science among young scientist by Turkish academy of sciences (TUBA) in 2013. Senar Aydın published 160 papers in international peer-reviewed journals and proceedings volumes; 20 national articles; 52 presentations in National symposiums; 3 national and 12 international book chapters.

MATHEMATICS AND BASIC SCIENCES IN GEOMATICS ENGINEERING: CONTRIBUTIONS TOWARDS SUSTAINABLE DEVELOPMENT GOALS

Taşkın Kavzoğlu

Alihan Teke

Elif Özlem Yılmaz

10.53478/TUBA.978-625-6110-22-9.ch04

Mathematics and Basic Sciences in Geomatics Engineering: Contributions Towards Sustainable Development Goals

Taşkın Kavzoğlu
Gebze Technical University

Alihan Teke
Gebze Technical University

Elif Özlem Yilmaz
Gebze Technical University

Abstract

Mathematics and basic sciences form an integral part of the Geomatics Engineering curriculum, serving as the cornerstone not only in shaping the educational framework of the discipline but also in making substantial contributions toward achieving the Sustainable Development Goals (SDGs) by gathering and analyzing geospatial data. This study examines the central role of these subjects by emphasizing their profound importance in both theory and practical applications, promoting a harmonious incorporation of core scientific and engineering courses. The study also highlights how geospatial data, one of the main end-products of the Geomatics engineering discipline, contributes to the accomplishment of a majority of SDGs, including eliminating poverty, climate action, smart cities, promoting sustainable agriculture, enhancing public health, and mitigating climate change. Remote sensing, geographical information systems (GIS), and global navigation systems (GNNS) can provide significant benefits in the pursuit of certain SDGs. The incorporation of cutting-edge technologies, including Internet of Things (IoT), artificial intelligence, and computer vision, into Geomatics engineering is required to promote sustainable environmental management and foster innovation in a wide spectrum of research fields. The study also advocates for further investigation into state-of-the-art technologies to achieve a better and more sustainable future in line with the SDGs.

Keywords
Basic science, engineering, geomatics engineering, sustainability, education

Introduction

Engineering is the transformation of materials and forces/energies in nature into structures, machines, products, and processes in the most efficient way by using knowledge gained through education and experience in basic sciences (Özçep et al., 2003). The Arabic word for engineer (hendese) means a person engaged in geometry. On the other hand, the English word engineer is known to have been first used in the Middle Ages. The origin of the word is engine and ingenious and comes from the Latin word *in generare*, which means to generate. Dealing with the practical application of scientific knowledge, engineering aims to deliver safe, efficient, and viable answers to various issues by employing the principles uncovered through scientific exploration. Proficiency in defining, conceptualizing, and resolving engineering problems arises from fundamental scientific knowledge. Therefore, basic sciences hold a crucial position in engineering education and the practical utilization of engineering knowledge, warranting adequate attention.

Having a deep-rooted history tracing back to 300 B.C., Geomatics Engineering is one of the oldest scientific disciplines at the intersection of basic sciences and specialized branches, including mathematics, geometry, trigonometry, geography, astronomy, and physics. It is internationally recognized under different names, including Geodesy and Photogrammetry Engineering, Geoinformatics Engineering, and Surveying Engineering. The important areas of research in Geomatics Engineering include photogrammetry, remote sensing, digital image processing, geographic information systems (GIS), geodesy, Global Navigation Satellite Systems (GNSS), cartography, and land administration. Geomatics Engineering also supports environmental studies, safeguarding biodiversity conservation, ecosystem sustainability, climate change monitoring, and natural resource management. It is evident that the interdisciplinary nature of Geomatics Engineering links technology, science, and the environment, creating an intricate network of sustainability and innovation. In conclusion, Geomatics Engineering is a field with enormous potential and benefits for society globally. It offers a unique opportunity for professionals in science, technology, and engineering to come together and provide innovative solutions to pressing environmental challenges. The advancement of Geomatics Engineering will continue to provide critical information to advance environmental policies, risk management, and sustainable development.

This study aims to investigate the pivotal role of mathematics and basic sciences, encompassing physics, astronomy, and geography, in shaping the Geomatics Engineering curriculum and its main sub-branches. This exploration goes beyond theoretical discussions, delving deeply into the practical applications of Geomatics Engineering. It elucidates how these applications actively contribute to advancing and achieving seven specific targets among the United Nations' Sustainable Development Goals (SDGs). By examining the intersection of these disciplines, this study also unveils the nuanced ways in which Geomatics Engineering actively supports and drives progress toward sustainable global development.

Curriculum of Engineering Education

Courses in basic sciences empower students to initiate their path to becoming well-educated engineers, fostering the growth of their analytical thinking skills. For engineering, education in the basic sciences is essential, highlighting the critical significance of strengthening engineering education programs in the basic sciences. Clearly, basic sciences guide engineers in cultivating innovative and productive thinking while providing explanations for natural phenomena. Basic sciences courses are usually compulsory in the freshman and sophomore years of engineering programs. A lack of proper education in fundamental sciences represents a substantial drawback, impacting the technological growth of nations and the cultivation of productive critical thinking skills. From the perspective of the engineering profession, engineers with a deficit in basic sciences may encounter challenges in practical applications, constraining their success in interpretation and the generation of innovative ideas. Several authors (e.g., Zakharov, 2000; Uriel et al., 2020) have discussed the necessity of redesigning the courses of basic sciences in modern engineering education and suggested reforming engineering education.

Recognizing and adopting the fundamental sciences, which constitute the underpinning of engineering sciences, is highly essential for the effective conduct of R&D activities. The incorporation of basic sciences in both engineering education and the execution of engineering duties is critical for addressing cause-and-effect relationships in applications, improving production quality, and ensuring ongoing success. Basic sciences elucidate natural phenomena and lead engineers to innovative and productive thinking. Engineering graduates are equipped with the capability to integrate scientific and engineering principles, allowing them to design products and processes that advance environmental sustainability, while also innovating new technologies and solutions for emerging problems.

Basic sciences form the foundation of engineering, as knowledge generated by one is converted into skills by the other. Insufficient emphasis on basic sciences deprives a country of scientific standing, impedes the attainment of advanced technology, and hinders the development of an innovative society. Therefore, it is highly important that subjects such as mathematics, physics, chemistry, biology, and others, which serve as essential foundations for vocational education in engineering faculties, are taught by faculty members actively involved in research within the relevant basic sciences disciplines. Zakharov (2000) argues that when a professor employing an 'engineering' teaching style delivers a basic science lecture, another extreme perspective emerges. This tendency involves molding fundamental science to fit the demands of engineering. Such an approach causes science being taught to lose its foundational nature and should be avoided. Additionally, there is a need to elevate the quality of education and laboratory facilities to ensure that students pursuing basic sciences are trained with the requisite skills for employment and can progress in their path to becoming scientists.

According to the Accreditation Board for Engineering and Technology (ABET), the courses in an engineering degree program should be balanced between basic sciences and mathematics, engineering sciences, humanities, social sciences and communication, and departmental courses. In a comprehensive study for electrical engineering, Bilsel et al. (1998) reported that Turkish engineering programs are stronger in mathematics, and they generally allocate more courses to this subject in their curricula compared with North American universities. The mean number of required mathematics credit-hours for engineering students at Turkish universities was 22.7 (lowest 19, highest 30), whereas it was 17.8 (lowest 13, highest 26) at North American universities. A striking observation is that the pattern is reversed when it comes to credit-hours in physics and chemistry. While total physics and chemistry credit-hours at Turkish universities were 9.4 and 3.2, those at North American universities were 10.3 and 5.0, respectively.

At present, we are witnessing a digital transformation that is profoundly shaping all dimensions of engineering technologies, necessitating substantial changes in university curricula. For this reason, the educational philosophy of today's technological society has shifted from training engineers who are only capable of solving technical problems to training engineers who can comprehend the problem as a whole. Engineering education should broaden students' horizons and help them identify fundamental problems (Baran & Kahraman, 1999). Therefore, the main objective of modern engineering education can be defined as teaching engineering principles and learning.

Basic Sciences in Geomatics Engineering

The principal aim of the Geomatics Engineering discipline is to collect, interpret, analyze, and disseminate valuable geospatial information on the Earth by employing various technologies, such as GNSS, remote sensing, GIS, and spatial data analytics (Figure 1). G. Leibniz (1646-1716), a distinguished German mathematician, once stated, "Geodesy is an excellent application area of mathematics", underscoring the crucial role of mathematical expertise in the field of Geomatics. To date, geomaticians have consistently employed an array of calculation tools, ranging from logarithm tables and slide rules to electric calculators and computers, to execute diverse calculation methodologies. Additionally, *geometry* and *trigonometry*, sub-branches of *mathematics*, constitute the primary domains in which geomaticians are deeply engaged. The use of terms such as "Ingenieur Geometer" or "Trigonometer" in certain countries underlines the proximity of their work to these mathematical disciplines. Furthermore, cartographers have played a significant role in developing subjects such as probability calculation, statistical theories, and the Least Squares Method, which are more closely associated with cartography than with pure mathematics (Şerbetçi, 1999).

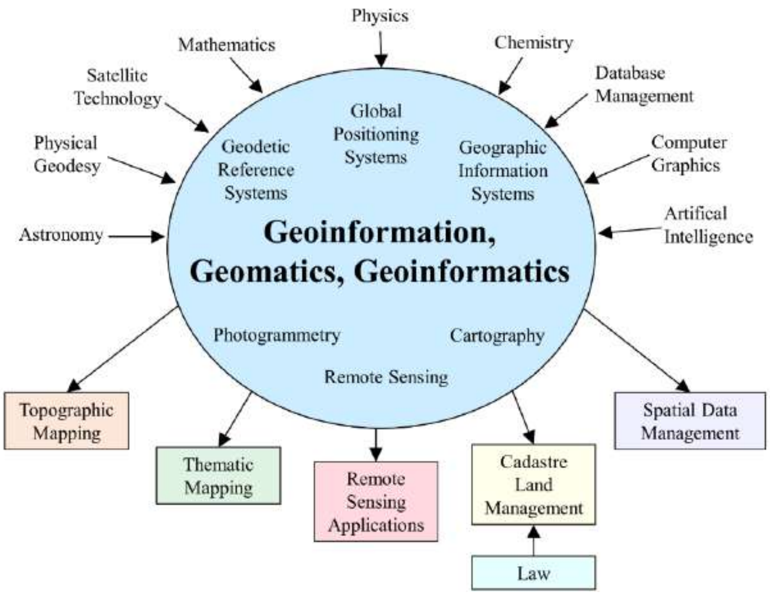
Within the domain of *astronomy*, geomaticians are tasked with the precise measurement of latitude, longitude, and azimuth values for specific points within established networks, such as the country triangulation network, during map creation. Geomaticians also calculate the amount of plumb deviation from these measured values and incorporate it into precise calculations on the ellipsoid. To determine the size of the Earth's ellipsoid, astronomical studies were conducted in conjunction with geodetic efforts. In contemporary measurements, positions are determined using the Global Positioning System (GPS) through Doppler measurements and dedicated satellites launched for this purpose.

The field of *geography* has been intertwined with Geomatics Engineering and exploration for centuries. In Greek, "Geo" translates to place, and "graphhein" to write or draw. While cartography remains highly significant in the realm of geography, it has evolved into a distinct discipline over time. The era of major discoveries has concluded, and there are no unexplored regions left on Earth. Consequently, Geomaticians have consistently relied on the definitions and descriptions provided by geographers, evaluating the discoveries and journeys undertaken. This symbiotic relationship has led to the acknowledgment of cartography as a scientific branch closely aligned with geography.

The field of *physics* also plays a crucial role in Geomatics, particularly in the context of measurements conducted in the physical environment. The precision achieved in measuring base lengths, even with tape elongation, owes its thanks to physicists who developed tools such as invar wires. Optical instruments such as levels, tachymeters, or theodolites are rooted in precision mechanics, with components such as binoculars and the paths of light through lenses, prisms, mirrors, etc., delving into the optical aspects of physics. Recent innovations, such as tools that use electro-optic and electromagnetic waves, are also entirely products of the field of physics. In geodesy, a range of topics related to physics finds application, reflecting the interdisciplinary nature of cartography and its reliance on principles from the physical sciences (Şerbetçi, 1999).

Figure 1.

Scientific fields and applications of Geomatics Engineering (Source: Konecny (2002))



Physics also plays a fundamental role in remote sensing, which involves acquiring information about the Earth's surface without direct physical contact. Remote sensing relies on the interaction between electromagnetic radiation and the Earth's surface features. Key physics concepts in remote observation include the spectrum of light, interaction with the atmosphere, sensor technologies, radiative transfer models, scattering and absorption, and thermal infrared remote observation. Remote sensing systems function across the electromagnetic spectrum, from visible light to microwaves. Understanding how different wavelengths interact with the Earth's surface and atmosphere is essential. Principles of physics are applied to model atmospheric effects such as absorption, scattering, and reflection, which can distort received signals. Multispectral sensors employ filters to identify particular wavelengths, whereas hyperspectral sensors offer more intricate spectral details. Physics-based radiative transfer models are employed to simulate the interactions of electromagnetic radiation with the Earth's surface and atmosphere. Remote sensing enables scientists to extract valuable information about the Earth's surface, monitor environmental changes, and investigate the risks and impacts of natural disasters (Kutlug Sahin et al., 2017; Kavzoglu et al., 2017; 2021; Kavzoglu & Teke, 2022).

Geomatics Engineering for Sustainable Development Goals

In 2015, all United Nations Member States adopted the 2030 Agenda for Sustainable Development Goals (SDGs), a comprehensive framework consisting of 17 goals and 169 targets aimed at addressing critical global challenges, including poverty, inequality, climate change, environmental degradation, peace, and justice (https://sdgs.un.org/goals) (Figure 2). The discipline of Geomatics Engineering, steeped in a rich history, and its sub-branches, have played a significant role, both directly and indirectly from various perspectives, in contributing to the effective achievement of most of these goals through the production, processing, and interpretation of its primary output–geospatial data. An essential question arises: What is the role of Geomatics Engineering, encompassing remote sensing, GIS, and earth observation, in this overarching pursuit?

Figure 2.

17 Sustainable Development Goals (SDGs) proposed by the United Nations (Source: https://www.un.org/sustainabledevelopment/news/communications-material/)

Geomatics Engineering, with its focus on geospatial data, plays a crucial role in contributing to the achievement of SDG 2, which aims to create a world free of hunger. Leveraging technology to enhance food security and increase crop yield in all farming practices significantly contributes to global economic advancement. Small-scale agricultural operators, empowered by precision farming technologies, have the potential to generate sufficient income to support their livelihoods. Introducing advanced agricultural practices in developing countries can effectively reduce the proportion of the population living below the global poverty line. Wang et al. (2022) conducted comprehensive research that introduced an approach for assessing the localization of SDG 1 in China, using various sources of geospatial data. This approach provides valuable information for the effective implementation of the 2030 Agenda for Sustainable Development. Moreover, the quantitative assessment approach proposed in this study can serve as a benchmark for developing medium- and long-term sustainable development policies, such as rural revival strategies. Furthermore, *SDG 2* specifically targets the aspiration of achieving “Zero Hunger”, standing out as directly addressing the crucial aspects of secure food supply and sustainable agriculture. Earth observation data have played a longstanding role in numerous applications within the agricultural domain, including but not limited to plant disease detection (Hasanaliyeva et al., 2022), crop yield estimation, and inventory mapping of particular plant species (Kavzoglu & Tonbul, 2017; Colkesen et al., 2023). Moreover, the assessment of land cover connectivity, a key indicator for ecosystem services, derived from the processing of this data, may reveal trade-offs with SDG 2 concerning food provision at the national scale (Cochran et al., 2020).

SDG 3 aims to "Good Health and Well-being", particularly highlighting ensuring the healthy lives of people and promoting well-being for all ages. Geospatial data also play a pivotal role in promoting this goal by contributing to various aspects of public health and well-being. The discipline facilitates natural disaster mitigation through early detection and monitoring, thereby providing pre-disaster early warning or post-disaster relief (Teke & Kavzoglu, 2024). Additionally, it supports air and water quality monitoring, aiding in the assessment of environmental factors that impact public health (Mehmood et al., 2020). Accessibility to public health facilities can be enhanced through spatial analysis, optimizing their locations based on population distribution and health needs. It should be underlined that GIS are used as a powerful tool for determining the extent of land and people in order to facilitate improved health care planning. The study undertaken by Som (2019) aims to evaluate the geographical accessibility of health services and examine their influence on infant mortality and fertility rates. Specially designed GIS can be employed to facilitate the daily activities of disabled people and transportation planning by integrating data from various sources and formats, such as environmental, census, traffic, land use and land cover and social data.

Geomatics Engineering is also instrumental in addressing *SDG 6* "Clean Water and Sanitation" by providing essential tools for effective water resource management. Remote sensing and earth observation technologies enable the monitoring and assessment of water bodies, identifying marine pollution sources and ensuring water quality (Kavzoglu & Goral, 2022; Dube et al., 2023; Sefercik et al., 2023). To achieve this objective, the integration of remotely sensed imagery (i.e., satellite and UAV imagery) with field survey data is being employed to generate up-to-date and cost-effective datasets for the purpose of monitoring water resources, particularly those used for water supply, in accordance with SDG6 (van den Homberg et al., 2020; Osiakwan et al., 2022). Also, GIS aids in the spatial analysis of water distribution and sanitation infrastructure, optimizing their planning and implementation. For instance, the study conducted by Wijesinghe et al. (2023) demonstrated that the utilization of GIS and geospatially based analysis enables the identification of possible groundwater zones and the generation of data that can aid in the development of a groundwater management plan. GNSS, especially Real Time Kinematic (RTK)-GNSS, contribute to the precise tracking of water-related activities, facilitating efficient resource management and the development of sustainable solutions for clean water and sanitation (Meron et al., 2022).

Geomatics Engineering contributes significantly to *SDG 11*, "Sustainable Cities and Communities", by supporting the development of sustainable and resilient urban areas. Implementing SDG 11 is transformative since it focuses on the step-by-step advancement of urban planning, the intricate provision of public space, access to essential services, and transit infrastructure for the expanding population in this unpredictable digital era (Avtar et al., 2019). Remote sensing and GIS assist in urban planning, land use mapping, and infrastructure development. Specifically, the analysis of spatial and temporal data in the geospatial big data domain is necessary to advance sustainable development in urban areas (Chang et al., 2023). Earth observation data provide valuable insights into environmental changes, helping cities adapt to climate variations and mitigate potential risks. Therefore, prior to establishing potential policies, it is necessary to conduct land use land cover classification and continuous change detection of cities with dynamic structures to protect sustainable cities from the impacts of climate and environmental changes (Kavzoglu, 2008; Kelly-Fair et al., 2022; Ramadan et al., 2022; Asuquo Enoh et al., 2023). On the other hand, GNSS navigation services have diverse uses encompassing aircraft, ships, and vehicle navigation, mapping, disaster prevention and management, emergency service geolocation, security management, communications, and people and object tracking (Alahmari et al., 2023). Thus, GNSS technologies play an important role in urban mobility and transportation planning, ensuring efficient and sustainable connectivity within cities (Olabi et al., 2023). On the other hand, a robust waste management system involves the use of GPS to track waste collection trucks in real-time (Joshi et al., 2022). In the context of smart cities, the field also becomes a driving force in harnessing technology for urban innovation. The integration of advanced technologies, such as the Internet of Things and Artificial Intelligence, into GIS and remote sensing technologies enhances the efficiency and effectiveness of urban planning processes (Gupta & Degbelo, 2023). These technologies facilitate real-time data collection, enabling cities to respond dynamically to changing conditions and optimize resource allocation (Mondejar et al., 2021; Papadopoulou, 2021; Bachmann et al., 2022).

Geomatics Engineering can also greatly contribute to *SDG 13*, "Climate Action", by providing essential tools for monitoring and mitigating climate change impacts. Remote sensing and earth observation technologies contribute to climate modeling, monitoring deforestation, and assessing changes in land cover. Moreover, remote sensing technology has demonstrated its utility in enhancing the comprehension of vegetation reactions to climate change and can provide crucial data for the sustainable management of ecosystems (Yang et al., 2020). GIS facilitates the analysis of climate-related data, supporting informed decision-making for climate adaptation and resilience strategies. For example, the integration of GIS and remote sensing data in forest canopy estimation studies proves to be a valuable approach for evaluating forest quality criteria and developing efficient forest conservation/management strategies, particularly for SGD 13 (Fasil et al., 2022). GNSS technologies aid in tracking and understanding climate-related phenomena, enhancing the accuracy of climate change assessments, and promoting effective climate action. In short, due to advancements in geospatial technology, the field of studying environmental change has progressed significantly through the use of satellite-based techniques such as remote sensing, GNSS navigation, and GIS (Taloor et al., 2022).

Moreover, Geomatics Engineering supports *SDG 14*, "Life Below Water", by providing crucial data for the sustainable management of marine and coastal ecosystems. Remote sensing and earth observation technologies assist in monitoring marine biodiversity, identifying critical habitats, and detecting changes in coastal areas. To exemplify, researchers have used remote sensing techniques to create indices and track environmental stressors that impact the health of corals in marine ecosystems. Additionally, the open access MODIS images were obtained using the Google Earth Engine (GEE) platform, which is a cloud-based solution for geospatial research. In order to support the objectives of SDG 14, GEE was employed to identify areas susceptible to coral bleaching (Callejas et al., 2022). Another study highlighted that remote sensing observations can aid in accomplishing the objectives outlined in SDG 14, which notably prioritize the restoration, preservation, and sustainable administration of aquatic and marine ecosystems. These observations offer openly available data that are very detailed and cover a wide range of time and space (Kulk et al., 2021). On the other hand, GIS contributes to the spatial analysis of marine resources and habitats, aiding in the development of conservation and management strategies. The combination of remote sensing and GIS could be applied to benefit the coastal community. Satellite imagery can be employed to visualize various water quality parameters, while a GIS system is able to interpolate and evaluate the accuracy of these parameters at known water sampling points. This approach greatly contributes to sustainable coastal planning and the estimation of natural resource productivity at the local level (Misbari & Hashim, 2023). In addition, GNSS technologies play a significant role in tracking maritime activities, modeling underwater ecology and supporting sustainable fisheries management and maritime safety. The study performed by Vozza et al. (2023) utilizes affordable intelligent sensors to acquire bathymetric data, while employing GNSS technology for three-dimensional modeling of both natural and artificial underwater habitats. Also, GNSS is employed to boost real-time geolocation accuracy. Through these applications, Geomatics Engineering makes a significant contribution to research on the preservation of life below water.

Lastly, the discipline plays a vital role in achieving *SDG 15*, “Life on Land”, by contributing to the conservation and sustainable use of terrestrial ecosystems. Remote sensing and earth observation technologies, in particular, assist in monitoring land use and cover changes, identifying deforestation trends, and assessing biodiversity. The utilization of remotely sensed data for examining the spatial and temporal patterns and alterations of diverse ecological resources has significant value in terms of both cost and time (Liu et al., 2019). GIS enable spatial analysis for habitat conservation and land use planning, supporting sustainable practices. Within the scope of SDG 15, by analyzing geospatial data, it can be observed that areas that have been degraded align with regions of human activity, such as urban centers. Additionally, the influence of natural events, such as catastrophes, on land degradation may be studied (Kavzoglu et al., 2018; Wang et al., 2020). On the other hand, GNSS technologies contribute to monitoring wildlife movements and tracking conservation efforts. The objective of GNSS applications is to investigate the challenges associated with the examination of natural formations such as valleys, the potential risks they present to agriculture and nearby villages, and the significance of monitoring erosion events in the valley for both the ecosystem and the local community. This monitoring can be enhanced by using GNSS and UAV imaging technologies for topographic analysis (Naş et al., 2021). Through these applications, Geomatics Engineering fosters biodiversity conservation and sustainable land management, promoting life on land.

Conclusions

In an era of growing global interconnection and complexity, the necessity for enhanced decision-making is paramount. Geomatics engineering is equipped with tools and technologies vital for extracting insights and knowledge that are crucial in supporting decision-making across various domains. The synergy between Geomatics Engineering and the basic sciences underscores the essence of education. This discipline not only benefits but also contributes significantly to the development of basic sciences. Through its applications, Geomatics Engineering breathes life into theoretical concepts, transcending the boundaries of classrooms and laboratories to actively shape the world we inhabit. It stands as a beacon of innovation that leverages technological advancements and scientific principles to address the SDGs of the United Nations. The field strives to advance state-of-the-art research across diverse fields by harnessing the primary end-product – geospatial data – obtained through technologies such as remote sensing, Earth observations, and GIS. The discipline goes beyond mere technological pursuits, engaging in interdisciplinary efforts to enhance our comprehension of human societies and their interconnected ecosystems. The ultimate goal is to effectively manage these systems and foster sustainable development and environmental conservation. This aligns seamlessly with ongoing global initiatives at various levels aimed at achieving the SDGs for the Agenda 2030 proposed by the United Nations. In this spirit, future studies may explore the integration of state-of-the-art technologies, including artificial intelligence, the internet of things, and computer vision, within Geomatics Engineering applications. Through these future-oriented strategies, it is aimed to substantially enhance livability within the SDG framework, introducing a novel phase of inventive advancements. In conclusion, the holistic approach of Geomatics Engineering, entwined with mathematics and basic sciences, is a catalyst for transformative change. Its contributions reverberate across disciplines, resonating in the pursuit of a more harmonious and sustainable planet, poised to meet the challenges and aspirations of generations to come.

References

Alahmari, N., Mehmood, R., Alzahrani, A., Yigitcanlar, T., & Corchado, J. M. (2023). Autonomous and Sustainable Service Economies: Data-driven optimization of design and operations through the discovery of multi-perspective parameters. *Sustainability*, 15(22), 16003. https://doi.org/10.3390/su152216003

Asuquo Enoh, M., Ebere Njoku, R., & Chinenye Okeke, U. (2023). Modeling and mapping the spatial–temporal changes in land use and land cover in Lagos: A dynamics for building a sustainable urban city. *Advances in Space Research*, 72(3), 694–710. https://doi.org/10.1016/j.asr.2022.07.042

Avtar, R., Aggarwal, R., Kharrazi, A., Kumar, P., & Kurniawan, T. A. (2019). Utilizing geospatial information to implement SDGs and monitor their progress. *Environmental Monitoring and Assessment*, 192(1), 35. https://doi.org/10.1007/s10661-019-7996-9

Bachmann, N., Tripathi, S., Brunner, M., & Jodlbauer, H. (2022). The contribution of data-driven technologies in achieving the Sustainable Development Goals. *Sustainability*, 14(5), 2497. https://doi.org/10.3390/su14052497

Baran, T., & Kahraman, S. (1999). Competent engineering and education, Symposium on Engineering Architecture Education Istanbul, Turkiye, pp. 239-249. [In Turkish]

Bilsel, A., Oral, O., & Pillai, J. (1998). Turkish and North American engineering programs: A comparative study of curricular emphases on mathematics, basic sciences, humanities and social sciences. *IEEE Transactions on Education*, 41(4), 247-252. https://doi.org/10.1109/13.728257

Callejas, I. A., Osborn, K., Lee, C., Mishra, D. R., Auil Gomez, N., Carrias, A., Cherrington, E. A., Griffin, R., Rosado, A., Rosado, S., & Jay, J. (2022). A GEE toolkit for water quality monitoring from 2002 to 2022 in support of SDG 14 and Coral Health in marine protected areas in Belize. *Frontiers in Remote Sensing*, 3, 1020184. https://doi.org/10.3389/frsen.2022.1020184

Chang, Y., Ouyang, X., Fei, X., Sun, Z., Li, S., Jiang, H., & Li, H. (2023). Comprehensive assessment of sustainable development goal 11 at the Sub-City Scale: A Case Study of Guilin city. *Remote Sensing*, 15(19), 4722. https://doi.org/10.3390/rs15194722

Cochran, F., Daniel, J., Jackson, L., & Neale, A. (2020). Earth observation-based ecosystem services indicators for national and subnational reporting of the sustainable development goals. *Remote Sensing of Environment*, 244, 111796.

Colkesen, I., Kavzoglu, T., Atesoglu, A., Tonbul, H., & Ozturk, M. Y. (2023). Multi-seasonal evaluation of hybrid poplar (P. Deltoides) plantations using Worldview-3 imagery and state-of-the-art ensemble learning algorithms. *Advances in Space Research*, 71(7), 3022-3044. https://doi.org/10.1016/j.asr.2022.10.044

Dube, T., Shekede, M. D., & Massari, C. (2023). Remote Sensing for Water Resources and Environmental Management. *Remote Sensing*, 15, 18. https://doi.org/10.3390/rs15010018

Fasil, M., Surendran, U. P., Gopinath, G., Karimbanakkuzhi, A., & Sahadevan, A. S. (2022). Integration of GIS, remote sensing, and spectral indices for evaluation of forest canopy density model in drought and wet years in Western Ghats region of humid tropical Kerala, India. *Arabian Journal of Geosciences*, 15(12). https://doi.org/10.1007/s12517-022-10368-z

Gupta, S., & Degbelo, A. (2023). An Empirical Analysis of AI Contributions to Sustainable Cities (SDG 11). In Mazzi, F., Floridi, L. (eds) The Ethics of Artificial Intelligence for the Sustainable Development Goals . *Philosophical Studies Series*, (vol 152). Springer, Cham. https://doi.org/10.1007/978-3-031-21147-8_25

Hasanaliyeva, G., Si Ammour, M., Yaseen, T., Rossi, V., & Caffi, T. (2022). Innovations in disease detection and forecasting: a digital roadmap for sustainable management of fruit and foliar disease. *Agronomy*, 12(7), 1707. https://doi.org/10.3390/agronomy12071707

Joshi, L. M., Bharti, R. K., Singh, R., & Malik, P. K. (2022). Real time monitoring of solid waste with customized hardware and internet of things. *Computers and Electrical Engineering*, 102, 108262. https://doi.org/10.1016/j.compeleceng.2022.108262

Kavzoglu, T. (2008). Determination of environmental degradation due to urbanization and industrialization in Gebze, Türkiye. *Environmental Engineering Science*, 25(3), 429-438. https://doi.org/10.1089/ees.2006.0271

Kavzoglu, T., Erdemir, M. Y., & Tonbul, H. (2017). Classification of semiurban landscapes from very high-resolution satellite images using a regionalized multiscale segmentation approach. *Journal of Applied Remote Sensing*, 11(3), 035016. https://doi.org/10.1117/1.JRS.11.035016

Kavzoglu, T., & Goral, M. (2022). Google earth engine for monitoring marine mucilage: Izmit Bay in spring 2021. *Hydrology*, 9(8), 135. https://doi.org/10.3390/hydrology9080135

Kavzoglu, T., & Teke, A. (2022). Advanced hyperparameter optimization for improved spatial prediction of shallow landslides using extreme gradient boosting (XGBoost). *Bulletin of Engineering Geology and the*

Environment, 81(5), 201. https://doi.org/10.1007/s10064-022-02708-w

Kavzoglu, T., Teke, A., & Yilmaz, E. O. (2021). Shared blocks-based ensemble deep learning for shallow landslide susceptibility mapping. *Remote Sensing*, 13(23), 4776. https://doi.org/10.3390/rs13234776

Kavzoglu, T., & Tonbul, H. (2017). A comparative study of segmentation quality for multi-resolution segmentation and watershed transform. *In 8th International Conference on Recent Advances in Space Technologies (RAST)*, Istanbul, Türkiye, pp. 113-117. https://doi.org/10.1109/RAST.2017.8002984

Kavzoglu, T., Tonbul, H., Yildiz Erdemir, M., & Colkesen, I. (2018). Dimensionality reduction and classification of hyperspectral images using object-based image analysis. *Journal of the Indian Society of Remote Sensing*, 46, 1297-1306. https://doi.org/10.1007/s12524-018-0803-1

Kelly-Fair, M., Gopal, S., Koch, M., Pancasakti Kusumaningrum, H., Helmi, M., Khairunnisa, D., & Kaufman, L. (2022). Analysis of land use and land cover changes through the lens of SDGs in Semarang, Indonesia. *Sustainability*, 14(13), 7592. https://doi.org/10.3390/su14137592

Konecny, G. (2002). Recent global changes in geomatics education. *Proceedings of 22nd FIG Congress 2002*, Washington, D.C.

Kulk, G., George, G., Abdulaziz, A., Menon, N., Theenathayalan, V., Jayaram, C., Brewin, R. J., & Sathyendranath, S. (2021). Effect of reduced anthropogenic activities on water quality in Lake Vembanad, India. *Remote Sensing*, 13(9), 1631. https://doi.org/10.3390/rs13091631

Kutlug Sahin, E., Ipbuker, C., & Kavzoglu, T. (2017). Investigation of automatic feature weighting methods (Fisher, Chi-square and Relief-F) for landslide susceptibility mapping. *Geocarto International*, 32(9), 956-977. https://doi.org/10.1080/10106049.2016.1170892

Liu, S., Bai, J., & Chen, J. (2019). Measuring SDG 15 at the county scale: Localization and practice of SDGs indicators based on geospatial information. *ISPRS International Journal of Geo-Information*, 8(11), 515. https://doi.org/10.3390/ijgi8110515

Mehmood, H., Liao, D., & Mahadeo, K., (2020). A review of artificial intelligence applications to achieve water-related sustainable development goals. *2020 IEEE / ITU International Conference on Artificial Intelligence for Good (AI4G)*, Geneva, Switzerland, 2020, 135-141, https://doi.org/10.1109/AI4G50087.2020.9311018

Meron, M., Chen, A., Rabinovitz, O., Traub, E., Levine-Orlov, V., & Marchaim, U. (2022). Water distribution analysis of a linear move irrigator by aerial survey and RTK-GNSS monitors. Precision Agriculture, 23, 894–911. https://doi.org/10.1007/s11119-021-09866-z

Misbari, S., & Hashim, M. (2023). Water quality changes using GIS-based approach at seagrass meadows along the Straits of Johor. *AIP Conference Proceedings*, 2682 (1), 050002. https://doi.org/10.1063/5.0114483

Mondejar, M. E., Avtar, R., Diaz, H. L., Dubey, R. K., Esteban, J., Gómez-Morales, A., Hallam, B., Mbungu, N. T., Okolo, C. C., Prasad, K. A., She, Q., & Garcia-Segura, S. (2021). Digitalization to achieve sustainable development goals: Steps towards a smart green planet. *Science of The Total Environment*, 794, 148539. https://doi.org/10.1016/j.scitotenv.2021.148539

Naş, S., Ciurean, O. M., Bondrea, M. V., & Radulescu, V. M. (2021). A sustainable approach to geomatic methods in ravine monitoring and associated natural disaster prevention. *Preprints*, 2021120251. https://doi.org/10.20944/preprints202112.0251.v1

Olabi, A. G., Wilberforce, T., Obaideen, K., Sayed, E. T., Shehata, N., Alami, A. H., & Abdelkareem, M. A. (2023). Micromobility: Progress, benefits, challenges, policy and regulations, energy sources and storage, and its role in achieving Sustainable Development Goals. *International Journal of Thermofluids*, 17, 100292. https://doi.org/10.1016/j.ijft.2023.100292

Osiakwan, G.M., Gibrilla, A., Kabo-Bah, A.T., Appiah-Adjei, E., & Anornu, G. (2022). Delineation of groundwater potential zones in the Central Region of Ghana using GIS and fuzzy analytic hierarchy process. *Modeling Earth Systems and Environment*, 8, 5305–5326. https://doi.org/10.1007/s40808-022-01380-z

Özçep, F., Karabulut, S., Alpaslan, N., Makaroğlu, Ö., Özçep, T., Çağlak, F., & Ceyhan, U. (2003). Engineering philosophy and its historical development. *The First Congress on Engineering Sciences Young Researchers*, 17-20 February. Istanbul, Turkiye. [In Turkish]

Papadopoulou, C.-A. (2021). Chapter 4 - Technology and SDGs in smart cities context. In A. Visvizi & R. Pérez del Hoyo (Eds.), *Smart Cities and the un SDGs* (pp. 45–58). Elsevier. https://doi.org/https://doi.org/10.1016 /B978- 0-323-85151-0.00004-X

Ramadan, R. H., Ramadan, M. S., Alkadi, I. I., Alogayell, H. M., Ismail, I. Y., & Khairy, N. (2022). Assessment of sustainable world heritage areas in Saudi Arabia based on climate change impacts on vulnerability using RS and GIS. *Sustainability*, 14(23), 15831. https://doi.org/10.3390/su142315831

Sefercik, U. G., Colkesen, I., Kavzoglu, T., Ozdogan, N., & Ozturk, M. Y. (2023). Assessing the physical and chemical characteristics of marine mucilage utilizing in-situ and remote sensing data (Sentinel-1,-2,-3). *PFG–Journal of Photogrammetry, Remote Sensing and Geoinformation Science*, 1-16. https://doi.org/10.1007/s41064-023-00254-y

Som, K. S. (2019). Assessment the relationship of maternal child health accessibility, infant mortality and fertility in Sagar district, Madhya Pradesh. *Indonesian Journal of Geography*, 51(1), 88. https://doi.org/10.22146/ijg.33060

Şerbetçi, M. (1999). History of Turkish Surveying (1895-1995). In commemoration of the 100th anniversary of the foundation of Turkish Surveying. *Bulletin of Chamber of Survey and Cadastre Engineers of Türkiye*, Istanbul. [In Turkish]

Taloor, A. K., Goswami, A., Bahuguna, I. M., Singh, K. K., & Kothyari, G. C. (2022). Remote sensing and GIS applications in water cryosphere and climate change. *Remote Sensing Applications: Society and Environment*, 28, 100866. https://doi.org/10.1016/j.rsase.2022.100866

Teke, A., & Kavzoglu, T. (2024). Towards artificially intelligent landslide susceptibility mapping: A critical review and open questions. In Panda, G.K., Shaw, R., Pal, S.C., Chatterjee, U., & Saha, A. (Eds.), *Landslide: Susceptibility, Risk Assessment and Sustainability. Advances in Natural and Technological Hazards Research*, (pp. 153-182). Springer, Cham. https://doi.org/10.1007/978-3-031-56591-5_6

Uriel, C., Sergio, S., Carolina, G., Mariano, G., Paola, D., & Martín, A. (2020). Improving the understanding of Basic Sciences concepts by using Virtual and Augmented Reality. *Procedia Computer Science*, 172, 389-392. https://doi.org/10.1016/j.procs.2020.05.165

van den Homberg, M., Crince, A., Wilbrink, J., Kersbergen, D., Gumbi, G., Tembo, S., & Lemmens, R. (2020). Combining UAV imagery, volunteered geographic information, and field survey data to improve characterization of rural water points in Malawi. *ISPRS International Journal of Geo-Information*, 9, 592. https://doi.org/10.3390/ijgi9100592

Vozza, G., Costantino, D., Pepe, M., & Alfio, V. S. (2023). Smart sensors system based on smartphones and methodology for 3D modelling in shallow water scenarios. *Applied System Innovation*, 6(1), 28. https://doi.org/10.3390/asi6010028

Wang, T., Giuliani, G., Lehmann, A., Jiang, Y., Shao, X., Li, L., & Zhao, H. (2020). Supporting SDG 15, life on land: Identifying the main drivers of land degradation in Honghe Prefecture, China, between 2005 and 2015.

ISPRS International Journal of Geo-Information, 9(12), 710. https://doi.org/10.3390/ijgi9120710

Wang, M., Wang, Y., Teng, F., Li, S., Lin, Y., & Cai H. (2022). China's poverty assessment and analysis under the framework of the UN SDGs based on multisource remote sensing data. *Geo-spatial Information Science*, 27(1), 111–131. https://doi.org/10.1080/10095020.2022.2108346

Wijesinghe, D.C., Mishra, P.K., Withanage, N.C., Abdelrahman, K., Mishra, V., Tripathi, S., & Fnais, M.S. (2023). Application of GIS, multi-criteria decision-making techniques for mapping groundwater potential zones: a case study of Thalawa Division, Sri Lanka. *Water*, 15, 3462. https://doi.org/10.3390/w15193462

Yang, R., Li, X., Mao, D., Wang, Z., Tian, Y., & Dong, Y. (2020). Examining fractional vegetation cover dynamics in response to climate from 1982 to 2015 in the Amur River basin for SDG 13. *Sustainability*, 12(14), 5866. https://doi.org/10.3390/su12145866

Zakharov, V. G. (2000). Role of basic sciences in modern engineering education. *Proceedings of the II. International Conference on Engineering and Computer Education (ICECE'2000)*, 27 - 30, August, São Paulo, Brazil.

About Authors

Prof. Taşkın KAVZOĞLU | Gebze Technical University | kavzoglu[at]gtu.edu.tr | ORCID: 0000-0002-9779-3443

Taskin Kavzoglu is a senior researcher with more than 25 years of experience in Earth observation and remote sensing. He received his B.Sc. as the first student in his class from Karadeniz Technical University, M.Sc. (with Distinction) and Ph.D. in Remote Sensing from Nottingham University (UK). His dissertation was selected and awarded as the best doctoral dissertation of 2001 by the Remote Sensing and Photogrammetry Society (UK). Since his first publication in 1998, he has now written more than 150 papers in peer-reviewed journals and conference proceedings. His research interests include remote sensing of natural resources, deep learning, machine learning, change detection, object-based image analysis and landslide susceptibility mapping. Acting as a chairman in many national and international conference sessions, Prof. Kavzoglu is in the editorial board of six journals and acts as a reviewer for more than 150 scientific journals. He is a member of Turkish Academy of Sciences, the Remote Sensing and Photogrammetry Society (UK), American Geophysical Union, American Association of Geographers, Turkish Photogrammetry and Remote Sensing Society and IEEE Geoscience and Remote Sensing.

Res. Asst. Alihan TEKE | Gebze Technical University | a.teke2020[at]gtu.edu.tr | ORCID: 0000-0003-4048-329X

Alihan Teke received his MSc degree in Department of Geomatics Engineering from Gebze Technical University with the thesis titled “Applications of Ensemble Learning Paradigm and Advanced Hyperparameter Optimization Techniques in Landslide Susceptibility Mapping”. During his master’s period, he contributed significantly, publishing four papers in SCI Indexed journals and presenting at numerous international conferences. Notably, his master’s thesis received the prestigious distinction of being awarded the Best Master Thesis of 2022 by the IEEE Geoscience and Remote Sensing Community. With four years of experience as a research assistant, Alihan is concurrently pursuing his Ph.D. studies in the same department. His research pursuits primarily focus on remote sensing, landslide susceptibility mapping, explainable artificial intelligence, ensemble machine learning, feature selection algorithms, and applications in geospatial data science.

Res. Asst. Elif Ozlem YILMAZ | Gebze Technical University | eoyilmaz[at]gtu.edu.tr | ORCID: 0000-0002-6853-2148

Elif Özlem Yılmaz was born in Turkey in 1994. She graduated as the third-ranked student in Geomatics Engineering from Istanbul Technical University, where she also completed a minor in Urban and Regional Planning. Currently pursuing a Ph.D. in Geodetic and Geographic Information Technologies, she has dedicated herself to advancing knowledge in this field. Since 2019, she has served as a Research Assistant at Gebze Technical University and has begun publishing academic papers and participating in national and international conferences. Her primary research focus revolves around the innovative processing methods of remotely sensed data, particularly delving into deep learning, machine learning, and explainable artificial intelligence. She has also worked on topics such as forest fires, land use/land cover classification, mucilage detection, object-based classification, and landslides. Through her academic journey, she aims to contribute significantly to the advancement of geospatial technologies and their applications. She is a member of IEEE Geoscience and Remote Sensing.

STANDING SIDE BY SIDE: THE INSEPARABLE UNITY OF BASIC SCIENCES WITH BASIC MEDICAL SCIENCES

Muzaffer Şeker

Haydar Yalçın

Standing Side by Side: The Inseparable Unity of Basic Sciences with Basic Medical Sciences

Muzaffer Şeker
Turkish Academy of Sciences

Haydar Yalçın
Ege University

Abstract

Our research seeks to highlight the important role of interdisciplinary collaboration between basic sciences and medical sciences. Using a Scientometric approach, we meticulously analyzed the 50 thousand most cited scientific research articles in both basic science and medical basic science. These analyzes are based on a comprehensive data set containing the top 50,000 scientific articles with the highest citation rates on Web of Science, all categorized as articles. Using advanced social network analysis techniques, we identified the important roles of nodes within the network and applied advanced data visualization methodologies to explain complex interdisciplinary relationships. Our findings illuminate a rich landscape of collaboration between basic science and medical basic science; It sheds light on findings that demonstrate close integration with the health sciences and have a profound impact on a variety of fields from oncology, exemplified by the deep connections observed in fields such as biochemistry and molecular biology to neurology. Moreover, our study finds that elucidating genetics and genetic diseases is an important nexus where basic science meets health sciences, enabling groundbreaking advances in the diagnosis and treatment of inherited diseases. Moreover, the synergy between biotechnology and mathematical biology is poised to catalyze innovations in systems biology and personalized medicine. In this regard, our research underlines the indispensable nature of interdisciplinary collaboration between basic and medical sciences to advance the frontiers of medical research and healthcare delivery. These collaborative efforts serve as catalysts in translating scientific discoveries into concrete healthcare solutions, thus promoting the development of more effective strategies for diagnosis, treatment, and disease prevention.

Keywords

Basic Sciences, Medical Basic Sciences, Collaboration Patterns, Scholarly Communication, Bibliometrics

Introduction

In his study, Starr (2013) examined in detail the great advances made in the fields of basic sciences such as mathematics, astronomy, medicine, chemistry and physics in Central Asia from the 8th century to the 14th century and stated that the important scientific centers and e-educational institutions in Central Asia were from different cultures (Starr, 2013). It states that it brings together scientists and encourages the exchange of information and has become the center of scientific research. Emphasizing that the blending of Islamic, Persian, Turkish and Indian cultures accelerated the spread and development of scientific knowledge, Starr said that names such as Al-Khwarizmi, Ibn Sina and Biruni, who were among the important scientists of this period, made groundbreaking studies in the fields of algebra, medicine and astronomy, and modern scientific knowledge was established. states that they laid the foundations of the methods. The scientific methodology developed in Central Asia took great steps in putting theoretical knowledge into practice by adopting an approach based on observations and experiments, and later inspired the scientific revolutions of the Renaissance and Enlightenment periods in Europe. He states that the knowledge produced in Central Asia was influential not only in the Islamic world, but also in other parts of Europe and Asia, and that the studies carried out in this period are considered an important legacy in the development of basic sciences today. In the Islamic world, significant progress was made in science and technology during a period when convergence occurred between the fundamental sciences and other disciplines. During this process, fundamental sciences such as mathematics and astronomy developed in close relationship with applied sciences like geography, navigation, and optics. For instance, mathematical calculations and astronomical observations played a crucial role in navigation and the development of geographical maps. Similarly, the science of optics combined with geometric principles enabled the creation of more complex optical instruments. The interaction between these scientific fields allowed Islamic scholars to establish a comprehensive and integrated system of knowledge (Sezgin, 2018). Basic sciences cover a wide range of subjects such as physics, chemistry, biology and mathematics. These sciences aim to investigate the basic principles, concepts and methodologies for understanding the natural world. Basic medical sciences focus on the basic knowledge required for medical practice and research, such as anatomy, physiology, biochemistry and pharmacology. The unity between these two fields is vital in several respects. Basic sciences help us understand the biological, chemical and physical mechanisms of medical science by providing information about the fundamental processes occurring in the human body. It also contributes to sustained healing by guiding medical researchers in the development of treatments and interventions. Basic medical sciences also use the principles of basic science to advance medical knowledge and practice. Researchers and healthcare professionals use discoveries and innovations in basic science to provide diagnostic tools, treatments, and medical advances. The inseparability of these fields is evident in the way they complement each other; Discoveries in one field often lead to breakthroughs in another. We found it necessary to conduct a data-based analysis to closely understand this relationship between scientific fields that have been in such a relationship since the early times of history.

Mathematics is the language of basic sciences. Mathematical models, theories, and calculations play a critical role in scientific research. Galileo's statement that "Nature is written in the language of mathematics" also emphasized the importance of mathematics in basic sciences (Galilei & Drake, 1990; Stillman, 1957). Mathematics provides the abstract structures and concepts necessary for theoretical physics and chemistry. For example, differential equations, probability theory, and linear algebra are basic tools used in modeling physical and chemical processes. Physics studies the fundamental laws and principles of nature. Fields such as mechanics, thermodynamics, electromagnetism and quantum mechanics form the basis of other branches of science such as chemistry and biology. Richard Feynman's statement "Physics is the basic science that is the basis of other sciences" also underlines the importance of this subject (Feynman, 1967). Physics is directly related to experimental methods and observations, just like chemistry and biology. It commonly plays a critical role in testing and validating theories. Chemistry deals with the composition, structure, properties and transformations of substances. This knowledge is essential for understanding processes in disciplines such as biology and materials science. Linus Pauling stated the importance of chemistry by saying, "Chemistry is the key to understanding biology and other natural sciences." (Hager & Hager, 2000). Chemistry provides the basis for other branches of science through the study of molecular structures and reaction mechanisms.

Convergence of Basic Sciences and Basic Health Sciences

Convergence between basic sciences (mathematics, physics, chemistry) and basic health sciences is possible if advances in the field of health are based on the principles of basic sciences. The interaction between these disciplines has played a critical role in diagnosis, treatment and disease management. When we look closely at this interaction, the provision, standardization and use of numerical values in clinical processes play a vital role in diagnosis and treatment processes. For example, accurately measuring and standardizing vital values such as blood pressure, pulse, and body temperature are critical in diagnosing and monitoring diseases (Pescatello et al., 2004). Calibration is necessary to ensure measuring devices provide accurate results (Greg Miller et al., 2011). Morphometric analysis, imaging methods (ultrasound, MRI, X-ray, CT) and interpretation of these images are of great importance in health sciences in terms of the data value of measurements. These technologies are important in that they enable the detection of anatomical and pathological changes (Bushberg et al., 2011). Applications such as remote consultation and robotic surgery improve healthcare using information technologies and artificial intelligence (Kwoh et al., 1988). It is used to monitor vital values such as EEG, EMG, ECG, pulse, pressure and blood pressure measurements, evaluate body functions and diagnose diseases (Teplan, 2002). These measurements enable patients' conditions to be monitored instantly and necessary interventions to be made in a timely manner (Izzo et al., 2008). Analysis of blood, urine and other body fluids is another issue of great importance in the diagnosis and treatment processes. Biochemistry, microbiology and molecular biology enable the detection of biological and chemical components in these fluids (Rifai, 2017). These analyzes are used to diagnose a variety of conditions such as infections, metabolic disorders and genetic diseases (Miller & Slovis, 2007). Radiology is used to image the internal structures of the body and detect diseases (Skundberg, 1998). Biochemistry investigates the causes and treatments of diseases by examining body chemistry and metabolic processes (Berg et al., 2015). Microbiology is used to identify microorganisms and determine the factors that cause diseases (Tortora et al., 1989). Molecular biology and genetics are critical for understanding diseases at the molecular level and developing treatment methods. Genetic analyzes identify genetic predispositions to diseases and enable personalized medicine practices (Alberts et al., 2014). Ecology studies the effects of environmental factors on human health. The body's metabolic activities interact with environmental factors, and monitoring these interactions is important in assessing health status (Odum

& Barrett, 1971) (Odum & Barrett, 2005). Hemostasis encompasses the biological processes that enable the body to maintain its internal balance. Monitoring these processes is important in managing bleeding disorders, clotting problems, and other related conditions (Hoffbrand et al., 2016). The nervous system analyzes the information coming from the body's internal and external receptors and allows the body to respond with this information. Information technologies and artificial intelligence contribute significantly to a better understanding of these processes and the development of treatment methods. For example, it is possible to identify and treat diseases by analyzing EEG and MRI data in the diagnosis of neurological disorders (Fisch & Spehlmann, 1999). In this context, the convergence between basic sciences and basic health sciences enables the development of modern medicine and the improvement of health services. While mathematics, physics and chemistry form the basis of measurement and analysis methods used in health sciences, the interdisciplinary collaboration is critical for more accurate diagnosis of diseases, development of treatment methods and increasing the overall quality of health services.

Our study aims to highlight the importance of collaboration and synergy between basic sciences and basic medical sciences by encouraging researchers, educators, and students to recognize and embrace the unity of these disciplines. It is critical for both fields to advance through joint efforts. In this context, in our study, we analyzed the 50 most frequently cited scientific research documents in the fields of basic sciences and medical basic sciences from a scientometric perspective. We performed cluster analysis, and the relationships between areas of scientific activity were visualized with a chord diagram. Interdisciplinary connections between various scientific fields are incredibly valuable for understanding complex and multifaceted topics, as these clusters demonstrate. Such connections create a collaborative environment where experts from different fields can address challenging problems by combining their knowledge, methodology, and insights. These collaborations often lead to groundbreaking discoveries, innovative solutions, and a more holistic view of the subject. In the context of the intersection between basic sciences and basic medical sciences, interdisciplinary connections may be particularly useful. It allows researchers to bridge the gap between basic scientific principles and practical applications in the medical field.

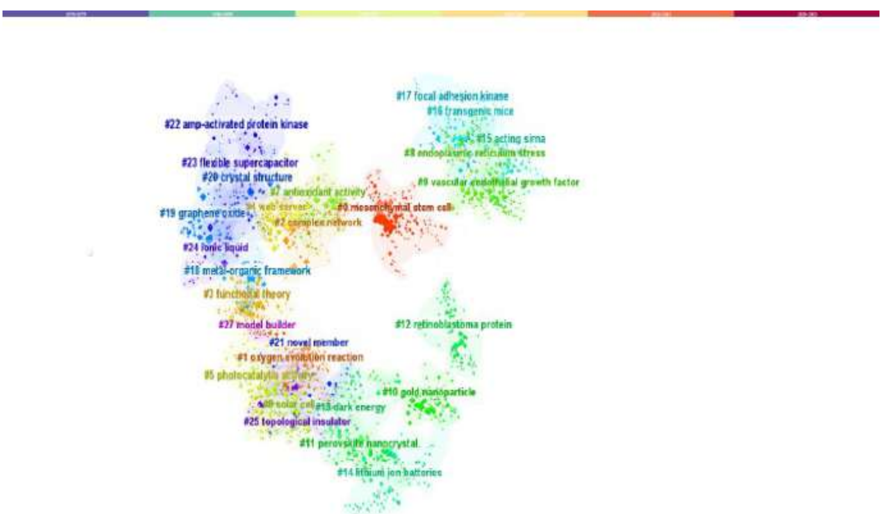
Our study aims to encourage researchers, educators, and students to recognize and embrace the unity of these disciplines by emphasizing the importance of cooperation and synergy between these two fields of scientific activity; It is critical for the advancement of both basic sciences and basic medical sciences through joint efforts. In this context, in our study, the 50 most frequently cited scientific research documents in the fields of basic sciences and medical basic sciences were analyzed from a scientometric perspective. Clustering analysis was carried out and the relationships between scientific activity areas were visualized with a chord diagram.

Cluster Analysis

Interdisciplinary connections among various scientific areas, as demonstrated by these clusters, are incredibly valuable for advancing our understanding of complex and multifaceted topics. Such connections foster a collaborative environment where experts from different fields can combine their knowledge, methodologies, and insights to address challenging problems. These collaborations often lead to groundbreaking discoveries, innovative solutions, and a more holistic perspective on the subject matter. In the context of the intersection between basic sciences and medical basic sciences, interdisciplinary connections can be particularly beneficial. They allow researchers to bridge the gap between fundamental scientific principles and their practical applications in the medical field (Figure 1).

Figure 1.

Major Clusters on the intersection of basic sciences between medical basic sciences



For example, the study of mesenchymal stem cells in Cluster 0 may have implications for regenerative medicine and tissue engineering, potentially leading to new treatments for various medical conditions. Furthermore, interdisciplinary connections promote cross-pollination of ideas, which can lead to the development of new research paradigms and the emergence of entirely new fields of study. In this age of rapidly advancing scientific knowledge, the ability to collaborate across disciplines is essential for tackling complex global challenges, such as healthcare, sustainability, and technology (Table 1).

Table 1.
Major Clusters

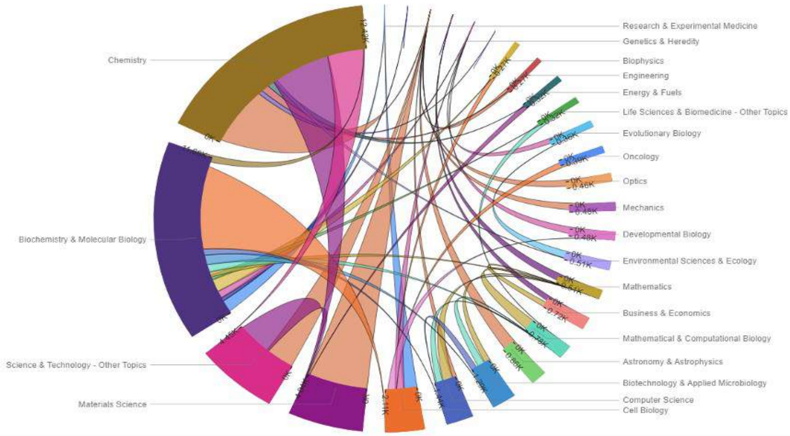
ClusterID	Size	Silhouette	Label (LLR)	Average Year
0	142	0.925	mesenchymal stem cell (62369.32, 1.0E-4)	1995
1	128	0.926	oxygen evolution reaction (20053.77, 1.0E-4)	2005
2	119	0.883	complex network (40258.84, 1.0E-4)	2007
3	118	0.942	functional theory (102156.16, 1.0E-4)	1992
4	116	0.888	web server (76543.49, 1.0E-4)	1997
5	98	0.879	photocatalytic activity (29492.65, 1.0E-4)	1999
6	98	0.861	solar cell (219814.75, 1.0E-4)	1999
7	96	0.898	antioxidant activity (115248.42, 1.0E-4)	1995
8	91	0.839	endoplasmic reticulum stress (22417.1, 1.0E-4)	1995
9	90	0.882	vascular endothelial growth factor (13128.83, 1.0E-4)	1992
10	86	0.862	gold nanoparticle (58295.91, 1.0E-4)	1999
11	85	0.868	perovskite nanocrystal (55852.69, 1.0E-4)	1998
12	81	0.916	retinoblastoma protein (18946.63, 1.0E-4)	1994
13	81	0.916	dark energy (41370.62, 1.0E-4)	1994
14	80	0.929	lithium ion batteries (22249.39, 1.0E-4)	2007
15	76	0.9	acting sirna (15744.19, 1.0E-4)	1996
16	68	0.919	transgenic mice (22514.15, 1.0E-4)	1993
17	60	0.885	focal adhesion kinase (21429.71, 1.0E-4)	1993
18	60	0.914	metal-organic framework (64099.98, 1.0E-4)	2003
19	58	0.861	graphene oxide (117374.06, 1.0E-4)	1997
20	57	0.914	crystal structure (80179.16, 1.0E-4)	1998
21	46	0.974	novel member (10512.55, 1.0E-4)	1989
22	43	0.908	amp-activated protein kinase (10376.6, 1.0E-4)	1992
23	33	0.935	flexible supercapacitor (9048.64, 1.0E-4)	2003
24	33	0.929	ionic liquid (45502.64, 1.0E-4)	2003
25	25	0.972	topological insulator (18143.62, 1.0E-4)	1994
27	10	0.997	model builder (391.59, 1.0E-4)	2010

Based on the data in the table, it seems that collaboration between basic sciences and basic sciences in the field of health is quite diverse and widespread. Biochemistry and molecular biology are especially closely associated with health sciences. While this discipline investigates the fundamentals of biological processes at the molecular level, it collaborates with other fields such as cell biology and biophysics to understand how these fundamental processes operate at the cellular level. These collaborations are important as they have a huge impact on many healthcare fields, from cancer research to neurological diseases and genetic disease research. Moreover, understanding genetics and genetic diseases can be called an important intersection of basic sciences and health sciences. Genetic research provides the basis for investigating the causes of genetic diseases and the potential to develop gene therapies. This has the potential to lead to major advances in the diagnosis and treatment of hereditary diseases. On the other hand, collaboration between biotechnology and applied microbiology, as well as mathematical and computational biology, is important in using genetics to analyze big data and mathematically model biological systems. This can be positioned among the important scientific developments that support the development of systems biology and personalized medicine. In conclusion, the data in the table show that collaboration between basic sciences and basic sciences in the field of health plays a fundamental role in the development of medical research and health care. In this regard, it can be said that the identified cooperation allows the transformation of scientific discoveries into health applications and will contribute to the development of more effective diagnosis, treatment, and disease prevention strategies.

All Degree is an indicator representing the number of connections within a network of a discipline. Higher All Degree values indicate more collaboration opportunities (Savanur & Srikanth, 2010; Wang et al., 2014). For example, "Biochemistry & Molecular Biology" and "Mathematics" have high All Degree values, suggesting that these disciplines are likely to collaborate frequently with Mathematics. Betweenness Centrality is used to identify key nodes in a network that facilitate communication between other disciplines. In this context, high Betweenness Centrality values indicate a discipline's potential to act as a bridge between other disciplines (Acedo et al., 2006; Goldman, 2014; Kong et al., 2019).

Collaboration Patterns Between Basic Sciences and Medical Basic Sciences

Figure 1.
Collaboration patterns among scientific research areas



Therefore, the high Betweenness Centrality value between "Physics" and "Ophthalmology" suggests a high potential for these two disciplines to bridge the gap between the health field and physics. High Aggregate Constraints indicate factors that limit a discipline's potential to collaborate with other disciplines (Ahuja, 2000; Burt, 2018; Lin et al., 2021). For instance, the high Aggregate Constraints between "Biochemistry & Molecular Biology" and "Acoustics" suggest limited collaboration potential between these two disciplines. Low Aggregate Constraints point to factors that do not limit, or even suggest a higher potential for, collaboration between disciplines. For example, the low Aggregate Constraints between "Neurosciences & Neurology" and "Psychiatry" indicate a high potential for collaboration between these two health-related disciplines (Table 2).

Table 2.
Social Network Analysis Parameters

All Degree	Betweenness centrality	High Aggregate constraints	Low Aggregate constraints
Biochemistry & Molecular Biology	Biochemistry & Molecular Biology	Mathematics	Acoustics
Chemistry	Chemistry	Behavioral Sciences	Parasitology
Cell Biology	Mathematics	Environmental Sciences & Ecology	Orthopedics
Mathematics	Cell Biology	Marine & Freshwater Biology	Microscopy
Physics	Life Sciences & Biomedicine - Other Topics	Geology	Ophthalmology
Science & Technology - Other Topics	Physics	Toxicology	Substance Abuse
Life Sciences & Biomedicine - Other Topics	Science & Technology - Other Topics	Zoology	Infectious Diseases
Biotechnology & Applied Microbiology	Environmental Sciences & Ecology	Computer Science	Astronomy & Astrophysics
Engineering	Mathematical & Computational Biology	Remote Sensing	Obstetrics & Gynecology
Materials Science	Research & Experimental Medicine	Biochemistry & Molecular Biology	Fisheries
Mathematical & Computational Biology	Computer Science	Mathematical & Computational Biology	Entomology
Computer Science	Biotechnology & Applied Microbiology	Veterinary Sciences	Pathology
Environmental Sciences & Ecology	Engineering	Instruments & Instrumentation	Psychiatry
Research & Experimental Medicine	Genetics & Heredity	Geography	Nutrition & Dietetics
Genetics & Heredity	Geology	Automation & Control Systems	Psychology
Biophysics	Materials Science	Science & Technology - Other Topics	Food Science & Technology
Developmental Biology	Evolutionary Biology	Radiology, Nuclear Medicine & Medical Imaging	Sociology
Evolutionary Biology	Developmental Biology	Imaging Science & Photographic Technology	Oceanography
Science & Technology - Other Topics	Immunology	Meteorology & Atmospheric Sciences	Mathematical Methods in Social Sciences
Geology	Agriculture	Biotechnology & Applied Microbiology	Business & Economics
Physiology	Marine & Freshwater Biology	Evolutionary Biology	Reproductive Biology
Immunology	Reproductive Biology	General & Internal Medicine	Agriculture
Oncology	Science & Technology - Other Topics	Engineering	Neurosciences & Neurology
Instruments & Instrumentation	Psychology	Life Sciences & Biomedicine - Other Topics	Paleontology
Marine & Freshwater Biology	Physiology	Pharmacology & Pharmacy	Biodiversity & Conservation

Discussion

The results presented in this study and the analysis of interdisciplinary connections among various scientific areas highlight the immense value of fostering collaborations between different fields. These interdisciplinary connections are incredibly valuable for advancing our understanding of complex and multifaceted topics, especially within the intersection of basic sciences and basic medical sciences (Council et al., 2010). Such connections foster a collaborative environment where experts from different fields can combine their knowledge, methodologies, and insights to address challenging problems (Boon et al., 2019; Saez-Rodriguez et al., 2016). These collaborations often lead to groundbreaking discoveries, innovative solutions, and a more holistic perspective on the subject matter. For instance, the close association between biochemistry and molecular biology with health sciences indicates significant collaboration opportunities that can impact many healthcare fields, from cancer research to neurological and genetic disease studies. The integration of mathematical and computational biology with biotechnology and applied microbiology further exemplifies how interdisciplinary approaches can enhance the analysis of big data and the mathematical modeling of biological systems, thereby supporting the development of systems biology and personalized medicine. In particular, the study of mesenchymal stem cells, as highlighted in Cluster 0, illustrates the potential implications for regenerative medicine and tissue engineering. Such interdisciplinary research can lead to new treatments for various medical conditions, showcasing the practical applications of basic scientific principles in the medical field. Moreover, interdisciplinary connections promote the cross-pollination of ideas, leading to the development of new research paradigms and the emergence of entirely new fields of study (Council et al., 2010; Madni, 2007; Richards, 2022; Saez-Rodriguez et al., 2016). This cross-disciplinary fertilization is crucial in the current age of rapidly advancing scientific knowledge, where tackling complex global challenges—such as healthcare, sustainability, and technological innovation—requires a collaborative and integrative approach. These insights underscore the critical need for ongoing interdisciplinary collaboration, highlighting how integrating basic sciences with health sciences is essential for advancing medical research and improving healthcare outcomes. The identified collaboration not only facilitates the transformation of scientific discoveries into health applications but also contributes to the development of more effective diagnosis, treatment, and disease prevention strategies (Cummings & Kiesler, 2005; Giansanti, 2024).

When evaluating the collaboration models between basic sciences and basic medical sciences, considering metrics such as All Degree, Betweenness Centrality, and Aggregate Constraints, it is evident that these two scientific research fields form an inseparable unity. These metrics help us understand the potential and limitations of collaboration between disciplines (Bright et al., 2017; Madni, 2007; Richards, 2022). For instance, the high All Degree values of "Biochemistry & Molecular Biology" and "Mathematics" indicate that these disciplines are likely to collaborate frequently. Mathematics plays a critical role in modeling and analyzing biochemical processes. Similarly, the high All Degree value for the "Physics" discipline suggests that it can establish strong collaborations with medical sciences; for example, physics knowledge is fundamental in fields such as medical imaging techniques. In our study, Betweenness Centrality was used to determine the potential for disciplines to act as bridges between each other (Bright et al., 2017; Jones et al., 2021; Ni et al., 2011). A high Betweenness Centrality value is significant for "Physics" and "Ophthalmology" as it indicates their potential to bridge the gap between health sciences and physics. The application of physical principles in the development of ophthalmologic imaging and optical devices is an example of how these two disciplines can effectively collaborate. Similarly, other disciplines with high Betweenness Centrality values can form critical bridges between health sciences and basic sciences, promoting multidisciplinary research projects and innovation. Aggregate Constraints are used to identify factors that either limit or encourage collaboration potential between disciplines. For example, the high aggregate constraints between "Biochemistry & Molecular Biology" and "Acoustics" suggest limited collaboration potential between these two disciplines. This may be due to methodological and theoretical differences between them. On the other hand, the low aggregate constraints between "Neurosciences & Neurology" and "Psychiatry" indicate a high potential for collaboration between these disciplines. Neurosciences and neurology play a critical role in understanding the biological foundations of psychiatric disorders, and research in these disciplines can provide significant theoretical and practical benefits.

In conclusion, the collaboration models between basic sciences and basic medical sciences vary according to their potential to act as bridges and their collaboration potential. Disciplines with high All Degree values and low aggregate constraints generally have higher collaboration potential. Additionally, disciplines with high Betweenness Centrality values play a crucial role in facilitating inter-disciplinary communication and collaboration. Such analyses play an important role in guiding research strategies and policy-making processes. The inseparable unity of basic sciences and basic medical sciences will continue to promote scientific progress and innovation.

Starr's detailed examination of advances in basic science in Central Asia from the 8th to the 14th centuries reveals how the convergence of different cultures and the establishment of major scientific centers fostered an environment conducive to scientific collaboration and innovation. This historical perspective highlights several important points that are highly relevant to the results of our current study of collaboration between basic sciences and basic medical sciences. It is possible to collect them under several headings

Cultural and Disciplinary Rapprochement:

Starr underlines how the blending of Islamic, Persian, Turkish and Indian cultures accelerated the spread and development of scientific knowledge. This convergence of different cultures has enabled the formation of a melting pot of ideas and methodologies, like how interdisciplinary collaborations in modern times combine knowledge from various scientific fields. Our study similarly demonstrates that interdisciplinary connections between basic sciences and health sciences can be used as a crucial lever to advance medical research and healthcare. Just as historical collaborations led to groundbreaking advances in fields such as algebra, medicine, and astronomy, contemporary interdisciplinary efforts have the potential to lead to innovations in medical diagnosis, treatment, and disease prevention.

Impact of Key Figures and Collaborative Efforts:

As Starr notes, the contributions of key scholars such as Al-Khwarizmi, Ibn Sina, and Biruni demonstrate the importance of key individuals in driving scientific progress through collaborative efforts. These figures worked at the intersection of multiple disciplines and laid the foundations of modern scientific methods. The high potential for collaboration between fields such as biochemistry, molecular biology, and health sciences in our study reflects the ongoing need for influential researchers to bridge gaps between disciplines. This collaboration is also vital for translating basic scientific discoveries into practical medical applications.

Methodological Developments:

While Starr emphasizes the methodological innovations developed in Central Asia, especially the adoption of observational and experimental approaches, he points out that this methodology contributed significantly to the practical application of theoretical knowledge, inspiring subsequent scientific revolutions in Europe. Our work similarly highlights how interdisciplinary collaborations between biotechnology, applied microbiology, mathematics, and computational biology are essential to advancing fields such as systems biology and personalized medicine. These collaborations are important in facilitating the development and application of complex models and large-scale data analysis in medical research.

Legacy and Global Impact:

Starr states that the scientific knowledge produced in Central Asia had a profound impact not only in the Islamic world, but also in Europe and Asia. This exchange of historical knowledge occurs in parallel with the global impact of contemporary scientific collaborations. Our study shows that interdisciplinary connections between basic sciences and health sciences can lead to significant advances in healthcare worldwide, reinforcing the idea that scientific progress is a collective, global effort. In the context of scholarly communication, the historical advancements in Central Asia, as highlighted by Starr, demonstrate the critical importance of effective information exchange and collaboration across diverse cultures and disciplines. The scientific achievements of this era were facilitated by vibrant scholarly networks that transcended geographical and cultural boundaries, promoting the free flow of knowledge and ideas. Similarly, our study underscores the necessity of robust interdisciplinary communication in the modern scientific landscape. Effective scholarly communication enables researchers from basic sciences and health sciences to share methodologies, data, and insights, fostering an environment where collaborative efforts can thrive and lead to significant medical and scientific breakthroughs. This exchange is essential for driving innovation and ensuring that scientific discoveries are translated into practical applications that benefit society.

Today, the important contributions of this convergence include digital health services, data security, fast and qualified service delivery, and archiving methods. Here are some current contributions on this subject. They have made a significant contribution to the digitalization of healthcare services. Electronic health records (EHR) and digital patient files increase the efficiency and accuracy of healthcare services and facilitate data sharing in the digital storage, processing and analysis of patient data B These digital systems provide quick access to patients' past health information and enable better management of treatment processes (Adler-Milstein & Jha, 2017). Storing health data digitally raises data security and privacy issues. Advanced encryption methods and security protocols are used to protect health information and prevent unauthorized access (Kruse et al., 2017). Blockchain technology is also used to securely store and share health data (Agbo et al., 2019). Technological advances provided by basic sciences contribute to accelerating diagnosis and treatment processes. Artificial intelligence and machine learning algorithms are used in early diagnosis of diseases and creation of treatment plans by analyzing large data sets (Topol, 2019). For example, artificial intelligence-supported analyzes in imaging techniques help radiologists make faster and more accurate diagnoses. (Litjens et al., 2017). Telemedicine increases access to healthcare by enabling patients to receive healthcare services remotely. These applications make it possible to treat patients in their homes through video conferences, mobile health applications and remote monitoring devices. (Dorsey & Topol, 2020). Telemedicine provides great convenience and benefit, especially for patients living in rural and remote areas. Long-term storage and management of health data is provided by digital archiving systems. These systems ensure that patient data is stored securely and accessed quickly when needed (Borycki & Kushniruk, 2022). Cloud-based solutions offer flexible and scalable platforms for storing and processing large data sets (Fernández-Alemán et al., 2013) (Fernández-Alemán et al., 2013).

The convergence between basic sciences and medical basic sciences has spurred digital transformation processes in recent years. To better understand the impact of these developments on the field, we examined digital technologies and digital transformation across various academic disciplines in Web of Science. The dataset presents a rich collection of 62,040 scientific documents compiled from 11,269 different sources spanning from 1900 to 2024. These documents examine the digitization between fundamental sciences (such as physics, chemistry, biology, mathematics, computer science, astronomy, geology, engineering, statistics, ecology) and medical basic sciences (like anatomy, physiology, biochemistry, molecular biology, genetics, pharmacology, microbiology, pathology, immunology, neuroscience). The dataset exhibits a continuous expansion with an annual growth rate of 6.58%, and on average, each document is 9.24 years old. There are on average 49.47 citations per document and a total of 2,219,409 references. The content includes 76,877 unique Keywords Plus (ID) and 119,228 unique Author's Keywords (DE). In this dataset encompassing 210,805 different authors, 6,086 documents are authored by a single author.

On average, each document is authored by 5.23 co-authors, with 25.21% of these collaborations being international. This dataset can be regarded as a rich academic resource covering extensive collaboration and diverse topics.

Table 3.

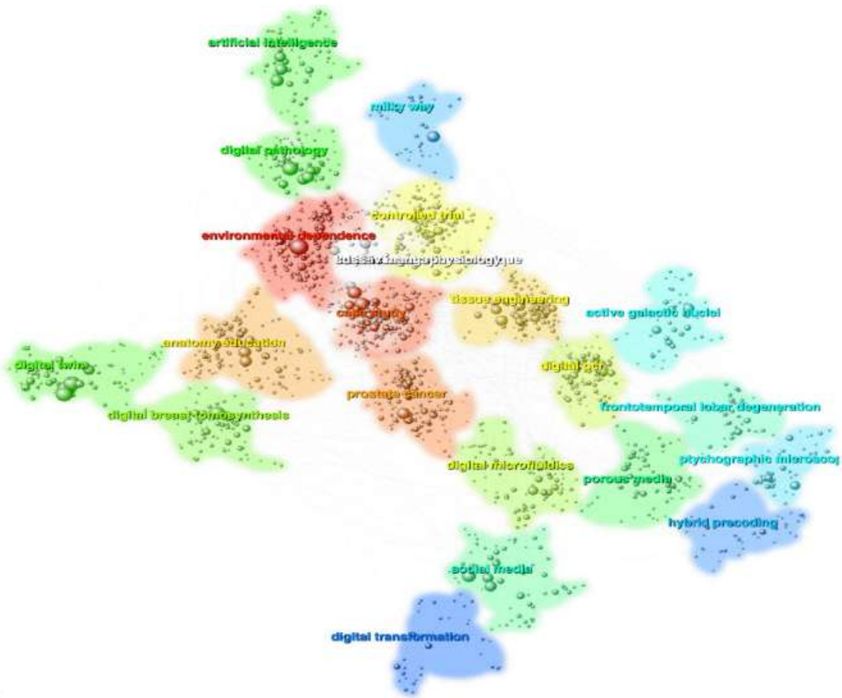
The dynamic interaction between basic sciences and digital transformation

ClusterID	Size	Silhouette	Label (LLR)	Average Year
0	186	0.897	environmental dependence (102440.38, 1.0E-4)	2005
1	159	0.863	case study (181355.56, 1.0E-4)	2004
2	134	0.827	prostate cancer (257985.75, 1.0E-4)	2002
3	127	0.947	anatomy education (34699.92, 1.0E-4)	2014
4	125	0.802	tissue engineering (170427.97, 1.0E-4)	2001
5	115	0.822	controlled trial (87161.27, 1.0E-4)	2008
6	98	0.833	digital pcr (171196.08, 1.0E-4)	2002
7	93	0.812	digital microfluidics (73658.54, 1.0E-4)	2005
8	86	0.804	digital breast tomosynthesis (197325.41, 1.0E-4)	2005
9	83	0.921	digital twin (267330.94, 1.0E-4)	2013
10	79	0.848	digital pathology (157251.06, 1.0E-4)	2007
11	72	0.891	artificial intelligence (174691.12, 1.0E-4)	2013
12	71	0.884	porous media (55969.01, 1.0E-4)	2011
13	68	0.921	social media (75901.56, 1.0E-4)	2011
14	53	0.837	frontotemporal lobar degeneration (23233.86, 1.0E-4)	2005
15	50	0.962	active galactic nuclei (69550.79, 1.0E-4)	2005
16	43	0.885	ptychographic microscopy (35561.96, 1.0E-4)	2005
17	42	0.887	milky way (19561.44, 1.0E-4)	2008
18	39	0.959	hybrid precoding (5020.77, 1.0E-4)	2015
19	33	0.977	digital transformation (28406.66, 1.0E-4)	2018
20	31	0.912	3d printing (32772.88, 1.0E-4)	2010
21	31	0.91	variance reduction technique (10450.86, 1.0E-4)	2005
22	22	0.947	cardiac electrophysiology (3984.99, 1.0E-4)	1996
23	14	0.982	human fetus (6845.69, 1.0E-4)	1995
24	7	0.999	sdss-iv manga (1427.95, 1.0E-4)	2010

The clusters identified in our study reveal the richness and diversity of interactions between basic sciences and digital transformation. While advances in basic sciences support the development and application of digital transformation technologies, digital transformation also accelerates research in basic sciences and paves the way for new discoveries. For example, in the fields of biochemistry and molecular biology, digital PCR and digital microfluidic technologies add new dimensions to genetic research by enabling sensitive and quantitative analysis of DNA and RNA. Similarly, digital breast tomosynthesis and digital pathology offer more accurate diagnosis and treatment opportunities as part of the digital transformation in medical imaging and radiology. Innovations such as artificial intelligence and digital twins are revolutionizing engineering and manufacturing processes while accelerating the development of systems biology and personalized medicine. Additionally, 3D printing technology supports innovations in bioengineering by providing the ability to produce complex structures quickly and at low cost in manufacturing and design. This interrelationship allows scientific and technological advances to develop synergistically, making it possible to investigate topics such as environmental interdependence, active galactic nuclei and the Milky Way in greater depth and on a larger scale. As a result, this dynamic interaction between basic sciences and digital transformation contributes to the development of more effective strategies by enabling the translation of scientific discoveries into health applications and industrial innovations.

Figure 3.

Major Clusters on the intersection of basic sciences with digital transformations



Throughout history, the development of science and technology has been possible because of the exchange of information and intellectual rapprochement between different cultures and civilizations. The Islamic world made significant contributions to basic sciences and engineering during the Middle Ages, and these contributions laid the foundations of modern science in the West with the Renaissance. While scientific developments in Islamic civilization advanced fields such as mathematics, astronomy, medicine and optics, scientists in this period took ancient Greek, Indian and Persian sciences and developed them further, developing new theories and applications. This information was revived in the West with the Renaissance and paved the way for the scientific revolution in the Western world. The contributions of the Islamic world, especially in mathematics and astronomy, were adopted and expanded by scientists in the West. This process was not limited to the transfer of scientific knowledge, but also led to the evolution of scientific methods. Experimental methods developed in the Islamic world, observational astronomy, mathematical modeling and systematic studies in medicine played a critical role in the formation of the scientific method in the West and became an event that emphasized the importance of convergence between sciences. Scientific developments in the Islamic world have not only been limited to basic sciences but have also manifested themselves in applied sciences and technological innovations. These innovations have demonstrated the superiority of Islamic civilization in practical areas such as navigation, cartography, agricultural techniques and architecture. On the other hand, it is obvious that scientific advances in the modern world have been enriched by social diversity, cooperation and mutual learning processes. Today, science and technology are being carried forward with the contributions of different cultural and ethnic groups, and this diversity nourishes scientific creativity. In this context, the scientific heritage that began in the Islamic world and continues in the West inspires today's interdisciplinary studies. Modern scientific processes are a natural result of the intellectual convergence in the past and the accumulation of different civilizations. The adoption and expansion of scientific developments that began in the Islamic world in the West has ensured the formation of a global scientific heritage. This heritage emphasizes the importance of diversity and cooperation in modern science and reveals the value of sharing knowledge and mutual learning among societies. Therefore, the nourishment of scientific developments by social and cultural convergence has contributed to the increase in humanity's common scientific knowledge. In this context, the scientific rapprochement that took place between the Islamic world and the West throughout history continues to inspire today's interdisciplinary scientific studies and technological innovations. In this context, the revival of scientific studies that were founded in the Islamic world in the West demonstrates how cooperation between basic and applied sciences enables the development of innovations that will benefit humanity. Findings obtained in basic sciences such as mathematics and astronomy have been transformed into practical applications in fields such as geography, medicine and engineering, which has led to an increase in scientific knowledge. This process demonstrates how basic and applied sciences complement and enrich each other, and how interdisciplinary cooperation is the key to scientific progress and technological innovations.

References

Acedo, F. J., Barroso, C., Casanueva, C., & Galán, J. L. (2006). Co-authorship in management and organizational studies: An empirical and network analysis. *Journal of management studies*, *43*(5), 957-983.

Adler-Milstein, J., & Jha, A. K. (2017). HITECH Act Drove Large Gains In Hospital Electronic Health Record Adoption. *Health Affairs*, *36*(8), 1416-1422. https://doi.org/https://doi.org/10.1377/hlthaff.2016.1651

Agbo, C. C., Mahmoud, Q. H., & Eklund, J. M. (2019). Blockchain Technology in Healthcare: A Systematic Review. *Healthcare*, *7*(2), 56. https://www.mdpi.com/2227-9032/7/2/56

Ahuja, G. (2000). Collaboration networks, structural holes, and innovation: A longitudinal study. *Administrative science quarterly*, *45*(3), 425-455.

Alberts, B., Johnson, A., Lewis, J., Morgan, D., Raff, M., Roberts, K., & Walter, P. (2014). Molecular biology of the cell 6th ed (new york, ny: Garland science).

Berg, J., Tymoczko, J., Gatto Jr, G., & Stryer, L. (2015). Protein synthesis. *Biochemistry*, *8*, 893-924.

Boon, M., van Baalen, S., & Groenier, M. (2019). Interdisciplinary expertise in medical practice: Challenges of using and producing knowledge in complex problem-solving. *Medical Teacher*, *41*(6), 668-677.

Borycki, E. M., & Kushniruk, A. W. (2022). Reinventing virtual care: Bridging the healthcare system and citizen silos to create an integrated future. *Healthcare Management Forum*, *35*(3), 135-139. https://doi.org/10.1177/08404704211062575

Bright, C. F., Haynes, E. E., Patterson, D., & Pisu, M. (2017). The value of social network analysis for evaluating academic-community partnerships and collaborations for social determinants of health research. *Ethnicity & disease*, *27*(Suppl 1), 337.

Burt, R. S. (2018). Structural holes. In *Social stratification* (pp. 659-663). Routledge.

Bushberg, J., Seibert, J., Leidholdt, E., & Boone, J. (2011). Modes of CT acquisition. *The Essential Physics of Medical Imaging*, *1*, 341-350.

Council, N. R., Earth, D. o., Studies, L., Engineering, D. o., Sciences, P., Sciences, B. o. C., Sciences, B. o. L., Physics, B. o., Physical, C. o. R. a. t. I. o. t., & Sciences, L. (2010). Research at the intersection of the physical and life sciences.

Cummings, J. N., & Kiesler, S. (2005). Collaborative research across disciplinary and organizational boundaries. *Social studies of science*, *35*(5), 703-722.

Dorsey, E. R., & Topol, E. J. (2020). Telemedicine 2020 and the next decade. *The Lancet*, *395*(10227), 859. https://doi.org/10.1016/S0140-6736(20)30424-4

Fernández-Alemán, J. L., Señor, I. C., Lozoya, P. Á. O., & Toval, A. (2013). Security and privacy in electronic health records: A systematic literature review. *Journal of Biomedical Informatics*, *46*(3), 541-562. https://doi.org/https://doi.org/10.1016/j.jbi.2012.12.003

Feynman, R. (1967). The character of physical law (1965). *Cox and Wyman Ltd., London*.

Fisch, B. J., & Spehlmann, R. (1999). Fisch and Spehlmann's EEG primer: basic principles of digital and analog EEG. *(No Title)*.

Galilei, G., & Drake, S. (1990). Discoveries and opinions of Galileo: including The starry messenger (1610), Letter to the Grand Duchess Christina (1615), and excerpts from Letters on sunspots (1613), The assayer (1623). *New York: Anchor Books*.

Giansanti, D. (2024). Joint Expedition: Exploring the Intersection of Digital Health and AI in Precision Medicine with Team Integration. In (Vol. 14, pp. 388): MDPI.

Goldman, A. W. (2014). Conceptualizing the interdisciplinary diffusion and evolution of emerging fields: The case of systems biology. *Journal of informetrics*, *8*(1), 43-58.

Greg Miller, W., Myers, G. L., Lou Gantzer, M., Kahn, S. E., Schönbrunner, E. R., Thienpont, L. M., Bunk, D. M., Christenson, R. H., Eckfeldt, J. H., & Lo, S. F. (2011). Roadmap for harmonization of clinical laboratory measurement procedures. *Clinical Chemistry*, *57*(8), 1108-1117.

Hager, T., & Hager, T. (2000). *Linus Pauling: And the Chemistry of Life*. Oxford University Press.

Hoffbrand, A. V., Higgs, D. R., Keeling, D. M., & Mehta, A. B. (2016). *Postgraduate haematology*. John Wiley & Sons.

Izzo, J. L., Sica, D. A., & Black, H. R. (2008). *Hypertension primer*. Lippincott Williams & Wilkins.

Jones, P. J., Ma, R., & McNally, R. J. (2021). Bridge centrality: A network approach to understanding comorbidity. *Multivariate behavioral research*, *56*(2), 353-367.

Kong, X., Shi, Y., Yu, S., Liu, J., & Xia, F. (2019). Academic social networks: Modeling, analysis, mining and applications. *Journal of Network and Computer Applications*, *132*, 86-103.

Kruse, C. S., Smith, B., Vanderlinden, H., & Nealand, A. (2017). Security Techniques for the Electronic Health Records. *Journal of Medical Systems*, *41*(8), 127. https://doi.org/10.1007/s10916-017-0778-4

Kwoh, Y. S., Hou, J., Jonckheere, E. A., & Hayati, S. (1988). A robot with improved absolute positioning accuracy for CT guided stereotactic brain surgery. *IEEE transactions on biomedical engineering*, *35*(2), 153-160.

Lin, Z., Zhang, Y., Gong, Q., Chen, Y., Oksanen, A., & Ding, A. Y. (2021). Structural hole theory in social network analysis: a review. *IEEE transactions on computational social systems*, *9*(3), 724-739.

Litjens, G., Kooi, T., Bejnordi, B. E., Setio, A. A. A., Ciompi, F., Ghafoorian, M., van der Laak, J. A. W. M., van Ginneken, B., & Sánchez, C. I. (2017). A survey on deep learning in medical image analysis. *Medical Image Analysis*, *42*, 60-88. https://doi.org/https://doi.org/10.1016/j.media.2017.07.005

Madni, A. M. (2007). Transdisciplinarity: Reaching beyond disciplines to find connections. *Journal of Integrated Design and Process Science*, *11*(1), 1-11.

Ni, C., Sugimoto, C., & Jiang, J. (2011). Degree, Closeness, and Betweenness: Application of group centrality measurements to explore macro-disciplinary evolution diachronically. Proceedings of ISSI,

Odum, E. P., & Barrett, G. W. (1971). *Fundamentals of ecology* (Vol. 3). Saunders Philadelphia.

Pescatello, L. S., Franklin, B. A., Fagard, R., Farquhar, W. B., Kelley, G. A., & Ray, C. A. (2004). Exercise and hypertension. *Medicine & science in sports & exercise*, *36*(3), 533-553.

Richards, M. (2022). Interdisciplinary Research: Bridging Gaps for Comprehensive Scientific Understanding. *International Journal of Open Publication and Exploration, ISSN: 3006-2853*, *10*(1), 19-25.

Rifai, N. (2017). *Tietz Textbook of Clinical Chemistry and Molecular Diagnostics: Tietz Textbook of Clinical Chemistry and Molecular Diagnostics-E-Book*. Elsevier Health Sciences.

Saez-Rodriguez, J., Costello, J. C., Friend, S. H., Kellen, M. R., Mangravite, L., Meyer, P., Norman, T., & Stolovitzky, G. (2016). Crowdsourcing biomedical research: leveraging communities as innovation engines. *Nature Reviews Genetics*, *17*(8), 470-486.

Savanur, K., & Srikanth, R. (2010). Modified collaborative coefficient: A new measure for quantifying the degree of research collaboration. *Scientometrics*, *84*(2), 365-371.

Sezgin, F. (2018). *İslam'da Bilim ve Teknik*. Türkiye Bilimler Akademisi.

Skundberg, P. A. (1998). Radiologic Science for Technologists: Physics, Biology, and Protection. *Radiology*, *207*(2), 310-310.

Starr, S. F. (2013). *Lost enlightenment: Central Asia's golden age from the Arab conquest to Tamerlane*. Princeton University Press.

Stillman, D. (1957). *Discoveries and opinions of Galileo* (Vol. 94). Anchor.

Teplan, M. (2002). Fundamentals of EEG measurement. *Measurement science review*, *2*(2), 1-11.

Topol, E. J. (2019). High-performance medicine: the convergence of human and artificial intelligence. *Nature Medicine*, *25*(1), 44-56. https://doi.org/10.1038/s41591-018-0300-7

Tortora, G. J., Funke, B. R., & Case, C. L. (1989). *Microbiology*. Benjamin-Cummings Publishing Company.

Wang, C., Rodan, S., Fruin, M., & Xu, X. (2014). Knowledge networks, collaboration networks, and exploratory innovation. *Academy of management journal*, *57*(2), 484-514.

About Authors

Prof. Dr. Muzaffer ŞEKER | Turkish Academy of Sciences | mseker[at]tuba.gov.tr | ORCID: 0000-0002-7829-3937

Prof. Dr. Muzaffer Şeker graduated from Uludağ University Veterinary Faculty in 1986. Subsequently, Prof. Şeker earned his Ph.D. in Human Anatomy at the University of Leicester, Faculty of Medicine in England, in 1995. He achieved the position of associate professor in 2000 and was promoted to full professorship in 2006. Throughout his career, Prof. Şeker worked as an instructor in the United Arab Emirates for two years and also held the position of the Head of the Department of Medical Education and Informatics at the Meram Faculty of Medicine at Selçuk University. He played a crucial role as a member of the Founding Board of Trustees of Istanbul Medipol University from 2008 to 2010. In December 2014, he was appointed as the founding rector of Konya Necmettin Erbakan University. He has also served on the selection committees of Türkiye Institutes of Health Administration (TÜSEB) Aziz Sancar Science, Service, and Incentive Awards; YÖK Doctorate Awards; TÜBA-GEBİP Awards; and TÜBİTAK Science, Service, and Incentive Awards. He began his role as President of Turkish Academy of Sciences in 2019. Prof. Şeker has also represented his country at the Science 20 Summits, World Science Forum, and many other international scientific events.

Assoc. Prof. Haydar YALÇIN | Ege University | haydar.yalcin[at]ege.edu.tr | ORCID: 0000-0002-5233-2141

Associate Professor Dr. Haydar Yalçın serves as the Head of the Department of Management Information Systems at Faculty of Economics and Administrative Sciences, Ege University. Dr. Yalçın has garnered attention for his significant contributions to the field, particularly through his works such as "Technology Mining: Artificial Intelligence in Manufacturing" and "Forecasting Technological Positioning through Technology Knowledge Redundancy: Patent Citation Analysis of IoT, Cybersecurity, and Blockchain." As a member of the Omega Rho International Honor Society at Portland State University, Dr. Yalçın has made substantial interdisciplinary contributions throughout his academic career. He has served as a Visiting Scientist in the Department of Engineering and Technology Management at Portland State University, and he also contributes as a faculty member at the Mark O. Hatfield Center for Cybersecurity and Cyber Defense Policy at the same institution. Known for his research in science management, technology forecasting, and data analytics, Dr. Yalçın also mentors students, fostering their academic achievements. His international projects include leading initiatives funded by armasuisse, the Swiss Federal Department of Defense, such as "Technology Monitoring and Forecasting for Quantum Technologies: A Scientometric Approach" and "Technology Monitoring and Forecasting for Cyberdefense: A Scientometric Approach." These projects underscore his ongoing contributions to cybersecurity and next-generation security technologies.

SUSTAINABLE DEVELOPMENT: WHY BASIC SCIENCE HAS BEEN THE CURSE AND IS THE CURE

Caroline Johnson

10.53478/TUBA.978-625-6110-22-9.ch06

Sustainable Development: Why Basic Science has been the Curse and is the Cure

Caroline Johnson
Fondazione Bruno Kessler

Abstract

Almost all aspects of global development, including economic, social, environmental, and even political progress, can arguably be traced back to discoveries in basic science. Basic science, originating from the curiosity and perseverance of pioneering minds, involves asking seemingly simple questions with complex answers, thereby laying the foundation for research. Scientific inquiry: the systematic search for evidence to validate or refute hypotheses, is a process that has evolved over time to incorporate structured approaches such as hypothesis testing. However, contemporary scientific research has increasingly become intertwined with considerations of potential benefits, societal impacts, and economic returns, often driving funding decisions. This trend raises questions about the commodification of scientific research and its potential impact on the pursuit of fundamental knowledge. Moreover, the decline in purely exploratory research coincides with the world's drift towards unsustainable practices. The question arises: has the methodical approach and emphasis on tangible outcomes contributed to the diminishing role of basic science? Conversely, could a resurgence in basic science research offer insights and solutions for a more sustainable future? By prioritizing curiosity-driven inquiry and revisiting the roots of scientific discovery, there is potential to unlock novel solutions and inform sustainable development strategies. Thus, a reinvigorated commitment to basic science research may hold the key to addressing the challenges of sustainability and fostering global development in innovative ways.

Keywords
Basic Science, Technology, Innovation, Global Development, Sustainable Development.

Introduction

Sustainable development stands at the forefront of global agendas, highlighting the need to balance economic growth, social equity, and environmental stewardship to meet the needs of present and future generations. As nations contend with pressing challenges such as climate change, biodiversity loss, and resource depletion, the role of basic science in shaping the trajectory of sustainable development has come under increasing scrutiny. On one hand, basic science has been criticized for fuelling unsustainable practices and exacerbating environmental degradation. On the other, it holds the promise of unlocking innovative solutions that could create transformative pathways towards a more sustainable future.

The relationship between basic science and sustainable development is multifaceted, reflecting both the opportunities and challenges inherent to scientific inquiry and technological advancement. At its core, basic science encompasses the pursuit of knowledge for its own sake, driven by curiosity, exploration, and the quest for understanding the fundamental principles of the natural world. This intrinsic curiosity has led to groundbreaking discoveries and paradigm shifts in scientific thinking, laying the foundations for technological innovations that have shaped civilization.

Unfortunately, the pursuit of knowledge through basic science has also had unforeseen and unintended consequences, contributing to environmental degradation, social inequalities, and economic disparities. Industrialization, enabled by scientific and technological developments, has led to the extraction and exploitation of natural resources on a massive scale, resulting in pollution, habitat destruction, and contributing to climate change. Furthermore, scientific and technological innovations have not always been deployed in ways that prioritize environmental sustainability or address the needs of marginalized communities, thus perpetuating patterns of inequity and injustice.

However, basic science also holds immense potential; it could catalyse sustainable development, offering insights, tools, and solutions to address the complex challenges facing society and the planet. By deepening our understanding of natural systems, basic science can provide the foundation for developing new sustainable technologies, designing resilient ecosystems, and fostering inclusive and equitable societies. More importantly, the critical thinking, creativity, and collaboration required in basic science would empower individuals and communities to engage in evidence-based decision-making and collective action for sustainability.

This paper explores the dual role of basic science as both the curse and the cure for sustainable development. Drawing on interdisciplinary perspectives from science, policy, and ethics, the historical and contemporary interactions between basic science and sustainable development are examined. Key challenges, opportunities, and pathways forward are presented. The complex dynamics that shape the relationship between basic science and sustainable development are highlighted and used to identify strategies that harness the transformative potential of science to build a more sustainable and resilient future.

The Foundations of Basic Science: Exploring Meaning, Historical Roots, and Evolution

Basic science, often referred to as fundamental or pure science, explores natural phenomena, principles, and laws through systematic observation, experimentation, and analysis. It is characterized by the pursuit of understanding without immediate practical applications or commercial objectives, aiming instead to uncover the underlying mechanisms governing the physical, biological, and social spheres. In practice, basic science expands the frontiers of knowledge and advances scientific theories, forming the foundations for applied research and technological innovation.

At its core, basic science embodies several key characteristics: firstly, it involves exploring fundamental concepts in all scientific disciplines, including physics, chemistry, biology, mathematics, and social sciences – often within but also across disciplinary boundaries. This approach fosters a comprehensive understanding of natural phenomena and their underlying principles. Secondly, basic science is driven by curiosity and determined inquiry. Researchers embark on open-ended exploration, posing fundamental questions and pursuing novel lines of investigation without expectations, predetermined outcomes, or practical applications in mind.

Empirical methods and rigorous analysis are integral to basic science. Researchers rely on controlled experiments, data collection, and meticulous analysis to generate evidence, test hypotheses, and refine scientific theories. An extension of this aspect is collaboration and peer review: researchers may collaborate across disciplines, engage in interdisciplinary exchange, and subject their work to peer review processes ensuring the validity and reliability of scientific findings. While basic science may not result in immediate practical applications, it often leads to exciting chance discoveries, breakthroughs, and "needle-moving" innovations that have far-reaching implications for society, technology, and human knowledge over the long term.

Examples of basic science research cover a broad range of studies, including investigations into fundamental particles in physics, genetic mechanisms in biology, chemical reactions in chemistry, mathematical principles, social behaviours, and cosmic phenomena. By creating the foundations for applied research, technological development, and innovation, basic science has been and continues to be critical for advancing medicine, engineering, agriculture, environmental science, and many other fields.

The roots of basic science can be traced back to ancient civilizations, where pioneering scholars observed, experimented, and theorized about the natural world. These early inquiries, born from the intellectual curiosity of early thinkers, gradually evolved into distinct disciplines that have remained throughout the advent of modern scientific practices. Some examples of the various civilisations that have contributed to the evolution of basic science are presented.

In Ancient Mesopotamia and Egypt, significant discoveries were made in early scientific knowledge, spanning disciplines such as mathematics, astronomy, and medicine. Mesopotamian astronomers devised methods for observing celestial phenomena and tracking time (Hunger & Pingree, 1989), while the Egyptians developed medical techniques and herbal remedies (early medicines), pioneering advances that were adopted by and elaborated on by other civilizations (Nunn, 1996).

The intellectual fever of Ancient Greece birthed a pantheon of luminaries; individuals often recognised as being both philosophers and scientists, who worked across many subject fields including the natural sciences, mathematics, botany, zoology, psychology, theology, ethics, metaphysics, and literary theory. Such individuals include, Thales who developed methods to predict the weather and a solar eclipse, and theorised the origins of earthquakes postulating that they occurred when the earth is rocked on the water on which it floats (Harris, 2005); Pythagoras, who recognised that the

Earth was a sphere, that the Moon was inclined to the equator of the Earth, and that the planet Venus was both the evening star and the morning star, and famously devised the Pythagorean theorem a notable contribution to mathematics (Zhmud, 2018); and Aristotle, who conceptualised the practice of scientific analysis and is known for creating formal logic using deduction to create a pathway to a conclusion (McKeon, 1947). By embracing observation, reason, and logic as tools for understanding the natural world, these luminaries provided ground-breaking insights across disciplines and formed enduring pillars of scientific thought (Lloyd, 1970; Barnes, 2001).

During the Islamic Golden Age, spanning the 8th to 14th centuries, scholars in the Islamic world translated classical texts – Greek and Sanskrit – into Arabic and furthered the pursuit of knowledge, contributing to a diverse range of subject domains. Amongst others, Abu Yusuf Yaqub Ibn Ishaq Al-Kindi, Muhammad ibn Musa al-Khwarizmi, and Ḥasan Ibn al-Haytham were notable scholars of the time. Abu Yusuf Yaqub Ibn Ishaq Al-Kindi, credited as being the ‘Father of Arab philosophy’, studied the natural sciences and was a strong mathematician. He made notable contributions to many fields including mathematics with his work ‘Manuscript on Deciphering Cryptographic Messages’, which forged the field of cryptanalysis; medicine, creating the earliest known medicine dosing administration device; and, physics, establishing the theory of sound and showing how the human voice creates waves that travel through the air and are received by the cochlea in the ear (Broemeling, 2011). Muhammad ibn Musa al-Khwarizmi, the ‘Father of Algebra’, progressed the fields of mathematics. The title of his book ‘Al-Jabr’, meaning ‘reunion of broken parts’, is the etymological root of the word *algebra*, the branch of mathematics he established (Gandz, 1926). He also advanced geography, using data collected by Ptolemy, he improved the accuracy of the coordinates for the Mediterranean Sea, Asia, and Africa (Mercier, 2020); astronomy, by calculating calendrical and astronomical data for the movements of the Sun, the Moon, and the classical planets – Venus, Jupiter, Mars, Mercury, and Saturn (Marini, 2023). Ḥasan Ibn al-Haytham was a pioneer notably in the field of optics, he wrote the book ‘Kitab al-Manazir’ (‘Book of Optics’) providing the earliest explanation for how eyesight works and detailing how vision results from the brain processing information. He was also an early champion of the scientific method, advocating that a hypothesis must be tested using a systematic, methodical approach to experimental analysis or mathematical reasoning (Gorini, 2003). Their works and those of their contemporaries during the Islamic Golden Age, forged new pathways of discovery, paving the way for the European Renaissance (Lindberg, 1992; Saliba, 2007).

The European Renaissance and Enlightenment periods (c. 14th century) through to the early modern period (c. 16th century) witnessed a revival in classical knowledge and learning and a deeper exploration of the natural world, giving way to modern scientific methodologies. Leading visionaries from this period include Leonardo di ser Piero da Vinci, who advanced anatomy and physiology with his intricate drawings and dissection of the human form, as well as early engineering inventions, for example, his infamous design of a flying machine (that bears an uncanny resemblance to a modern-day helicopter); Nicolaus Copernicus, a Renaissance polymath, who devised a model placing the Sun, not the Earth, at the centre of the universe; and, Galileo di Vincenzo Bonaiuti de' Galilei, the 'father of observational astronomy', a classical physicist and progressor of the scientific method and modern science. The discoveries of this period not only built on earlier findings but also challenged widely held beliefs and advanced the skill of scientific method (Westfall, 1980; Kuhn, 1996).

These transformative historical epochs led to the establishment of modern scientific disciplines and institutions, marking the earliest stages of basic science as a systematic pursuit of knowledge about the natural world (Lindberg, 1992). From the subsequent Scientific Revolution of the 16th to 18th centuries emerged new scientific methodologies, experimental techniques, and theories, propelling humanity into the modern era of science and enlightenment (Kuhn, 2012). The institutionalization of science through scientific establishments and societies provided vital support for scientific research, collaboration, and knowledge dissemination, furthering the advancement of scientific progress (Shapin, 1996).

The Industrial Revolution of the 18th and 19th centuries ushered in a new era of rapid technological advancements and scientific discoveries, catalysed by innovations in chemistry, physics, engineering, and biology (Landes, 1969). These developments built on earlier scientific investigative findings that can be traced back to the aforementioned curiosity of ancient thinkers and scholars, whose work formed the basis for modern science.

Empowering Global Progress: The Role of Basic Science in Driving Development

The history of industrialization and global development spans centuries, marked by significant shifts in economic, social, and technological landscapes. Industrialization, characterized by the mechanization of production processes and the rise of factories, began in the 18th century in Europe before spreading globally, transforming societies and economies. The Industrial Revolution brought about rapid urbanization, increased productivity, and economic growth, leading to the formation of modern industrial societies (Mokyr, 1990).

Science and technology played pivotal roles in driving industrialization and global development. Advances in science, particularly in physics, chemistry, and engineering, led to innovations such as steam power, the mechanization of textile production, and the development of new materials and transportation systems (Landes, 1969). These technological breakthroughs revolutionized agriculture, manufacturing, and transportation, leading to increased efficiency, productivity, and economic output.

The second wave of industrialization, which occurred in the late 19th and early 20th centuries, saw further advancements in science and technology, including the harnessing of electricity, the mass production of goods, and the development of telecommunications and infrastructure (Landes, 1969). These innovations facilitated globalization, enabling the movement of goods, capital, and ideas across borders and continents. In the post-World War II era, science and technology continued to drive global development through innovations such as computers, telecommunications, and the internet. These advances seeded the information age, transforming industries, communication, and commerce on a global scale (Perez, 2002).

The history of industrialization and global development demonstrates the transformative power of science and technology in driving economic growth, innovation, and social progress. From the Industrial Revolution to the information age, scientific advancements have been instrumental in shaping the trajectory of human civilization and advancing global development.

The role of basic science has been pivotal in propelling global development through its expansive and enduring contributions to knowledge enrichment, innovation facilitation, and solution provision across a diverse range of industry sectors and social domains. There are many ways in which basic science has underpinned, and subsequently impacted, global advancement. These are an important consideration when reflecting on and learning from the world's pathway to the unsustainable present, assessing the ambiguity of the immediate future, and creating a vision for a long-term sustainable future.

Technological advancements are a testament to how basic science research has catalysed groundbreaking innovations in technology, engineering, and medicine. Noteworthy breakthroughs such as the transistor, laser, MRI, and DNA sequencing are exemplary of the transformative impacts of fundamental research, leading to profound shifts in industries and augmenting human well-being on a global scale (Landes, 1969; Collins & McKusick, 2001).

Healthcare and medicine have been significantly influenced by basic science research, particularly in the disciplines of biology, genetics, and biochemistry. Insights gained from such research have propelled advancements in disease understanding, pathogen characterization, and human physiology comprehension (Collins & McKusick, 2001). Consequently, the development of vaccines, antibiotics, medical treatments, and diagnostic tools has ensued, thereby lowering mortality rates, and enhancing public health outcomes, all leading to substantially improved global health (Plotkin et al., 2013).

Similarly, economic growth and innovation have depended on basic science research, which has provided the foundational knowledge and technological underpinnings that have driven productivity, competitiveness, and job creation across industries (Mazzucato, 2013). From biotechnology to information technology, materials science, and renewable energy sectors, basic science has served as an indispensable catalyst for fostering innovation, entrepreneurship, and economic prosperity on a global scale.

Education and capacity building constitute another domain wherein basic science research has an integral role, through its contribution to scientist, researcher, and innovator training. By nurturing critical thinking, problem-solving, and scientific literacy, basic science research emphasizes the imperatives of addressing global challenges and advancing sustainable development efforts, nurturing human capital which has been essential for global-scale progress (National Research Council, 2002).

Basic science research has been instrumental in driving sustainable development and environmental conservation efforts providing critical insights into ecosystem functioning, climate dynamics, and anthropogenic impacts on the environment. These insights serve as cornerstones for informing governmental policies, social practices, and industry technologies aimed at fostering environmental sustainability, biodiversity conservation, and climate resilience fortification, thereby engendering a more harmonious coexistence with the natural world (Millennium Ecosystem Assessment, 2005).

The Evolution and Significance of Sustainability: A Societal Imperative

The concept of sustainability, within the context of contemporary discourse, emerged in the 20th century and gained substantial attention and momentum, particularly in the latter half of the century. However, sustainability has a much longer, deeper-rooted past extending back to earlier philosophies and practices that have developed and evolved over time.

Early sustainability influence came from indigenous cultures: many indigenous societies worldwide have long upheld sustainable practices, acknowledging the intricate and delicate interplay between humans and the natural environment. Their ethos is to preserve natural resources for posterity, an idea rooted in an acute awareness of the interconnectedness of all life forms and the importance of preserving the ecosystem within which they live and are a part of (Berkes, 2012). Complementary to the values of indigenous cultures are those of the Ancient Greek philosopher, Aristotle. His insights, particularly those relating to the natural sciences, ethics, and natural philosophy, resonate with contemporary sustainability principles. Aristotle championed living in harmony with nature, emphasizing the need to balance the interactions of humans respectfully and sensitively with the natural world, an idea that is paralleled today by the modern concept of small-footprint living (Nelson, 2018).

In the twenty-first century, the term “sustainability” carries more weight today than ever before. The rapid rise of the sustainability movement has been two-fold, partly caused by the global population explosion; there being more people has led to more demand for natural resources, and partly the result of society’s increased awareness of environmental issues (Samways, 2022). Examples of two high-profile environmental issues include the hole in the ozone layer caused by chlorofluorocarbons (CFCs) and biodiversity loss – the result of climate change, deforestation, pesticide use, and pollution combined – that has led to the reduction and in some cases extinction of flora and fauna (Rowland, 1989; Singh & Singh, 2017).

The modern concept of sustainability began with the environmental movement in the 1960s and became established in the 1970s. It was catalysed by events such as Rachel Carson's publication of "Silent Spring" in 1962 and the inaugural Earth Day in 1970, causing environmental concerns to be thrust into the spotlight. These two decades witnessed a heightened realization of the finite nature of natural resources and the detrimental consequences of unchecked and mismanaged human activities on the environment. The period marked the onset of social awareness of there being a problem. A seminal moment came in 1987, when the Brundtland Report, 'Our Common Future' was released by the United Nations World Commission on Environment and Development. This landmark report outlined sustainable development as a crucial requirement for the security of the future. It coined the definition of "sustainable development", which still stands today: a mode of progress that satisfies present needs without compromising the ability of future generations to meet their own requirements.

The growing understanding of sustainability, not only as a concept but more importantly as a practice, has seen a host of concerns emerge across all sectors, spanning industry, government, and academia. To try and manage these, numerous strategies and frameworks have been developed such as the triple bottom line sustainability practice that incorporates economic, social, and environmental considerations into corporate social responsibility and best practice (Milne & Gray, 2013). These approaches have gained prominence and increasingly governments require businesses to adopt the principles and integrate them into their business models. For example, resource industries such as the mining industry (minerals and metals) and the petroleum industry (oil and gas) are legally required to demonstrate through audit inspections and reporting how they adhere to and implement environmentally responsible practices and sustainable operations (Böhling et al., 2019). Failure to meet environmental standards results in penalties. Such measures reflect the widespread acknowledgment of the critical need for sustainable practices.

Sustainability is by no means a new term; however, its long and established history – throughout time and across civilisations – means that its definition has evolved since its first use. It no longer solely refers to the balance between the coexistence of nature and humans but is now a fusion of environmental, social, and economic considerations and advocating for the equitable and responsible stewardship of resources to safeguard the well-being of both present and future generations.

Since its emergence as a critical concern for society, sustainability has been influenced by a myriad of factors including environmental degradation, social inequality, economic instability, and an increasing awareness of finite resources. Environmental degradation, encompassing issues such as pollution and climate change, threatens ecosystems and human health, necessitating the urgent adoption of sustainable practices (WCED, 1987). Social justice and equity are central to sustainability, realising the need to address disparities in access to resources and create opportunities to promote resilient and cohesive communities (WCED, 1987). Economic stability and long-term prosperity are contingent upon sustainable approaches that prioritize responsible resource management, innovation, and investment in renewable technologies and efficient recycling, contrasting with unsustainable practices like overconsumption (Milne & Gray, 2013). Globalization has highlighted the interconnectedness of sustainability challenges, emphasizing the need for coordinated international efforts (Sachs, 2015). Public awareness and advocacy, driven by media coverage, high-profile scientific research, and grassroots movements, have raised awareness of the urgent need for sustainable policies and practices, and more so action. Concurrently, the persistence of unsustainable practices stems from historical, economic, social, and institutional factors. Industrialization and technological advancements drive economic growth but contribute to environmental degradation. Population growth and urbanization strain ecosystems, exacerbating environmental challenges. Market-driven economies and consumer culture encourage unsustainable consumption patterns, while policy failures and cultural norms perpetuate unsustainable practices. Addressing the root causes of unsustainability demands transformative changes in governance, institutions, technologies, and societal values; these changes are essential for transitioning towards more equitable, resilient, and sustainable development pathways (Schlaile & Urmetzer, 2019).

Creating a Sustainable Future

Global development aims to enhance the economic, social, and environmental well-being of individuals and communities across the globe. It encompasses a range of efforts focused on reducing poverty, promoting human rights, achieving sustainable development goals, and addressing disparities in access to resources, opportunities, and basic services. Ultimately, global development seeks to create a more equitable, prosperous, and sustainable world for present and future generations.

Economic development plays a crucial role in global development by improving the standard of living, productivity, and prosperity of individuals and societies. This involves initiatives aimed at stimulating economic growth, creating employment opportunities, enhancing infrastructure, and promoting sustainable industries (Todaro & Smith, 2011). By fostering self-sustaining economic systems and improving livelihoods, economic development seeks to reduce poverty, inequality, and dependency on external aid, thereby building greater economic resilience and self-reliance within communities (World Bank, 2021).

Social development complements economic efforts by focusing on enhancing human capabilities, well-being, and social inclusion. It encompasses initiatives to improve the availability and access to education, healthcare, housing, gender equality, and social protection. Through these systems, social development aims to empower individuals, strengthen communities, and reduce social inequalities by addressing barriers to human development and promoting equity and social justice. Through greater social cohesion and inclusivity, social development contributes to creating more resilient and cohesive societies that can better withstand and adapt to global challenges (Sen, 1999; UNDP, 2020).

Environmental sustainability, another critical dimension of global development, aims to conserve natural resources, protect ecosystems, and mitigate climate change to ensure the long-term viability of the planet. Efforts include promoting renewable energy, sustainable agriculture, biodiversity conservation, and climate resilience, while at the same time preserving natural resources and minimizing pollution and waste (United Nations, 2015; IPCC, 2018). By balancing human development with ecological integrity, environmental sustainability aims to safeguard the health and well-being of present and future generations, ensuring that future development is environmentally responsible, economically stable, and socially just (Roseland, 2000).

Sustainability and Economic Growth: Striking a Balance

The compatibility between sustainable development and economic growth is a hotly debated topic among academics, policymakers, and practitioners alike. One school of thought is that sustainable development can coexist harmoniously with economic growth, while others advocate for a re-evaluation of traditional growth models, stating the need to place greater emphasis on environmental and social welfare. The question is contentious, yet the answer may be a turn of the key to unlocking the path to truly sustainable development. Society has reached a point where sustainability, much like research, has been monetised; for example, greenwashing falsely promotes a business or product as being environmentally friendly with the aim of improving its image and marketability, thus attracting more clients or customers (Lashitew, 2021). Transparency and honesty are essential. The spectrum of perspectives includes models such as decoupling growth from resource use, emerging investment opportunities, growth limitations, and using alternative metrics to redefine and evaluate growth as being broader and more diverse than an economic success measure (Hickle & Kallis, 2020).

Decoupling economic growth from resource use proposes that it is possible to achieve economic development and prosperity without corresponding increases in resource extraction, consumption, and environmental degradation (European Environment Agency, 2011). This concept is central to sustainable development as it aims to break the traditional link between economic growth and resource depletion and promotes long-term environmental sustainability and resilience. Advances in technology, coupled with a focus on resource efficiency and the transition to a green economy, complemented by policy instruments and sustainable consumption and sustainability practices, offer pathways to economic growth that do not compromise natural resources or cause environmental harm. The model champions the concept of "green growth" or “green economics”, suggesting it presents a viable means of reconciling economic prosperity with sustainability objectives (United Nations Environment Programme, 2011; Hickle & Kallis, 2020). An offshoot from this model is the view that progressing sustainable development will create new markets and investment opportunities that arise from the adoption of sustainable practices. Advocates for this model claim that transitioning towards sustainability can catalyse innovation, foster job creation, and bolster economic resilience, consequently paving the way for sustained prosperity over the long term (Hickle & Kallis, 2020).

In contrast, critics of the conventional economic growth model argue there are limits to economic growth; a trajectory of continual economic growth, particularly as measured by metrics like Gross Domestic Product (GDP), is unfeasible, citing its inherent unsustainability within a finite global ecosystem (Rees, 2003; Washington 2021). This perspective draws attention to the ecological footprint engendered by relentless economic expansion, the disproportionate distribution of its benefits, and the hidden social and environmental tolls incurred along the way. Extending from this perspective is the idea to use alternative, arguably more meaningful metrics to gauge societal progress and well-being, beyond the confines of GDP. Suggestions such as the Genuine Progress Indicator (GPI) or the Human Development Index (HDI) offer more holistic assessments of human welfare and environmental sustainability, thus challenging the traditional approach of equating economic growth with societal progress (Berik, 2020; Sinha, 2023).

Despite some inviting arguments and evidence supporting the alignment of sustainable development with economic growth, critics contend that conventional growth frameworks warrant scrutiny and review. The approach proposed; to reframe the narrative of progress and encourage the adoption of inclusive and environmentally responsible models of prosperity, offers a different way to measure growth and success. Navigating these tensions and charting a course toward sustainable development requires a candid review of traditional economic systems and current policies, and prioritising environmental stewardship, social equity, and human well-being above all else. That said, it would be shortsighted to entirely overlook the economics of sustainability.

Exploring how sustainable development can offer opportunities for innovation, efficiency gains, market expansion, and creating long-term value (which could fuel economic prosperity) allows any potential benefits of the traditional economic model to be leveraged. Several sustainable development pathways offer economic advantages.

The pursuit of sustainable development is a catalyst for innovation across all sectors. Developing and using clean technologies, renewable energy, resource-efficient products, and sustainable business models all offer benefits. These innovations cultivate new markets and industries, as well as unlock new avenues for investment, fuelling economic growth and generating employment opportunities (Mazzucato & Perez, 2015). Sustainable practices, such as energy efficiency measures, waste reduction initiatives, and resource optimization strategies, could lead to substantial cost savings for both businesses and households. The rewards are realised by reduced energy bills, diminished waste disposal expenditures, and increased operational efficiency (DeSimone & Popoff, 2000).

Adopting sustainable development practices equips businesses and communities with the knowledge and means to strengthen their position against a range of environmental, social, and economic risks. From climate change impacts to supply chain disruptions, sustainable initiatives facilitate risk mitigation by encouraging diversification of revenue streams, reducing dependencies on finite resources, and bolstering social license to operate. Through these measures, enterprises can enhance their resilience and withstand uncertainties more effectively (Fiksel & Fiksel, 2015). Furthermore, by implementing sustainable practices companies strengthen their brand reputation and gain a competitive edge. Demonstrating environmental and social responsibility, businesses can garner greater consumer trust, attract a broader clientele base, and recruit top-tier talent. This consequently enhances sales figures, augments market share, and bolsters shareholder value, positioning sustainable enterprises as leaders within their respective industry sectors (Maignan et al., 1999).

Governmental policies, regulations, and incentives aimed at promoting sustainable development play an important role in nurturing the business environment. Measures such as carbon pricing mechanisms, subsidies for renewable energy sources, green procurement practices, and sustainability standards encourage the private sector to invest in sustainable solutions (Abdmouleh et al., 2015). By aligning regulatory frameworks with sustainability goals, policymakers pave the way for enhanced economic opportunities and societal well-being.

When rethinking the sustainability-growth model, prioritising environmental stewardship, social equity, and human well-being need to be balanced with economics. Sustainable development offers economic prospects for businesses, investors, and societies, inviting a future shaped by innovation, efficiency, resilience, and competitive advantage amidst a dynamically evolving global landscape.

Science as a Pathway to Sustainable Development

Basic science is a cornerstone in the pursuit of sustainable development, providing an avenue to fundamental insights, innovative technologies, and evidence-based policies. Science is currently the catalyst for sustainable development across all sectors and disciplines offering alternatives to unsustainable practices and informing remediation, mitigation, and adaptation strategies when managing sustainability issues. To highlight this, some examples of advances made in the fields of environmental systems, technology development, agriculture, and policy and decision-making are presented.

Disciplines underpinned by the study of natural processes typically strongly depend on basic science; research driven by the desire to broaden and deepen our knowledge of the natural world. Understanding systems such as geological, ecological, climatological, and oceanographical systems, provide valuable and original insights into the processes and mechanisms that govern the natural world. Practical examples include how findings from mapping ecosystem dynamics, deciphering climate patterns, and modelling natural resource systems, have been used to inform and assess environmental risks, predict future changes, and develop sustainable resource management and responsible conservation strategies (Tallis & Polasky, 2009).

Advances made in fields like materials science, chemistry, and biotechnology have seeded new ideas and possibilities for sustainable technology development. Sustainable technologies have helped improve the efficiency, reliability, and scalability of renewable energy systems, efficient energy storage devices, clean water technologies, and eco-friendly materials, helping improve environmental footprints, enhance resource efficiency, and support sustainable development (Chu, 2022).

In agricultural science, research into agronomy, genetics, and soil science formed the platform for sustainable farming practices, developing resilient crop varieties and eco-friendly cultivation techniques. This has led to many benefits such as enhancing food security, bolstering soil health, curbing agricultural inputs, and mitigating some of the environmentally negative impacts associated with conventional farming practices. Such developments have and continue to contribute to the transition toward agricultural sustainability (Mrabet, 2023).

Evidence-based policies, regulations, and decision-making processes are informed and developed by research findings. By using scientific evidence and empirical data relevant to environmental protection, public health, energy transition, and natural resource management, the application of basic science bridges the gap between scientific knowledge and policy implementation. This contributes to identifying and constraining sustainability objectives and helps with developing mitigation methods and strategies to address global challenges (Sarewitz et al., 2000).

Science has been and continues to be an indispensable tool informing and aiding the progress of sustainable development. However, the vast majority of science currently being done is applied research – transforming basic science knowledge into practical outputs – since science has become an investment that must guarantee returns if it is to be funded. Yet through the development of innovative technologies, and the implementation of empirically grounded solutions, the environmental, social, and economic challenges faced by humanity are being recognised, managed, and resolved, albeit slowly.

Radical Transformation: Let History Repeat Itself

History has shown clearly, the evidence is irrefutable that basic science is essential for driving scientific progress and innovation, yet numerous challenges and barriers are faced that impede its advancement and hamper the pursuit of new knowledge. These challenges, ranging from funding constraints to ethical considerations, shape the landscape of scientific research and require concerted unified efforts to address them effectively. Key challenges include securing sufficient funding amidst competing priorities and budgetary limitations, lack of support due to risk aversion, and the bias towards short-term, applied research over long-term, curiosity-driven investigations. Additionally, engrained disciplinary boundaries and institutional silos hinder interdisciplinary collaboration, while concerns about reproducibility, replicability, and ethical implications reinforce the need for rigorous research standards and practices. Science communication – the effective dissemination of results and engaging the public in scientific discourse – is another critical challenge since it is the means of maximising the value of research and realising its full potential. Addressing these challenges requires collaborative efforts from stakeholders across sectors to create an environment conducive to curiosity-driven inquiry, interdisciplinary collaboration, scientific integrity, and equitable access to scientific opportunities. Achieving such an environment would advance the frontiers of basic science and facilitate transformative discoveries.

The critical need for sustainable development comes after being on an unsustainable trajectory for too long; the planet is no longer able to naturally reestablish equanimity: intervention is needed. The pursuit of basic science led to the wealth of original knowledge discovered before the 18th century and formed the platform for the technological advances of the Industrial

Revolution. The exponential rate of industrialisation and global development propagated seismic shifts resulting in strong economic growth and rapid urbanisation. Governments have sought to maintain continued growth, particularly economic growth, for more than three centuries, seemingly at any cost; the cost is the future. Globally, governance is helping to raise awareness across industry and society, but the effects of their efforts are incremental step-changes and improvement is slow. Currently, many of the greatest impacts of research come from applied science and are often linked to improving sustainability: the transformational change urgently required is not being achieved. It seems reasonable, even logical, to assume that greater investment in basic science would result in revolutionary, groundbreaking discoveries, as it has historically revolutionary, groundbreaking discoveries. The greatest barrier to new discoveries and transformational scientific breakthroughs is money, ironically at the most prosperous time in history; this must change. It is unquestionable that to create and maintain a sustainable world a multitargeted approach is necessary, yet a promising component to the solution is continuously being overlooked, which given the stakes – an unsustainable future – requires serious consideration: basic science.

References

Abdmouleh, Z., Alammari, R. A., & Gastli, A. (2015). Review of policies encouraging renewable energy integration & best practices. Renewable and Sustainable Energy Reviews, 45, 249-262.

Barnes, J. (2001). *Aristotle: A Very Short Introduction*. Oxford University Press.

Berik, G. (2020). Measuring what matters and guiding policy: An evaluation of the Genuine Progress Indicator. *International Labour Review*, 159(1), 71-94.

Berkes, F. (2012). *Sacred Ecology* (3rd ed.). Routledge.

Böhling, K., Murguía, D. I., & Godfrid, J. (2019). Sustainability Reporting in the Mining Sector: Exploring Its Symbolic Nature. *Business & Society*, 58(1), 191-225. https://doi.org/10.1177/0007650317703658

Broemeling, L. D. (2011). An Account of Early Statistical Inference in Arab Cryptology. *The American Statistician*. 65 (4): 255–257. https://doi.org/10.1198/tas.2011.10191

Carson R. (2002). *Silent spring.* (40th anniversary ed.). Boston, MA: Houghton Mifflin. (Original work published 1962)

Chu, L. K. (2022). Determinants of ecological footprint in OCED countries: do environmental-related technologies reduce environmental degradation?. Environmental Science and Pollution Research, 29(16), 23779-23793.

Collins, F. S., & McKusick, V. A. (2001). Implications of the Human Genome Project for Medical Science. *JAMA*, 285(5), 540–544. https://doi.org/10.1001/jama.285.5.540

Conceição, P. (2020). Human development report 2020-the next frontier: Human development and the Anthropocene. *United Nations Development Programme: Human Development Report*. http://hdr.undp.org/en/2020-report

DeSimone, L. D., & Popoff, F. (2000). Eco-efficiency: the business link to sustainable development. MIT press.

European Environment Agency. (2011). *Environment and Economic Competitiveness: Review of Challenges and Opportunities*. https://www.eea.europa.eu/publications/environment-and-economic-competitiveness

Fiksel, J., & Fiksel, J. R. (2015). Resilient by design: Creating businesses that adapt and flourish in a changing world. Island Press.

Gandz, S. (1926). The Origin of the term "Algebra". *The American Mathematical Monthly*, 33(9), 437-440.

Gorini, R. (2003). Al-Haytham the man of experience. First steps in the science of vision. *Journal of the International Society for the History of Islamic Medicine*, 2(4), 53-55.

Harris, R. (2005). *The semantics of science*. A&C Black.

Hickel, J., & Kallis, G. (2020). Is green growth possible?. *New political economy*, 25(4), 469-486. Hunger, H., & Pingree, D. (1989). *Astral Sciences in Mesopotamia*. Brill.

Intergovernmental Panel on Climate Change (IPCC). (2018). *Global Warming of 1.5°C*. https://www.ipcc.ch/sr15/

Kuhn, T. S. (1996). The Copernican Revolution: Planetary Astronomy in the Development of Western Thought. Harvard University Press.

Kuhn, T. S. (2012). The Structure of Scientific Revolutions: 50th Anniversary Edition. University of Chicago Press.

Landes, D. S. (1969). The Unbound Prometheus: Technological Change and Industrial Development in Western Europe from 1750 to the Present. Cambridge University Press.

Lashitew, A. A. (2021). Corporate uptake of the Sustainable Development Goals: Mere greenwashing or an advent of institutional change?. *Journal of International Business Policy*, 4(1), 184-200. Lindberg, D. C. (1992). *The Beginnings of Western Science: The European Scientific Tradition in Philosophical, Religious, and Institutional Context, Prehistory to A.D. 1450*. University of Chicago Press.

Lloyd, G. E. R. (1970). *Early Greek Science: Thales to Aristotle*. W. W. Norton & Company.

Maignan, I., Ferrell, O. C., & Hult, G. T. M. (1999). Corporate citizenship: Cultural antecedents and business benefits. *Journal of the Academy of marketing science*, 27(4), 455-469.

Marini, D. L. (2023). Mathematics and Astronomy from Origin to Eighteenth Century. *Imago Cosmi* (pp. 7-31). Springer, Cham.

Mazzucato, M. (2013). The Entrepreneurial State: Debunking Public vs. Private Sector Myths. Anthem Press.

Mazzucato, M., & Perez, C. (2015). Innovation as growth policy. The Triple Challenge for Europe, 229-64.

McKeon, R. (1947). Aristotle's Conception of the Development and the Nature of Scientific Method. *Journal of the History of Ideas*, 8(1), 3-44.

Mercier, E. (2020). Mathematical geography in the western Islamic world: geographical coordinates of localities in the al-Maghreb and al-Andalus localities (9th-18th centuries). Suhayl. *International Journal for the History of the Exact and Natural Sciences in Islamic Civilisation*, 8, 25-

49. Millennium Ecosystem Assessment. (2005). *Ecosystems and Human Well-being: Synthesis*. Island Press.

Milne, M.J. & Gray, R. (2013) W(h)ither Ecology? The Triple Bottom Line, the Global Reporting Initiative, and Corporate Sustainability Reporting. *Journal of Business Ethics* 118, 13–29. https://doi.org/10.1007/s10551-012-1543-8

Mokyr, J. (1990). The Lever of Riches: Technological Creativity and Economic Progress. Oxford University Press.

Mrabet, R. (2023). Sustainable agriculture for food and nutritional security. *Sustainable Agriculture and the Environment* (pp. 25-90). Academic Press.

National Research Council. (2002). Learning and Understanding: Improving Advanced Study of Mathematics and Science in U.S. High Schools. National Academies Press.

Nelson, A. (2018). Small is necessary: shared living on a shared planet. Pluto Press.

Nunn, J. F. (1996). *Ancient Egyptian Medicine*. University of Oklahoma Press.

Perez, C. (2002). Technological Revolutions and Financial Capital: The Dynamics of Bubbles and Golden Ages. Edward Elgar Publishing.

Plotkin, S. A., Orenstein, W. A., & Offit, P. A. (Eds.). (2013). *Vaccines (6th ed.)*. Elsevier Saunders.

Rees, W. E. (2003). Economic development and environmental protection: an ecological economics perspective. *Environmental monitoring and assessment*, 86, 29-45.

Roseland, M. (2000). Sustainable community development: integrating environmental, economic, and social objectives. *Progress in planning*, 54(2), 73-132.

Rowland, F. S. (1989). Chlorofluorocarbons and the Depletion of Stratospheric Ozone. *American Scientist*, 77(1), 36–45. http://www.jstor.org/stable/27855550

Sachs, J. D. (2015). *The Age of Sustainable Development. New York*. Columbia University Press.

Saliba, G. (2007). Islamic Science and the Making of the European Renaissance. MIT Press.

Samways, D. (2022). "Population and Sustainability: Reviewing the Relationship Between Population Growth and Environmental Change". *The Journal of Population and Sustainability* 6(1):15-41. https://doi.org/10.3197/JPS.63772239426891

Sarewitz, D., Pielke, R. A., & Byerly, R. (2000). *Prediction: science, decision making, and the future of nature*. Island Press.

Schlaile, M.P., Urmetzer, S. (2019). Transitions to Sustainable Development. Leal Filho, W., Azul, A., Brandli, L., Özuyar, P., Wall, T. (eds) *Decent Work and Economic Growth. Encyclopedia of the UN Sustainable Development Goals*. Springer, Cham. https://doi.org/10.1007/978-3-319-71058-7_52-1

Sen, A. (1999). *Development as Freedom*. Oxford University Press.

Shapin, S. (1996). *The Scientific Revolution*. University of Chicago Press.

Singh, R. L., & Singh, P. K. (2017). Global environmental problems. Principles and applications of environmental biotechnology for a sustainable future, 13-41.

Sinha, A. R. (2023). Genuine Progress Indicator (GPI)-A Real Indicator of Economic Progress. *PURUSHARTHA-A journal of Management, Ethics and Spirituality*, 16(1), 78-92.

Tallis, H., & Polasky, S. (2009). Mapping and valuing ecosystem services as an approach for conservation and natural-resource management. *Annals of the New York Academy of Sciences*, 162(1), 265-283.

Todaro, M. P., & Smith, S. C. (2011). *Economic Development* (11th ed.). Pearson.

United Nations. (2015). Transforming our world: The 2030 agenda for sustainable development. *New York: United Nations, Department of Economic and Social Affairs*, 1, 41.

United Nations Environment Programme. International Resource Panel, United Nations Environment Programme. Sustainable Consumption, & Production Branch. (2011). *Decoupling natural resource use and environmental impacts from economic growth*. UNEP/Earthprint.

Washington, H. (2021). Questioning the assumptions, sustainability and ethics of endless economic growth. *Journal of Risk and Financial Management*, 14(10), 497.

Westfall, R. S. (1980). *Never at Rest: A Biography of Isaac Newton*. Cambridge University Press.

World Bank. (2021). *World development report 2021: Data for better lives*. World Bank Publications. https://www.worldbank.org/en/publication/wdr2021

World Commission on Environment and Development (WCED) (1987). *Our Common Future*. Oxford University Press.

Zhmud, L. (2018). *Early Mathematics and Astronomy* (pp. 171-194). Oxford University Press.

About Author

Dr. Caroline JOHNSON | Fondazione Bruno Kessler | Cjohnson[at]fbk.eu | ORCID: 0009-0001-7297-0861

Caroline Johnson is a project manager for the Fondazione Bruno Kessler, Sensors and Devices Centre, in Trento, Italy. Her research background is in geology, she holds an MSci in Geology from Imperial College London and a PhD in Geochemistry from Cardiff University, Wales. On completing her PhD, she accepted a postdoctoral fellowship at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia to study the physical chemistry of uranium dissolution. After, she transitioned to a research project coordinator role. From 2017 to 2018, she pursued interests in Environmental Science studying a Postgraduate Diploma at the University of East Anglia, England and qualified as a PRINCE2 Project Management Practitioner. While studying, she joined the World Energy Meteorological Council (WEMC) to manage the European-funded SECLI-FIRM H2020 and Copernicus C3 Energy projects, expanding her management experience topically and internationally. On completion of her studies, she returned to Australia and continued working with CSIRO until 2023 when she joined the Fondazione Bruno Kessler Sensors and Devices Centre as a proposal writer and project manager.

RECENT APPLICATIONS OF WASTE DERIVED INNOVATIVE MATERIALS IN HEALTHCARE AND ENVIRONMENTAL SUSTAINABILITY

Arzum Erdem

Ece Eksin

Hüseyin Şentürk

10.53478/TUBA.978-625-6110-22-9.ch07

Recent Applications of Waste Derived Innovative Materials in Healthcare and Environmental Sustainability

Arzum Erdem
Ege University

Ece Eksin
Izmir Democracy University

Hüseyin Şentürk
Ege University

Abstract

Waste-derived innovative materials are the one of the recent topics that have gained importance today in terms of contributing to sustainability. The development and use of such materials in many areas such as health, environment, food, etc. offers new alternatives to traditional methods available today. Research in this area not only addresses the current pressing problems of waste management, but also unlocks new possibilities for developing cost-effective and environmentally friendly solutions that can adapt to the needs of many different fields. The current studies on the use of waste-derived innovative materials in health fields such as drug delivery, tissue engineering, biosensing as well as in environmental fields such as the remediation of wastewater, soil pollution and air pollution are overviewed in this chapter. The advantages, limitations, possible solutions and the future of such materials are also discussed furtherly.

Keywords
Waste-derived innovative materials, sustainability, healthcare applications, environmental applications

Introduction

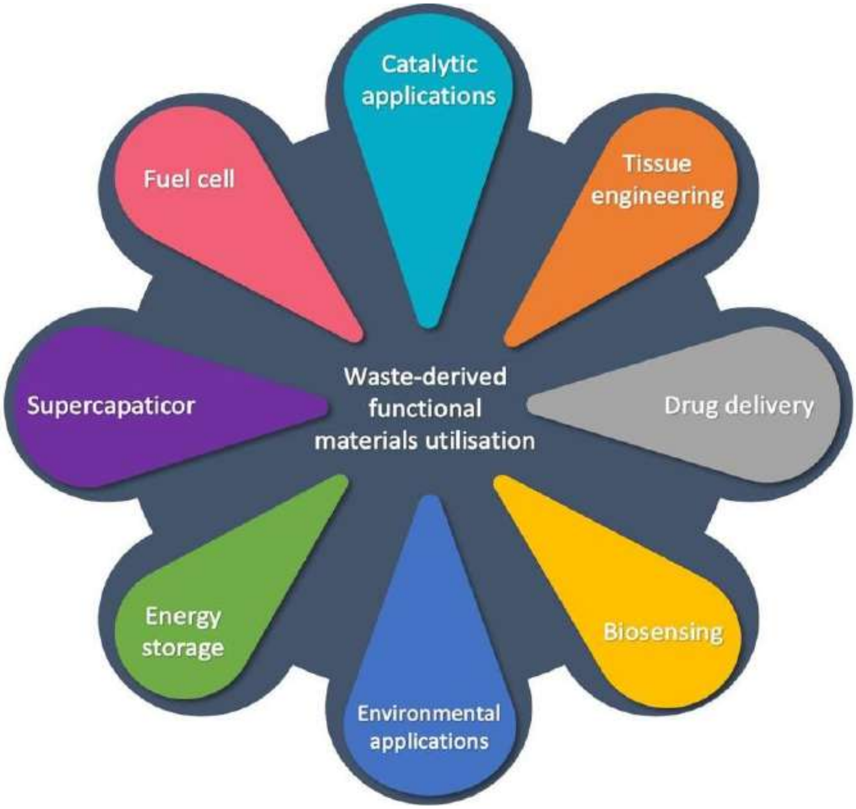
The increasing consumption of both durable and nondurable consumer goods, accompanied by the consequent generation of waste materials, is raising concerns among the global population. This has prompted a sense of urgency for the adoption of more efficient measures in environmental protection (Ikram et al., 2023). In recent years, generating functional materials from waste using effective strategies has become more prominent. The principle of "waste-to-value" holds substantial economic and environmental importance. In this regard, significant emphasis has been placed on utilizing natural and renewable materials to create cost-effective and environmental friendly adsorbents for water pollution remediation (Soffian et al., 2022).

Waste materials originate from various sources, including commercial, construction, household, industrial, institutional, imported, and public goods or products. One practical approach to categorizing waste materials is based on their environmental impact levels. Bertram et al. (Bertram et al., 2018) classified wastes into four categories: (i) eco-friendly, (ii) biodegradable, (iii) non-biodegradable, and (iv) toxic wastes.

Recently, the increased global concerns about the sustainability of the Earth have raised public and industrial awareness regarding the harmful impacts of chemical toxins and non-biodegradable materials. The accumulation of waste materials is a growing problem, posing threats not only to the environment but also to public safety. Addressing this issue involves recycling and utilizing these waste materials in industries instead of disposing of them. Consequently, there is a rising demand for the efficient transformation of wastes into benign materials, aiming to minimize the amount of waste released into the environment.

The utilization of waste-derived materials in various fields including energy storage, supercapacitor, fuel cell, catalytic applications, tissue engineering, drug delivery, biosensing, and environmental analysis is possible (see Figure 1) In this chapter, numerous waste-derived materials and their applications in the field of health care and environmental management are introduced and discussed in detail.

Figure 1.
Utilization of waste-derived materials in different fields.



Recent Applications of Waste Materials

Healthcare Applications

In today's world, where sustainability and environmental responsibility hold significant importance, the healthcare industry is actively adopting innovative strategies to minimize its impact on the environment. An interesting approach gaining attraction involves the use of innovative materials derived from waste materials in various healthcare applications. This shift not only tackles the pressing issue of waste management but also unlocks new possibilities for developing cost-effective and eco-friendly solutions that can adapt to the dynamic needs of healthcare. These materials, once considered discarded remnants, are now finding purpose in advancing healthcare technologies and practices. From by-products to recycled plastics and electronic waste, these materials are smartly repurposed to meet the demanding requirements of the healthcare sector. This sustainable approach not only reduces environmental impact but also aligns with the principles of a circular economy, where waste transforms into a valuable resource. Beyond environmental consciousness, the exploration of waste-derived materials within healthcare signifies a convergence of management and cutting-edge medical innovations. It demonstrates the potential to revolutionize how the industry sources and produces materials (Y. C. E. Li, 2019). This section reviews the applications of waste-derived materials, shedding light on how these seemingly ordinary sources are actively shaping a greener and more sustainable future for healthcare. Different types of new innovative materials derived from different types of wastes, possess characteristics that can be effectively utilized in applications in healthcare field. These materials are frequently used in many different healthcare fields such as bioimaging, drug delivery, biosensing, tissue engineering (Choi et al., 2014; Faikrua et al., 2009; George et al., 2019; Hu et al., 2015; L. Li et al., 2018; Y. Li et al., 2018, 2023; Mauney et al., 2011; Patel et al., 2021; Shan et al., 2019; Tseng et al., 2015; L. Wang et al., 2014; Zheng et al., 2022).

Drug delivery has critical importance in the healthcare industry as it plays a critical role in improving clinical outcomes and patient well-being. Efficient drug delivery maximizes the bioavailability of drugs, ensuring that therapeutic agents reach their targets in optimal doses and minimize side effects. Furthermore, new drug delivery technologies enable controlled delivery of drugs, enabling consistent use, which is crucial for chronic conditions. The continuous evolution of drug delivery strategies holds the promise of revolutionizing healthcare by maximizing therapeutic benefits while minimizing adverse effects (Y. C. E. Li, 2019; Pillai & Panchagnula, 2001; Prausnitz & Langer, 2008; Tibbitt et al., 2016). For these reasons, numerous studies are currently being conducted with waste-based materials for drug delivery (L. Li et al., 2018; Y. Li et al., 2018, 2023; Patel et al., 2021; Rudzinski et al., 2016). Polysaccharide-based materials are widely used because they are biocompatible and biodegradable. Since they have different functional groups in their structures, they can easily bind to biomolecules and release drugs through various mechanisms (Y. C. E. Li, 2019). Among these materials, chitosan, lignin, cellulose and their derivatives are frequently used. Chitosan, a natural polymer originating from chitin found in the exoskeletons of crustaceans like shrimp and crabs, as well as in fungal cell walls, has become a focus of interest in drug delivery applications. Biomass-based chitosan, derived from renewable biomass sources, offers an environmentally friendly alternative to traditional extraction methods. Its appeal lies in features like biocompatibility, biodegradability, low toxicity, and distinctive physicochemical properties (Dash et al., 2011; Zhang et al., 2010). This variant of chitosan can be skillfully crafted into diverse drug delivery vehicles, including nanoparticles, microparticles, and hydrogels (Ahsan et al., 2018; Jayakumar et al., 2010; Kravanja et al., 2019; Zhang et al., 2010). These vehicles serve to encapsulate and shield drugs, enabling their controlled release precisely at the target site (Ahsan et al., 2018; Ali & Ahmed, 2018; Bernkop-Schnürch & Dünnhaupt, 2012; Bhattarai et al., 2010; Nagpal et al., 2010). Patel et al. prepared a bioactive multifunctional chitosan/cellulose nanocrystal scaffold. An increase in the mechanical strength of the developed structure has been reported. It was also reported that the developed composite scaffold of chitosan/cellulose nanocrystal showed improved sustained drug release. In addition, it was also stated that the developed structure can be used not only in drug delivery but also in tissue engineering and as an antimicrobial agent (Patel et al., 2021). In another study, a biomass-based magnetic fluorescent nanoparticles were synthesized using magnetic core of Fe_3O_4 nanoparticles, fluorescent marker of carbon dots and chitosan. In the study, it was reported that the addition of the synthesized material effectively improved the drug loading capacity in 5-fluorouracil encapsulation and release experiments (L. Li et al., 2018).

Lignin, a complex and polymeric compound naturally occurring in the cell walls of plants, has emerged from its traditional role as a byproduct of the paper and pulp industry to capture attention for its versatile applications, particularly in biomedicine. Derived from biomass, especially wood and other plant materials, lignin is increasingly recognized for its potential in various fields. In the realm of drug delivery, lignin takes on a crucial role. It can be transformed into nanoparticles or microparticles, serving as effective carriers for pharmaceuticals (Alqahtani et al., 2019; Figueiredo et al., 2017; Garg et al., 2022; Kumar et al., 2021; Yiamsawas et al., 2017). These lignin-based particles present an opportunity for controlled release, enhancing the therapeutic effectiveness of drugs. Moreover, the adaptability of lignin-based materials allows for potential modifications to improve targeting capabilities, facilitating precise and efficient drug delivery to specific tissues or cells. The inherent properties of lignin, including its ability to form films and matrices, position it as a promising candidate for sustained release drug delivery systems, ensuring a prolonged and sustained therapeutic impact (Alqahtani et al., 2019; Figueiredo et al., 2017; Garg et al., 2022; Kumar et al., 2021;

Yiamsawas et al., 2017). Li et al. developed poly(ε-caprolactone) (PCL)-containing lignin-chitosan biomass-based nanocomposite porous scaffolds. It is reported that the scaffolds obtained exhibit interconnected and adjustable pore structures. In the study, scaffolds loaded with the anti-bacterial drug enrofloxacin were reported to show a slow drug release profile, adjustable release rate and favourable long-term anti-bacterial activity (Y. Li et al., 2023). In the study of Li et al. alkali lignin was first modified and then treated with sodium dodecyl benzenesulfonate. Controlled release of avermectin is demonstrated with the developed material (Y. Li et al., 2018).

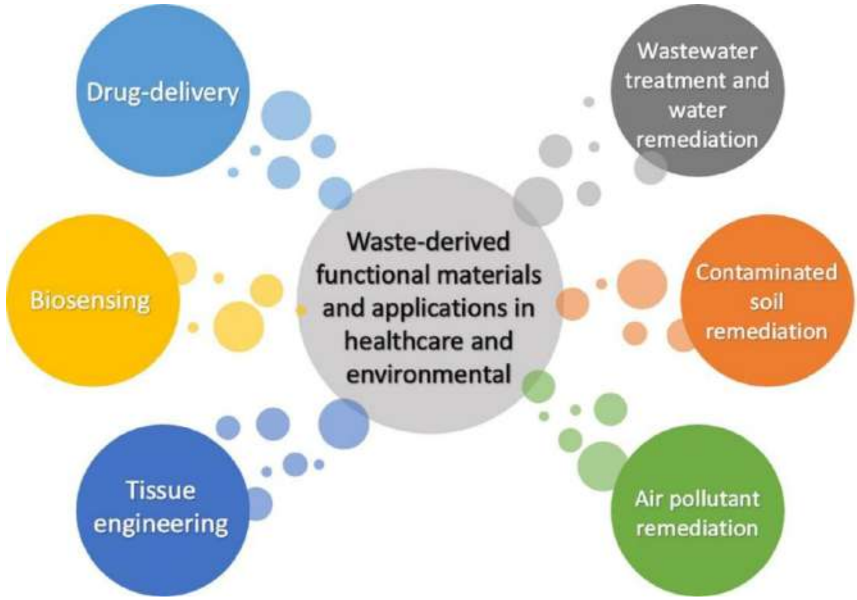
Cellulose, the most abundant biopolymer on Earth, is a natural polysaccharide found in plant cell walls. Biomass-based cellulose, derived from renewable sources like wood, cotton, or other plant materials, is gaining attention for its potential applications, owing to its abundance, biocompatibility, and biodegradability. This versatile cellulose variant can undergo processing to yield nanocellulose, encompassing cellulose nanocrystals (CNC) and cellulose nanofibers (CNF). These nanocellulose materials emerge as promising drug carriers, leveraging their high surface area, biocompatibility, and capacity to encapsulate and release pharmaceutical agents (Habibi, 2014; Klemm et al., 2011). Moreover, cellulose-based hydrogels offer another avenue, providing a platform for controlled drug release by efficiently absorbing and retaining water over time. This multifaceted approach underscores the significance of biomass-based cellulose in advancing drug delivery technologies (Chang & Zhang, 2011; Habibi, 2014; Zainal et al., 2021). In the study of George et al. biomass-based nanocomposite hydrogel was prepared and curcumin delivery was demonstrated. In the study, zinc oxide nanoparticles (ZnO NPs) phytosynthesised using musk melon (*Cucumis melo*) seed extract were placed in hydrogel matrices and crosslinking was performed using dialdehyde cellulose prepared from sugarcane (*Saccharum officinarum*) bagasse (SCB) (George et al., 2019).

These materials and their derivatives have many applications in the field of biosensing. Biosensors are small devices that enable selective analysis by specifically detecting the target analyte. The advantages of biosensors compared to traditional analysis methods are that they perform sensitive and selective analysis, reach low detection limits, are inexpensive and easy to use. Recently, there have been many studies on biosensor designs with innovative materials developed from waste-based materials in order to contribute to sustainability (Shan et al., 2019; L. Wang et al., 2014; Zheng et al., 2022). There are biosensor studies for the determination of biomarkers such as glucose, uric acid, determination of various heavy metals or determination of various physiological parameters. In the study by Wang et al, Kenaf stem based macroporous carbon material was synthesized and biosensor application was demonstrated (L. Wang et al., 2014). The electrocatalytic activity of the electrodes prepared with the synthesized material was investigated by cyclic voltammetry and amperometry techniques and it was stated that the material provides large surface area and accelerates mass and electron transfer. Glucose, amino acid and H_2O_2 determination was performed with the developed sensor. Zheng et al. synthesized phosphated lignin-based carbon nanofibers and developed a wearable biosensor using this material (Zheng et al., 2022). In the study, determination of uric acid in urine was carried out with the developed biosensor. Shan et al. developed a biosensor for glucose determination by enzymatic biosensing using biomass derived carbon material (Shan et al., 2019). In the study, the electrode surface was modified with carbon material derived from three-dimensional (3D) porous cane vine (wisteria) stalk and then glucose oxidase enzyme was immobilized on this surface. Electrochemical characterizations were performed with cyclic voltammetry and electrochemical impedance spectroscopy techniques. The developed biosensor was reported to have a wide linear range (0.58 μM to 16 mM) and low detection limit (0.19 μM).

Tissue engineering is this incredible field that brings together ideas from engineering, biology, and materials science, all with the aim of crafting functional biological tissues. The big mission here is to create artificial organs or tissues—ones that can step in to replace, repair, maintain, or even boost the function of tissues in the human body that have taken a hit from damage or disease. It's like a crossroads where science, technology, and health meet to open up possibilities for improving and restoring our bodies. Recently, in order to contribute to sustainability, studies have been carried out with innovative materials produced from waste materials in the field of tissue engineering (Choi et al., 2014; Faikrua et al., 2009; Hu et al., 2015; Mauney et al., 2011; Tseng et al., 2015). Choi et al. developed a crosslinkable chitosan derivative by modifying chitosan with various functional groups. As a result of the treatments, the degradation rate of chitosan hydrogel decreased, promoting the proliferation of encapsulated chondrocytes, ECM deposition and enhanced repair of damaged cartilage (Choi et al., 2014). There are also studies for the treatment of defects in the central nervous system or skin after modification of chitosan with various polymers (Faikrua et al., 2009; Tseng et al., 2015). Mauney and colleagues used silk to produce a bladder alternative. It was reported that the developed silk-based bladder alternative increased the bladder capacity and was resistant to stresses (Mauney et al., 2011). In another study, a structure to be used as a bone substitute was developed by preparing silk mixed material (Hu et al., 2015).

The scheme for the use of waste-derived materials in the field of healthcare and environmental is given in Figure 2.

Figure 2.
Utilization of waste-derived materials in healthcare and environmental



Application in Environmental Management

Wastewater Treatment and Water Remediation

According to the United States Environmental Protection Agency (EPA), the Basics of Water Remediation involve a series of actions by water utilities to restore normal service following a confirmed contamination incident. This incident is defined as the presence of chemical, biological, or radiological substances at concentrations significant enough to adversely affect public health or the environment. The remediation process, with a timeframe determined case-specifically, comprises three phases: Characterization, Decontamination, and Clearance. The characterization phase aims to understand the contamination extent, identifying contaminants, their interactions in water, and their concentrations. Information from strategic sampling guides protective measures, and a clearance goal is set based on defined risks. Public health and environmental risks are continually assessed. Decontamination phase involves choosing and implementing water treatment methods based on factors like effectiveness, resource availability, time, and cost. Infrastructure decontamination may be necessary, including cleaning or replacing contaminated surfaces. Proper management and disposal of contaminated wastes are integral to this phase. Lastly, clearance involves sampling and data review to assess if clearance goals have been met. Sampling is conducted using EPA-approved methods, ensuring compliance with regulations. If clearance is achieved, the water system can return to normal service, with the possibility of clearing specific areas while others undergo decontamination. Long-term monitoring may be necessary to confirm the remediation process's effectiveness after the system is restored to normal service (EPA, 2023).

The contamination of water resources is a highly contentious issue globally, given its potential for long-term or even lethal consequences for living things. Addressing water pollution is a significant challenge for both public health and a sustainable future. Currently, the rapid growth of industrialization and urbanization has resulted in significant water pollution, imposing considerable strain on both ecosystems and human health (Miklos et al., 2018). More than a third of the world's renewable freshwater resources are allocated for industrial, residential, and agricultural needs. Unfortunately, a significant portion of these activities leads to water pollution through the introduction of various geogenic and synthetic substances, such as dyes, pesticides, fertilizers, radionuclides, and heavy metals. Therefore, there is an immediate need to employ efficient methods for elimination of harmful pollutants such as heavy metals, microplastics, antibiotics, and viruses from water to guarantee a supply of clean water (N. Li et al., 2022). To address this issue, innovative methods for wastewater remediation, including adsorption, photocatalysis degradation, electrochemical treatment, and Advanced Oxidation Processes (AOPs), have been developed (Chen et al., 2019). These existing techniques for wastewater remediation heavily depend on functional materials, making cost-effective alternatives highly desirable. The development of materials derived from waste for wastewater remediation has experienced rapid expansion, holding substantial environmental and economic importance (Chen et al., 2022). In recent years, biomass and waste-derived carbon-based adsorbents have attracted considerable attention (Soffian et al., 2022). Carbonaceous substances constitute a highly advanced category of materials integral to modern material science and technology, playing an important role in industry due to their robust characteristics. Within environmental remediation, carbon-based materials hold significant promise (Nasir et al., 2018). The fusion of carbon-based materials with nanotechnology has introduced unique functionalities compared to their original forms. Engineered carbon-based materials have gained a remarkable attention in addressing global environmental challenges, with a particular emphasis on wastewater treatment. These materials have been effectively employed in water purification, demonstrating high efficiency in the removal of various environmental pollutants (Smith & Rodrigues, 2015). Graphene is a carbon allotrope with a single layer of atoms arranged in a two-dimensional hexagonal lattice and it finds extensive applications in wastewater treatment. Tohamy et al. (Tohamy et al., 2020) explored the adsorption of nickel (Ni(II)) on graphene oxide produced through a one-step oxidation process using various agricultural biomass sources (sugarcane bagasse, rice straw, mature pine wood sawdust, and lignin). The rice straw-based graphene oxide had the highest Langmuir Ni (II) uptake capacity at 7.75 mg/g, followed by mature pine wood sawdust (6.34 mg/g), lignin (5.66 mg/g), and rice straw (3.22 mg/g) derived graphene oxides. In another work, graphene oxide derived from polyethylene terephthalates found in waste plastic bottles exhibited significant Langmuir uptake capacity for methylene blue (867.2 mg/g) and acid blue-25 (641.4 mg/g) dyes (El Essawy et al., 2017). Gupta et al. have developed a graphene-like porous carbon nanostructure (BGBH-C-K) by utilizing Bengal gram bean husk (BGBH), an agricultural waste biomass, through alkali activation. Bengal gram bean, scientifically known as *Cicer arietinum* or chickpea, belongs to the Fabaceae family and is recognized for its nutrient-rich composition, including substantial amounts of protein, dietary fibers, and minerals. The BGBH- C-K, characterized by its graphene-like lamellar structure and abundant micropores, demonstrated significant potential for the adsorption of organic dyes from industrial water (Gupta et al., 2019). Goswami et al. published the first study on using rice straw-derived biochar as an eco-friendly substitute for graphite in the synthesis of Graphene Oxide Nanoplatelets (GONp) through the Hummers method. In this research, biochar derived from rice straw biomass (RSB), a widely produced agricultural waste, served as the primary material for GONp synthesis. The functional characteristics of these GONps were assessed based on their adsorption efficiency. Adsorption experiments were conducted using Crystal

Violet (CV), a common azine dye employed in the manufacturing of paint and printing industries (Goswami et al., 2017).

Lignin, constituting the second most abundant aromatic compound after cellulose, accounts for approximately 20 % of the world's organic carbon. It is the substance responsible for the woody characteristics of plants.

Recognized as a valuable material, lignin can be transformed into high-value products. Its cost-effectiveness, widespread availability, and versatile properties have captured the attention of researchers globally. Numerous studies focus on utilizing lignin and lignin-based materials for the removal of heavy metals from wastewater. For instance, Wu et al. (Wu et al., 2008) conducted adsorption using lignin as an adsorbent for the removal of Cr(III) from water. Srivastava et al. (1994) characterized lignin in its application to remove zinc and lead. Meng et al. (Meng et al., 2020) investigated the use of lignin-based adsorbents for the removal of azo dye from aqueous solutions.

Pine-derived adsorbents have been extensively studied due to their widespread availability on various continents and have been employed in numerous adsorption research in the literature. In a chapter by Philippou et al. (2021), it was concluded that pine biomass and waste, encompassing components like bark, needles, and cones, have effectively been utilized to create innovative adsorbents (raw, modified, activated carbon, etc.) for capturing toxic metal ions from wastewater. On the other hand, adsorbents derived from sunflower residue have proven to be highly efficient for decontaminating (waste) waters from dyes. Studies indicate that activated carbon produced from sunflower residues exhibits a higher adsorption capacity compared to the pristine form. This enhancement is attributed to the increased surface area and the presence of available functional groups on the adsorbent's surface (Anastopoulos et al., 2022).

Several studies have investigated the efficacy of corn cob as an adsorbent. Arunkumar et al. (2014) highlighted the significant role of corn cob as an effective absorbent for the adsorption of nickel (II). They observed an increase in adsorption capacity with a rise in the concentration of heavy metal ions, reaching a maximum of 70.08%. Research has indicated that incorporating active ingredients, such as zinc chloride, into corn cob can enhance the adsorption properties of activated biochars derived from raw biomass. In a study by Tsai et al. (1998), activated carbon was synthesized from corn waste (cob) using chemical activation with zinc chloride. The impregnation of zinc chloride into biochar was found to be crucial for adsorbing metal ions from wastewater, as it blended with biochar, forming activated carbon with a higher surface area due to its smaller particle size, resulting in increased adsorption efficiency.

Contaminated Soil Remediation

Soil contamination is a global concern and acts as a significant obstacle to sustainable development attenuating heavy metals in contaminated soil. It affects the equilibrium of ecosystem, leading to escalating economic losses and human health damage. Inadequate or irresponsible disposal practices, such as improper industrial discharge, mining tailings, waste disposal, and stockpiles, are the primary contributors to soil contamination. Common soil contaminants encompass heavy metals, toxic organic compounds, and radionuclides (Xu et al., 2019). To mitigate the high risks posed to human health and ecological security, it is essential to remediate contaminated soils for their recovery. Various remediation efforts, including the application of cutting-edge technologies, have been undertaken to achieve environmentally sound and cost-effective restoration of polluted lands (Mao et al., 2015).

Shellfish farming has become a globally expanding economic venture. However, the intensive production of shellfish results in substantial waste. Recycling shell waste proves to be a good alternative, addressing environmental concerns and providing economic benefits. Mussel shells, a plentiful by-product of the canning industry, constitute 32% of the animal's total weight and are particularly rich in calcium carbonate (Barros et al., 2009). Through calcination, these shells can be transformed into a useful calcium oxide catalyst (Benni et al., 2021). Notably, calcium carbonate surfaces, especially in the form of calcite, are known to adsorb metals like Zn^{2+}, Cd^{2+}, and Pb^{2+} (Jurinak & Bauer, 1956; McBride, 1980). Given its predominant composition of calcium carbonate, mussel shells serve as an ideal adsorbent for various heavy metals. Therefore, there are many works in the literature related to the decontamination of soil by mussel shells (Fernández-Calviño et al., 2014, 2018; Garrido-Rodriguez et al., 2014; Garrido-Rodríguez et al., 2013; Ramírez-Pérez et al., 2013). For instance, Ahmad et al. (2012). utilized mussel shells, cow bones, and biochar to mitigate lead (Pb) toxicity in heavily contaminated soil from a military shooting range in Korea. Their findings revealed that the tested amendments or soil dilution effectively reduced Pb availability in the military shooting range soil, thereby mitigating the risk of ecotoxicity (Ahmad et al., 2012). Ok et al. (2010). evaluated the utilization of oyster shell waste as a liming material in stabilizing metal-contaminated soil. Their study aimed to remediate soils contaminated with cadmium (Cd) and lead (Pb), which are often encountered in areas near abandoned mines, by employing oyster shell waste as a soil stabilizer (Ok et al., 2010). In the study that was published by Soares et al. (2015) it was aimed to evaluate the feasibility of using a compost obtained from composting industrial eggshell with other organic wastes, as a soil amendment for immobilization of Pb and Zn in acidic contaminated mining soil.

Air Pollutant Remediation

One of the most significant challenges of our time is air pollution, as it not only contributes to climate change but also has detrimental effects on public and individual health, leading to a rise in morbidity and mortality. Air contamination signifies alterations in the natural atmospheric composition resulting from the introduction of biological, physical, or chemical substances released from biogenic, geogenic, or anthropogenic sources. Both outdoor and indoor air contaminants might be present in particulate or gaseous forms. Particulate form encompasses small-sized masses with complex chemical constituents, ranging from nanometers to micrometers, including biologically originated aerosols like fungi, bacteria, and viruses. The gaseous form includes various chemical molecules such as ozone (O_3), sulfur dioxide (SO_2), and carbon monoxide (CO) (Manisalidis et al., 2020).

Poor air quality has detrimental effects on the natural environment, including living organisms and vegetation, as well as on human health. It is associated with various potentially fatal diseases, such as cardiovascular diseases, respiratory diseases, and cancer. According to the World Health Organization (WHO), air pollution causes approximately seven million deaths globally each year. WHO data reveals that nearly nine out of ten people breathe air with elevated levels of contaminants (WHO, 2018). Therefore, obtaining comprehensive information about air pollutant sources and developing innovative technologies for air remediation is crucial (Saleem et al., 2022). In this regard, solid adsorbents that derived from industrial wastes and their utilization for CO_2 capture were reviewed by Kaithwas et al. and Wang et al. (Kaithwas et al., 2012; J. Wang et al., 2019).

Serafin et al. (Serafin et al., 2021) conducted a study on the production of activated carbons using various biomass residues from the Amazonian fruit waste, for low-pressure CO_2 storage. Employing a two-step method with KOH activation, microporous activated carbons characterized by a significant volume of small pores were prepared using four different Amazonian biomasses (Cupuassu shells, andiroba seeds, assai seeds and Brazilian nutshells) as carbon precursors. The activated carbon derived from andiroba seeds exhibited the highest CO_2 adsorption at 1 bar, reaching 7.18 mmol/g at 273 K and 4.81 mmol/g at 298 K.

Fly ash (FA) is a byproduct, typically consisting of fine particles, generated from the flue gases of furnaces using pulverized coal. Maroto-Valer et al. (Mercedes Maroto-Valer et al., 2008) created two types of activated carbon-based adsorbents from fly ash with high content of LOI values (ranging from 59% to 97%) to capture CO_2 at different temperatures. These adsorbents were further modified with various amine compounds. Their findings indicated that steam treatment could increase the surface area of the synthetic adsorbent, while amine impregnation had the opposite effect, decreasing the surface area.

Coconut shell, being an excellent carbon precursor, is known for its high purity, lack of dust, and consistent porous structure. Son et al. (Son et al., 2005) produced carbon molecular sieves using coconut shell char as the primary material. They doped magnesium (Mg), calcium (Ca), cobalt (Co), copper (Cu), and nickel (Ni) onto the coconut char, followed by calcination at a specified temperature. Under conditions of 25°C and 1 bar, carbon molecular sieves synthesized from magnesium-impregnated coconut char exhibited a relatively high uptake performance for CO_2, reaching 2.23 mmol/g.

Almond shell is also considered as a raw material for the production of activated carbon. Plaza et al. (Plaza et al., 2011) created two types of activated carbon materials from almond shells intended for CO_2 adsorption. The study compared two modification approaches: conventional activation with CO_2 and heat treatment with ammonia gas. Both resulting samples exhibited commendable CO_2 uptake performance, demonstrated in both 100% CO_2 and a binary mixture containing 15% CO_2 in N_2.

Sustainability Reflections in Health and Environmental Management And Ultimate Remarks

In this chapter, various applications of waste materials in the field of healthcare and environmental management have been overviewed. Recently, the increased global concerns about the sustainability of Earth have brought increased attention to the public and industrial sectors regarding the damaging effects of chemical toxins and non-biodegradable materials. The accumulation of waste materials constitutes a growing problem, posing threats not only to the environment but also to public safety. Addressing this issue involves recycling and utilizing these waste materials in industries instead of disposing of them. Consequently, there is an urgent demand for the efficient transformation of wastes into useful materials, aiming to minimize the amount of waste released into the environment. While the idea of transforming waste into advanced technologies for environmental purposes appears attractive, there are substantial knowledge gaps related to engineered materials that need to be addressed before these concepts can be effectively implemented in the real world. These knowledge gaps include considerations about energy utilization, the generation of secondary wastes, the behavior of fate and transport, exposure routes in diverse environments, and toxicity levels across various organisms. Although functional materials can be derived through sustainable methods, it's essential to recognize that the sustainability of these materials doesn't guarantee their safety or assure that their use and release into the environment won't have adverse effects. The economic and functional advantages of composites created from renewable and sustainable resources should be complemented by proactive engagement from industry leaders and government officials to propel global expansion in this innovative category of materials, ensuring positive impacts on society, the environment, and the economy.

References

Ahmad, M., Soo Lee, S., Yang, J. E., Ro, H. M., Han Lee, Y., & Sik Ok, Y. (2012). Effects of soil dilution and amendments (mussel shell, cow bone, and biochar) on Pb availability and phytotoxicity in military shooting range soil. *Ecotoxicology and Environmental Safety*, *79*, 225–231. https://doi.org/10.1016/j.ecoenv.2012.01.003

Ahsan, S. M., Thomas, M., Reddy, K. K., Sooraparaju, S. G., Asthana, A., & Bhatnagar, I. (2018). Chitosan as biomaterial in drug delivery and tissue engineering. *International Journal of Biological Macromolecules*, *110*, 97–109. https://doi.org/10.1016/j.ijbiomac.2017.08.140

Ali, A., & Ahmed, S. (2018). A review on chitosan and its nanocomposites in drug delivery. *International Journal of Biological Macromolecules*, *109*, 273–286. https://doi.org/10.1016/j.ijbiomac.2017.12.078

Alqahtani, M. S., Alqahtani, A., Al-Thabit, A., Roni, M., & Syed, R. (2019). Novel lignin nanoparticles for oral drug delivery. *Journal of Materials Chemistry B*, *7*(28), 4461–4473. https://doi.org/10.1039/c9tb00594c

Anastopoulos, I., Giannopoulos, G., Islam, A., Ighalo, J. O., Iwuchukwu, F. U., Pashalidis, I., Kalderis, D., Giannakoudakis, D. A., Nair, V., & Lima, E. C. (2022). Chapter 13 - Potential environmental applications of Helianthus annuus (sunflower) residue-based adsorbents for dye removal in (waste)waters. In I. Anastopoulos, E. C. Lima, L. Meili, & D. A. Giannakoudakis (Eds.), *Biomass-Derived Materials for Environmental Applications* (pp. 307–315). Elsevier.

Arunkumar, C., Perumal, R., Narayanan, L., & Arunkumar, J. (2014). Use of Corn Cob as Low Cost Adsorbent for the Removal of Nickel (II) From Aqueous Solution. *International Journal of Advanced Biotechnology and Research*, *5*(3), 325–330. http://www.bipublication.com

Barros, M. C., Magán, A., Valiño, S., Bello, P. M., Casares, J. J., & Blanco, J. M. (2009). Identification of best available techniques in the seafood industry: a case study. *Journal of Cleaner Production*, *17*(3), 391–399. https://doi.org/10.1016/j.jclepro.2008.08.012

Benni, S. D., Munnolli, R. S., Katagi, K. S., & Kadam, N. S. (2021). Mussel shells as sustainable catalyst: Synthesis of liquid fuel from non edible seeds of Bauhinia malabarica and Gymnosporia montana. *Current Research in Green and Sustainable Chemistry*, *4*(May), 100124. https://doi.org/10.1016/j.crgsc.2021.100124

Bernkop-Schnürch, A., & Dünnhaupt, S. (2012). Chitosan-based drug delivery systems. *European Journal of Pharmaceutics and Biopharmaceutics*, *81*(3), 463–469. https://doi.org/10.1016/j.ejpb.2012.04.007

Bertram, F., Tuxen, A., & Nielsen, T. B. (2018). Development of Environmentally Friendly Epoxies for Well Conformance. *Proceedings - SPE International Symposium on Formation Damage Control*, *2018-Febru*(1), 1–9. https://doi.org/10.2118/189475-ms

Bhattarai, N., Gunn, J., & Zhang, M. (2010). Chitosan-based hydrogels for controlled, localized drug delivery. *Advanced Drug Delivery Reviews*, *62*(1), 83–99. https://doi.org/10.1016/j.addr.2009.07.019

Chang, C., & Zhang, L. (2011). Cellulose-based hydrogels: Present status and application prospects. *Carbohydrate Polymers*, *84*(1), 40–53. https://doi.org/10.1016/j.carbpol.2010.12.023

Chen, Z., Liu, Y., Wei, W., & Ni, B. J. (2019). Recent advances in electrocatalysts for halogenated organic pollutant degradation. *Environmental Science: Nano*, *6*(8), 2332–2366. https://doi.org/10.1039/c9en00411d

Chen, Z., Wei, W., Chen, H., & Ni, B. J. (2022). Recent advances in waste-derived functional materials for wastewater remediation. *Eco-Environment and Health*, *1*(2), 86–104. https://doi.org/10.1016/j.eehl.2022.05.001

Choi, B., Kim, S., Lin, B., Wu, B. M., & Lee, M. (2014). Cartilaginous extracellular matrix-modified chitosan hydrogels for cartilage tissue engineering. *ACS Applied Materials and Interfaces*, *6*(22), 20110–20121. https://doi.org/10.1021/am505723k

Dash, M., Chiellini, F., Ottenbrite, R. M., & Chiellini, E. (2011). Chitosan - A versatile semi-synthetic polymer in biomedical applications. *Progress in Polymer Science (Oxford)*, *36*(8), 981–1014. https://doi.org/10.1016/j.progpolymsci.2011.02.001

El Essawy, N. A., Ali, S. M., Farag, H. A., Konsowa, A. H., Elnouby, M., & Hamad, H. A. (2017). Green synthesis of graphene from recycled PET bottle wastes for use in the adsorption of dyes in aqueous solution. *Ecotoxicology and Environmental Safety*, *145*(April), 57–68. https://doi.org/10.1016/j.ecoenv.2017.07.014 EPA. (2023). *The Basics of Water Remediation*.

Faikrua, A., Jeenapongsa, R., Sila-Asna, M., & Viyoch, J. (2009). Properties of β-glycerol phosphate/collagen/chitosan blend scaffolds for application in skin tissue engineering. *ScienceAsia*, *35*(3), 247–254. https://doi.org/10.2306/scienceasia1513-1874.2009.35.247

Fernández-Calviño, D., Cutillas-Barreiro, L., Nóvoa-Muñoz, J. C., Díaz-Raviña, M., Fernández- Sanjurjo, M. J., Álvarez-Rodríguez, E., Núñez-Delgado, A., Arias-Estévez, M., & Rousk, J. (2018). Using pine bark and mussel shell amendments to reclaim microbial functions in a Cu polluted acid mine soil. *Applied Soil Ecology*, *127*(February), 102–111. https://doi.org/10.1016/j.apsoil.2018.03.010

Fernández-Calviño, D., Garrido-Rodríguez, B., Arias-Estévez, M., Díaz-Raviña, M., Álvarez-Rodríguez, E., Fernández-Sanjurjo, M. J., & Nuñez-Delgado, A. (2014). Effect of crushed mussel shell addition on bacterial growth in acid polluted soils. *Applied Soil Ecology*, *85*, 65–68. https://doi.org/10.1016/j.apsoil.2014.09.010

Figueiredo, P., Lintinen, K., Kiriazis, A., Hynninen, V., Liu, Z., Bauleth-Ramos, T., Rahikkala, A., Correia, A., Kohout, T., Sarmento, B., Yli-Kauhaluoma, J., Hirvonen, J., Ikkala, O., Kostiainen, M. A., & Santos, H. A. (2017). In vitro evaluation of biodegradable lignin-based nanoparticles for drug delivery and enhanced antiproliferation effect in cancer cells. *Biomaterials*, *121*, 97–108. https://doi.org/10.1016/j.biomaterials.2016.12.034

Garg, J., Nee Chiu, M., Krishnan, S., Kumar Tripathi, L., Pandit, S., Farasati Far, B., Kumar Jha, N., Kumar Kesari, K., Tripathi, V., Pandey, S., & Kumar Gupta, P. (2022). Applications of lignin nanoparticles for cancer drug delivery: An update. *Materials Letters*, *311*(December 2021), 131573. https://doi.org/10.1016/j.matlet.2021.131573

Garrido-Rodriguez, B., Cutillas-Barreiro, L., Fernández-Calviño, D., Arias-Estévez, M., Fernández- Sanjurjo, M. J., Álvarez-Rodríguez, E., & Núñez-Delgado, A. (2014). Competitive adsorption and transport of Cd, Cu, Ni and Zn in a mine soil amended with mussel shell. *Chemosphere*, *107*, 379–385. https://doi.org/10.1016/j.chemosphere.2013.12.097

Garrido-Rodríguez, B., Fernández-Calviño, D., Nóvoa Muñoz, J. C., Arias-Estévez, M., Díaz-Raviña, M., Álvarez-Rodríguez, E., Fernández-Sanjurjo, M. J., & Núñez-Delgado, A. (2013). pH-dependent copper release in acid soils treated with crushed mussel shell. *International Journal of Environmental Science and Technology*, *10*(5), 983–994. https://doi.org/10.1007/s13762-013- 0201-8

George, D., Maheswari, P. U., Sheriffa Begum, K. M. M., & Arthanareeswaran, G. (2019). Biomass- Derived Dialdehyde Cellulose Cross-linked Chitosan-Based Nanocomposite Hydrogel with Phytosynthesized Zinc Oxide Nanoparticles for Enhanced Curcumin Delivery and Bioactivity. *Journal of Agricultural and Food Chemistry*, *67*(39), 10880–10890. https://doi.org/10.1021/acs.jafc.9b01933

Goswami, S., Banerjee, P., Datta, S., Mukhopadhayay, A., & Das, P. (2017). Graphene oxide nanoplatelets synthesized with carbonized agro-waste biomass as green precursor and its application for the treatment of dye rich wastewater. *Process Safety and Environmental Protection*, *106*, 163–172. https://doi.org/10.1016/j.psep.2017.01.003

Gupta, K., Gupta, D., & Khatri, O. P. (2019). Graphene-like porous carbon nanostructure from Bengal gram bean husk and its application for fast and efficient adsorption of organic dyes. *Applied Surface Science*, *476*(December 2018), 647–657. https://doi.org/10.1016/j.apsusc.2019.01.138

Habibi, Y. (2014). Key advances in the chemical modification of nanocelluloses. *Chemical Society Reviews*, *43*(5), 1519–1542. https://doi.org/10.1039/c3cs60204d

Hu, J. xiao, Cai, X., Mo, S. bo, Chen, L., Shen, X. yu, & Tong, H. (2015). Fabrication and characterization of chitosan-silk fibroin/hydroxyapatite composites via in situ precipitation for bone tissue engineering. *Chinese Journal of Polymer Science (English Edition)*, *33*(12), 1661–1671. https://doi.org/10.1007/s10118-015-1710-3

Ikram, R., Mohamed Jan, B., Nagy, P. B., & Szabo, T. (2023). Recycling waste sources into nanocomposites of graphene materials: Overview from an energy-focused perspective. *Nanotechnology Reviews*, *12*(1), 1–45. https://doi.org/10.1515/ntrev-2022-0512

Jayakumar, R., Menon, D., Manzoor, K., Nair, S. V., & Tamura, H. (2010). Biomedical applications of chitin and chitosan based nanomaterials - A short review. *Carbohydrate Polymers*, *82*(2), 227–232. https://doi.org/10.1016/j.carbpol.2010.04.074

Jurinak, J. J., & Bauer, N. (1956). Thermodynamics of Zinc Adsorption on Calcite, Dolomite and Magnesite-Type Minerals. *Soil Science Society of America Journal*, *20*(4), 466–471. https://doi.org/10.2136/sssaj1956.03615995002000040006x

Kaithwas, A., Prasad, M., Kulshreshtha, A., & Verma, S. (2012). Industrial wastes derived solid adsorbents for CO 2 capture: A mini review. *Chemical Engineering Research and Design*, *90*(10), 1632–1641. https://doi.org/10.1016/j.cherd.2012.02.011

Klemm, D., Kramer, F., Moritz, S., Lindström, T., Ankerfors, M., Gray, D., & Dorris, A. (2011). Nanocelluloses: A new family of nature-based materials. *Angewandte Chemie - International Edition*, *50*(24), 5438–5466. https://doi.org/10.1002/anie.201001273

Kravanja, G., Primoži˘c, M., Knez, Ž., & Leitgeb, M. (2019). Chitosan-Based (Nano)Materials for Novel Biomedical Applications. *Molecules*, *24*(1960), 1–23. https://doi.org/10.1016/B978-0-12- 816911-7.00023-2

Kumar, R., Butreddy, A., Kommineni, N., Guruprasad Reddy, P., Bunekar, N., Sarkar, C., Dutt, S., Mishra, V. K., Aadil, K. R., Mishra, Y. K., Oupicky, D., & Kaushik, A. (2021). Lignin: Drug/gene delivery and tissue engineering applications. *International Journal of Nanomedicine*, *16*, 2419– 2441. https://doi.org/10.2147/IJN.S303462

Li, L., Wang, F., & Shao, Z. (2018). Biomass-based magnetic fluorescent nanoparticles: One-step scalable synthesis, application as drug carriers and mechanism study. *Carbohydrate Polymers*, *184*(October 2017), 277–287. https://doi.org/10.1016/j.carbpol.2017.12.079

Li, N., He, M., Lu, X., Yan, B., Duan, X., Chen, G., Wang, S., & Hou, L. (2022). Municipal solid waste derived biochars for wastewater treatment: Production, properties and applications. *Resources, Conservation and Recycling*, *177*(135), 106003. https://doi.org/10.1016/j.resconrec.2021.106003

Li, Y. C. E. (2019). Sustainable Biomass Materials for Biomedical Applications. *ACS Biomaterials Science and Engineering*, *5*(5), 2079–2092. https://doi.org/10.1021/acsbiomaterials.8b01634

Li, Y., Peng, Y., Hu, Y., Liu, J., Yuan, T., Zhou, W., Dong, X., Wang, C., Binks, B. P., & Yang, Z. (2023). Fabrication of Poly(ϵ-caprolactone)-embedded Lignin-Chitosan Nanocomposite Porous Scaffolds from Pickering Emulsions. *Langmuir*, *39*(20), 6947–6956. https://doi.org/10.1021/acs.langmuir.2c02942

Li, Y., Yang, D., Lu, S., Lao, S., & Qiu, X. (2018). Modified Lignin with Anionic Surfactant and Its Application in Controlled Release of Avermectin. *Journal of Agricultural and Food Chemistry*, *66*(13), 3457–3464. https://doi.org/10.1021/acs.jafc.8b00393

Manisalidis, I., Stavropoulou, E., Stavropoulos, A., & Bezirtzoglou, E. (2020). Environmental and Health Impacts of Air Pollution: A Review. *Frontiers in Public Health*, *8*(February), 1–13. https://doi.org/10.3389/fpubh.2020.00014

Mao, X., Jiang, R., Xiao, W., & Yu, J. (2015). Use of surfactants for the remediation of contaminated soils: A review. *Journal of Hazardous Materials*, *285*, 419–435. https://doi.org/10.1016/j.jhazmat.2014.12.009

Mauney, J. R., Cannon, G. M., Lovett, M. L., Gong, E. M., Di Vizio, D., Gomez, P., Kaplan, D. L., Adam, R. M., & Estrada, C. R. (2011). Evaluation of gel spun silk-based biomaterials in a murine model of bladder augmentation. *Biomaterials*, *32*(3), 808–818. https://doi.org/10.1016/j.biomaterials.2010.09.051

McBride, M. B. (1980). Division S-2-soil chemistry. Chemisorption of Cd^{2+} on calcite surfaces. *Soil Sci. Soc. America J.*, *44*(1), 26–28.

Meng, X., Scheidemantle, B., Li, M., Wang, Y. Y., Zhao, X., Toro-González, M., Singh, P., Pu, Y., Wyman, C. E., Ozcan, S., Cai, C. M., & Ragauskas, A. J. (2020). Synthesis, Characterization, and Utilization of a Lignin-Based Adsorbent for Effective Removal of Azo Dye from Aqueous Solution.

ACS Omega, *5*(6), 2865–2877. https://doi.org/10.1021/acsomega.9b03717

Mercedes Maroto-Valer, M., Lu, Z., Zhang, Y., & Tang, Z. (2008). Sorbents for CO2 capture from high carbon fly ashes. *Waste Management*, *28*(11), 2320–2328. https://doi.org/10.1016/j.wasman.2007.10.012

Miklos, D. B., Remy, C., Jekel, M., Linden, K. G., Drewes, J. E., & Hübner, U. (2018). Evaluation of advanced oxidation processes for water and wastewater treatment – A critical review. *Water Research*, *139*, 118–131. https://doi.org/10.1016/j.watres.2018.03.042

Nagpal, K., Singh, S. K., & Mishra, D. N. (2010). Chitosan Nanoparticles: A Promising System in Novel Drug Delivery. *Chem Pharm Bull, 58*(11), 1423–1430. https://doi.org/10.1248/cpb.58.1423

Nasir, S., Hussein, M. Z., Zainal, Z., & Yusof, N. A. (2018). Carbon-based nanomaterials/allotropes: A glimpse of their synthesis, properties and some applications. *Materials*, *11*(2), 1–24. https://doi.org/10.3390/ma11020295

Ok, Y. S., Oh, S. E., Ahmad, M., Hyun, S., Kim, K. R., Moon, D. H., Lee, S. S., Lim, K. J., Jeon, W. T., & Yang, J. E. (2010). Effects of natural and calcined oyster shells on Cd and Pb immobilization in contaminated soils. *Environmental Earth Sciences*, *61*(6), 1301–1308. https://doi.org/10.1007/s12665-010-0674-4

Patel, D. K., Dutta, S. D., Ganguly, K., & Lim, K. T. (2021). Multifunctional bioactive chitosan/cellulose nanocrystal scaffolds eradicate bacterial growth and sustain drug delivery. *International Journal of Biological Macromolecules*, *170*, 178–188. https://doi.org/10.1016/j.ijbiomac.2020.12.145

Philippou, K., Anastopoulos, I., Pashalidis, I., Hosseini-Bandegharaei, A., Usman, M., Kornaros, M., Omirou, M., Kalderis, D., Milojković, J. V., Lopičić, Z. R., & Abatal, M. (2021). Chapter 6 - The application of pine-based adsorbents to remove potentially toxic elements from aqueous solutions. In A. Núñez-Delgado (Ed.), *Sorbents Materials for Controlling Environmental Pollution Current State and Trends* (pp. 113–133). Elsevier.

Pillai, O., & Panchagnula, R. (2001). Polymers in Drug Delivery. *Current Opinion in Chemical Biology, 5,* 447–451. https://doi.org/10.1016/S1367-5931(00)00227-1

Plaza, M. G., Pevida, C., Pis, J. J., & Rubiera, F. (2011). Evaluation of the cyclic capacity of low-cost carbon adsorbents for post-combustion CO2 capture. *Energy Procedia*, *4*, 1228–1234. https://doi.org/10.1016/j.egypro.2011.01.178

Prausnitz, M. R., & Langer, R. (2008). Transdermal drug delivery. *Nature Biotechnology*, *26*(11), 1261–1268. https://doi.org/10.1038/nbt.1504

Ramírez-Pérez, A. M., Paradelo, M., Nóvoa-Muñoz, J. C., Arias-Estévez, M., Fernández-Sanjurjo, M. J., Álvarez-Rodríguez, E., & Núñez-Delgado, A. (2013). Heavy metal retention in copper mine soil treated with mussel shells: Batch and column experiments. *Journal of Hazardous Materials*, *248–249*(1), 122–130. https://doi.org/10.1016/j.jhazmat.2012.12.045

Rudzinski, W. E., Palacios, A., Ahmed, A., Lane, M. A., & Aminabhavi, T. M. (2016). Targeted delivery of small interfering RNA to colon cancer cells using chitosan and PEGylated chitosan nanoparticles. *Carbohydrate Polymers*, *147*, 323–332. https://doi.org/10.1016/j.carbpol.2016.04.041

Saleem, H., Zaidi, S. J., Ismail, A. F., & Goh, P. S. (2022). Advances of nanomaterials for air pollution remediation and their impacts on the environment. *Chemosphere*, *287*, 132083. https://doi.org/10.1016/j.chemosphere.2021.132083

Serafin, J., Ouzzine, M., Cruz, O. F., Sreńscek-Nazzal, J., Campello Gómez, I., Azar, F. Z., Rey Mafull, C. A., Hotza, D., & Rambo, C. R. (2021). Conversion of fruit waste-derived biomass to highly microporous activated carbon for enhanced CO2 capture. *Waste Management*, *136*(May), 273–282. https://doi.org/10.1016/j.wasman.2021.10.025

Shan, B., Ji, Y., Zhong, Y., Chen, L., Li, S., Zhang, J., Chen, L., Liu, X., Chen, Y., Yan, N., & Song, Y. (2019). Nitrogen-containing three-dimensional biomass porous carbon materials as an efficient enzymatic biosensing platform for glucose sensing. *RSC Advances*, *9*(44), 25647–25654. https://doi.org/10.1039/c9ra04008k

Smith, S. C., & Rodrigues, D. F. (2015). Carbon-based nanomaterials for removal of chemical and biological contaminants from water: A review of mechanisms and applications. *Carbon*, *91*, 122–143. https://doi.org/10.1016/j.carbon.2015.04.043

Soares, M. A. R., Quina, M. J., & Quinta-Ferreira, R. M. (2015). Immobilisation of lead and zinc in contaminated soil using compost derived from industrial eggshell. *Journal of Environmental Management*, *164*, 137–145. https://doi.org/10.1016/j.jenvman.2015.08.042

Soffian, M. S., Abdul Halim, F. Z., Aziz, F., A. Rahman, M., Mohamed Amin, M. A., & Awang Chee, D. N. (2022). Carbon-based material derived from biomass waste for wastewater treatment. *Environmental Advances*, *9*(June), 100259. https://doi.org/10.1016/j.envadv.2022.100259

Son, S. J., Choi, J. S., Choo, K. Y., Song, S. D., Vijayalakshmi, S., & Kim, T. H. (2005). Development of carbon dioxide adsorbents using carbon materials prepared from coconut shell. *Korean Journal of Chemical Engineering*, *22*(2), 291–297. https://doi.org/10.1007/BF02701500

Srivastava, S. K., Singh, A. K., & Sharma, A. (1994). Studies on the uptake of lead and zinc by lignin obtained from black liquor - a paper industry waste material. *Environmental Technology (United Kingdom)*, *15*(4), 353–361. https://doi.org/10.1080/09593339409385438

Tibbitt, M. W., Dahlman, J. E., & Langer, R. (2016). Emerging Frontiers in Drug Delivery. *Journal of the American Chemical Society*, *138*(3), 704–717. https://doi.org/10.1021/jacs.5b09974

Tohamy, H. A. S., Anis, B., Youssef, M. A., Abdallah, A. E. M., El-Sakhawy, M., & Kamel, S. (2020). Preparation of eco-friendly graphene oxide from agricultural wastes for water treatment. *Desalination and Water Treatment*, *191*, 250–262. https://doi.org/10.5004/dwt.2020.25652

Tsai, W. T., Chang, C. Y., & Lee, S. L. (1998). A low cost adsorbent from agricultural waste corn cob by zinc chloride activation. *Bioresource Technology*, *64*(3), 211–217. https://doi.org/10.1016/S0960-8524(97)00168-5

Tseng, T. C., Tao, L., Hsieh, F. Y., Wei, Y., Chiu, I. M., & Hsu, S. H. (2015). An injectable, self-healing hydrogel to repair the central nervous system. *Advanced Materials*, *27*(23), 3518–3524. https://doi.org/10.1002/adma.201500762

Wang, J., Yang, Y., Jia, Q., Shi, Y., Guan, Q., Yang, N., Ning, P., & Wang, Q. (2019). Solid-Waste- Derived Carbon Dioxide-Capturing Materials. In *ChemSusChem* (Vol. 12, Issue 10). https://doi.org/10.1002/cssc.201802655

Wang, L., Zhang, Q., Chen, S., Xu, F., Chen, S., Jia, J., Tan, H., Hou, H., & Song, Y. (2014). Electrochemical sensing and biosensing platform based on biomass-derived macroporous carbon materials. *Analytical Chemistry*, *86*(3), 1414–1421. https://doi.org/10.1021/ac401563m

WHO. (2018). *9 out of 10 people worldwide breathe polluted air, but more countries are taking action*. https://www.who.int/news/item/02-05-2018-9-out-of-10-people-worldwide-breathe-polluted-air- but-more-countries-are-taking-action

Wu, Y., Zhang, S., Guo, X., & Huang, H. (2008). Adsorption of chromium(III) on lignin. *Bioresource Technology*, *99*(16), 7709–7715. https://doi.org/10.1016/j.biortech.2008.01.069

Xu, J., Liu, C., Hsu, P. C., Zhao, J., Wu, T., Tang, J., Liu, K., & Cui, Y. (2019). Remediation of heavy metal contaminated soil by asymmetrical alternating current electrochemistry. *Nature Communications*, *10*(1), 1–8. https://doi.org/10.1038/s41467-019-10472-x

Yiamsawas, D., Beckers, S. J., Lu, H., Landfester, K., & Wurm, F. R. (2017). Morphology-Controlled Synthesis of Lignin Nanocarriers for Drug Delivery and Carbon Materials. *ACS Biomaterials Science and Engineering*, *3*(10), 2375–2383. https://doi.org/10.1021/acsbiomaterials.7b00278

Zainal, S. H., Mohd, N. H., Suhaili, N., Anuar, F. H., Lazim, A. M., & Othaman, R. (2021). Preparation of cellulose-based hydrogel: A review. *Journal of Materials Research and Technology*, *10*, 935–952. https://doi.org/10.1016/j.jmrt.2020.12.012

Zhang, J., Xia, W., Liu, P., Cheng, Q., Tahirou, T., Gu, W., & Li, B. (2010). Chitosan modification and pharmaceutical/biomedical applications. *Marine Drugs*, *8*(7), 1962–1987. https://doi.org/10.3390/md8071962

Zheng, H., Han, X., Wei, Q., Liu, X., Li, Y., & Zhou, J. (2022). A green flexible and wearable biosensor based on carbon nanofibers for sensitive detection of uric acid in artificial urine. *Journal of Materials Chemistry B, 10,* 8450– 8461. https://doi.org/10.1039/D2TB01547A

About Author

Prof. Arzum ERDEM | Ege University | arzum.erdem[at]ege.edu.tr | ORCID: 0000-0002-4375-8386

Arzum Erdem received the PhD degree on Analytical Chemistry in Ege University (Izmir, Türkiye) in 2000. She has been working as a Full Professor since 2009 at Analytical Chemistry department in the Faculty of Pharmacy of Ege University. Prof. Dr. Arzum Erdem who is the principal investigator of the research team at nanoBioSensLab (Ege University, Izmir, Türkiye), has initiated many national and international collaborative research on development and applications of electrochemical (bio)sensors based on drugs, nucleic acids, enzymes, proteins, toxins etc. Prof. Arzum Erdem has authored more than 210 papers in refereed journals and conference proceedings, she has given more than 25 invited talks in international meetings and conferences, is the author / co-author of 20 book chapters and review papers. She has 7 national patents approved between 2018-2022. She has received 7439 citations according to the records on Web of Science (WoS) obtained in June 2023 with h-index: 45. Prof. Arzum Erdem received "Juniour Science Award" in 2006, and "Science Award" in 2015 given by The Scientific and Technological Research Council of Türkiye (TÜBİTAK). She was elected member of Turkish Academy of Sciences (TÜBA) since 2007, the Special Committee member of Association of Academies and Societies of Sciences in Asia (AASSA)- Women In Science and Engineering (WISE) for the period of 2017-2019, 2019-2021 and 2021-2023. She was elected as the fellow of Royal Society of Chemistry (FRSC) in December, 2017. The recent research of Prof. Arzum Erdem is centred on the development of novel transducers and chemical and biological recognition systems by using different nanomaterials (e.g, graphenes, magnetic nanoparticles, carbon nanotubes, gold and silver nanoparticles, dendrimers, nanowires, nanorods etc.) designed for electrochemical sensing of nucleic acid (DNA, miRNA) hybridization, and also the specific interactions between drug and DNA, or protein and DNA, or aptamer and its target (protein, drug, toxin, biomarker etc.), analytical systems for environmental monitoring, food safety, industry and biomedical monitoring. More details available in web site:
http://www.arzumerdem.com

**Assoc. Prof. Ece EKSIN | Izmir Demokrasi University |
ece.eksin[at]idu.edu.tr | ORCID: 0000- 0001-7175-2857**

Dr. Ece Eksin is an Associate Professor at the Vocational School of Health Services, Izmir Demokrasi University in Türkiye. She obtained B.Sc. degree in Biochemistry in the Faculty of Science of Ege University (Izmir, Türkiye) in 20011. She received her master's degree and PhD in Biotechnology from the Institute of Natural and Applied Sciences at Ege University in 2014 and 2019, respectively. Her research focuses on the design of electrodes modified with nanomaterials and the development of electrochemical (bio)sensor technologies for analyzing biomolecules, such as enzymes, proteins, amino acids, etc., serving as vital biomarkers for the diagnosis of various diseases. Additionally, she is engaged in the development of nucleic acid biosensors designed for electrochemical detection through nucleic acid (DNA, RNA) hybridization, with a specific emphasis on early diagnosis in genetic, infectious diseases, or cancer.

**Hüseyin ŞENTÜRK | Ege University |
huseyin.senturk[at]ege.edu.tr | ORCID: 0000-0002-3268-8319**

Huseyin Senturk is a PhD student and research assistant at the Analytical Chemistry Department in the Faculty of Pharmacy of Ege University in Türkiye. He obtained B.Sc. degree in Pharmacy in the Faculty of Pharmacy of Ege University (Izmir, Türkiye) in 2019. He started Analytical Chemistry PhD program at the Faculty of Pharmacy of Ege University in 2019 and continues. His research interest development of electrochemical biosensors based on nanomaterials and their applications on drug-DNA, aptamer-protein, antibody-antigen interactions and monitoring of nucleic acids.

BASIC SCIENCES, EARTHQUAKES, AND SUSTAINABILITY

Muzaffer Elmas

10.53478/TUBA.978-625-6110-22-9.ch08

Basic Sciences, Earthquakes, and Sustainability

Muzaffer Elmas
Kocaeli Health and Technology University

Abstract

Technological advancements have brought significant changes to society in recent years. These changes have made various fields of work more complex, with increasing benefits. In turn, the importance of basic sciences such as mathematics, physics, chemistry, and biology has become even more crucial in understanding world events and applying them accordingly. A solid basic science education is the first step in dealing with this complexity. As the pace of change picks up, studies and practices that lack good basic science knowledge will become difficult to control and may lead to a misinterpretation of facts. Sustainable development aims to balance economic, environmental, and social needs to ensure the well-being of current and future generations. The United Nations' 17 Sustainable Development Goals are all directly related to the basic sciences of mathematics, physics, chemistry, and biology, with most of the topics covered being sub-branches of these sciences. Countries can achieve these goals and beyond by placing greater importance on basic sciences. Earthquakes are among the leading natural disasters in the world. Seismology, geology, geophysics, soil mechanics, structural dynamics, and material branches play a vital role in understanding the mechanisms of earthquake formation, monitoring the movement of the earth's crust, predicting and determining earthquakes, as well as building and protecting structures appropriately. Basic sciences are at the core of these branches, and equations from basic sciences are used in predicting and determining earthquake magnitude. Mathematics and science, as basic sciences, have a critical role in achieving sustainability goals by helping us understand, predict, and control developmental processes. This study emphasizes the importance of basic sciences such as mathematics, chemistry, physics, and biology in understanding earthquake problems and sustainability issues.

Keywords
Mathematical Modeling, Physics, Chemistry, Biology, Earthquake Prediction

Introduction

The Relationship Between Basic Sciences and Sustainability

Basic sciences, which include physics, chemistry, biology, and mathematics, are the branches of science that explain all the developments in the world. The progress and studies in this field demonstrate this fact. The United Nations Sustainable Development Goals consist of 17 headings, which are:1. No Poverty, 2. Zero Hunger, 3. Good health and well-being, 4. Quality education, 5. Gender equality, 6. Clean water and sanitation, 7. Affordable and clean energy, 8. Decent work and economic growth, 9. Industry, innovation, and infrastructure, 10. Reduced inequality, 11. Sustainable cities and communities, 12. Responsible consumption and production, 13. Climate action, 14. Life below water, 15. Life on land, 16. Peace, justice, and strong institutions, 17. Partnerships for the goals. On September 25, 2015, leaders from around the world gathered at the Sustainable Development Summit held in New York, where they agreed on the Sustainable Development Goals. These goals consist of 17 objectives and 169 targets to eradicate poverty and ensure the well-being of humanity by 2030. To achieve these goals, the basic sciences and their products are crucial in each target. Some headings have a stronger association with science, while others rely on it to make remarkable contributions to their fields.

Mathematics is a key aspect of this since it is crucial in medicine, dentistry, and pharmacy. The use of technology with materials in education, such as AI and robotics, is also prevalent. Technology in the medical field has cost roughly $300 billion in the past century, and this figure is expected to increase in the next five years. Mathematics and physics have had a significant influence on the creation of these tools. Diagnosis tools, including X-rays, testing apparatus, and other detectors, owe their genesis to mathematical methodologies. Moreover, the age of robotic surgery and other pieces of equipment, as well as medications outside of the manual domain, is a paradigmatic advancement deriving from chemistry and biology. Currently, AI and technology are considerably shortening the time for diagnosis and treatment.

Quality education is heavily associated with advancing technologies such as the internet, robotics, AI, big data, and others. These changes have been prominent in the last fifty years, and the pace of this very alteration has grown exponentially in the past five years. As a result, the components, assessment plans, and architecture of teaching have seen massive variations. The World Economic Forum and UNESCO predicted a shortfall of graduates due to a deficit in their qualifications, which can sit up to seventy percent. This means that a further curriculum concentrated on these modern-day technologies and abilities should be accommodated in the schooling system. Particularly, universities should establish atmospheres in which undergraduates acquire proficiency utilizing tools such as digital techniques, AI, and robotics, and those aimed at verbal, visual, and written communication, leadership, analytical, and critical thinking.

Clean water and purification demand potent utilization of disciplines such as chemistry, biology, mathematical proficiency, and physics. The analysis of usable water and the purification of wastewater utilizing bacteria and other living organisms, the transportation and dissemination of water, and the responsible dumping of wastewater are aspects that borrow significantly from physics and mathematics. All of this is independent of the development of problem-solving devices through mathematical models, the construction of mathematical models to address and remedy real-world issues, and the consequence of such modeling on the way to sustainable development. Therefore, to ensure a resolute grasp of the complexity and peculiarities of these technologies, it is fundamental for individuals to improve their fundamental knowledge of the sciences (Kundu, 2018).

Mathematical modeling plays a vital role in sustainable management practices, encompassing social, environmental, and economic studies. Most developmental challenges can be resolved with mathematical models capable of defining them. The sustainability of planet Earth depends on the science of mathematics. Other areas where mathematical modeling is used include medicine, climate change, water resources, hazardous wastes, nuclear wastes, population dynamics, and many more. Mathematical modeling helps in understanding and managing epidemic diseases, preserving biological diversity, mitigating climate change, and ensuring ocean sustainability. All these issues fall under linear and nonlinear differential equations, which can be solved using mathematical models. Mathematics plays a crucial role in evaluating and tracking sustainability objectives, forecasting in various fields, and monitoring progress. Calculations are fundamental in assessing poverty levels, comparing regions within a country, or contrasting areas to other nations. Basic sciences like mathematics are directly linked to decent employment, economic development, production, innovation, and transportation. As sustainable management practices become more complex and require scientific, mathematical, or statistical tools, mathematical modelling and systems become essential. These models, based on dynamic systems within control theory, reconcile the ecological and economic spheres using a congruent modelling strategy. Mathematical modelling is vital to solving real-world problems such as estimating India's population in 2050, understanding global warming, modelling satellite launches, controlling pollution from vehicles, fluid flow within drains, lakes, rivers, catchment areas, and more. Mathematical modeling also plays a crucial role in sustainable management practices encompassing the social, environmental, and economic aspects of development challenges. These models can solve issues such as climate change, water resources, hazardous wastes, nuclear wastes, population dynamics, and more. The sustainability of the Earth is dependent on the science of mathematics. Mathematical models also show the impact of medicine on the human system. Linear and nonlinear differential equations are used to tackle global sustainability development issues like climate change, biological diversity preservation, pollution control, epidemic disease management, and ocean sustainability (Levin, 2015).

The understanding of the physical domain, power assets, climate shift, and sustainability goals are closely related to the field of physics. The transition from fossil fuels to renewable energy sources, work in this area, and the increase in energy efficiency are all linked to physics. In addition, understanding the factors contributing to climate change is related to the core sciences. Biosphere science provides the foundation for a multitude of aspirations, such as enhancing biodiversity, controlling contagions, and improving healthcare systems. The correction of ecological degradation caused by air pollution has strong ties to biosphere science.

The Relationship Between Basic Sciences and Earthquake Engineering

Earthquake engineering is closely related to the basic sciences. To fully understand the physical mechanisms of earthquakes and investigate changes in the physical variables of the energy that causes earthquakes in time and space, it is essential to evaluate all the variables together. The physicochemical structure of earthquakes is complex, and variables such as the energy source, tectonic history, faulting, and triggering mechanism all have direct impacts. Therefore, analyzing these variables independently, in terms of time or space, is not systematic and does not provide a singular solution. Instead, it is necessary to take a multifaceted approach that emphasizes the continually evolving nature of this scientific field.

With the increase in natural disasters in recent years and a growing global population, it is clear that our disaster reduction technology is lagging behind. To address this, we must not only study new geological events but also examine as many historical earthquake examples as possible for comparison and reference. In the Middle East, earthquake engineering relies heavily on the basic sciences and covers recent natural disasters as well as events such as landslides and avalanches (Gates & Ritchie, 2007).

Earthquakes are a complex natural phenomenon that results from a transformation of energy. Some experts have likened the process to that of a machine, with energy acting as the driving force. In fact, this concept was introduced by Kasahara in the field of seismology back in 1969. However, to fully grasp the inner workings of earthquakes, it's crucial to simulate this machine and understand the physical processes involved. The severity of an earthquake is determined by its magnitude and intensity, which can be measured using various scales. One such scale was developed by Charles Richter in the 1930s, and subsequent scales have been based on his original idea. The moment magnitude scale, for example, measures the amount of energy released at the earthquake's epicenter.

Physics and earthquake engineering share a close relationship. Calculations related to earthquake engineering have been carried out using principles of physics for centuries. Over time, various engineering disciplines have emerged, considering these principles. One such discipline is rock mechanics, which is particularly relevant to earthquake engineering. It deals with topics such as frictional stress analysis, design, planning, structural dynamics, and preservation. Physics forms the foundation of earthquake engineering, enabling predictions, analyses, and efforts to reduce earthquake damage.

The occurrence of earthquakes is explained by fundamental sciences such as physics, chemistry, and biology. The accumulation of stress measurements in geological layers, where space-time dimensions are involved, is a significant factor that directly influences the intensity of earthquakes. Earthquake engineers use the basic principles of physics to determine the intensity, duration, frequency, and the region where the earthquake occurred. They provide information that other scientific disciplines can utilize. The development of physics has given rise to various subfields like wave theories, elasticity theory, geophysics, geology, and seismology, which now form the main axis of earthquake engineering.

To understand the behavior of structures during an earthquake, it is important to apply the fundamental principles of physics. Earthquake-resistant structures rely on various aspects of physics, such as structural rigidity, natural frequencies, modes, capacity design, and step calculations. These calculations require a strong foundation in physics, as complex mathematical processes are involved. Earthquake engineers use different branches of physics, including mechanics, quantum mechanics, statistical mechanics, and electromagnetism to design structures that can withstand earthquakes.

Chemistry and earthquake engineering have significant relationships. The Earth's crust composition and changes resulting from earthquakes have connections to chemical factors. For instance, the movement of the magma layer beneath the Earth's crust, which can cause earthquakes, involves a complex chemical system of various minerals and gases. Changes in gas pressure or chemical alterations in this layer can affect the occurrence, size, frequency, and impact of earthquakes. The selection of construction materials is crucial in earthquake-resistant building design, and this decision is closely related to chemistry. Cement, aggregates, and steel are materials used in building construction, and their properties, chemical reactions, and interactions with each other play a significant role in the durability of structures.

Earthquakes are also intertwined with biological changes and ecological effects. Some living organisms can detect seismic waves in advance and react accordingly by relocating or taking precautions. Changes in the natural environment due to the stress created by pre-earthquake phenomena can affect the quality of life of organisms. The timing and effects of these biological changes are important in predicting earthquakes.

Conventional parameters used to evaluate well water, spring water, and groundwater such as pH, total dissolved solids (TDS), electrical conductivity, and the presence of dissolved gases like nitrogen, argon, CO2, helium, and others, are not sufficient to predict earthquakes. However, when combined with additional changes in water chemistry, they can be useful for generating insights. Similarly, radon as a precursor becomes evident only when assessed alongside factors beyond mechanical and microfracturing, coupled with a deeper understanding of radon's release mechanisms. Unlike certain anomalies that have been sporadically detected only once before significant seismic events, changes in groundwater parameters preceding earthquakes have been consistently observed over extended periods and across various geographical regions. This offers hope that, through sustained efforts, significant strides can be made in earthquake prediction by leveraging groundwater precursors. Anthropogenic influences present challenges, but they are not insurmountable. Advancements in the field of earthquake prediction and forecasting may be on the horizon, stemming from the recognition that stressed rocks serve as sources of electronic charge carriers, specifically electrons and positive holes when subjected to stress. These positive holes have the remarkable capacity to migrate through Earth's crust over considerable distances, possibly spanning tens or even hundreds of kilometers. When these positive holes encounter a boundary between the Earth's crust and water, they initiate a sequence of chemical reactions, including the generation of free hydroxyl radicals (•OH). These hydroxyl radicals are integral to advanced oxidation processes, which can lead to intricate electrochemical reactions unlikely to be triggered by other mechanisms. An example of such a reaction is the oxidation of arsenite to arsenate, a phenomenon that holds promise as a noteworthy earthquake precursor, warranting further investigation within the domain of geology and earthquake engineering (Paudel et al., 2018).

Determining the earthquake-prone area of buildings, the impact direction, and the cross-sectional effects, as well as understanding how loads affect them are crucial steps in earthquake engineering calculations. Nowadays, computer programs are mostly used for these calculations. However, relying solely on the results obtained from these programs can be dangerous. Many extensive buildings that have been designed and approved projects have failed due to the lack of basic knowledge among engineers. Without a sufficient understanding of physics principles, engineers cannot interpret the results and recognize the mistakes made, which can lead to catastrophic results. Understanding the behavior of earthquakes and seismic accelerations in the superstructure requires a solid foundation in physics principles. The earthquake resistance, rigidity, natural frequencies, modes, damping capacity, and step calculations of structures are all based on physics principles. Calculations made without understanding these principles are prone to errors, as complex mathematical operations are involved (Şeker & Korkut, 2023).

The use of Artificial Intelligence (AI) has the potential to improve our capacity for managing natural disasters, such as earthquakes. However, there are constraints associated with its application that must be acknowledged and addressed. To fully harness its benefits, it is important to establish interdisciplinary, multistakeholder, and international collaborations aimed at setting standards necessary for its effective implementation in fields such as geology, earthquake engineering, and disaster risk reduction.

Natural disasters can have devastating consequences on both society and the environment. These disasters are caused by various natural phenomena such as atmospheric, hydrological, geophysical, oceanographic, and biological events. They pose unique challenges, especially in areas with limited resources and vulnerable populations, including women and children. Geoscientists and disaster risk reduction experts recognize the importance of addressing these challenges, as reflected in scientific literature and Sustainable Development Goals.

Incorporating innovative technologies such as AI into natural disaster management has emerged as a significant development. In fields like medicine and finance, AI has gained recognition due to advancements in algorithms, increased computational power, and the availability of extensive datasets. In the context of natural disaster management, the hope is that AI can utilize geospatial data to improve our understanding of natural disasters, optimize the speed of detection, increase the accuracy and lead times of forecasts, and enhance the effectiveness of emergency communication systems.

This commentary discusses the advantages and limitations of data collection methods and AI-driven developments in natural disaster management. It explores the complexities of modeling, such as the suitability of model architectures, evaluation criteria, and the expectations of generalizability across different regions. For example, AI-based algorithms have shown better performance than classical models in predicting earthquakes across various shaking thresholds. Similarly, in avalanche forecasting, AI algorithms achieved an 80% agreement with human forecasts, despite the inherent complexities of assessing avalanche danger.

Nevertheless, these advancements in AI-based methods are met with challenges, particularly in the absence of clear guidelines or standards to guide researchers, developers, and those tasked with implementing the resulting solutions, including policymakers, government agencies, consumers, and humanitarian organizations.

AI has made significant strides, but it is not without challenges. The lack of clear guidelines or standards to guide researchers, developers, and those tasked with implementing the resulting solutions has become a significant obstacle. This lack of guidance extends to policymakers, government agencies, consumers, and humanitarian organizations.

After validating AI-based algorithms for detecting and forecasting natural disasters, the challenge lies in effectively implementing them for disaster management. Bridging the gap between AI developers and implementers is crucial. These algorithms are often created by experts in geoscience or machine learning in academic settings, with limited interaction with stakeholders and end-users, such as governmental emergency management agencies and humanitarian organizations. This disconnect can impede the integration of AI-based solutions into disaster management strategies.

Effective cross-sectoral collaboration is a crucial factor in addressing today's challenges. For example, IBM's Operation Risk Insights platform is a successful interdisciplinary cooperation with humanitarian organizations. There are already many programs promoting these approaches, such as the Resilient America Program, which integrates AI with new data sources like social media for predictive analysis. The European Union's CLINT project brings together experts and stakeholders from various sectors to harness AI for climate services and policymaking. The African Union's Africa Science and Technology Advisory Group (Af-STAG) on Disaster Risk Reduction actively collaborates with experts worldwide to enhance risk information transmission through AI technologies. The UN Environment Programme's Focus Group on AI for Natural Disaster Management (FG-AI4NDM) works towards establishing standards for AI use in natural disaster management, ensuring a diverse range of perspectives is considered within the standardization landscape. These collaborative efforts represent a promising path forward in revolutionizing the field of geology, earthquake engineering, and disaster risk reduction through the power of AI (Kuglitsch et al., 2022).

Earthquake prediction is a difficult task as the timing, location, and magnitude of seismic events are essentially unpredictable. However, AI techniques have shown great potential in discovering patterns within data. In their study, Banan et al. (2020) review 84 scholarly research papers that explore the application of AI-based methods in earthquake prediction. The studies cover a range of AI methodologies, including rule-based approaches, shallow machine learning, and deep learning algorithms. The paper provides a comprehensive overview of the available methods and conducts a comparative assessment of their performance using various datasets and evaluation metrics. The objective is to help researchers select the most suitable techniques for earthquake prediction and identify persistent challenges and potential avenues for future research in this field.

Earthquake prediction models operate by detecting seismic indicators calculated from earthquake catalogs. However, certain precursory events, such as variations in radon gas concentration, shifts in soil temperature, and anomalous cloud formations, may occur a few days prior to an earthquake, but they do not definitively confirm an impending seismic event. P-waves and S-waves detected through seismographs serve as a means of earthquake prediction. Some nations use dedicated satellites to monitor earthquake-related parameters, aiding in the identification of potential precursors. This data is then fed into the prediction model and subjected to preprocessing, including the removal of missing values and formatting to align with classification and regression algorithms. These algorithms categorize and forecast the timing, location, and magnitude of impending earthquakes, leveraging their capacity to unveil concealed patterns within the data. AI-based methods have introduced a new frontier in enhancing the accuracy of earthquake prediction, exhibiting superior performance in comparison to alternative techniques. These advancements have the potential to significantly reduce damages, as areas of concern can be evacuated based on forecasts. This marks a notable advancement in the fields of geology and earthquake engineering (Banna et al., 2020).

As mentioned earlier in the text, the relationship between earthquake engineering and mathematics is of great importance. Earthquakes can occur in various areas, including earthquake prediction, building design, earthquake intensity measurement, and more. Predicting the effects of earthquakes, designing earthquake-resistant structures, and evaluating, reducing, and rebuilding damage caused by earthquakes are all part of earthquake engineering. Mathematics is one of the fundamental tools of earthquake engineering, along with physics. Mathematical calculations enable the calculation of earthquake intensity, performance evaluations, seismic vibration analysis, structural analysis, and statistical calculations. By considering a structure's behavior with the ground and applied seismic loads, mathematical calculations can be used to determine the safety of buildings.

Earthquake engineering comprises several branches, with engineering seismology being one of the most important. It focuses on the dynamic characteristics of structures and uses complex mathematical methods like Laplace transformations and series to analyze them. Using these calculations, the effects of earthquake loads on building elements such as mat foundations, beams, columns, and slabs can be reduced by using methods such as seismic dampers, passive control devices, active control devices, recorders, modal analysis, and spectral analysis. Mathematics plays a crucial role in predicting, calculating, designing structures, ensuring their safety, and minimizing damage caused by seismic effects.

Earthquakes result from a combination of (1) physico-chemical processes operating in fault zones that allow the nucleation of fractures and reduction of rock friction by increasing slip or shear rate, and (2) the geometric complexity of fault zones. Recent experimental findings from rock friction experiments (conducted at high speed, approx. 1 m/s sliding speed, or typical seismic sliding speeds) have led to a better understanding of potential dynamic weakening mechanisms like melt lubrication, nanopowder lubrication, etc. It is important to recognize how these mechanisms can be identified through mineralogical and microstructural studies in exposed fault zones. Field and laboratory experiments can help obtain earthquake source parameters (seismic fault strength, attenuation distances, energy budgets, etc.). Fault zone geometry and morphology need to be considered while developing realistic models of fault surfaces. Theoretical considerations for microphysical modeling of laboratory data at seismic slip rates are also presented.

Experimental data and microphysical models indicate that faults must be very weak ($\mu < 0.1$) during seismic slip. Moreover, the slip attenuation distance during seismic slip is at most on the order of a few tens of centimeters under natural conditions, which is consistent with inferences from field observations (Neimeijner et al., 2012).

The current earthquake prediction methods suffer from a high rate of false alarms, making it difficult to assess the actual occurrence of earthquakes. This lack of precision in the prediction process contributes to the catastrophic outcomes associated with earthquakes in geology and earthquake engineering. To clarify the concept of earthquake prediction, the United States National Research Council Panel on Earthquake Prediction proposed a consensus definition. According to the definition, earthquake prediction should specify the expected magnitude range, the geographic area where it will occur, and the time frame in which it will happen with enough precision to easily evaluate its success or failure. It is crucial to evaluate both failures and successes to determine the overall effectiveness of earthquake prediction and guide future directions.

It should be noted that many of the supposed precursors mentioned in earthquake forecasting literature are not reliable predictors. For instance, even the most advanced and regularly updated short-term forecasts for the Northwest (NW) and Southwest (SW) Pacific cannot be considered as credible predictions unless a specific probability threshold is established to define the areas that will be affected. Furthermore, an independent evaluation of predictions based on setting a threshold probability or probability ratio on top of daily forecasts has shown that neither method is significantly more effective than random guessing, even when the predicted aftershocks are considered successful.

Many people believe that earthquake prediction involves short-term forecasts, which offer warnings of hours to days in advance and are expected to be 100% reliable. This mindset is similar to classical oracles, and expectations and preparations for making a short-term prediction of a major earthquake in the Tokai region of Japan exemplify this. Nevertheless, we ought to ask ourselves whether there are inherent temporal, spatial, and physical characteristics in the earthquake process that could lead to alternative forms of prediction, and what measures can be taken in response to such predictions to mitigate losses.

Many researchers concentrate on predicting the specific fault segment to rupture, rather than exploring spatial prediction modes. This is exemplified by the Parkfield earthquake prediction experiment. Predicting earthquakes is a highly challenging task and there is a possibility that it may be unsolvable. The modes of earthquake rupture, which are associated with the size of the impending earthquake, can be classified based on the location of the source zone within a broader prediction range. Approaching the earthquake prediction problem in a hierarchical, step-by-step manner that considers the multiscale escalation of seismic activity leading to the primary rupture is a natural approach. This situation excludes imprecise predictions, but identifying earthquake-prone areas through pattern recognition methods is a fundamental way to pinpoint the location of a target earthquake. Additionally, the Gutenberg-Richter law suggests that the range of magnitude for prediction should be limited to approximately one unit. Otherwise, the statistics derived from real data might predominantly reflect the occurrence of smaller earthquakes, potentially leading to misleading attributions to larger events. Predicting earthquakes is as straightforward as one-two-three. Step 1: Deploy your precursor detection instruments at the anticipated earthquake site. Step 2: Detect and identify the precursors. Step 3: Gain consensus from your peers and publicly announce the earthquake prediction through approved channels.

There are instruments called "precursor detection instruments" which are currently being used worldwide. Routine seismological observations are collected into databases such as the US GS/NEIC Global Hypocenter Data Base. These records are accessible for general use. Some "precursors" have already been detected, including reproducible intermediate-term algorithms like the M8 and MSc algorithms. Furthermore, some earthquakes have already been publicly predicted. The ongoing real-time monitoring of global seismic activity is aimed at predicting major earthquakes in the intermediate term. This has a substantial history. Several significant earthquakes have been predicted successfully, while some predictions have proven inaccurate. It is noteworthy that the real-time monitoring would have to encounter four consecutive prediction failures to reduce the confidence level achieved below 95%, an eventuality that appears unlikely. The results warrant special attention, as the estimates use the most cautious measure of alarm volume, accounting for the empirical distribution of epicenters. The accomplishments in pattern recognition for designing reproducible algorithms that predict large earthquakes and the confirmed statistical validity of these predictions over the past decade affirm several fundamental paradigms: 1. Seismic premonitory patterns exist; 2. The formation of earthquake precursors for years involves extensive fault systems; 3. These phenomena exhibit similarity across a wide range of tectonic environments; 4. These phenomena possess a universality that is observed in other complex nonlinear systems (Kossobokov, 2004).

The use of mathematical modeling in predicting earthquakes has advanced to the point where it can now be applied to social forecasting as well. Just like in geology and earthquake engineering, politics and its outcomes are also variables that can be estimated and forecasted. Studies have shown that, as with the output of mathematical modeling, certain index values must be met before a presidential candidate can be elected successfully. For instance, if a candidate garner 8 index points out of 13, then the chances of being elected successfully are 55%. It's amazing to see how basic sciences and earthquake engineering can become a social construct that even impacts our daily lives and who governs our countries. This knowledge and science could open tremendous opportunities for our society in the future.

Conclusion

The significance of Basic Sciences concerning earthquakes and sustainability goals is made clear by the explanations above. With the rapid advancements in technology and other fields across the world, every sector becomes even more complicated. Some developments, such as climate change, make it difficult to predict the occurrence, impact, and damage of natural disasters. These factors add to the complexity of work in all fields. A solid understanding of basic sciences, including mathematics, physics, chemistry, and biology, is crucial in coping with the chaotic and complex world we live in. Therefore, the importance of basic sciences is further emphasized. Only by receiving a good education in basic sciences can we deal with the complexity of this world.

Mathematical modeling, based on basic sciences, is the application of mathematics to solve real-life problems. Sustainable development, on the other hand, entails development that meets the needs of the present without jeopardizing the ability of future generations to meet their own needs. Mathematical modeling plays an important role towards sustainable development in understanding, predicting, and controlling the development process. Most of the issues covered under 17 headings in the United Nations Sustainable Development Goals are related to the basic sciences of mathematics, physics, chemistry, and biology. Most studies conducted in this field focus on sub-branches of basic sciences. By prioritizing basic sciences, countries can achieve these goals in 2030 and beyond.

Basic sciences have a direct correlation with disasters, particularly earthquake disasters. It has been observed that seismology, geology, geophysics, soil mechanics, structural dynamics, and material branches play a crucial role in understanding the formation mechanisms of earthquakes, monitoring the movement of the earth's crust, predicting, and comprehending the occurrence of an earthquake, constructing, and safeguarding appropriate structures. Additionally, equations from basic sciences are employed to predict and determine earthquake magnitude.

Mathematics and science are vital in understanding, predicting, and controlling developmental processes, and they play an essential role in comprehending disasters such as earthquakes. Project engineering calculations have been made for most of the buildings destroyed in the Kahramanmaraş, Hatay, Adıyaman, Malatya and Adana earthquakes that occurred on February 6 in our country. Despite this, one of the most important reasons for the collapse of buildings is the insufficient knowledge of engineers in basic sciences such as physics, mathematics and chemistry.

A thorough understanding of basic sciences such as mathematics, chemistry, physics, and biology is crucial for successfully predicting earthquakes, taking precautions against them, conducting post-earthquake studies, and achieving the United Nations' sustainability goals.

References

Banna, H. A., Taher K.A., M. Kaiser S., Mahmud M., Rahman S., Hosen A. S. M. S., and Cho G. H. (2020). Application of Artificial Intelligence in Predicting Earthquakes: State-of-the-Art and Future Challenges. *IEEE Access*, 8, 192880-192923. doi: 10.1109/ACCESS.2020.3029859

Gates, A. E., & Ritchie, D. (2007). *Encyclopedia of earthquakes and volcanoes* (3. ed). Facts on File.

Kossobokov, V. G. (2004). Earthquake Prediction: Basics, Achievements, Perspectives. *Acta Geoph. Hung.*, 39(2-3), 205-221. doi:10.1556/ageod.39.2004.2-3.6

Kuglitsch, M.M., Pelivan, I., Ceola, S. *et al.* Facilitating adoption of AI in natural disaster management through collaboration. *Nat Commun* **13**, 1579 (2022). https://doi.org/10.1038/s41467-022-29285-6

Kundu, S. (2018) Mathematical modeling as a tool for sustainable development. *J. Artic. Math. Educ*, *5*, 348-350. E ISSN 2348 –1269, PRINT ISSN 2349-5138

Levin, S. (2015). What Mathematics Can Do for Sustainability. *Bulletin of Mathematical Biology*, *77*(2), 251-253. doi:10.1007/s11538-014-0038-4

Lichtman, Allan J. (2008). The keys to the white house: An Index Forecast for 2008. *International Journal of Forecasting*, 24, 301-309. doi:10.1016/j.ijforecast.2008.02.004

Niemeijer, A., Di Toro, G., Griffith, W. A., Bistacchi, A., Smith, S. A., & Nielsen, S. (2012). Inferring earthquake physics and chemistry using an integrated field and laboratory approach. *Journal of Structural Geology*, *39*, 2-36. doi:10.1016/j.jsg.2012.02.018

Paudel, S. R., Banjara, S. P., Wagle, A., & Freund, F. T. (2018). Earthquake chemical precursors in groundwater: a review. *Journal of Seismology.* doi:10.1007/s10950-018-9739-8

Şeker, M., & Korkut, C. (Ed.). (2023). Doğu Anadolu Fay Hattı Depremleri: Tespitler ve Öneriler (1.). Türkiye Bilimler Akademisi Yayınları. doi:10.53478/TUBA.978-625-8352-47-4

About Author

Prof. Muzaffer ELMAS | Kocaeli Health and Technology University | muzaffer.elmas[at]kocaelisaglik.edu.tr | ORCID: 0000-0003-3202-6689

He was born in Giresun in 1956. He graduated from the Faculty of Civil Engineering at Istanbul Technical University (ITU) in 1980. He completed his Master's degree in 1983 and his Doctorate in 1988 at the same university. In 1980, he started his career as an Assistant at the Sakarya State Architecture and Engineering Academy. In 1988, he became an Assistant Professor in the Civil Engineering Department at ITU Sakarya Faculty of Engineering, and later became an Associate Professor in 1994 and a Professor in 2000. He served as the Vice Rector starting in 2002, focusing on "strategic planning, quality, education and training, and investments" at the university. In 2010, he was appointed Rector of the same university. During this period, he led the establishment of the University Management System to facilitate national and international processes in Higher Education Quality, Institutional Evaluation in Universities, and Accreditation. He also managed the Turkey Excellence Award, EFQM Excellence Award, Global Excellence Award processes, EUA IEP, YÖKAK external evaluation processes, and nearly 50 program accreditation processes with national/international accreditation agencies. Additionally, he is a member of the AFAD Earthquake Advisory Board, Deputy Chairman of the YÖK Vocational Qualifications Institution, Chairman of the Interuniversity Council Education Commission, Full Member of the Turkish Academy of Sciences (TÜBA), and a council member of TÜBA. Since April 1, 2018, he has been serving as the President of the Higher Education Quality Council.

THE CURRENT STATE AND OUTCOMES OF BASIC SCIENCES EDUCATION IN TÜRKİYE

Zeynep Aysan-Şahintaş

Gülben Avşar

Muzaffer Şeker

10.53478/TUBA.978-625-6110-22-9.ch09

The Current State and Outcomes of Basic Sciences Education in Türkiye

Zeynep Aysan-Şahintaş
Turkish Academy of Sciences

Gülben Avşar
Turkish Academy of Sciences

Muzaffer Şeker
Turkish Academy of Sciences

Abstract

Curiosity about the natural world around us drives a deeper understanding of life and fosters new advancements through basic sciences. With the announcement of the International Year of Basic Science for Sustainable Development, the crucial role of basic sciences in our lives has been increasingly emphasized, highlighting its impact on basic human needs, the economy, and social and environmental benefits. In this chapter, the education of individuals in basic sciences, from secondary to tertiary levels, and its effects on international exams and employment have been examined in the Turkish context. It has been concluded that up-to-date, hands-on experiments, technology-integrated lesson plans with real-life examples, and role models are needed throughout education. Additionally, multidisciplinary strategies and collaborative, supported projects/activities are essential to meet 21st-century skills. The performance of Turkish students in international exams has been shown to be below the OECD average. Despite a recent increase in student demand for basic sciences, supported by government initiatives, challenges in securing employment in high-skill sectors remain significant obstacles for individuals.

Keywords
Basic sciences, Science education, Tertiary level education, Employment, Skill mismatch

Introduction

The United Nations (UN) General Assembly declared 2022 the International Year of Basic Sciences for Sustainable Development (IYBSSD) on 2 December 2021. While UNESCO organized the opening ceremony of IYBSSD in Paris on 8 July 2023, CERN hosted the closing ceremony in Geneva on 15 December 2023. During this international and comprehensive organization, the main objective was to highlight and raise awareness of the link between the basic sciences and the UN's sustainable development goals. In addition IYBSSD also provided opportunities to give due credit and value to the basic sciences that have allowed us to make sense of the planet and to unlock the potential of the basic sciences to transform our world for the better.

Even though our universe is enormous and complicated, basic science satisfies our curiosity and drives us to understand the fundamental concepts of the natural world. Investigating the underlying principles and processes that govern the universe, this field of science lays the foundation for future developments in the applied sciences and technologies beyond the national boundaries and cultural barriers.

We cannot overstate the importance of basic science since it establishes the basis for development and innovation throughout many disciplines such as applied science, engineering, health, philosophy, and education. The research findings from the basic science studies result with advantageous applications and technical breakthroughs (Adams & Clemmons, 2008; Malva et al., 2015; March & Smith, 1995; Şen, 2022). Technological developments in disciplines such as biology, chemistry, and physics have produced a number of innovations, including medical procedures, communication tools, and renewable energy sources. While conducting basic research, scientists frequently work on challenging and complicated problems, so they require thinking differently and breaking the boundaries across multiple fields. A curious, critical thinking, and problem-solving mindset which are essential to overcome a variety of challenges can be promoted by basic science. Basic science provides the foundation for evidence-based decision-making which is derived by the science process skills (Bell & Lederman, 2003; Şimşek & Kabapınar, 2010). In order to handle global challenges such as resource management, public health emergencies, and climate crisis, policymakers rely on scientific understanding and transform the skills to the applications. The research in basic science and the sharing of knowledge play a crucial role in cultivating a culture of scientific inquiry and discovery. It generates a society that values inquisitiveness, versatile examination, and lifelong learning as well as upcoming generations of scientists.

The researches have shown that only two targets of two different goals in 17 Sustainable Development Goals meet the substantial progress/on track level (Malekpour et al., 2023). These two targets are "increase access to mobile networks" and "increase internet use". Moreover, the estimations on 2030 have indicated that only three targets of different goals can reach the level of on track. One of these targets is "Increase research-and-development spending" which also highly affects the educational focus and the status of the countries, and vice versa. The knowledge transform from university to industry is a key factor in the research-and-development associated activities which are fed by the natural science and engineering studies (Landry et al., 2007).

In the industrial sector, basic sciences form the foundation of human knowledge, driving creativity, technological advancements, and enriching society as a whole (Adams & Clemmons, 2008; Schlagwein, 2021). Without adequate attention to basic science, it is impossible for a country to excel on the international stage. It is widely recognized that the success behind technological and industrial advancements relies on investments in and the development of basic science, as seen in countries such as the United States, the United Kingdom, Germany, Russia, South Korea, and China (Yükseköğretim Kurulu, 2022).

For Türkiye, the general trade system, from January 2021 to January 2022, showed an increase in both import and export rates by 17.2% and 54.2%, respectively. The share of imports was 63.2%, while the share of exports was calculated at 93.3% for manufacturing industry products in January 2022. However, the share of high-technology products in these manufacturing industries was just 9.9% for imports and 2.4% for exports (Turkish Statistical Institute, 2022). Given the key role of basic science in the production of value-added, innovative, and high-tech products, incentives and efforts should be increased in these disciplines.

In the context of basic science for sustainable development, this chapter presents the strategies Türkiye has followed in basic science education at both secondary and tertiary levels. Data regarding curricula, student motivation, educator approaches, and environmental opportunities are presented, based on reports published by the Economic Cooperation Organization Educational Institute (ECOEI). ECOEI organized a series of workshops between 2018 and 2023, each focusing on different fields of basic science and education. The reports from these workshops (e.g., Altun et al., 2023; Arıkan, 2018; Mirici et al., 2023; Şen et al., 2023), which involved researchers, teachers, academics, and students, provided valuable insights into current challenges, possible solutions, and best practices for basic science education in Türkiye.

Furthermore, international assessment test results are included as informative indicators of secondary-level education, and statistics on the employment outcomes of individuals with a background in basic science education are detailed.

Secondary School Level Science Education in Türkiye

Overview of Reports by ECO Educational Institute

Various challenges limit effective learning and knowledge retention in middle school basic science education. With no individual courses for physics, biology, and chemistry offered until grade 5, the curriculum needs to be comprehensive, covering basic concepts and models, renowned scientists, conducting experiments, and making inferences. In addition to the insufficient number of laboratories relative to the high number of schools, there are other challenges such as a lack of materials, inadequate physical conditions, and insufficient teacher time for active lab use. One of the major issues, stemming from limited practical learning, is the rapid forgetting of acquired knowledge. To address these challenges, a shift towards hands-on experiences, engaging with experimental tools, and providing proper guidance is crucial to foster a deeper and more lasting understanding. The problems associated with memorization-based learning can be mitigated by emphasizing connections between concepts and using visualization and real-world applications. Additionally, raising awareness about the interdisciplinary nature of basic science, such as the connections between biology, physics, chemistry, and mathematics, can contribute to long-lasting understanding. Furthermore, developing 21st-century skills such as collaboration, communication, problem-solving, critical thinking, and creativity is necessary to enhance curricula and ensure future generations can adapt to technological advancements.

A common curriculum is followed in all schools, despite the existence of different types of high schools. It is essential to consider individual differences among students and school types, ensuring these differences are not overlooked in tailored curricula. Additionally, the Ministry of National Education has conducted significant measurement and evaluation studies at both national and international levels. These studies serve various purposes, aligning with the changes brought by the emphasis on 21st-century skills (Reyhanlıoğlu & Tiryaki, 2021). While they focus on assessing different skills, the current measurement and evaluation processes fail to account for individual differences among students. A more comprehensive approach that monitors students' progress and guides the educational process could be more effective, potentially increasing student motivation and engagement.

Maintaining high levels of student motivation and curiosity is a challenging aspect of the entire education system. The intensive nature of lessons and limited time for content delivery can lead to a loss of student interest. In the 21st century, we are witnessing rapid advancements in technology, which should be integrated into lessons to capture students' interest (Esen et al., 2023). Traditional, uninspiring, and technology-limited lessons, coupled with inadequate practical experiments, diminish student motivation by preventing connections between theoretical knowledge and real-life concepts. Furthermore, the lack of hands-on experiences negatively impacts students' confidence and ability to work with laboratory equipment and chemicals. Like other education systems around the world, Türkiye has started transforming its teaching methods to enhance student learning by redesigning the primary and secondary curricula since 2005-2006 (Alpaydın & Demirli, 2022).

The successful implementation of teaching processes is essential for sustaining continuity in education at all levels. To adapt to alternative teaching methods, teachers need up-to-date knowledge and lesson plans. Seminars, webinars, and training programs are found to be beneficial in this regard. These activities also promote networking, knowledge-sharing, collaboration, and professional growth, while enhancing teaching skills and encouraging innovative teaching methodologies. Collaboration between institutions, particularly with universities, can also be improved through seminars and conferences. Improvements to lesson plans and curricula should incorporate valuable feedback from students. These feedback mechanisms and their implementation ensure a dynamic and responsive educational environment. On the other hand, financial limitations, intense competition, and potential demotivation may prevent teachers from keeping up with innovation in their profession. Therefore, school funding must be managed wisely to support materials and activities that enrich the teaching and learning experience, fostering a more engaging and effective classroom atmosphere. Prioritizing these aspects will provide an environment where the educational community can work collaboratively to overcome challenges, improve teaching practices, and contribute to the holistic development of both teachers and students.

Both students and teachers face challenges such as an intense curriculum, overcrowded classrooms, and a lack of material and moral support. Flexibility and adaptability are also limited due to standardized classroom designs. Traditional desk arrangements are believed to restrict students' development of 21st-century skills by limiting collaboration and communication. Challenges like inadequate course materials for distance learning, limited technological resources, poor textbooks, the absence of teacher guidebooks, insufficient school funding, and a lack of lab equipment hinder effective learning and teaching. However, the increased budget per student and the decreased average number of students per teacher have contributed to a positive school climate, especially in the last 20 years (Özer, 2022).

A collaborative effort is needed to build effective networks, manage dense curricula, and improve classroom and laboratory environments. Promoting flexibility, adopting modern classroom designs, and investing in quality course materials and technological resources are crucial steps toward creating a more advantageous learning environment for both students and educators.

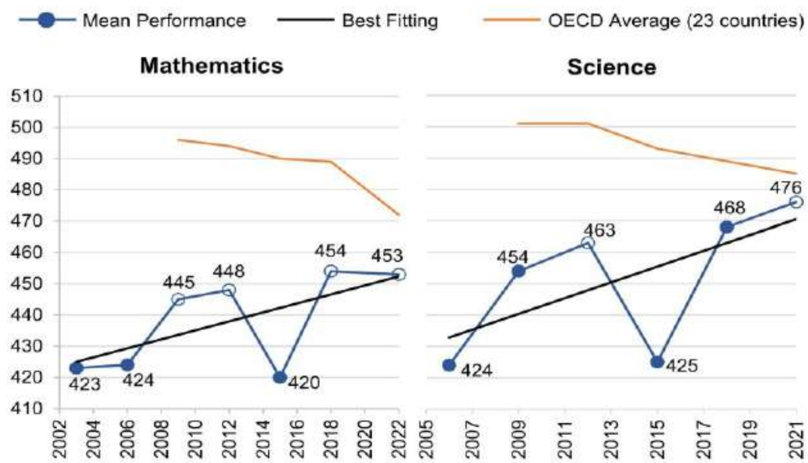
Türkiye’s Mathematics & Science Performance in PISA 2022

The results of the Programme for International Student Assessment (PISA), an international assessment test, provide valuable insights into secondary-level basic science education in Türkiye. PISA, last conducted in 2022 with participation from 81 countries, including Türkiye, assessed the knowledge and skills of 15-year-old students in mathematics, reading, and science. The results, released in December 2023, involved approximately 690,000 students globally, including 7,250 students from Türkiye. Overall, the PISA 2022 results indicate a notable decline in student performance across OECD countries, particularly in mathematics. For instance, when compared to the previous assessment in 2018, there was a decrease of nearly 15 points in average mathematics scores across OECD countries (Figure 1).

In the specific case of Türkiye, the average performance in mathematics remained relatively stable between 2018 and 2022, while the average performance in science showed improvement. Despite this increase, Türkiye's science scores have consistently surpassed its mathematics scores in recent years. Moreover, OECD reports have highlighted a significant improvement in Türkiye's PISA performance since 2003 (Özer, 2023).

Figure 1.

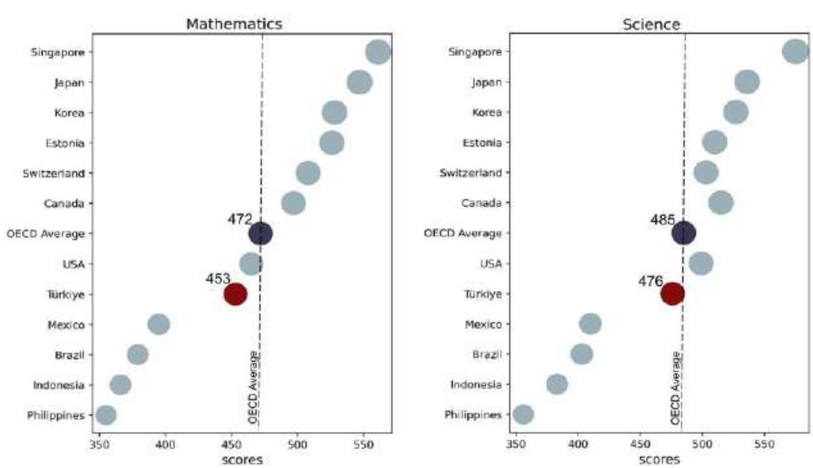
The results of PISA in mathematics and science (OECD, 2023)



As seen in Figure 2, on the other hand, the performance of the Turkish student group in both areas was below the OECD average.

Figure 2.

The top 13 PISA results among the OECD countries (OECD, 2023).



These results indicate that while Türkiye maintained its performance in the latest PISA assessment and even improved in science, it remains below the OECD average in both subjects. For instance, 61% of Turkish students in the 2022 assessment performed at Level 2 in mathematics, which is regarded as the minimum proficiency level expected of 15-year-old students. This is notably lower than the OECD average of 69%. In comparison, countries such as Singapore, Macao, Japan, and Hong Kong saw at least 85% of their students achieve the same proficiency level. Furthermore, while 9% of students across OECD countries reached the highest proficiency levels (Level 5 or 6) in mathematics, only 5% of Turkish students achieved these levels.

In science, 75% of Turkish students achieved Level 2 proficiency, approaching the OECD average of 76%. However, only 4% of Turkish students reached the highest proficiency levels (Level 5 or 6) in science, compared to the OECD average of 7%.

Another notable finding from the 2022 PISA results is the link between preschool education and performance in basic sciences. Only 76% of Turkish students reported having received at least one year of preschool education, significantly below the OECD average of 94%. The data further show that, even when controlling for socioeconomic factors, students from OECD countries who had at least one year of preschool education outperformed their peers who had less than one year or no preschool education, particularly in mathematics.

Tertiary-Level Basic Sciences and Basic Sciences Education Programs in Türkiye

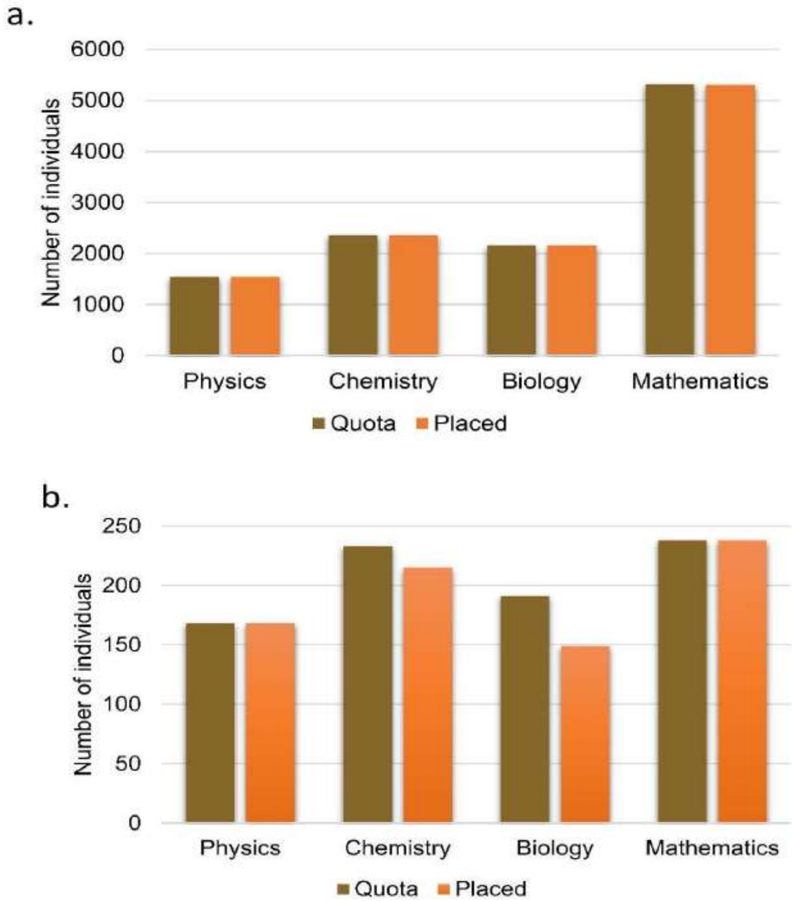
Overview of Reports by ECO Educational Institute

The curricula for basic sciences vary across universities in Türkiye, with each institution employing distinct educational strategies tailored to their specific academic focus. Despite these differences, the general structure of the curricula remains comprehensive, encompassing fundamental knowledge and the core sub-disciplines. For instance, the chemistry curriculum typically includes foundational courses in general chemistry, organic chemistry, physical chemistry, analytical chemistry, biochemistry, and polymer chemistry. However, one of the primary challenges faced by universities is the insufficiency of practical, experiment-based instruction. The limited number of laboratory course hours restricts students' development of practical skills and hinders their ability to learn current techniques. To address this issue, a potential solution involves diversifying the areas covered in experimental courses and incorporating virtual laboratory applications to supplement traditional learning methods. Furthermore, updating experiments and integrating contemporary information into the curriculum is essential to bridge the gap between academia and real-world applications, thus maintaining students' motivation. Internship programs are also valuable for fostering industry collaboration and providing students with practical exposure and real-world insights. While internship periods are incorporated into the curricula, they are often deemed insufficient in duration and diversity. Extending the duration of internships and offering more varied experiences would better prepare students for professional life by allowing them to engage with real-world problems. Additionally, curricula that encourage interdisciplinary experiences through a variety of courses and programs can broaden students' perspectives.

Between 2007 and 2013, annual statistics revealed a significant decline in the average occupancy rate of basic science departments, from 99.13% to 46.38% by 2012. However, in 2013, the average occupancy rate sharply increased to 69.74%. This improvement is attributed to the closure of certain departments and the establishment of new universities, which helped enhance occupancy rates (Gunay et al., 2013). Policy reforms initiated by the Ministry of National Education (MoNE) and the Council of Higher Education (CoHE) have contributed to this trend. As a result, the average occupancy rate in 2022 reached 99.95% (YÖK Meslek Atlası, 2023). According to the 2022 Higher Education Institutions Exam (YKS) statistics, CoHE reported that the mathematics department was the only discipline within the faculty of science where the number of students placed was lower than the total annual quota (Figure 3). In contrast, both the mathematics and physics departments in the faculty of education fulfilled their respective quotas (YÖK Meslek Atlası, 2023).

Figure 3.

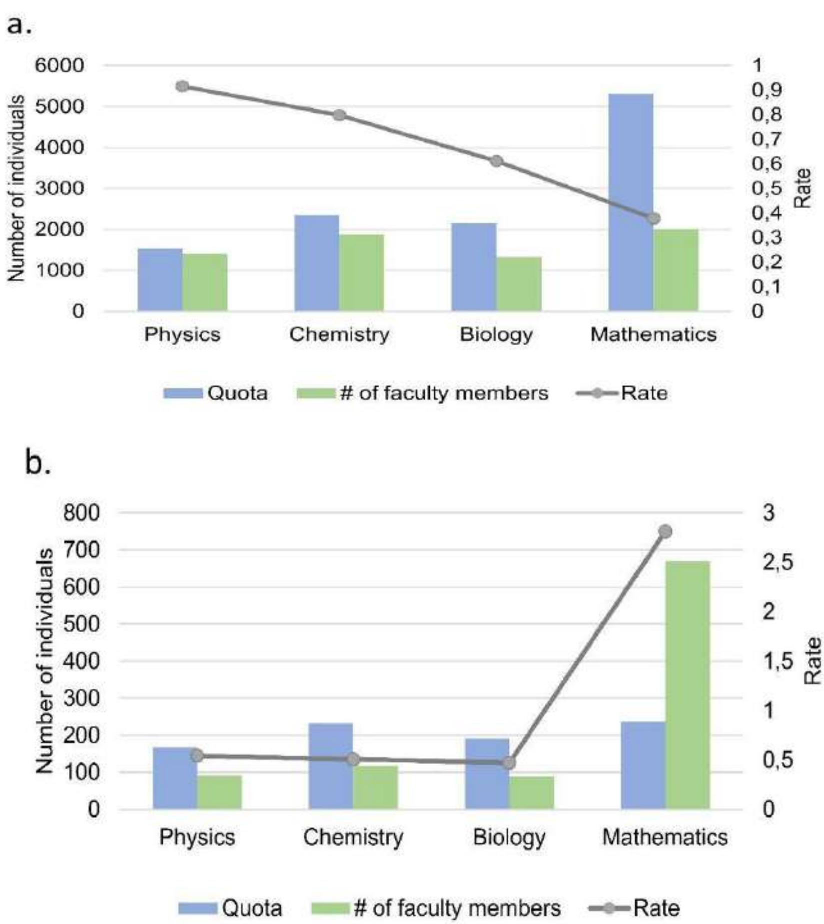
The visualization of quota and number of placed students in ***a.*** *faculty of science and* ***b.*** *faculty of education.*



CoHE provided data on the total number of faculty members across various departments. In mathematics, the number of faculty members was higher compared to other basic science disciplines (Figure 4), while the lowest number of faculty members was observed in biology departments. However, the faculty-to-student ratio is much lower in mathematics compared to the other disciplines, with ratios of 0.91, 0.79, 0.61, and 0.37 for physics, chemistry, biology, and mathematics, respectively. In contrast, the education departments demonstrated even lower ratios, except for the mathematics education department. The ratios were 0.54 for physics, 0.50 for chemistry, 0.47 for biology, and 2.81 for mathematics in the education faculties. Developing a rich and diverse academic environment can be achieved through collaboration between faculties, which is essential to enhancing the effectiveness of training across all departments. Increasing cooperation and interdisciplinary engagement among faculty members could significantly contribute to the overall growth and success of both the basic science and education departments. Addressing these issues is critical for optimizing the potential of academic institutions and ensuring a well-rounded and thriving educational experience.

Figure 4.

*The distribution of the number of students and faculty members in **a.** basic science departments and **b.** education departments.*



Similar challenges are faced at universities and high schools, where outdated lecture content, uninspiring lesson design, and a lack of hands-on experimentation result in decreased student motivation. Additionally, traditional experiment report formats limit students' ability to develop individualized approaches to research, design, and presentation of findings. The situation is further exacerbated by the lack of technological integration, which diminishes student interest even more. To address these concerns, modernizing teaching methods, encouraging student autonomy, and incorporating technology to create dynamic and engaging learning environments are transformative strategies that should be implemented. Training programs, conferences, workshops, and seminars are also essential resources for keeping both instructors and students up to date with the latest developments in their fields.

Moreover, insufficient collaboration between institutions, particularly between universities and industry organizations, presents a significant challenge. This lack of synergy restricts the exchange of knowledge and resources crucial for academic and practical advancements. Establishing collaborations with departments and institutes at national and international levels can also enhance student motivation by involving them in current developments. Furthermore, outdated and limited laboratory facilities hinder students from developing the practical skills essential for both academic and professional growth.

Addressing the issue of outdated laboratories and classrooms requires a comprehensive approach to modernization, integrating the latest technological advancements. While universities typically have higher budgets compared to middle and high schools, these resources must be strategically allocated to ensure the provision of essential devices, technological equipment, chemicals, and other course-related materials. Such targeted investment is crucial for creating a conducive and up-to-date educational environment that fosters innovation and prepares students to meet the demands of the modern world.

Additionally, aging infrastructure in older university buildings poses several technical challenges, such as power outages, water leaks, and inadequate temperature control. These issues not only disrupt lectures and laboratory sessions but also negatively affect student motivation and the overall sustainability of the educational experience. To enhance the effectiveness of education, learning environments that prioritize student-centered activities may be more successful in capturing and sustaining student interest. Curricula that incorporate a greater number of hands-on experiences, modern experiments, collaborative programs, and technology-assisted approaches are essential for fostering significant advancements in learning outcomes. By addressing these elements, basic science education can evolve to meet the needs of both students and the ever-changing landscape of scientific progress.

Uni-Veri Data

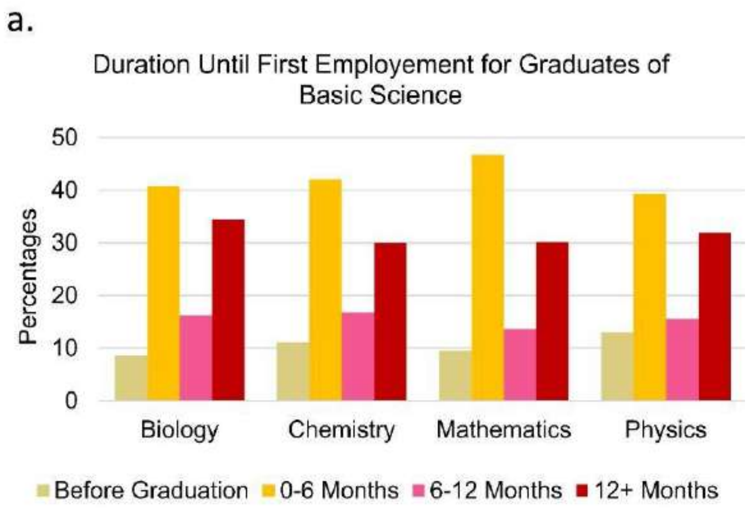
Uni-Veri, an online database provided by the Presidency of the Republic of Türkiye Human Resources Office, is an outcome of a national research project aimed at providing up-to-date data on labor market profiles and the conditions of tertiary-level graduates across different disciplines. This section draws on data from the Uni-Veri platform to compare graduates of basic sciences and basic sciences education programs across several dimensions, including: (i) duration until first employment, (ii) skill mismatch, and (iii) sectoral distribution of graduates.

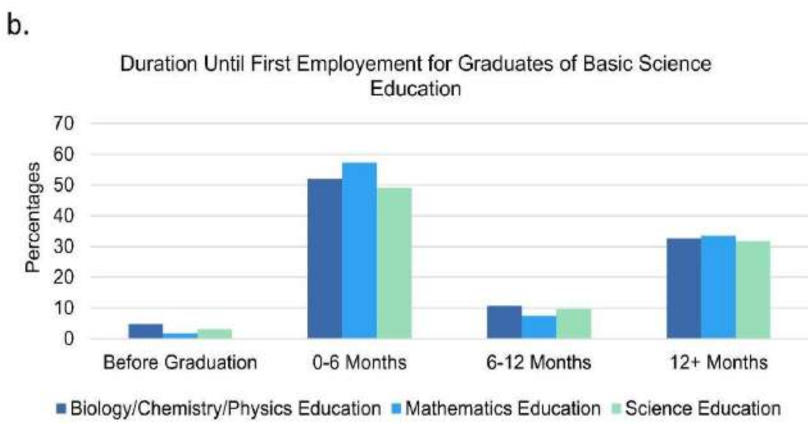
To begin with, the duration and reasons for unemployment, as well as the time it takes for young graduates to secure their first employment, depend on a variety of factors. While some of these factors are related to a country's level of socio-political and economic development, individual factors such as age, gender, marital status, level of education, and relevant work experience also significantly influence employment outcomes (Çağlar et al., 2015).

The graphs presented below highlight the time to first employment for graduates of basic sciences programs and basic sciences education programs across four separate time intervals (Figure 5). For graduates of basic sciences, the proportion of first employment before graduation is the lowest across all time periods, whereas the share of graduates securing employment within the first six months post-graduation is significantly higher, with mathematics graduates leading at 46.7%. A similar trend is observed for graduates of basic sciences education programs. In these fields—biology/chemistry/physics education, mathematics education, and science education—the share of first employment before graduation remains the lowest, while the share of graduates securing a job within the first six months after graduation is consistently the highest.

Figure 5.

*Duration for the first employment of graduates from **a.** basic science and **b.** basic science education departments. Adapted from (UniVeri, 2023).*





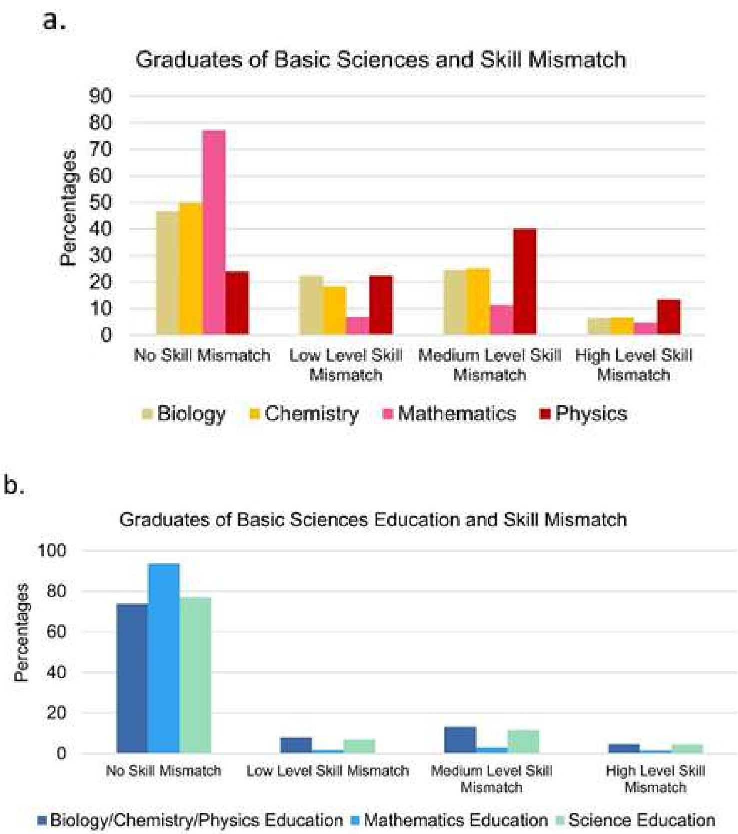
Notably, mathematics and mathematics education graduates exhibit the highest percentages of employment within the first six months following graduation, with 46.7% and 57.3%, respectively. However, the proportion of mathematics education graduates securing employment during this time is clearly higher than that of mathematics graduates.

Skills mismatch occurs when employees' qualifications either exceed or fall short of the demands of their jobs (Handel, 2003). Employees who possess more skills than required are considered over-skilled, while those lacking the necessary skills for their role are under-skilled. Despite the low correlation between over-education and over-skilling (Sloane, 2014), it is fair to suggest that tertiary education has a strong potential to provide specialized skills (Van Damme, 2022).

The graph provided illustrates that among undergraduate programs in basic sciences, the highest proportion of graduates who believe their jobs align with their skills is found among mathematics graduates, while physics graduates report the lowest alignment (Figure 6). Furthermore, physics graduates are more likely to report experiencing a quality mismatch across all levels (low, medium, high), whereas mathematics graduates are the least likely.

Figure 6.

*Skill mismatch for the graduates of **a.** basic science and **b.** basic science education departments. Adapted from (UniVeri, 2023).*

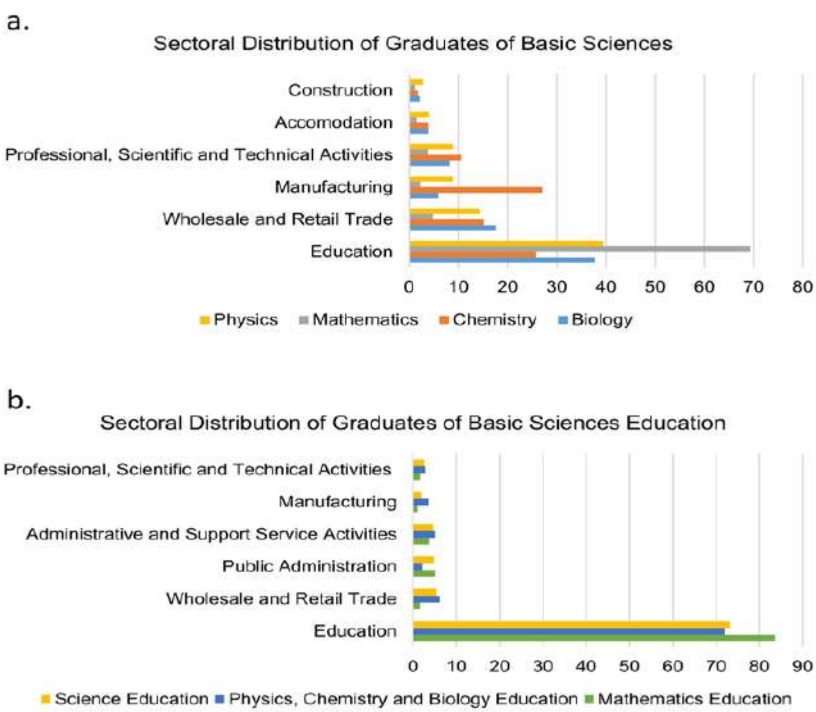


Both mathematics and mathematics education programs stand out for having a high degree of skill overlap between what graduates learned during their education and what their current jobs require. This is particularly pronounced for mathematics education graduates, of whom 93.6% report no skill mismatch. On the other hand, graduates from all fields of basic sciences education report a higher rate of job-skill alignment compared to their counterparts in basic sciences programs. This suggests that basic sciences education graduates generally experience less skills mismatch than basic sciences graduates.

While both basic sciences and basic sciences education graduates share certain employment sectors after graduation, basic sciences graduates also work in fields such as construction and accommodation, sectors less common among education graduates (Figure 7). Conversely, graduates of basic sciences education programs are more frequently found in public administration and administrative and support service sectors.

Figure 7.

*Distribution of employment sectors for graduates of **a.** basic science and **b.** basic science education departments. Adapted from (UniVeri, 2023).*



As expected, the majority of basic sciences education graduates work in the education sector, with mathematics education graduates leading in this area. Similarly, a considerable proportion of basic sciences graduates also work in education, with mathematics graduates showing a particular preference for this sector. In contrast, chemistry graduates are predominantly employed in the manufacturing sector, which aligns with the chemical processes central to the discipline's academic and practical focus.

Discussion, Suggestions and Conclusion

Based on the review, several key issues and recommendations can be drawn regarding the current and future state of basic sciences and basic sciences education in Türkiye.

One notable initiative is the CoHE's Undergraduate Support Scholarship, designed to increase student enrollment in basic sciences programs. However, this can also be viewed as an attempt to fill program quotas rather than addressing the root of the demand for these fields. It remains unclear whether students choose these programs out of genuine interest or due to external motivators like scholarships. Even with filled quotas, employment challenges persist for basic sciences graduates, who often find themselves working in positions unrelated to their field of study. A large portion of basic sciences graduates, for example, are employed in the education sector, just like those from basic sciences education programs. This trend suggests a broader issue: many basic sciences graduates may turn to teaching not out of choice but due to limited job opportunities in their fields, coupled with difficult working conditions (Öztürk Akar, 2014). Additionally, family influence plays a significant role in career choices, as families often steer graduates toward teaching, a profession perceived as stable and familiar (Öztürk Akar, 2014). This dynamic further underscores the need for targeted career guidance for students in basic sciences programs, so they can make informed decisions about their futures.

The practice of directing basic sciences graduates toward pedagogical formation programs to increase employability exacerbates the issue by contributing to an already competitive job market for education graduates. Instead, integrating mandatory internships within the basic sciences curriculum, similar to those in education programs, could offer a more effective solution. These internships would provide students with hands-on experience, helping them better understand their competencies, interests, and potential career paths before they graduate.

Another suggestion is to provide double major or minor program options for students with high academic performance, offering a more comprehensive route into teaching. This would be a more integrated approach compared to the current certificate programs, and it would ensure that graduates entering the teaching profession have a well-rounded education. This could also reduce the number of graduates becoming teachers by default, while enhancing the quality of those who do pursue teaching careers.

It is also essential to develop policies that increase the employability of new graduates across all fields. Increasing the quality, rather than the quantity, of programs is a priority. For example, the 2008 policy to eliminate the requirement for universities to maintain both a Faculty of Science and a Faculty of Letters was a step in the right direction, reflecting the need for adaptable, efficient structures in higher education.

Additionally, insights from the PISA 2022 results emphasize the importance of early childhood education in boosting academic performance, particularly in mathematics. While 94% of students in OECD countries who took the PISA test had attended preschool for at least one year, this figure was only 76% for students in Türkiye. Expanding access to quality preschool education could significantly enhance students' future success in basic sciences, as early exposure to structured learning environments is linked to better academic outcomes.

Frequent curriculum changes in undergraduate basic sciences programs over the last three decades have posed challenges, as there has been insufficient time to assess the long-term impact and effectiveness of these updates. Such rapid modifications can waste valuable resources, including time and budget, and diminish the overall effectiveness of the programs. To avoid this, future curriculum reforms should be innovative, genuinely empowering, and aligned with local and national needs, ensuring that changes are meaningful and sustainable.

A more holistic approach to basic sciences education is needed, one that takes into account interdisciplinary connections and the emergence of new sub-disciplines. The integration of basic science disciplines with one another has given rise to specialized fields that reflect the growing complexity of science in today's world. To fully appreciate the relevance of basic sciences, educators and policymakers must embrace this interdisciplinary perspective, ensuring that graduates are equipped with the skills and knowledge to navigate an increasingly interconnected scientific landscape. Addressing the challenges facing basic sciences and basic sciences education in Türkiye requires a multi-faceted approach. This includes improving employment outcomes, rethinking curriculum changes, expanding early education access, and fostering interdisciplinary collaboration. By doing so, the field can better meet the needs of students and the evolving demands of the scientific community.

The key issue in basic science education at the secondary school level is the need to show students how basic sciences are interconnected with other disciplines and relevant to daily life. Adopting an interdisciplinary approach can increase student motivation and improve their attitudes toward science, leading to higher academic achievement. For teachers, curriculum developers, and textbook authors, emphasizing these connections would foster a deeper interest in basic sciences, making the subjects more appealing and accessible.

Science high schools in Türkiye, such as the TÜBİTAK Science High School, accept students with the highest academic achievement, providing advanced education in mathematics and science. However, data from 2011 to 2019 shows that the majority of graduates prefer medicine and engineering over basic sciences (Suna et al., 2020). This preference is influenced by factors such as job market conditions, ease of employment, program prestige, and guidance from parents and teachers (Kurt & Fidan, 2021; Suna et al., 2021). To counter this trend, policies that create better job prospects for basic science graduates should be developed. Additionally, efforts should be made to raise awareness among parents and teachers about the importance and opportunities in basic sciences.

TÜBA's reports highlight the need to improve the quality of doctoral education and increase the number of doctoral graduates to support Türkiye's research and development efforts. While increasing the number of PhD graduates is important, the problem cannot be resolved solely through this measure. Well-planned employment policies are essential to ensure PhD graduates find suitable academic positions, particularly in faculties of science and education, where student-to-teacher ratios are often too high. Better planning in this area could help alleviate this issue by reducing the workload on faculty members and improving the overall quality of education.

In Türkiye, students must take the Core Proficiency Test (TYT) and the Advanced Proficiency Test (AYT) to gain university admission. However, the representation of basic sciences in these tests is both inadequate and limited in scope. Physics, chemistry, and biology are underrepresented, which affects the content validity of these tests. This has a backwash effect on the teaching and learning of basic sciences in secondary schools, as teachers and students may prioritize topics that are likely to appear on the exams, leaving out important areas of study. This weak alignment between testing and comprehensive subject learning negatively impacts students' motivation and engagement with basic sciences.

Improving basic science education requires collaboration between academic institutions, reducing the workload of extensive courses, and upgrading laboratory and learning environments. Collaborative efforts between disciplines and institutions should focus on implementing contemporary teaching strategies and allocating resources for advanced technology in education. Flexibility in course design and content delivery is crucial for creating a more effective educational environment.

Technology-assisted approaches, hands-on experiences, and student-centered activities can enhance the relevance of basic sciences in today's rapidly changing scientific landscape. Science high schools, particularly those like TÜBİTAK Science High School, with their modern technologies, advanced science workshops, and five-year programs, hold significant promise for the future of basic sciences education.

In conclusion, to strengthen basic sciences in Türkiye, a holistic approach is needed, encompassing curriculum reform, early engagement in interdisciplinary learning, and policies that improve the employability of graduates. High-stakes testing must better reflect the breadth of scientific knowledge, and the alignment between secondary education and university entrance exams should be improved. Science high schools must continue to evolve, and investment in modern teaching practices and technology will be key in shaping the future of basic sciences education in Türkiye. Finally, increasing awareness among parents, teachers, and policymakers about the value of basic sciences will be critical for creating a more supportive environment for students to pursue careers in these fields.

References

Adams, J. D., & Clemmons, J. R. (2008). Science and industry: Tracing the flow of basic research through manufacturing and trade. *Economics of Innovation and New Technology, 17*(5), 473–495. https://doi.org/10.1080/10438590701407216

Akçiğit, U., & Özcan-Tok, E. (2020). *Türkiye Bilim Raporu*. TÜBA.

Alpaydín, Y., & Demirli, C. (Eds.). (2022). *Educational theory in the 21st century: Science, technology, society and education* (1st ed.). Springer. https://doi.org/10.1007/978-981-16-9640-4

Altun, Y., Çelik, A. Y., Kadayıfçı, H., Yeşiloğlu, S. N., & Dinçdemir, D. (2023). *Report on Chemistry Education in Türkiye: Issues, Solutions, Best Practices*. Economic Cooperation Organization Educational Institute.

Arıkan, A. (Ed.). (2018). *Türkiye'de Matematik Eğitimi: Sorunlar, Çözüm Önerileri ve İyi Örnekler*. Ekonomik İşbirliği Teşkilatí Eğitim Enstitüsü.

Bell, R. L., & Lederman, N. G. (2003). Understandings of the nature of science and decision making on science and technology based issues. *Science Education, 87*(3), 352–377. https://doi.org/10.1002/sce.10063

Çağlar, A., Kumaş, H., & Moralı, T. (2015). Türkiye'de işsizlerin iş arama süresini belirleyen faktörler: 2007-2013 dönemi. *Sosyal Güvenlik Dergisi, 1*, 68-103.

Demir, Ö. (2020). Değerlendirme Raporu 3: Türkiye Bilim Raporu'na Dair. In U. Akçiğit & E. Özcan-Tok (Eds.), *Türkiye Bilim Raporu* (pp. 93-99), TÜBA.

Esen, S., Geçer, S., & Çetin, H. (2023). İlkokulda 5E Öğrenme Modeli Destekli Matematik Dijital Çalíşma Yapraklarí: Bir Durum Çalışmasí. *Eğitim ve Bilim, 48*(216), 1-38. http://dx.doi.org/10.15390/EB.2023. 11645

Günay, D., Günay, A., & Atatekin, E. (2013). Shake in the basic sciences in Türkiye: the country's shake. *Journal of Higher Education and Science, 3*(2), 85. https://doi.org/10.5961/jhes.2013.063

Handel, M. J. (2003). Skills Mismatch in the Labor Market. *Annual Review of Sociology, 29*, 135–165. http://www.jstor.org/stable/30036964

Kurt, T., & Fidan, T. (2021). University for career construction: Expectations and realities. *Yükseköğretim Dergisi, 11(*2Pt2), 421-437. https://doi.org/10.2399/yod.20.591001

Landry, R., Amara, N., & Ouimet, M. (2007). Determinants of knowledge transfer: evidence from Canadian university researchers in natural sciences and engineering. *The Journal of Technology Transfer, 32*(6), 561–592. https://doi.org/10.1007/s10961-006-0017-5

Malekpour, S., Allen, C., Sagar, A., Scholz, I., Persson, Å., Miranda, J. J., Bennich, T., Dube, O. P., Kanie, N., Madise, N., Shackell, N., Montoya, J. C., Pan, J., Hathie, I., Bobylev, S. N., Agard, J., & Al-Ghanim, K. (2023). What scientists need to do to accelerate progress on the SDGs. *Nature, 621*(7978), 250–254. https://doi.org/10.1038/d41586-023-02808-x

Malva, A. D., Kelchtermans, S., Leten, B., & Veugelers, R. (2015). Basic science as a prescription for breakthrough inventions in the pharmaceutical industry. *The Journal of Technology Transfer, 40*(4), 670–695. https://doi.org/10.1007/s10961-014-9362-y

March, S. T., & Smith, G. F. (1995). Design and natural science research on information technology. *Decision Support Systems, 15*(4), 251–266. https://doi.org/10.1016/0167-9236(94)00041-2

Mirici, S., Sönmez, D., Özel, Ç. A., & Uzel, N. (2023). *Report on Biology Education in Türkiye: Issues, Solutions, Best Practices*. Economic Cooperation Organization Educational Institute.

Organisation for Economic Co-operation and Development (OECD). (2023, December 5*). PISA 2022 Results FactSheets Türkiye*. https://www.oecd.org/publication/pisa-2022-results/country-notes/turkiye-d67e6c05/#section-d1e17

Özer, M. (2023). *Türkiye'de Eğitimin Geleceği*. Vakífbank Kültür Yayínlarí.

Özer, M. (2022). *The universalization of education in Türkiye and new orientations*. TRT Research Center.

Özer, M. (2020). Değerlendirme Raporu 1: Yükseköğretimde Genişleme ve Bilimsel Üretim Kapasitesi. In U. Akçiğit & E. Özcan-Tok (Eds.), *Türkiye Bilim Raporu* (pp. 83-90), TÜBA.

Öztürk Akar, E. (2014). Fen Edebiyat Fakültesi Biyoloji Bölümü Mezunlarí Neden Öğretmen Olmak İstiyor? *Kastamonu Eğitim Dergisi, 22*(1), 259-272.

Reyhanlıoğlu, Ç., & Tiryaki, İ. (2021). Ülkemizde Gerçekleştirilen Ölçme ve Değerlendirme Faaliyetlerine Genel Bir Bakış. *Uluslararası Türk Eğitim Bilimleri Dergisi, 2021*(16), 70–93. https://doi.org/10.46778/goputeb.766689

Schlagwein, D. (2021). Natural sciences, philosophy of science and the orientation of the social sciences. *Journal of Information Technology Impact, 36*(1), 85–89. https://doi.org/10.1177/0268396220951203

Suna, H. E., Gür, B. S., Gelbal, S., & Özer, M. (2021). Science high school students' socioeconomic background and their preferences regarding their transition into higher education. *Yükseköğretim Dergisi, 10*(3), 356-370. https://doi.org/10.2399/yod.20.734921

Şen, Z. (2022). *Geometrik Düşünce İlkeleri*. İTÜ Yayınevi.

Şen, A. İ., Oktay, Ö., Peşma, H., Ekinci, S., & Parmaksízoğlu, A. (2023). *Report on Physics Education in Türkiye: Issues, Solutions, Best Practices*. Economic Cooperation Organization Educational Institute.

Şimşek, P., & Kabapínar, F. (2010). The effects of inquiry-based learning on elementary students' conceptual understanding of matter, scientific process skills and science attitudes. *Procedia, Social and Behavioral Sciences, 2*(2), 1190-1194. https://doi.org/10.1016/j.sbspro.2010.03.170

TÜBA. (2006). *Türkiye'de doktora eğitiminin durumu üzerine görüşler*. TÜBA.

TÜBA. (2008). *Türkiye'de doktora eğitiminin iyileştirilmesine yönelik öneriler*. TÜBA.

Turkish Statistical Institute. (2022, February 28). *Foreign Trade Statistics.* Retrieved April 18, 2024 https://data.tuik.gov.tr/Bulten/Index?p=Foreign-Trade-Statistics-January-2022-45536&dil=2

Türk, E. (2008). Fen lisesi öğrencileri üstün yetenekli mi? Üstün yeteneklilerin eğitiminde fen liselerinin önemi. *Milli Eğitim Dergisi*, *47*(1), 437- 444.

UNI-VERI (2023). Retrieved April 29, 2024 https://www.cbiko.gov.tr/en/projects/uni-veri

Van Damme, D. (2022). Do higher education students acquire the skills that matter? In D. Van Damme & D. Zahner (Eds.), *Does Higher Education Teach Students to Think Critically?* (pp. 18-38), OECD Publishing.

Yükseköğretim Kurulu. (2022, Mayís). *Temel Bilimler Toplantísí Raporu.* https://www.yok.gov.tr/Documents/Yayinlar/Yayinlarimiz/2022/temel-bilimler-toplantisi-raporu.pdf

Yükseköğretim Kurulu (YÖK) Meslek Atlasí. (2023). Retrieved April 22, 2024 https://yokatlas.yok.gov.tr/meslek-anasayfa.php

About Authors

Dr. Zeynep AYSAN ŞAHİNTAŞ | Turkish Academy of Sciences | zeynep.aysan[at]tuba.gov.tr | ORCID: 0000-0002-0125-3048

Dr. Zeynep Aysan-Şahintaş graduated from the Department of English Language Teaching (ELT) at Boğaziçi University. Having taught several years at Adnan Menderes University Preparatory School, she got her M.A. in TEFL Program at Bilkent University. She then was accepted to Middle East Technical University (METU), where she worked as a research assistant, to pursue Ph.D. in ELT. She published research articles and worked as a researcher in international research projects. Her main interests are teacher education, multilingualism and sociolinguistics. She is currently working at the Turkish Academy of Sciences as an expert and also teaching sociolinguistics at METU as a part time instructor.

Dr. Gülben AVŞAR | Turkish Academy of Sciences | gulben.avsar[at]tuba.gov.tr | ORCID: 0000-0002-7144-9767

Dr. Gülben Avşar graduated from Ege University Department of Bioengineeering in 2014 with a bachelor's degree. After the Msc degree which has been taken from Marmara University Department of Bioengineering, she completed her PhD in Gebze Technical University Department of Bioengineering under Bioinformatics and Systems Biology PhD Program in 2023. From her undergraduate studies to the present, Gülben has worked on several national and international projects at Ege University, Sabancı University, Marmara University and Gebze Technical University. Including these projects, a number of studies that she participated in have been published, and several oral and poster presentations have been performed. Meanwhile, she worked as a teaching and research assistant in Gebze Technical University between 2017 and 2023. Since May 2023, she has been working as a TUBA Expert at Turkish Academy of Sciences. Additionally, she is also a lecturer at Ankara Medipol University, focusing on data science and its applications in healthcare.

Prof. Muzaffer ŞEKER | Turkish Academy of Sciences | mseker[at]tuba.gov.tr | ORCID: 0000-0002-7829-3937

Prof. Dr. Muzaffer Şeker graduated from Uludağ University Veterinary Faculty in 1986. Subsequently, Prof. Şeker earned his Ph.D. in Human Anatomy at the University of Leicester, Faculty of Medicine in England, in 1995. He achieved the position of associate professor in 2000 and was promoted to full professorship in 2006. Throughout his career, Prof. Şeker worked as an instructor in the United Arab Emirates for two years and also held the position of the Head of the Department of Medical Education and Informatics at the Meram Faculty of Medicine at Selçuk University. He played a crucial role as a member of the Founding Board of Trustees of Istanbul Medipol University from 2008 to 2010. In December 2014, he was appointed as the founding rector of Konya Necmettin Erbakan University. He has also served on the selection committees of Türkiye Institutes of Health Administration (TÜSEB) Aziz Sancar Science, Service, and Incentive Awards; YÖK Doctorate Awards; TÜBA-GEBİP Awards; and TÜBİTAK Science, Service, and Incentive Awards. He began his role as President of Turkish Academy of Sciences in 2019. Prof. Şeker has also represented his country at the Science 20 Summits, World Science Forum, and many other international scientific events.

ATOMIC THEORY IN THE OLD UYGHUR TEXTS

Hacer Tokyürek

10.53478/TUBA.978-625-6110-22-9.ch10

Atomic Theory in the Old Uyghur Texts*

Hacer Tokyürek
Erciyes University

Abstract

The majority of Old Uyghur texts consist of religious works that were translated from languages such as Sogdian, Tocharian, Chinese, Tibetan, and Sanskrit, often related to Buddhism. These Buddhism-themed texts contain views on the foundation of the formation of the macro- and micro-cosmos or the smallest building block of matter, the atom. Most of these views are associated with the ancient Indian schools of thought. Particularly significant are the views on atom theory from the Vaiśeṣika school, which accepts atomism, and the Vaibhāṣika school of Hīnayāna Buddhism. In addition, it is possible to find the views of the Mādhyamika and Yogācāra schools, which are associated with Mahāyāna Buddhism and opposed to the atomic material theory, in these texts. The views of these schools in Old Uyghur texts are often presented within a religious framework. In this context, there are some terms related to atoms in Old Uyghur, such as *par(a)manu, ärtiŋü inčgä, kog, kıčmık*. These terms are interpreted in accordance with the Old Uyghur texts. Therefore, in texts that embrace an atomist approach, these terms carry the meaning of "atom, very small particle," whereas in texts that reject atomism, they express the meaning of "dust, very small particle." Consequently, the meanings of Old Uyghur words or terms are also subject to variation based on the religious sects and schools they are associated with.

Keywords
Atom theory, Ancient Indian schools, Old Uyghur, Par(a)manu, ärtiŋü inčgä,

* This paper is supported by Tübitak 1001 project number 122K196. I would like to thank TÜBİTAK
I would like to thank Erciyes University Dean of Research for providing the necessary infrastructure and laboratory facilities at the ArGePark research building.

Introduction

God wanted to be "known"[1] and thought that this would be possible by "creating", and thus with the onset of creation, existence began for other living beings. He created the universe(s), the stars, the moon and the sun, the planets, and thus the earth, objects, plants, animals, and humans. He also wanted to see "destruction", and "extinction". For this reason, "existence", and "destruction" emerged in everything. God's creations were perfect. The most perfect and curious among them was man, and man heard, saw, smelled, touched, tasted, and thought. Thus, this curious creature has struggled for centuries against the ideas of existence and non-existence. Throughout history, man has always been preoccupied with how existence and extinction occur and has put forward various thoughts about how the universe, the world, living things, and non-living things are created and destroyed. Some of these ideas were mythological and theological, while others were philosophical and scientific.

The introductory sentences above were written with a mythological and theological approach. However, it is known that man, who was looking for the hows of creation and destruction, later looked at them within the framework of philosophical and scientific theories and thus moved away from mythology and theological approaches. In the creation and destruction of the macrocosm and microcosm, first philosophical and then scientific theories were developed, the most important of which is the "atomic" theory.

It is thought that the atomic theory, which is an important subject of modern science today, first appeared in Ancient Greece. The main topic of discussion among ancient Greek philosophers was nature, and they asked many questions about it: What are the basic substances that make up natural substances? Do basic substances become sensory objects? *Thales* thinks that the origin of everything is water. According to him, everything is created from water and returns to water again. He says that the world is like a disk floating on water. There is no answer to the question of why Thales adopted this idea (Stace, 1920, p. 21; Pullman, 2001, pp. 13-14; Sarkar, 2022, p. 2). *Anaximander*

---

[1] "God brings the living out of the dead, brings the dead out of the living, and resurrects the earth in the spring after its death in winter. This is how you will be resurrected after death and taken out of your graves." (Kur'an-ı Kerim, Surah Ar-Rum, Verse 19); "I was an unknown hidden treasure, I wanted to be known, I created the people (the universe) so that I could be known" (Aclûnî, II, p. 132); "In the beginning God created the heavens and the earth. The place was formless and void, and darkness was over the surface of the deep, and the Spirit of God was moving over the the water." (Bible, Genesis, Verses 1-2).

agrees with Thales that the ultimate principle of all things is matter, but he does not call it water. In fact, he does not believe that it is any substance. He does not accept any of the four material elements, such as earth, water, fire, and air, as primitive elements. In general, the essential matter of an object is formless, indeterminate, and absolutely characterless (Stace, 1920, pp. 24-27; Pullman, 2001, p. 16; Sarkar, 2022, pp. 2; 25). *Anaximenes* accepts matter as having endless and uninterrupted motion and states that the first element of the world is air. Air is infinitely vast, constantly moving and changing. Since it is dynamic, the power resides in the air, and the movement of the earth originates from the air (Stace, 1920, p. 28; Pullman, 2001, pp. 17-18; Sarkar, 2022, p. 2). This movement enabled the universe to consist of air. He divides the process of this development into two parts: dilution and concentration. The air becomes thinner and turns into fire and air, and the carried fire turns into stars. Through the reverse process of condensation, air first turns into clouds and, with subsequent degrees of condensation, into water, soil, and rocks, respectively.

Over time, the earth evolves back into the air. Like *Anaximander, Anaximenes* defends the theory of "innumerable worlds", and these worlds, according to the traditional view, are consecutive (Stace, 1920, p. 28). *Pythagoreans* explain everything with numbers. Moreover, it is not possible to imagine a universe where there is no number. They point out that proportion, order, and harmony are the dominant notes of the universe. A number is the world from which the universe is made. The universe consists of odd and even opposites, which brings about limitation and limitlessness (Stace, 1920, pp. 34-36; Pullman, 2001, pp. 25-26). *Xenophanes* identifies god with the world, and the world is god, who is a sentient being even though he has no sense organs. Looking at the vast skies, he accepts the idea that "There is only one God." His god is immutable, indivisible, motionless, passionless, and undisturbed (Stace, 1920, p. 42). According to him, he thinks that "Everything is one" and "There is one God". This is eternal; he thinks that the world was created from the sea, and then the world will sink into the sea, but the world will rise again from the sea, and a new human race will be created (Stace, 1920, p. 42; Pullman, 2001: p. 20; Sarkar, 2022, pp. 2; 26; 109). According to *Parmenides*, there is only existence, non-existence does not exist and is unthinkable. Absolute reality is existence; non-existence is unreal. The world of sense is unreal, illusory, and only an appearance. Only "existence" really exists. For *Parmenides*, the only reality, the first principle of things, is "existence", which is not completely confused with non-existence and is completely excluded from any formation (Stace, 1920, p. 44; Pullman, 2001, pp. 21-22). Existence has no origin or destruction; it can never arise from nothingness and cannot be destroyed.

What exists remains the same (Sarkar, 2022, pp. 2; 27; 28). *Zeno* did not develop any philosophical thought, but he supported Parmenides' doctrine of existence. He opposed multiplicity and movement and proved that multiplicity and movement were impossible. *Zeno* wanted to show that if multiplicity and movement were accepted as real, a contradictory result would be achieved (Stace, 1920, pp. 53-55; Sarkar, 2022, pp. 2; 28). *Heraclitus* acts as the exact opposite of *Parmenides* and *Zeno* and according to him, there is only "Being". Existence is a permanent illusion; these are all illusions. Heraclitus not only rejected any absolute permanence but also pointed out that the relative permanence of things is illusory. According to him, everything is constantly changing and renewing. Objects are constantly changing and never the same again. This is an indication that both existence and non-existence are equal. Origin is the transition from non-existence to existence.

Death is the transition from existence into non-existence. Then, "being" includes only the elements of existence and non-existence and refers to the shift from one state to the other. According to *Heraclitus*, the basic principle is "fire". All objects are created from fire; this world is one with everything, not created by God or man. This world is eternal, and it is a fire that will live forever. Everything is born from fire; the end of everything is it; fire is the basic element. Heraclitus also claims that all elements can be transformed. According to him, the first element, fire, transforms itself into the air, air into water, and water into the soil, and while he calls this the "downward path", he calls its opposite transformation the "upward path" (Stace, 1920, pp. 73-78; Pullman, 2001, p. 19; Sarkar, 2022, pp. 3; 26, 28-30). *Empedocles* argues that an object as a whole arises or disappears, but objects composed of matter have no origin and destruction; they are not created and cannot be destroyed. *Empedocles* refers to the elements as the "root of all things." The combination and separation of elements involves the movement of particles, and some force of motion must be present to account for this. *Empedocles* rejects this. For him, matter is absolutely dead and lifeless, without any principles of motion within itself. Therefore, it must be assumed that forces act on matter from outside. For this, love and hate or harmony and disagreement are accepted.

Everything in the world consists of the combination and separation of four elements, but these four basic elements have no origin. For this theory to develop, it must be shown that all properties based on the position and arrangement of particles are composed of exactly four elements (Stace, 1920, pp. 82-84; Pullman, 2001, pp. 22-23; Sarkar, 2022, pp. 3-4; 30-31). *Anaxagoras* is also among the defenders of primitive matter. He is in stark contrast to the Milesians, monists who consistently attributed this quality to a single environment. Starting from the doctrine that nothing can come into being from nothing and that nothing can be destroyed, he declared that everything that exists contains infinitesimal particles that bear the qualities of all other beings: "There is a little piece of everything in everything." He called these particles omoiomer. Therefore, according to him, prime substances were infinite in quality and quantity. The unique essence of the Milesians is replaced by a set of qualities contained in infinitesimal particles, and the change resulting from their blend and separation eliminates the need for their formation and destruction. All objects in nature contain all possible *omoiomers* but in variable proportions. How a particular object looks depends on which particular type of *omoiomer* is dominant (Pullman, 2001, p. 24).

The founder of atomic philosophy is generally considered to be *Leucippus*. Democritus appeared much later than Leucippus, and both accepted the atomic theory. *Leucippus* and *Democritus* developed *Empedocles*' particle theory. According to *Leucippus* and *Democritus*, if we divide matter over and over again, the atom remains, which is the only thing that cannot be divided. The atom is the ultimate unit of matter. The number of these atoms is infinite and very small. Therefore, we cannot perceive it with our sense organs. *Leucippus* and *Democritus* do not accept four primitive elements; they argue that there is only one type of matter: the atom. Atoms have no qualities. Atoms are solid. They differ from each other in size and shape. These are too small to see. They are shaped like a circle, triangle, or quadrilateral, and each one is different. There is no reason why these shapes are different. Atoms are infinite and cannot be destroyed.

Atomists argue that no external force is needed for primordial movement. The endless movement of atoms is self-sufficient. Everything arises from a completely blind mechanical cause. *Leucippus* thinks that no external force or motive force is required for the initial movement. In the beginning, the atom is in the void, or empty space, and this physical world is created from it. In atomic philosophy, the beginningless and endless movement of atoms is self-sufficient in explaining the origin of the world. Atomists think that any movement is inevitable. *Leucippus* states that nothing is without a reason; everything has a reason and a necessity. *Democritus* also agrees with *Leucippus*. *Democritus* claims that nothing happens by chance; on the contrary, everything happens according to the laws of nature. Atoms are in constant motion, hitting each other in infinite space and collapsing, causing them to move in different directions. Democritus thought that atoms had hooks and grooves and that they could stick together. Atoms moving in infinite space collide with each other and bounce back; atoms come into close contact with other atoms; and some atoms move away while others cling to each other. Thus, objects are formed. He also thinks that there would be no movement without space. There is no empty space, and there is no absolute absence in the existing object because the truly existing object is absolute plenitude. It is not filled with a substance but is infinite in number. It is not visible due to its subtlety. Additionally, *Democritus* explains the doctrine of primary and secondary qualities. Shape, size, and extension are primary or fundamental attributes, while color, temperature, smell, and taste are secondary attributes of an object. Democritus thinks that secondary qualities do not actually exist in objects but that these qualities arise from our sense organs. Primary qualities already exist in the object. *Melissus* does not accept that atoms can be infinite and countless.

The Greek atomists were not only materialists but also mechanical. In other words, they believe that the world and humans are governed by mechanical forces. They argue that everything is causal. Nothing is accidental; everything happens according to the laws of nature. *Democritus* defined human mental action as the presence of a certain life force in the body and called it the “soul”. Like other external objects in the world, the soul consists of atoms. However, there is a difference between the atoms of objects and the atoms of the soul. The atoms that make up the soul are round. The soul is composed of round atoms, as it is suitable for penetrating objects and moving. The soul is a composition of fiery atoms that are smooth, subtle, and mobile. These fiery atoms are abundant in humans. Democritus thinks that there is a special connection between life and heat. The surrounding air pressure causes soul atoms to move out of the body, but other soul atoms enter the body through the air we breathe. Human life depends on this uninterrupted renewal. Spirit atoms are miserable in the face of death. In other words, Democritus believes that the soul consists of atoms and consciousness is a physical process. Atoms exist throughout the universe among animals, plants, and other things. Although he believed in the existence of the soul, *Democritus*, who thought that there were atoms in the soul, was a strict materialist. Thus, atomists opposed gods and religions. God has no role in the materialist and mechanical philosophy of the atomists (Stace, 1920, pp. 86-92; Pullman, 2001, pp. 31-36; Sarkar, 2022, pp. 2-4; 31-38).

While the atomic theory had an important place in Greek philosophy, this theory was also discussed in Indian philosophy and gave rise to many ideas. Accordingly, there are two different systems in the Indian philosophical system: *āstika*, which accepts the existence of god, and *nāstika*, which denies the existence of god. However, this distinction is also interpreted as accepting or rejecting the Vedic texts rather than accepting or rejecting the existence of God. Those with *Āstika*, that is, orthodox structure, are listed as *Nyāya*, *Vaiśeṣika, Sāṁkhya, Yoga, Mīmāṁsā,* and *Vedānta*, and these are called ṣaḍdarśana. *Nāstika*, that is, heterodox ones, are *Cārvāka, Buddhists,* and *Jainas* (Sarkar, 2022, p. 4). It is difficult to consider *Cārvākas* as atomists or anti-atomists. While Jainas are definitely atomists, Buddhists have two different views: atomist and anti-atomist. While Hīnayāna Buddhism is atomist, *Mahāyāna Buddhism* is anti-atomist. *Hīnayāna* believes in the reality of the external world and that everything is made up of atoms. *Mahāyāna*, on the other hand, harshly rejects the reality of the external World. *Sāṁkhya* and *Vedānta* reject the atomic theory.

Yogists also do not subscribe to the atomic theory, and the reason why they do not subscribe to this theory is entirely because they accept the epistemology and metaphysics of *Sāṁkhya* with its twenty-five principles. Both schools of *Nyāya-Vaiśeṣika* and *Mīmāṁsā* are atomists (Gangopadhyaya, 1980, pp. 2-6). The metaphysical doctrine of the *Cārvākas* is considered materialism, and they constitute the material world from four elements (*caturbhūta*) called earth, water, fire, and air. These four elements do not have atoms; they are infinite, but when they come together, they create something that is not infinite. These have only transformations but not destruction, and their combination provides the creation of this world and everything in it. According to the *Cārvākas*, the laws of nature (*svabhāva*) are the sole cause of diversity in the world. They say that the continuous manifestation of energy in matter constitutes *svabhāva*. *Svabhāva niyam* is the law of energy underlying the four elements. Four elements come together to form the basis of a different world. Again, when these four elements separate from each other, it destroys everything that exists. According to the *Cārvākas*, consciousness is only the product of these four elements. They claim that the material world was created accidentally and mechanically with the help of these four elements. Consciousness is only a quality of the body (Sarkar, 2022, pp. 4-5). Jainas, on the other hand, attribute everything to matter (*pudgala*) and argue that all matter consists of atoms. Each atom occupies a point in space, but the matter is either in gross or subtle form.

In its subtle state, its countless atoms occupy the space of one larger atom. Atoms are eternal in terms of matter. Everything we see, touch, hear, and drink is pudgala. Matter is the basis of the physical world. Everything physical is produced from pudgala, except the soul and space (Gangopadhyaya, 1980, p. 7). According to *Jainas*, there are two types of matter: 1. Atom, namely, *aṇu* or *paramāṇu*; 2. Compound, namely, *skandha*. According to them, the part of matter that cannot be divided is called an atom. An atom is the ultimate limit of division; it is very small, infinite, and formless. It cannot be created or destroyed. Each atom occupies only one point in space. Although atoms are shapeless, they are the basis of the objects they form. Atoms are not perceived because they are shapeless and homogeneous; there is no qualitative difference between them. The way they are all perceived is the same, and they are not permanent and fixed; they can change and be improved. *Jainas* accept that atoms can attract and repel, and they argue that the creation of all material objects is possible through the connection of atoms for mutual attraction. When two or more atoms come together, they form compounds, or skandhas. These compounds also form union, that is, *saṁghāta*. *Skandhas* occur when one of the atoms is sticky and the other is dry, or when both are different, and in fact, the union is achieved when the atoms have different qualities. Jainas accept the attraction and repulsion forces of atoms. They claim that the movement of atoms can also occur through space, *dharma* "law" and *adharma* "chaos". Mind/consciousness, speech, life, and breath are the products of matter, namely, the atom. *Dvyaṇuka*[2] *skandha* depends on the union of atoms. In this way, many skandhas are created. Every perceptible object is a *skandha*, and the material/physical world as a whole is considered the *mahāskandha* "great unified" (Sarkar, 2022, pp. 5-6).

Two important schools of atomistic *Hīnayāna Buddhism* are the *Vaibhāṣika* and *Sautrāntika* schools. These accept the existence or reality of external

---

[2] union of two atoms

objects. However, while Vaibhāṣikas say that we can know external objects directly, *Sautrāntika* claims that this can be achieved through inference. These schools accept both the external world and the mental world. That's why they are called *Sarvāstivāndis*. They talk about conditionality (samskṛta) and unconditionality (*asamskṛta*), in which there are five skandhas of the law of *samskṛta*. Of these five skandhas, the *rūpa-skandha* "shape component" is related to atomic theory. Accordingly, both *Vaibhāṣika* and *Sautrāntika* schools adopt the atomic theory. According to them, rūpa-skandha accepts the existence of four elements, such as earth, water, fire, and wind or air. Earth is solid, water is fluid, fire is hot, and air is mobile. According to *Vaibhāṣika* and *Sautrāntika*, the outer world is created from the atoms of these four elements. *Vasubandhu*, the founder of the *Yogācāra* school of philosophy, believes that the smallest particle of rūpa is the atom that cannot be pierced, taken, or thrown. *Vaibhāṣika* and *Sautrāntika* accept that matter is a four-layered composition consisting of color, taste, smell, and contact, and the atom, or paramāṇu, is the unit with these four qualities. *Paramāṇu* cannot be perceived. When seven *paramāṇu* combine, *aṇu* is formed, and only *aṇu* can be perceived. When atoms come together, one atom remains in the center, and the others remain around it. There are two types of atoms: *dravya paramāṇu* (simple) and *samghāta paramāṇu* (compound). Additionally, atoms have two types of properties: natural (*svabhāva*) and derived (*upādāya*). Again, four material elements have four natural properties: solidity, stickiness, heat, and movement. There are five sensory properties in these material elements, expressed as *rūpa, rasa, gandha, sparśa*, and *śabda* (Gangopadhyaya, 1980, pp. 10-13; Sarkar, 2022, pp. 6, 9, 57-64). In addition, according to *Vaibhāṣikas* who do not accept the idea of *guṇa*, all *rūpas* are just a combination of atoms, each of a special type, and since they are composite in nature, they can be equivalent to matter in some way. No single sense atom or object atom is capable of producing awareness on its own, because all forms of awareness are related to the whole (Gangopadhyaya, 1980, p. 13; Sarkar, 2022, p. 61).

Nyāya-Vaiśeṣikas are also one of the important āstika systems of Indian philosophy. According to the *Vaiśeṣikas*, there are nine types of substances: earth, water, fire, air, ether, time, space, spirit, and consciousness. Matter may or may not be infinite. While the atoms of earth, water, fire, and air are infinite, their compound products are not infinite. In addition to these, ether, time, space, the soul, and consciousness are considered eternal. *Nyāya-Vaiśeṣika* asserts that there are four different types of atoms in the four elements. These atoms are the smallest and indivisible units of material entities. Atoms are indivisible, infinite, partless, spherical, and imperceptible. There is no empty space within the atom, and atoms cannot enter into each other. They differ in quality from one another. Each atom has its own reality and unique attributes. The atoms of earth, water, fire, and air have different qualities, and these qualities, like the atoms themselves, are infinite. *Praśastapāda* discusses twenty-four qualities that consist of two types: *sāmānya*, which are "common qualities," and *viśeṣa*, which are "specific qualities." Common qualities exist in multiple substances, while specific qualities are unique to a single substance. The specific quality of the earth atom is smell; that of water is taste; that of fire is color; and that of air is touch. These atoms are inherently inert and stable. Atoms are set in motion and made active by an external force or an imperceptible power. According to the earlier *Vaiśeṣikas*, motion in atoms is generated by an imperceptible force called *adṛṣṭa*. This imperceptible force, *adṛṣṭa*, is considered to be the virtue and flaw of individual souls. In later developments, it is proposed that when God imparts motion to the atoms, they combine to form compound products. Atoms are the material cause of the physical world, and the imperceptible force, or God, is the efficient cause. According to *Vaiśeṣikas*, when the imperceptible force or God imparts motion to atoms, two atoms combine to form dvyaṇuka, three atoms combine to form tryaṇuka, and the triad is the smallest perceptible unit of matter. An active quaternary combines to form caturaṇuka, and quaternaries combine with each other to form larger objects. In this context, *Nyāya-Vaiśeṣikas* expresses that atoms of the same type can combine themselves to form binary, triad, etc., but it is stated that atoms of different types cannot combine with each other (Gangopadhyaya, 1980, pp. 17-21; Sarkar, 2022, pp. 7-9). Furthermore, the *Nyāya-Vaiśeṣikas* accepted a separate category called quality or guṇa. This quality or guṇa, while found in matter, is entirely distinct from matter. The five objects of the senses belong to it. According to them, matter is composed of atoms but not composed of *guṇas* (Sarkar, 2022, p. 61).

Another of the *āstika* systems in Indian philosophy is *Mimāṁsā*. *Mimāṁsā* has two schools: *Bhāṭṭa* and *Prābhākara*. The founder of the *Bhāṭṭa* school is *Kumārila Bhāṭṭa*, while *Prābhākara Miśra* founded the *Prābhākara* school. According to *Kumārila Bhāṭṭa*, substance (*dravya*) is a positive category, and matter is composed of eleven essentials, including earth, water, fire, air, ether, self, consciousness, time, space, darkness, and sound. Earth, water, fire, air, and ether are created from atoms. According to him, compound things are composed of atoms. He accepts the atom as the ultimate unit of matter, but his explanation does not clearly specify whether the ultimate unit of matter is the atom or triads (*tryaṇuka*). *Manameyodaya* rejects the atom as the ultimate unit and instead accepts triads as the ultimate unit. Matter is one of the eight categories recognized by *Prābhākara*. There are nine types of matter, including earth, water, fire, air, ether, self, consciousness, time, and space. Even when earth, water, fire, and air are not atomic, they can still be perceived (Sarkar, 2022, p. 8).

Since the end of the 9th century, many Islamic scholars have adopted atomic theory and interpreted the nature of objects and the role of the atom in the formation of matter. During this period, the person who first put forward the atomic theory was *Abū al-Hudhayl al-'Allāf*. Adopting the theory of atomism, *Abū al-Hudhayl al-'Allāf* swears that everything consists of indivisible parts called *jawahir*, which is the plural of the word *jawhar*. He thinks that each jawhar has no qualities other than existing within itself and occupying space. This is Mu'tazilite's theory of atomism. They are of the opinion that bodies consist of parts, the smallest of which is jawhar, and that they cannot be divided further (Elkaisy-Friemuth, 2017, p. 43). While Badawi states that *Abū al-Hudhayl* was influenced by the ancient Greek and Indian atomists while making his definition of an atom, he leans more towards the view that he knew it from the translation of Greek books that were going on at that time (Elkaisy-Friemuth, 2017, p. 181).

On the other hand, some Mu'tazilite scholars, such as *al-Naẓẓām* (d. 836/845) and other theologians from the Baghdad sect, predict that the atom can be divided to a large extent, leading to the theory of the infinity of the world. These particles come together from side to side with certain abilities, and these abilities are successively built into them (Elkaisy-Friemuth, 2017, p. 47). Kalām interpretations include clear and visible atomic ideas and naturalistic philosophy. These comments can be classified into three aspects. These are: (a) the doctrine that objects or bodies are formed from a series of coincidences; (b) the doctrine that things or sensible bodies consist of bundles of material bodies penetrating each other; and (c) the doctrine that bodies are composed of atoms and natural accidents. Created according to *Ḍirār ibn 'Amr* (d. 200/815), *Ḥafṣ al-Fard* (fl. ca. 195/810), and *al-Ḥusayn al-Najjār* (d. 220-230/835-845), adherents of the first doctrine The world consists only of accidents and therefore, the objects of the world consist of a bundle of accidents that determine their qualities and properties. Those who accepted the second theory can be listed as *Ḥishām ibn al-Ḥakam* (d. 179/795?), *al-Aṣamm* (d. ca. 200/815), *İbrāhīm ibn Sayyār al-Naẓẓam* (d. ca. 220-230/835-845), and their followers. The second theory posits that the created world is composed of bodies, with objects being bundles of interpenetrating material bodies that define their properties and qualities. The third doctrine, widely accepted by theologians, asserts that the created world consists of solid atoms and their inherent accidents, determining the properties of objects. Also, atoms may spontaneously combine within themselves to form larger units, like the human body, which is considered a living compound. Atomism, the third doctrine focusing on the nature and qualities of things, was the dominant and defining feature of Kalām cosmology (Dhanani, 1994, pp. 4-5). *ʻAbd al-Jabbār*, a Muʻtazilite theologian, developed the theory of atomism while interpreting human nature.

According to him, God, who is the first cause of all objects, must be absolutely free from matter and accidents because if God's existence included atoms and accidents, He would have a beginning and an end, like all objects. Therefore, if God is proven to be the first cause, then God must be immaterial, having no relation to matter. This crucial element in God's nature has two main consequences: First, just as accidents are related to bodies, as explained above, not all of God's attributes can be related to Him. Secondly, God is immutable as he is entirely immaterial, accepting only growth and destruction as changes in matter (Elkaisy-Friemuth, 2017, p. 44). Man, like all other creatures, operates through various contingencies that remain within him. When he explains the nature of man, he believes that man, like all creation, is made up of indivisible pieces of land, and with him, many of the creatures called them the atom, or jawhar. He explains the determination element, which has the ability to transfer things to their kind, taking into account that matter can be made up of more than one atom (Elkaisy-Friemuth, 2017, p. 52). Accidents, by contrast, are made up of only one component or atom and trigger the elements of change that occur in matter. Traditional Kalāmists and Muʻtazilites adopted atomism because atomism adopted only one duality between God and the world. It is a fact that nothing spreads on its own and without an external stimulus that will ignite or reinforce it. The atom has the internal capacity to disrupt the existing structure of an entity. Nothing exists, therefore nothing moves by itself, except God; an He often creates accidents that give the world the power to move (Elkaisy-Friemuth, 2017, pp. 152-162). In addition, scholars such as *Al-*

Asha'rī, *Mu'ammer*, and *Abū 'Alī el-Jubbā'ī* also see the jawhar substance as an atom (Dhanani, 1994, pp. 180).

The atomic theory, which plays a significant role in modern physics and chemistry, became a subject of scientific investigation again in the 18th century. Chemists started to discuss matter and how it undergoes changes. They combined substances to create new materials and analyzed how matter changes. They found that some substances couldn't be further divided into simpler substances and realized that all matter is composed of elements. An element is a substance consisting of a single type of atom. As a result, the atomic theory that entered the laboratory in modern science was developed with new theories by scientists like John Dalton, William Crookes, Joseph John Thomson, Ernest Rutherford, Niels Bohr, Erwin Schrödinger, Louis de Broglie, Werner Heisenberg, Max Planck, Albert Einstein, Dmitri Mendeleev, Francis Aston, James Chadwick, Enrico Fermi, and others. These theories, developed after the discovery of the heavy nucleus inside the atom, revealed that the atom could be broken down, and its fundamental particles were identified as electrons, protons, and neutrons (Ronan, 2003, pp. 548-572). In the subsequent process, Otto Hahn and Lise Meitner discovered that a neutron could split the nucleus of an atom (Sime, 1998, pp. 80-81). Later on, research related to atoms gained momentum.

It has been determined that the atomic theory, a brief history of which is presented above, is also found in Old Uyghur Turkish texts, and in this study, the place of atomic theory in Old Uyghur is revealed based on these texts, which are translation-copyright texts. When their state collapsed in 840, the majority of the Uyghurs came to the Turfan region and encountered the Buddhist Sogdians, Tocharians, and Chinese there. In addition, it is known that Buddhism has existed among the Uyghurs since the Kokturk State period. The Uyghurs, who made Manichaeism the official state religion in 762, quickly adopted Buddhism in the Turfan region after 840 and translated many texts related to Buddhism from Chinese, Tocharian, Sogdian and Sanskrit into Uyghur (Wilkens, 2016a, pp. 191-225). As an example of these translated texts, the original Chinese text of the *Altun Yaruk Sudur* text, which was translated into Old Uyghur by *Şinko Şeli Tutuŋ* in the 11th century, was translated by *I-tsing* (Yi Jing) in 703. The first translation of this text was made in 417 by *Dharmakṣema*, who came to China in 414, and the second was created by *Pao-ku* in 597 (Emmerick, 2016, p. XII). *The Biography of Xuan Zang*, which was translated from Chinese into Uyghur by *Şinko Şeli Tutuŋ* in the 11th century, also describes the pilgrimage of Chinese pilgrim *Xuan Zang* to India between 629 and 645, and the visit contains a lot of religious, cultural, and social information. The original text of the *Abhidharmakośa* text, which is not known exactly when it was translated into Old Uyghur but is thought to have been translated in the 11th century, is Sanskrit. This text was written by *Vasubandhu* in the 4th or 5th century. This text was translated into Chinese by *Paramārtha* in the 6th century and again by *Xuan Zang* in the 7th century (Sangpo&de La Vallée Poussin, 2012, p. 92). The Old Uyghur version is a translation of the Chinese text. The DKPAM text is a text about the ten sins in Buddhism, translated from Tocharian into Old Uyghur. Although it is not known when this text was translated, it seems that its language is older than the works translated by *Şinko Şeli Tutuŋ* listed above (Wilkens, 2016b, p. 9). Therefore, this period is a period in which there are many works related to Buddhism, and it is possible to multiply these works. In this article, no comparison will be made with modern science, but an examination and evaluation will be made based on sample texts according to the understanding of the period. Additionally, the meanings of the Old Uyghur terms will be clearly elucidated.

Atom in Old Uyghur: par(a)manu, ärtiŋü inčgä, kog, kıčmık

Most of the Old Uyghur texts are translations from languages such as Sogdian, Tocharian, Chinese, and Sanskrit, and they primarily consist of Buddhist content. The majority of the ideas in these translated texts are linked to the religious and philosophical structures of the nations from which they were translated. Consequently, the original texts from which the Uyghur texts were translated hold special significance. Additionally, the thought system found in Old Uyghur texts is related not only to the Buddhist thought system but also to the philosophical systems of India and China. In this paper, the focus will be on the concept of the atom, particularly on the atomistic thought of *Vaiśeṣika* and *Hīnayāna*, as well as the rejection of atomism in *Mahāyāna* thought. In this context, three different words in Old Uyghur texts convey the meaning of "atom." It is possible to list these as *par(a)manu* < Tocharian A/B *paramāṇu ~ paramānu* < Sanskrit *paramāṇu* "atom, particle," (Wilkens, 2021, p. 551), *kog* "atom, particle, dust" (Wilkens, 2021, p. 389) and *kıčmık* "atom, particle, dust" (Wilkens, 2021, p. 368) in Old Uyghur. These words can be used independently and can also appear together in texts. Accordingly, there is important information related to atomic theory in *Xuan Zang's Biography*

8. In this section, *Xuan Zang* criticizes a Chinese scholar named *Lü Cai* and provides some information related to atoms.

> Taishō.2053.50.0265b14-17: 勝論立常極微數乃無窮。體唯極小。後漸和合生諸子微。數則倍減於常微。體又倍增於父母。迄乎終已體遍大千。究其所窮數唯是一。
>
> HT8.1150-1163: *takı ymä vaišašikelıg bahšilar nomınta ärtiŋü inčgä mäŋü par(a)manu sanın alkınčsız ol tözi yana ärtiŋü kičigk(i)yä ol, ken ärü arü birlä kavıšıp ogul kız par(a)manug turgurdačı ol, ogul kız [par(a)manug] tugurdukta sanı sakıšı [yitlindäči ol, san sa]kıš yitlintüktä ög kaŋ par(a)m[a]nu üstälür, iši küdöki tükäginčäkätägi tözi ulug miŋ yertinčüdä tözü yadılur, tüpgärsär anıŋ tüpin sanı yalŋuz bir tetir tep munčulayu sözleyür* "Furthermore, the teachings of the Vaiśeṣika masters claim the following: The number of extremely subtle, infinite atoms is inexhaustible. The essence/substance of these atoms is also very small. Then, gradually, they combine to produce subsidiary atoms/child atoms/particles. When they have produced subsidiary atoms/child atoms/particles, and when their number reaches zero, the parent atoms multiply until the end of the multiplication process, and their substances/essences spread throughout every part of the great universe. In essence, if you look into it (the matter), there is only one."

VS.560-565: *takı ymä vaišašikelıg bahšılar monınta ärtiŋü inčgä meŋü parmanu sanın alkınčsız ol tözi yänä ärtiŋü kičigk(i)yä ol ken ärü ärü birlä kavıšıp ogul kız parmanug turgurtačı ol* "And again, in the teachings of the Vaiśeṣika masters, it is said: Atoms are infinite in number, extremely subtle, and permanent particles. The essence of these atoms is also quite small. Then, gradually, they combine, and the particles of atoms will emerge."

Here, a comparison has been made between the Chinese text of *Xuan Zang's Biography* and the Uyghur text, and the understanding of the Uyghur terms has been assisted by the Chinese text. In the Chinese text, 勝論 *shenglun* corresponds to "Vaiśeṣika-śāstra," which is fully represented in Old Uyghur as *vaišašike* "Vaiśeṣika," referring to the Vaiśeṣika school from ancient Indian traditions. The terms related to atoms in both Chinese and Old Uyghur texts are as follows. It is an equivalence of the Chinese words 極微 *jiwei* "atom, very thin" (Giles, 1912, pp. 99&859, 1516&12586), the Uyghur *ärtiŋü inčgä* "very thin, very subtle" and *par(a)manu* "atom, very subtle". The striking point in the texts is that the expression 極微 *jiwei* is encountered in the Uyghur text with both the Turkic word *ärtiŋü inčgä* and the Sanskrit word *par(a)manu*. Besides, another noteworthy point is Old Uyghur calls *ogul kız par(a)manu* "subsidiary atoms/child atoms/particles", Chinese calls 諸子微 *zhuzi wei* "child atom" (Giles, 1912, pp. 322&2571, 1524&12317, 1516&12586), again Old Uyghur names *ög kaŋ par(a)m[a]nu* "the parent atoms." The Chinese expression 父母 *fumu* "parent" (Giles, 1912, pp. 466&3736, 998&8067) is used. An important term in this text is the Old Uyghur word töz, for which the Chinese 體 *ti* "body, substance" (Giles, 1912, pp. 1363&11025), "the essence of something, *bhāva, ātman, sva-bhāva, dhātu, dravya*"[3] is shown. Based on the above Chinese and Uyghur texts, the characteristics of atoms according to the *Vaiśeṣika* school's explanation can be summarized as follows: Atoms are extremely thin, infinite in number, and inexhaustible. The substance of these atoms is very small. They gradually combine to produce subsidiary atoms, and when their number reaches zero, parent atoms multiply. As a result of the collision of these atoms, the substances of atoms spread throughout the entire universe, and everything is ultimately composed of a single substance. In general, according to the Vaiśeṣika school's view, atoms are indivisible, infinite, partless, spherical, and imperceptible. There is no empty space within the atom, and atoms cannot enter into each other (Sarkar, 2022, p. 7), also they are the ultimate constituents of all objects (Chakrabarty, 1973, p. 14). They are part of an approach that posits that they are the cause and effect of everything that exists.

The ultimate causes or constituents of all large material objects are these subtle subatomic particles (*paramāṇus*). The hierarchical arrangement of these particles coming together is considered the material cause of the visible universe by these systems. Of course, the senses and īśvara are shown as two instrumental or efficient causes (Chakrabarty, 1973, p. 16). According to *Kaṇāda's Vaiśeṣika sūtra*, knowledge is divided into seven categories. These categories are *dravya* (substance), *guṇa* (quality), *karma* (action), *sāmānya* (generality), *viśeṣa* (particularity), *samavāya* (inherence), and the subsequently added *abhāva* (non-existence) (Gangopadhyaya, 1980, p. 156). A substance is the basis of qualities and actions but is distinct from both. There are nine substances. The first five of these, air, water, fire, earth, and ether, are referred to as physical elements, and all except ether are composed of four types of atoms. These atoms are the indivisible and indestructible particles of matter and possess unique qualities such as smell, taste, color, touch, and sound. Atoms are the indivisible components of matter; they are

---

[3] DDB: 體 | body (buddhism-dict.net) [Date of access: 10.10.2023]

infinite, and they are uncreated. According to *Kaṇāda*, atoms are so tiny that they cannot be perceived. He believed in the imperceptibility of atoms because, in his view, perceptible entities are destructible, so he associated the eternal nature of atoms with their imperceptibility. Ether, space, and time are infinite, pervasive and imperceptible substances. The mind is infinite but as small as an atom, and it is directly or indirectly related to all physical functions of the body. The self is eternal. The individual self is internally perceived by the individual's mind.

The world, its composition, and decomposition, as well as the origins and destruction of objects in the world, are explained to be created from atoms. Atoms cannot move on their own; the source of their motion is the invisible forces that operate according to the law of causation (Chakrabarty, 1973, pp. 23-24). In addition, atoms are moved by an invisible force (*adṛṣṭa*) or by God, and two atoms combine to form a dyad (*dvyaṇuka*). The dyad cannot be perceived, but it is active. When three active dyads combine, they form a triad (*tryaṇuka*). A triad is the smallest perceivable particle. A quartad (*caturaṇuka*), which is active, is formed from the combination of four triads. Quartads combine with each other to create larger compound matter. Thus, atoms of the same type combine to form dyads, triads, and so on, but atoms of different types cannot combine (Sarkar, 2022, p. 7). The Old Uyghur expression *ogul kız par(a)manu* "subsidiary atoms/child atoms/particles" likely represents dyads, triads, quartads, and so on, formed by atoms of the same type coming together. Similarly, *ög kaŋ par(a)m[a]nu* "the parent atoms" probably represents the parent atoms or the fundamental atoms. In fact, the Old Uyghur text goes on to mention the multiplication of these atoms, emphasizing that the essence of matter is "one." Furthermore, the Old Uyghur text expresses that matter, or atoms, spreads throughout the entire universe. The following text, quoted from the *Abhidharma*, is also significant in expressing the views of the *Vaiśeṣikas* regarding atoms.

> Üİ.99b14-100a1: *yana bir bahšı sözlär čın kertü munda etigsiz ärsär vaysešikilıg bahšılar sözlägüči par(a)manu bag bolur etigsiz tep* "Once again, a teacher says: Indeed, if the situation here is unconditional, the atom bond, as the Vaiśeṣika school teachers have said, becomes unconditional or unattached."

Here, *par(a)manu* "atom" is described as having the quality of being uncombined, unconditional, or *asaṃskṛta*. As mentioned earlier, the *Vaiśeṣikas*, in contrast to other Indian thinkers, accept the existence of ether and assert that matter consists of five elements, which they call *pañca-bhuta*.

Unlike the other elements, ether is singular and eternal, having no parts. In other words, it has no atoms (Sarkar, 2022, p. 73). Ether is an indivisible and infinite substance (Sarkar, 2022, p. 87). So, the other four elements are composite, meaning they are associated with atoms. The process by which other atoms combine to become visible was previously explained. According to the Vaiśeṣikas, for something to be a substance, like the substance of *ākāśa*/ether, it is not necessary to have matter inside it. At the same time, just like *ākāśa*/ether, atoms are also eternal. When describing matter, the *Vaiśeṣikas* talk about its motion and quality. Something that is not eternal is destroyed either due to the destruction of its material cause, meaning its components, or due to the disintegration of its components. For example, a piece of cloth is lost when its threads are destroyed or when the specific arrangement of its threads is disrupted. However, an atom has no material cause or component; hence, it must be eternal. The conditions for the visibility of matter are that it exists in many matters or that it is composite (Gangopadhyaya, 1980, p. 122). However, an atom is individually indivisible and uncomposite. According to the *Vaiśeṣikas*, an atom is unconditional but forms visibility by combining within itself. Thus, the creation or destruction of an object or matter is entirely related to the combination and dissolution of atoms. In addition to all of this, the following text is quoted from the tradition of *Sarvāstivāda-Vaibhāṣika*, which is a branch of *Hīnayāna Buddhism* and comes from the Abhidharma tradition. The excerpt from the text describing the formation of the world is as follows:

> DKPAM.4451-4470/BT37.07899-07917: *kayu bo tört divip yertinčülär ol birisi miŋär miŋär bolsar ol tämin čaturdivipig atlıg yerinčü uguši tep atanur: kayu ol čaturdivipig yertinčü uguši: yänä miŋär yertinčü ugušları bolsar tämin ök čuḍik atlıg baštınkı kičig miŋ yertinčü tep atanur: kayu ol čuḍik atlıg kičig miŋ yertinčü yänä miŋär bolsarlar tämin ök divasahasirip iki miŋ orton yertinčü tep atanur: ol iki miŋ orton yertinčülär: yänä miŋär bolsarlar tämin üč miŋ ulug miŋ yertinčü yer suv tep tetir: bo munı täg käŋ ulug üč miŋ ulug miŋ yertinčü yär suvda toz tuprak parmanu kog kıčmık ot yäm sanınca nara urugı täg tolu bošgutlug bošgutsuz sortapan sakrdagam anagam arhant pratikabut tüzgärinčsiz burhanlar bolsarlar* "If each of these four continents were a thousand times a thousand, only then would it be called the system of the four continents. When this system of four continents is present in a thousand world systems (multiplied by a thousand), only then it is called 'cūḍika,' meaning initially a small thousand worlds. If these small thousand worlds, called cūḍika, are present a thousand times, then one speaks of a 'dvisāhasra,' that is, two thousand, a middle world. If each of these two thousand middle worlds is present a thousand times, then it is called 'the three thousand large thousand

> worlds.' If there were as many śaikṣas, aśaikṣas, srotāpannas, sakṛdāgāmins, anāgāmins, arhats, pratyekabuddhas and mysterious Buddhas on earth as there are dust or paramāṇus (atoms)"

The above text explains the formation of the world, which consists of four continents, according to Buddhist cosmology. Although an infinite number is mentioned for religious figures in the text, this explanation is essential for us, as it is used to indicate that the entire world is filled with *paramāṇu*, meaning atoms. As mentioned earlier, the DKPAM text is written based on the views of the *Vaibhāṣika* school. The *Vaibhāṣika* school is a branch of the Sarvāstivāda school. In this context, it can be said that the Vaibhāṣika school accepts the existence of separate entities in the mind and external objects. They believe that external objects are directly known and that there is no need for inference (Sarkar, 2022, p. 58). *Vaibhāṣikas*, who accept the reality of the external world, recognize two types of objects: external (*bāhya*) and internal (*abhyantara*). The term "external object" refers to the object composed of *bhūta*, meaning elements, and *bhautika*, meaning physical elements. "Internal object" refers to citta, which encompasses intellect and everything associated with it. Vaibhāṣikas acknowledge the existence of four elements: earth, water, fire, and air. *Vaibhāṣikas* assert that these four elements are atomic, with each having distinct characteristics. They believe that earth atoms possess hardness, water atoms have stickiness, fire atoms manifest heat, and air atoms represent motion. When these atoms come together, they give rise to the formation of mundane objects. *Vaibhāṣikas* hold the belief that both matter and mind exist, and according to them, matter and mind are composed of these four elements. Dharma, in their perspective, is an elemental component. Vaibhāṣikas classify seventy-five dharmas into *saṁskaṛta* (compounded) and *asaṁskaṛta* (uncompounded) categories. *Saṁskaṛta dharmas* are further categorized into four groups by *Vaibhāṣikas*: *rūpa* (matter), *citta* (mind), *caitta* (thought/mental), and *cittaviprayukta* (non-mental). *Rūpa* pertains to material entities and includes eleven types: the five sensory organs, the five corresponding objects of the senses, and *avijñapti* (beyond thought, the sky). *Vaibhāṣikas* perceive the five sensory objects as compounds of atoms. The following text is also from the DKPAM text.

> DKPAM.3729-3744: *anta ötrü yertinčü yer suv täprämišin körüp maitre bodis(a)t(a)v yašomaitre bodis(a)t(a)v birlä kök kalık yolınča yorıyu k(ä)ltilär .. ötrü maitre bodis(a)t(a)v inčä tep [tedi] .. tözün yašomaitr(e)-y-a bo č(a)stane älig bäg säziksiz bo tün ök alku yäklärig barča bulun yıŋak sačgay bo t(ä)ŋrilär yoksuz ämgänürlär .. birök yagız yer arkasıntaki topraknıŋ par(a)manu kog kıčmuk sanı näčä ärsär .. yänä ymä alku tınlıglarnıŋ sanı sakıšı näčä täñlig*

> *bol[sar nä]čä täŋlig kalın küčlüg yavl(a)k yäk i[čgäk] bolsarlar bodis(a)t(a)v ugušlug elig bägniñ ʻäŋ mıntın ätözüntäki bir ävin tüšinä ymä ada tuda tägürgäli uguluk ärmäzlär* "Afterward, seeing the shaking of the Earth, Bodhisattva Maitreya, accompanied by Bodhisattva Yaśomitra, descended from the sky, walking through the air. Then, Bodhisattva Maitreya said to Yaśomitra, 'Noble Yaśomitra, tonight, without a doubt, this King Castana will scatter demons everywhere. These gods are enduring torment in vain. Even if the number of these demons were as numerous as the atoms of the black earth and the entire count of living beings, no matter how vast, powerful, or wicked they might be, they could not harm even a single hair of a Bodhisattva's body from a noble lineage.'"
>
> DKPAM.131-140/BT37.00607-00615: *kök kalıkdakı yagız yer arkasıntakı topraknıŋ näčä täŋlig kog kıčmık sanı sakıšı ärsär: anča täŋlig tınlıglar üč yavlak yollarta tugarlar: kačan birök tuggalı äŋ ašnu ugrıntakı ačıg ämgäklärig täginür* "As many atoms as there are in the sky and underground, an equal number of living beings are born in three unfortunate life forms, and being born here, they suffer pain."

The mentioned *Yaśomitra* in the text is a commentator on the *Abhidharmakośa* (Mano, 1970, p. 22; Skilling, 2000, p. 329). Therefore, the text is associated with the Abhidharma tradition. In fact, the *Vaibhaṣika* school is also affiliated with the Abhidharma school. Even though the above text talks about something different, the expressions here *topraknıŋ par(a)manu kog kıčmık sanı* "the atomic number of the earth" and *kök kalıkdaki kog kıčmık sanı sakıšı* "the number$_2$ of atoms in the sky" are mentioned, and here the atoms of the elements are mentioned along with the multiplicity of the number of atoms. Actually, everything is composed of atoms. According to the *Vaibhāṣika* school, external objects are created from the atoms of the four elements: earth, water, fire, and air. Atoms are momentary, existing both visibly and invisibly. While they do not accept atomic contact, they do accept the accumulation of atoms. Atoms can never exist alone; they always exist in clusters. Earth, water, fire, and air each have four different qualities. Among atoms, the only difference is in quality; there is no difference in quantity. Although the world is not mechanically created from atoms, it is created for a specific purpose. It is also different from atoms and the soul.

The self is nothing more than a discontinuous series of mental and physical processes (Sarkar, 2022, p. 9). *Vaibhāṣikas* do not consider *ākāśa*/ether as one of the elements. These four material elements are also atomic. Although ether elements are considered to be composed of atoms, they are kept separate because they do not form an object and are not seen in the external world. External objects are real clusters of atoms. *Vaibhāṣikas* assert that atoms have six sides but are still one because they claim that the space inside an atom cannot be divided (Sarkar, 2022, p. 62). In fact, Buddhists say that the atom is not without parts but with parts (Sarkar, 2022, 91). Although Buddhist assertion that atoms are divisible is similar to some modern scientific theories, these similarities are limited. While Buddhists view atoms as inexhaustible particles, they believe that beneath these particles are smaller particles, which can be compared to the six subatomic particles discovered in modern science, such as quarks or leptons. However, the Buddhist understanding of atoms is embedded in a complex philosophical and religious context, distinct from the subatomic particles in modern science. Buddhists consider atoms not only as the fundamental building blocks of matter but also as part of karmic interactions. Therefore, interactions between atoms are significant not only on the physical level but also on the spiritual or karmic level. Hence, the Buddhist atomic understanding, while sharing similarities with science, is evaluated within a broader religious and philosophical framework.

> Taishō.0235.08.0752b09-13: 所以者何。佛説微塵衆則非微塵衆。是名微塵衆。世尊。如來所説　三千大千世界則非世界。是名世界。何以故。若世界實有者則是一合相。如來説一合相則非一合相。是名一合相。須菩提。

> BT28. D.116-126*: yana inčä tep y(a)rlıkadı kayu ol üč miŋ ulug miŋ yertinčü yer suv ärsär kertüdin kälmiš yertinčü ärmäz tep yarlıkayur üčün yertinčü tep tetir munta üč miŋ ulug miŋ yertinčü yer suv temäk üze par(a)manular yıgını üzä bütmiš igid b(ä)lgülüg yertinčüg ukıtur yertinčü yer suv ärmäz temäk üzä yertinčü tözin čın kertü ärmäzin ukıtur anın yertinčü yer suv tetir tep temäk üzä birikmäk yertinčüg tükäl bilgä bilig t(ä)ŋri t(ä)ŋrisi burhan yeläyü at üzä yertinčü ärür tep yarlıkamıš yörügüg ukıtur* "He preached like this again: "For whatever three thousand and great thousand worlds exist, the Tathāgata has taught that this is not one world. By speaking of three thousand and great thousand worlds, he illustrates the false world of signs resulting from the accumulation of atoms; by speaking of non-existence, he explains that the regions of the world, the true origin of the world, are not real and true. By saying, 'Therefore, this is a region of the world,' he conveys the explanation taught by the God of Gods, the wise Buddha."

When the Chinese and Old Uyghur texts are examined in general, it can be observed that the text describes that the external world is composed of a collection of atoms. In the Chinese text, the phrase 微塵衆 *weichen zhong* (Giles, 1912, pp. 1561&12586, 73&661, 363&2900) corresponds to the Old Uyghur expression *par(a)manular yıgını* "a heap of atoms or a collection of atoms," signifying the aggregation of an infinite number of particles. According to the Buddhist understanding in this text, the external world is indeed a heap of atoms, but this external world is illusory. In the Buddhist perspective, the external world is entirely an illusory realm. According to them, everything is like froth; consciousness perceives them, but consciousness is also like a magician's illusion. In short, everything is a mere illusion (Harvey, 2013, pp. 58-59). The text below is also from the Abhidharmakośa.

> ÜI.102a14-18: 一師云*bir bahšı sözlär kök kalık bir ärür bolmaz bölgäli adırtlagalı tep* 有部一師云*sarva-astivadni'kaylıg bir bahšı sözlär kök kalık uučsuz kıdıgsız ärür bir bir parmanuta 'äŋäyü bar kök kalık parmanu uučsuz kıdıgsız üčün anın kök kalık yme ök uučsuz kıdıgsız ärür tep* "A teacher has said, "The sky is one; it cannot be divided and distinguished." However, a teacher from the Sarvāstivāda school says, "The sky is boundless; there is sky specifically in each atom. Since the atom is boundless, the sky is also boundless."

> ÜI.102a18-102b9: *mundata ulatı alku bahšılarnıŋ sözlämiši muntag bälgülär üzä sözlär bo kök kalıkta alku nomlar yaruk yašuk ukulur üčün anın atamıš ol kök kalık tep* 疏主云 *ästiramate bahšı sözlär birök sözläsär sizlär kök kalık bir ärür bolmaz bölgäli adırtlagalı tep nätägin bolur sözlägäli alku nomlar anda tüzü yapa yaruk yašuk ukulur üčün tep birök sözläsär sizlär bir bir par(a)manuta 'äŋäyü bar kök kalık tep inčip nätägin parmanu ülüšindäki kök kalıkta alku nomlar yaruk yašuk ukulur anın bo iki bahšılarnıŋ kayu sözlämiš abipirayı üze adırtlıg otgurak bililmäti bo kök kalıknıŋ tözlüg tözsüz bolmaklıg yörügi* "With these and all the other teachers' signs "They say: 'This sky was called the sky because all the dharmas were clearly understood from this sky." Sthiramati Master says, "If you say, 'The sky is one; it cannot be divided and distinguished,' how can you then say, 'It is called the sky because all dharmas are perfectly understood in it?' If you say, 'There is sky/ether specifically in each atom,' in this case, how can all dharmas be distinctly understood in the sky within the atom?' Therefore, the statements of these two teachers did not convey the precise and clear meaning of whether this sky is substantial or insubstantial."

The *Abhidharmakośa* is primarily based on the *Sarvāstivāda* Abhidharma tradition. According to the *Abhidharmakośa*, atoms are the smallest particles. Buddhism, in addition to its theory of the structure of the universe, also presents ideas about elements and atoms. The *Abhidharmakośa*, dating back to the fifth century, discusses elements and atoms in a section titled "Analyzing the World (*dhātu*)." These Buddhist texts describe atoms as the "smallest, indivisible, indestructible, ungraspable part of matter." They are neither long nor short, neither square nor round. Atoms cannot be analyzed, seen, heard, or touched. Individually, *paramāṇus* cannot exist, but when many *paramāṇus* come together, they can occupy space and undergo change. Only when seven *paramāṇus* come together does a single aṇu, or molecule, form. These seven *paramāṇus* exist in seven directions: center, east, west, south, north, down, and up. Thus, increasingly larger particles are formed, eventually giving rise to the perceptible matter. This process occurs through the power of *adṛṣṭa*, the "unseen force." All matter is composed of the "four great elements": earth, water, fire, and wind. While *paramāṇus* make up the matter, the four great elements seem like energies. They are not the physical earth, water, fire, and wind that we see or feel, even though they occupy space. Energy, the four great elements, make up *paramāṇus*, and it is only when a large number of *paramāṇus* come together that they create earth, water, fire, air, or any existing substance. Each element has its own unique characteristics and functions.

The Earth is solid and provides support to objects; water is moist and can dissolve everything; fire is hot and can boil everything; and air is mobile and causes the growth of objects. Elements do not manifest in equal proportions in all types of substances. Some specific elements are found in abundance in one thing, while other elements are abundant in something else. Therefore, some substances are solid, some are flexible, some are moist, and some are hot. Another explanation is that in any substance, the four elements are evenly mixed, but only a particular element among them has the power to determine the characteristics of that substance (Sadakata, 1997, pp. 20-22; 185). While *Vaiśeṣikas* see the atom as indivisible, Buddhist thinkers claim it is divisible. Hence, a divisible atom must contain the ether. According to Buddhism, an indivisible entity, such as an atom, can never be logically established because atoms always permeate the ether. Ether spreads both outside and inside an atom. That is to say, atoms are composed of the parts penetrated by the ether and are not infinite. *Vaiśeṣikas*, on the other hand, talk about ether as an omnipresent substance. Therefore, since ether is a substance found everywhere, it must adhere both inside and outside an atom, and it is understood that there is nothing more than the inside and outside of the atom. Thus, it must be accepted that the atom has parts. If we do not accept the atom as having parts, then ether cannot exist (Sarkar, 2022, p. 91). If the existence of similar substances in the creation of the universe, the Earth, and humans is accepted, and their contents are examined, it will be understood that these substances are generally composed of elements.

Therefore, the essence of the entire universe, Earth, and humans is elements. Everything is produced from them, and elements exist without change, they are infinite, unobstructed, united, interpenetrating, and pervasive. The external world depends on the five elements: earth, water, fire, air, and ether (Snodgrass, 1985, p. 373). The following text is also an excerpt from an Abhidharma text.

> Abhidharma.3112-3123: 一师云*bir bahšı sözlär kök kalık bir ärür bolmaz bölgäli adırtlagalı tep* 有部一师云*sarvaasdivat nikaylıg bir bahšı sözlär kök kalık uučsuz kıdıgsız ärür bir bir parmanuta äŋäyü bar kök kalık parmanu uučsuz kıdıgsız üčün anın kök kalık ymä ök uučsuz kıdıgsız ärür tep mundata ulatı alku bahšılarnıŋ sözlämiši muntag bälgülär üzä sözlär bo kök kalıkta alku nomlar yaruk yašuk ukulur üčün anın adamıš ol kök kalık tep* 疏主云 *ästiramati bahšı sözlär birök sözläsär sizlär kök kalık bir ärür bolmaz bölgäli adırtlagalı tep nätägin bolur sözlägäli alku nomlar anta tüzü yapa yaruk yašuk ukulur üčün tep birök sözläsär sizlär bir bir parmanuta äŋäyü bar kök kalık tep inčip nätägin parmanu ülüšindäki kök kalıkta alku nomlar yaruk yašuk ukulur* "A teacher says, 'Space is one. It is impossible to separate them.' A master of the Sarvāstivāda nikāya says, 'Space/ether is limitless, boundless. There is individual space/ether in each atom. Since the atom is boundless, space is also limitless, and that's why all masters have preached it with this feature: (that is) the laws are explained in this space, that's why they named it 'Space.' If you say, as Master Sthiramati did, 'Space is one and indivisible,' can you also say, 'All the laws are written and clear there?' How can all the laws be explained in the space within the atom?"

The text provides an important expression that sheds light on us: *sarvaasdivat nikay* "Sarvāstivāda nikāya," which means the *Sarvāstivāda* community. Therefore, the views expressed in the text are related to the perspective of the *Sarvāstivāda* School, which suggests that just as the atom is infinite, space/sky/ether is also infinite. It is understood from Sarvāstivāda's division of seventy-five dharmas into five groups that *ākāśa*, i.e. space/sky/emptiness/ether, is included in *asaṃskṛta dharma*. *Asaṃskṛta* means "unconditioned." (Dhammjoti, 2015, p. 42). However, it is clear from the following fact of Sarvāstivādin that "emptiness" (虚空 *xukong*) refers to unconditioned *ākāśa*. The Ābhidharmikas sharply distinguish *ākāśa* from ākāśa-dhātu (空界 *kongjie*), which is *rūpa* in nature (Dhammjoti, 2015, p. 221). According to the *Vaiśeṣika* view, the four atomic substances, fire, air, water, and earth, are physical materials. The self, time, space, and ether are infinite and intermingle with all material objects. Ether and the four atomic substances, either alone or in various combinations, constitute the fundamental constituents of material things and serve as their causes.

Substances are further categorized as eternal and non-eternal, with atoms, ether, time, space, self, and mind being eternal, while composite entities are non-eternal (Keith, 121, p. 185). In the continued text of the Old Uyghur, there is a reference to *ästiramati bahšı* "Master Sthiramati," which is why the views of the Yogācāra School, to which Sthiramati is affiliated, regarding atoms and the external world should be considered. According to the Mahāyāna Buddhism-based *Yogācāra* School, an "external" object can never be experienced separately from its parts, so it cannot exist as a single whole. It also cannot be created from its parts because these parts can be further broken down into their components and ultimately into atoms. However, atoms are defined as imperceivable, and therefore, the coarse objects composed of these imperceivable atoms are also imperceivable. Moreover, atoms cannot exist. If atoms are defined as the smallest units of physical reality, they cannot partially combine with other atoms because that would imply that atoms have parts and thus, in theory, the potential to be further divided. If they combine fully with other atoms, no matter how many atoms come together, they would still occupy only the space of a single atom and therefore remain imperceptible. In this view, neither atoms nor their combinations can exist. If objects were to exist independently as separate realities from their parts, then the entire object could be perceived all at once. Therefore, the only way to explain the perception of objects is through the analogy of a dream (Williams, 2009, p. 95). The following text is a small excerpt from a commentary on the *Vajracchedikā Sūtra*, an important scripture in the Mahāyāna tradition.

> Taishō.2732.85.8a26-29: 界塵何一以/報應亦同然/非因亦非果/誰後復誰先/事中通一合/理則兩俱捐/欲達無生路/應當識本源。
>
> BT28.C.520-526: *yertinčüli kog kıčmıklı nägü birtä öŋi ol tüšinli tıltagınlı nägü ymä inčip bir täg ol ärmäz tıltag tegülük ärmäz ymä tüš tegülük kim ol keni yana ymä kim ol öngräsi yertinčülük savda biriktürmäklig bir täg ärürlär kertü tözkä tägdüktä ikigüni birgärü ketärürlär* "Why are the world and a speck of dust different from each other? Why is the cause not one with the effect? There is no cause, and there is no effect. Who comes after, and who comes first? In the affairs of the world, they are a whole. When one reaches the truth, they become one."

In the text above, 塵 *chen* means "dust, dirt; this world, evil" (Giles, 1912, p. 73&661), which is greeted with *kog kıčmık* "dust" in Old Uyghur. The term *kog kıčmık* here differs from the previous texts and refers to a larger entity or a speck of dust, which is the larger state of an atom. This is because Mahāyāna Buddhism explicitly rejects atomism. The *Mādhyamika* and *Yogācāra* schools, which are affiliated with Mahāyāna Buddhism, are opposed to the atomic matter theory (Majumdar, 2002, p. 66). The *Mādhyamika* School asserts that there is no such thing as matter or mind. Everything is empty, both the material world and the mental world are illusory. On the other hand, the Yogācāra School believes that only the mental world is real, while the material world is devoid of reality (Williams, 2009, 95; Sarkar, 2022, p. 57). In the above Old Uyghur text, it is emphasized that the world or the speck of dust, the cause or the result, the before or the after, in short, everything is indistinguishable from each other and that everything is essentially one. Kumarajiva, the author of the *Vajracchedikā Sūtra*, in line with the views of the *Mādhyamika* School, has put forward his ideas about the external world. According to this perspective, "since the object does not exist, consciousness does not exist." (Williams, 2009, p. 95). In addition, according to Mahāyāna Buddhism, everything in the external world is impermanent and subject to change. Everything in the external world has arisen as a result of various combinations. They are not self-existent but have arisen from the combination of other things (McGovern, 1919, p. 246). This approach is reminiscent of the story of King Milinda. King Milinda asked Nāgasena various questions about individuality, self, or the nature of the seen entity.

"If, most reverend Nāgasena, there be no permanent individuality involved in the matter, who is it, pray, who gives to you members of the Order your robes and food and lodging and necessaries for the sick? Who is it who enjoys such things when given? Who is it who lives a life of righteousness? Who is it who devotes himself to meditation? Who is it who attains to the goal of the Excellent Way, to the Nirvāna of Arahatship? And who is it who destroys living creatures? Who is it who takes what is not his own? Who is it who lives an evil life of worldly lusts, who speaks lies, who drinks strong drink, who (in a word) commits any one of the five sins which work out their bitter fruit even in this life? ...'

'Or is it the nails, the teeth, the skin, the flesh, the nerves, the bones, the marrow, the kidneys...?'

And to each of these he answered no." (Davids, 1890, pp. 41-44).

Here, Milinda's questions to Nāgasena continue, and it is argued that there can be nothing "on its own," leading the discussion in this story to the idea of emptiness or absolute nothingness. Additionally, the following text is an example from the Altun Yaruk Sudur.

Taishō.0665.16.0423a06: 所有過去一切佛/ 數同大地諸微塵/ 未來現在十方尊/ 亦如大地微塵衆。

AYS.9402-9407/AY5.350.6-11: *ärtmiš üḍki burhanlar „ yagız yerkä tayaklıg „ par(a)manular sanınča „ ken käligmä üḍki amtıkı „ onṭın sıŋarkı burhanlar „ y(ä)mä ök k(a)ltı yerdäki „ kog kıčmıklar kolusınča* "The past Buddhas are as many as there are very small particles on Earth, and the future and present Buddhas in the ten directions are as numerous as the dust particles on the ground."

The Old Uyghur expressions *par(a)manular* and *kog kıčmıklar* used here are also interpreted as Chinese 微塵 *weichen* "extremely small particles" (Giles, 1912, pp. 1561&12586, 73&661). The use of different Old Uyghur words for the same Chinese expression in different places in the text is interesting. It is also noteworthy that the concept of atoms or very small particles is employed to make inferences about the numbers of past, present, and future Buddhas. The example from the Altun Yaruk Sudur text is written in accordance with the philosophy of Mahāyāna Buddhism. In this context, it would be more accurate to describe the words *par(a)manu* and *kog kıčmık* as "tiny particles" or "dust particles" rather than "atoms." because there is no idea of atoms in Mahāyāna Buddhism, and the expression in the Chinese text is defined as 微塵 *weichen* "extremely small particles". Again, the text below is quoted from Altun Yaruk Sudur.

Taishō.0665.16.0410a27-28: 譬如虛空煙雲塵霧之所障蔽。若除屏已是空界淨非謂無空。

AYS.2777-2783/BT21.912-918: "*inčä kaltı bulıt toz tuman par(a)manular üzä köšiksiz tüz kök kalık ugušı nätäg arımıš süzülmiš ärsär ančulayu ok kök kalık ugušı artokrak arıg süzök bolur ol kök kalık ymä yok ärmäz bar tetir* "The space/ether element/void is pure, just as the entire space/ether element is cleansed (as) uncovered by clouds, dust, and fog particles. That space/ether does not exist; it exists."

The Old Uyghur term *par(a)manu* in this context is equivalent to the Chinese word 塵 *chen* "dust, dirt; this world, evil" (Giles, 1912, p. 73&661), and it is definitely not in the sense of "atom." Therefore, when analyzing terms in Old Uyghur texts, one should consider the sects and schools to which these texts are related and evaluate them accordingly.

Conclusion

The creation of the universe, the world, and humans has always been a subject of curiosity, leading many philosophers to develop significant theories on the matter. Ancient Greek and Indian philosophers made inferences regarding the existence or creation of the universe, the world, and especially matter, ultimately concluding that the smallest building block of matter is the "atom." The acceptance of atomic theory in the Islamic civilization coincided with the end of the 9th century. Kalāmists, who were probably influenced by the atomic theory of both Greek and Indian thinkers during this period, developed the theory. Besides, in Old Uyghur literary texts, which are predominantly based on translations or translations with original content, there are expressions related to atoms. These expressions include *par(a)manu* < TochA/B *paramāṇu* ~ *paramānu* < Skt. *paramāṇu*, which can be translated as "very fine, atom, dust," *ärtiŋü inčgä* meaning "very fine, very subtle, atom," *kog* for "atom, dust," and *kıčmık* for "atom, dust." When examining Old Uyghur texts, it becomes evident that in addition to the views of the Vaiśeṣika School on atoms, there are also references to the beliefs of the Sarvāstivāda-Vaibhāṣika School, which originated from the Abhidharma tradition of the Hīnayāna sect. The Old Uyghur words related to atoms can be found not only in the works that present the above-mentioned views but also in the Mahāyāna Buddhist texts that entirely reject atoms, such as the *Altun Yaruk Sudur* and *Vajracchedikā Sūtra*. In texts that accept atomism, these words are interpreted as "atoms," while in texts that reject atomism, they are interpreted as "dust" or "very small particles." In that case, the words used in Old Uyghur should be interpreted according to the views of the ancient Indian religious and cultural schools. Additionally, the importance of Chinese in interpreting these words should not be overlooked, and textual comparisons must be made. When comparing Chinese texts with Old Uyghur texts in this study, it is observed that different words related to atoms are used. Furthermore, despite originating from translated texts in Old Uyghur, there is information and terminology related to atomic theory, which is of great value from the perspective of the history of science. Finally, the atomic theory in Old Uyghur corresponds to Indian thought, originating from translated texts.

References

Aydın, İ. H. (2002). Kenz-i Mahfî. *Türkiye diyanet vakfı İslâm ansiklopedisi, 25. Cilt*, 258-259. Aclûnî

Barutçu, F. S. (1998). *Sthiramati'nin Vasubandhu'nun Abhidharmā kośa koşavardi şastirtakı çınkirtü yöröglerniñ kingürüsi'nden üç itigsizler, giriş-metin-tercüme-notlar-indeks, XXX. levha*. Türk Dil Kurumu Yayınları. (Üİ)

Chakrabarty, D. (1973). *Vaiśeṣika-sūtra of Kaṇāda*. D.K. Printworld.

Davids, T. W. R. (1890). *The questions of king Milinda*. Dalton House.

Dhammajoti, K. L. (2015). *Sarvāstivāda Abhidharma*. Published in Hong Kong by The Buddha-Dharma Centre of Hong Kong.

Dhanani, A. (1994). *The physical theory of kalām, atoms, space, and void in Basrian muʿtazilī comology*. E.J. Brill.

Elkaisy-Friemuth, M. (2017). *God and Humans in Islamic Thought,* 'Abd al-Jabbār, Ibn Sīnā and al-Ghazālī. Rutledge.

Elmalı, M. (2022). *Daśakarmapathâvadânamâlâ: on günahın zincirleme hikâyesi*. TDK Yayınları. (DKPAM)

Elmalı, M. (2022). *Eski Uygurca dil bilgisi terimleri: vvibakti samaz*. TDK Yayınları. (VS)

Emmerick R. E. (2016). The Sutra of Golden Light: A Translation of the Suvarnabhasottamasutra (1st ed.).Motilal Banarsidass.

Gangopadhyaya, M. (1980). *Indian atomism: history and sources*. K.P. Bagchi & Company.

Giles, H. A. (1912). *A Chinese-English dictionary* [2nd ed.]. Revised & Enlarged.

Kaya, C. (2021). *Uygurca altun yaruk, giriş, metin ve dizin*. Türk Dil Kurumu Yayınları. (AYS)

Keith, A. B. (1921). *Indian logic and atomism, an exposition on the nyaya and vaiçeṣika systems*. Clarendon Press.

Kur'an-ı Kerim. Türkiye Diyanet Vakfı Yayınları.

Majumdar, P.Kr. (2002). The Bauddha atomism. *《佛學與科學》3卷2期*. 65-67.

Majumdar, A. (2002). *Buddhist cosmology: philosophy and origins*. (Translated by Gaynor Sekimori). Kosei Publishing Co.

Mano, Ryūkai (1970). On the "three jñatās". *IBK 18* (2). 1042-1036 (21-27).

McGovern, Wm. M. (1919). Notes on mahayana buddhism. *The Monist*, Vol. 29, No. 2, 238-258.

Pullman, B. (2001). *The atom in the history of human thought*. (Translated by Axel Reisinger). Oxford University Press.

Ronan, C. A. (2003). *Bilim tarihi: dünya kültürlerinde bilimin tarihi ve gelişmesi*. (Translated by Ekmeleddin İhsanoğlu and Feza Günergun). Tübitak Yayınları.

Röhrborn, K. (1996). *Die alttürkische Xuanzang-biographie VIII*. nach der handschriftvon Paris, Peking und St. Petersburg sowie nach dem trankript von Annemarie v. Gabain, Harrassowitz Verlag Wiesbaden. (HT8)

Sangpo, L. & de La Vallée Poussin, L. (2012). *Abhidharmakośa-Bhāṣya of Vasubandhu: the treasury of the abhidharma and its (auto) oommentary, 1. Volume*. Motilal Banarsidass Publishers.

Sarkar, D. (2022). *Atamist from Indian and Greek perspective: a critical study*. (Unpublished Ph.D. dissertation), Raiganj University.

Shōgaito, M. (2008). ウイグル文 アビダルマ論書の文獻學的研究 *(Uyghur abhidharma texts: a philological study)*. Nakanishi Printing Co., Ltd. Kyotu Japan. (Abhidharma)

Sime, R. L. (1998). Lise meitner and the discovery of nuclear fission. *Scientific American*, Vol. 278, No. 1, 80-85.

Skilling, P. (2000). Vasubandhu and the vyākhyāyukti literature. *Journal of the International Association of Buddhist Studies*, Volume 23, Number 2, 297-350.

Snodgrass, A. (1985). *The symbolism of the stopa*. Seap.

Stace, W.T. (1920). *A critical history of Greek philosophy*. Macmillan and Co.

Taishō (1924-1935). 大正新脩大藏經 Taishō, shinshū daizōkyō. (prepared for publication: 高楠 順次 郎 Takakusu Junjirō, Watanabe Kaigyoku), Tōkyō.

The Holy Bible, Nashville, Tennessee: Holman Bible Publishers.

Uçar, E. (2009). *Altun yaruk sudur V. kitap Berlin koleksiyonundaki fragmanların transliterasyonu ve transkiripsiyonu açıklamalar ve dizin*. (Unpublished Ph.D. dissertation), Ege Üniversity Social Sciences Institute. (AY5)

Wilkens, J. (2001). *Die drei körper des buddha (trikāya) das dritte kapitel der uigurischen fassung des goldglanz-sūtras (Altun Yaruk Sudur)*. Brepols Publishers. (BT21)

Wilkens, J. (2016a). Buddhism in the West Uyghur Kingdom and Beyond. in: Transfer of Buddhism Across Central Asian Networks (7th to 13th Centuries) (ed.: Carmen Meinert). Brill.

Wilkens, J. (2016b). *Buddhistische erzählungen aus dem alten zentralasien edition der altuigurischen daśakarmapathāvadānamālā (3 volume)*. Brepols Publishers. (BT37)

Wilkens, J. (2021). *Handwörterbuch des altuigurischen: altuigurisch – Deutsch –Türkisch (eski Uygurcanın el sözlüğü: eski Uygurca – Almanca – Türkçe)*, Akademie der Wissenschaften zu Göttingen, erschienen im Universitätsverlag Göttingen.

Williams, P. (2009). *Mahāyāna buddhism: the doctrinal foundations* [2nd ed.]. Routledge, Taylor & Francis Group.

Yakup, A. (2011). *Prajñāpāramitā literature in old uyghur*. Brepols Publishers. (BT28)

Internet address:

DDB: 體 | body (buddhism-dict.net) [date of access: 10.10.2023]

About Author

Prof. Dr. Hacer TOKYÜREK | Erciyes University | htokyurek[at]hotmail.comORCID: 0000-0002-0008-1213

After completing her master's degree at Erciyes University, Institute of Social Sciences, Department of Old Turkish Language Science, in 2005, the researcher received her doctorate from the relevant department of the same university in 2011. Tokyürek, who worked as an assistant professor at Nevşehir Hacı Bektaş Veli University between 2011 and 2015, started working at Erciyes University in 2015. She became an associate professor in 2016 and then served as a guest lecturer at Shanghai International Studies University, China, between 2016 and 2018. The researcher, who returned to Türkiye in 2018, continued his duty at Erciyes University and was deemed worthy of the TÜBA GEBİP (Turkish Academy of Sciences-Outstanding Young Scientists Awards) award in 2019. She was appointed to the position of professor in 2021. Tokyürek's fields of study are on Old Turkic, Old Uyghur, Buddhism and Manichaeism. She is currently running a Tübitak 1001 project and an Adep project.

MAKING NANOFABRICATION GREENER: HARNESSING THE POWER OF BOTTOM-UP METHODOLOGIES

Alberto Alvarez-Fernandez

10.53478/TUBA.978-625-6110-22-9.ch11

Making Nanofabrication Greener: Harnessing the Power of Bottom-up Methodologies

Alberto Alvarez-Fernandez
Centro de Física de Materiales

Abstract

The interest in nanostructured materials is expanding across many fields of research and technology due to their unique properties, including high surface area, versatile chemical functionalization, and distinct magnetic, electrical, optical, and catalytic characteristics compared to their bulk counterparts. As a result, nanostructured materials find utility in a wide range of fields, including sensing, medicine, and energy storage. However, the fabrication of these nanostructures presents challenges that intersect with the goals of sustainable development. Thus, traditional nanofabrication techniques, often involve hazardous chemicals, high energy consumption, and generate significant waste. Additionally, their scalability is often limited. Addressing these challenges requires the development of greener fabrication processes that minimize environmental harm and energy usage, as well as the integration of sustainable practices throughout the entire lifecycle of nanostructured materials. In this regard, bottom-up approaches, and in particular colloids, biomolecules, and block copolymers, offer promising solutions. These versatile materials can self-assemble into precise nanostructures with minimal energy input, reducing environmental impact. Finally, innovations involving to the usage of bio-based building blocks have put the focus not only on addressing the environmental footprint of nanostructure fabrication but also on promoting the use of renewable resources and enhancing their recycling.

Keywords
Nanofabrication, Bottom-up, Block copolymers, Bio-molecules, Bio-based,

Introduction

Nanoscience, a long history short

Nanomaterials are materials characterized by dimensions within the nanoscale range, typically between 1 and 100 nm in any external dimension, internal structure, or surface feature (ISO n.d.) While nanomaterials and nanotechnology are often perceived as contemporary terms associated with cutting-edge science, it is important to recognize that the synthesis and applications of such materials data back to ancient times. Even though the precise history of the use of nanosized objects by humanity is difficult to elucidate, early examples, such as the use of asbestos nanofibers or carbon nanotubes to reinforce ceramic mixtures, as well as the employment of metallic nanoparticles to create colour effects on pottery or glass surfaces, trace back as far as the thirteenth or fourteenth century A.D. (Caiger-Smith, 1985) In this sense, one of the most renowned examples of the usage of nanomaterials in early times is the Lycurgus Cup, crafted by the Romans in the fourth century A.D. (Heiligtag & Niederberger, 2013) This dichroic cup presents a jade-like appearance under direct light, transitioning into a translucent red colour when light passes through it, showcasing also colour variations depending on incident light angles. During the modern age, painters, artists, and artisans were continuing employing these materials without knowing the cause of these surprising effects (Heiligtag & Niederberger, 2013).

The modern concept of nanotechnology and the study of the unique properties that derive from them was introduced by the American physicist and Nobel Prize Richard Feynman in 1959 during his lecture entitled "There's Plenty of Room at the Bottom" at the California Institute of Technology (Caltech), in which he described the possibility of directly manipulate individual atoms as a design tool more powerful than conventional chemistry. Two more events remain as stepping stones in the progress of nanoscience, one is the invention of scanning tunnelling and atomic force microscopies in the 1980s, (Anderson et al., 1982; Binnig & Rohrer, 1983)and the other is the development of powerful lithographic tools started in the 1980s-1990s. (Lawson & Robinson, 2016) While the first one allowed for the first time not only to observe but also to manipulate surfaces at the atomic scale, the introduction of lithographic approaches allowed the creation of ordered and controllable structures at the nanoscale over large surface areas. Since then, researchers have directed their efforts toward refining fabrication methodologies for greater efficiency and precision, alongside investigating the distinctive optical, mechanical, electrical, magnetic, and chemical properties arising from the resulting nanostructures.

The several nanofabrication technologies developed during the last decades for the production of structures with sub-100 nm dimensions can be broadly categorized into two groups depending on the direction of structure creation: top-down and bottom-up approaches. In the following section, more details about both approaches will be provided, with a special focus on their advantages and limitations in terms of their sustainability and environmental impact.

Top-down: lights and shadows

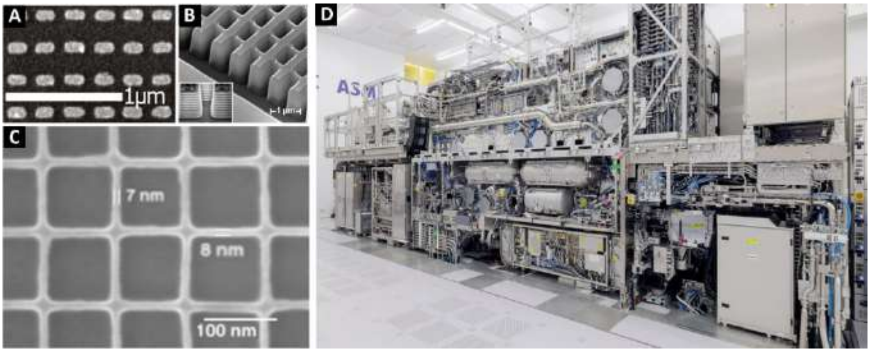
Top-down approaches can be likened to sculpting from a block of stone to obtain the desired shape. In these methodologies, external experimental parameters such as light, electrons, ions, or mechanical forces, among others, are typically employed to pattern materials and create nanostructures through the selective etching or partial removal of material. As previously highlighted, lithography stands as one of the most crucial top-down methodologies in nanofabrication. Lithographic-based techniques involve transferring a pattern from a mask or template onto a substrate through selective exposure to radiation, typically light or electrons. Widely adopted in the semiconductor industry, techniques such as optical lithography, electron-beam lithography, and X-ray lithography enable the fabrication of integrated circuits and intricately defined nanostructures with exceptional precision (see Figure 1A). Another category within lithographic techniques involves scanning probe methods. In this approach, a sharp tip is directly employed to pattern substrates at the nanoscale using techniques like scanning tunnelling microscopy (STM) and atomic force microscopy (AFM). These methods enable the precise manipulation of atoms or molecules, facilitating the creation of highly controllable and adjustable nanostructures. Also part of the lithographic techniques family is nanoimprinting lithography (NIL), which involves pressing a template with predefined patterns into a deformable material, such as a polymer resist, and the subsequent transfer of the pattern. It has attracted growing interest in recent years due to its cost-effectiveness compared to other lithographic methods and its capability for facilitating large-scale pattern creation. Alternative top-down methodologies such as chemical or dry etching have also been successfully applied in the preparation of materials at the nanoscale. The selective removal using chemical reactive solutions (chemical etching) or plasma (dry etching) enables the fabrication of high-precision patterns and features over large surface areas (around cm^2) by the usage of a mask and the etching of the exposed material.

Even though top-down methodologies have historically been pivotal in nanofabrication, various concerns regarding their environmental impact, economic costs, and technical constraints have impeded their further advancement and widespread application across many research fields and industries. Technical restrictions are related to material compatibility, restricting the range of materials that can be used for nanomaterials fabrication, and resolution limitations. Thus, constraints inherent to the top-down fabrication approach such as the diffraction limit, lateral spread during the patterning process, or imperfection at the mask used, have limited the obtention of ultra-small (sub-10 nm scale) using standard top-down fabrication methodologies. These technical problems have been partially solved with the introduction of more complex technologies such as Extreme Ultraviolet Lithography (EUV) but the adoption of these new methodologies has exacerbated the concerns about their environmental and economic impact. Thus, the cost of one of the most advanced EUV machines, fabricated by the Dutch company ASML can be over $380 million (ExtremeTech, 2024). This new machine focused on high numerical-aperture (high-NA) EUV, allows the fabrication of complex nanopatterns down to 4-8 nm. However, the associated high cost, together with the complex technologies involved during the manufacturing and subsequent fabrication process make this technology not accessible to the majority of industries. In addition to this, access to these technologies has been recently used as a weapon in the economic conflict between the USA and China.

In terms of sustainability (the focus of this work) concerns are common to all the top-down approaches such as high energy consumption or waste generation. Thus, the high complexity of the required setups, which often include powering motors, heating and cooling elements, vacuum pumps, light, x-ray, electron sources, and other components, makes the top-down-based fabrication methodologies energy-intensive. Thus, the energy consumption of a standard EUV machine is estimated at around several tens of megawatts during typical operation, ASML Annual Report (2020) which could be roughly equivalent to the annual energy usage of approximately 2.000 average households in Europe. Another important factor that needs to be considered is also the water consumption of these machines. Top-down methodologies often require cooling systems for the refrigeration of various equipment, including lasers, vacuum pumps, or processing chambers. Thus, for example, cooling water flow for standard immersion double-patterning optical lithography is estimated at 75 L/min which means 39.5 million water litters per year are needed for the correct operation of the machine. With the increase in the complexity of the techniques and required setups, water consumption grows exponentially. Standard EUV machines need around 1600 L of water per minute only to refrigerate all their components ASML Annual Report (2020).

Figure 1.

Scanning Electron Microscopy (SEM) images of different nanostructures recently proposed in the literature fabricated by top-down techniques ***(A-C).*** *Reprinted with permission.(X. Li & Gilchrist, 2016a) Copyright 2016 American Chemical Society. Setup of the high-NA EUV equipment of ASML* ***(D)***



The increase in the complexity of the required machines has also another collateral impact: the weight of the top-down setups is also growing. While a standard optical photolithography system had an average weight of a few hundred kilograms, a typical EUV tool weighs around 180 tons (Figure 1B). With the assembly sites placed often far away from the industrial facilities where the top-dawn machines are going to be used, their transportation has a big impact in terms of CO_2 emissions. To put it in context, according to the International Maritime Organization (IMO), the average emissions from maritime shipping are approximately 13 grams of CO_2 per ton-kilometre (gCO2/ton-km). (*Third IMO GHG Study 2014*, n.d.) Extrapolating these numbers, the transportation of a standard EUV machine with a weight of around 180 tons from Rotterdam (Netherlands) to Shanghai (China), covering roughly 22,000 kilometres, would result in emitting approximately 52 tons of CO_2, equivalent to the annual CO_2 absorption of approximately 2,300 to 2,360 mature trees.

In addition to their energy and water consumption, and related shipping costs, another significant concern regarding the ecological impact of top-down fabrication approaches is their substantial waste production. One of the most significant portions of the generated waste is related to their water consumption, i.e., water used for cleaning, cooling, or even at some chemical processing can be contaminated with chemicals or particles and therefore requires treatment before disposal to avoid environmental harm. Additionally, chemical processes used in top-down fabrication, such as wet etching or photoresist development, generate waste solutions which often contain hazardous or toxic chemicals. Finally, as highlighted in this section, the ongoing advancement and evolution of top-down methodologies underscore the importance of managing end-of-life considerations for fabrication equipment and components. Over time, these components may reach the end of their lifecycle, contributing to electronic waste (e-waste).

For all these reasons intensive research has been developed in the last decades to explore alternative fabrication approaches that allow more sustainable and environmentally friendly nanofabrication methodologies. It is within this context that bottom-up fabrication approaches emerge as a contrasting counterpart to traditional top-down methodologies. In the following section, they will be introduced and their advantages and disadvantages discussed.

Bottom-up: the revolution of the small things

Bottom-up nanofabrication refers to the process of building structures or materials from the bottom or atomic/molecular level up. Contrary to previously mentioned top-down methodologies, here atoms, molecules, or nanoparticles are manipulated and arranged to construct the desired nanostructures or nanomaterials. One of the main advantages of these approaches is their scalability since they do not suffer from the limitations previously mentioned such as the diffraction limit or lateral spread during the patterning process. Moreover, they do not normally require big infrastructures or restrictive environments, making nanofabrication and nanoscience potentially available for many industrial applications and research environments. The main bottom-up methodologies are focused on the usage of colloidal or polymeric species that spontaneously arrange themselves into the desired structure under the right conditions, such as the nature of the solvent, the chemistry of the substrate surface, or the interactions between the molecules or particles used as building blocks. The following sections will be focused on the key bottom-up approaches, highlighting the diverse nanostructures achievable through each technique.

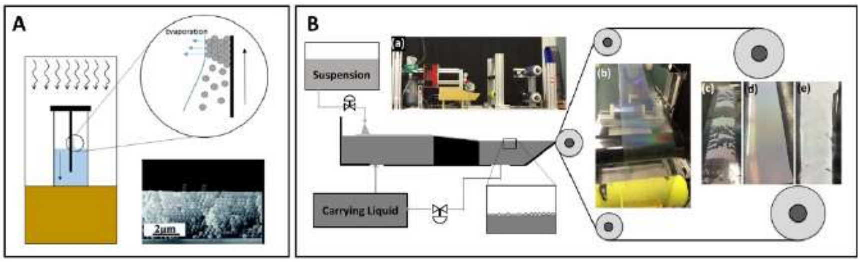
Colloidal self-assembly

Self-assembly of colloidal particles has proven to be an inexpensive method to fabricate nanometric structures, from monolayers to 3D nanomaterials with a wide variety of possible shapes (Galisteo-Lõpez et al., 2011; S. H. Kim et al., 2010, 2011). 3D structures have been mainly produced using the so-called evaporation-induce colloidal self-assembly by vertical, or convective deposition method(Dimitrov & Nagayama, 1996; Jiang et al., 1999). This technique relies on capillary forces to organise colloids during the evaporation of a liquid (Figure 2A), leading to the crystallization of spheres into a multilayered three-dimensional FCC lattice (Kralchevsky & Nagayama, 1994). Colloidal crystals, inverse opals and photonic glasses have been developed using this technique (Bian et al., 2018; Finlayson & Baumberg, 2013; Mishchenko et al., 2012; Wong et al., 2003). Thereby, using this approach, Xiao et al. have recently shown the versatility of bio-inspiring artificial opals, composed of colloidal dielectric spheres, to present specific structural colour responses by tuning the thickness and concentration of the assembled particles (Xiao et al., 2015).

One of the main limitations of colloidal assembly is the difficulty of obtaining larger nanostructured surface areas. To address this, colloidal assembly is frequently complemented by other conventional deposition techniques, including drop-casting,(Hoang et al., 2015) spin-coating, (Brasse et al., 2018; Müller et al., 2014) and Langmuir-Blodgett deposition.(König et al., 2014; Volk et al., 2015) In this sense, Li and coworkers have presented an automated Langmuir–Blodgett deposition design that allows continuous roll-to-roll deposition of particles into well-ordered arrays (Figure 2B) (X. Li & Gilchrist, 2016b). Other limitations inherent to the colloidal assembly are for example the obtention of nanostructures with a high number of defects, due to the spontaneous nature of the assembly. This can be important for applications where long-range order is required such as the microelectronics industry, however, it may be less critical for other high-end applications like optics or sensing, where the emphasis lies more on specific functionalities rather than perfect structural regularity.

Figure 2.

Self-assembly of multi-layer colloidal arrays through the vertical deposition technique and SEM image of the cross-section of SiO2 NPs ***(A).*** *Schematic illustration of experiment setup using an automated Langmuir–Blodgett* ***(B)*** *Reprinted with permission (X. Li & Gilchrist, 2016a). Copyright 2016 American Chemical Society.*



From the environmental perspective, colloidal self-assembly overpasses many of the concerns specified for the top-down methodologies. Thus, since colloidal self-assembly techniques rely on processes driven by thermodynamic or kinetic principles, they typically require minimal energy input compared to the high energy consumption associated with top-down approaches discussed previously. Additionally, concerns regarding the quantity and toxicity of generated waste, as well as water consumption, can often be minimized through the application of colloidal self-assembly techniques. This makes colloidal self-assembly a potentially more environmentally friendly option for nanostructure fabrication.

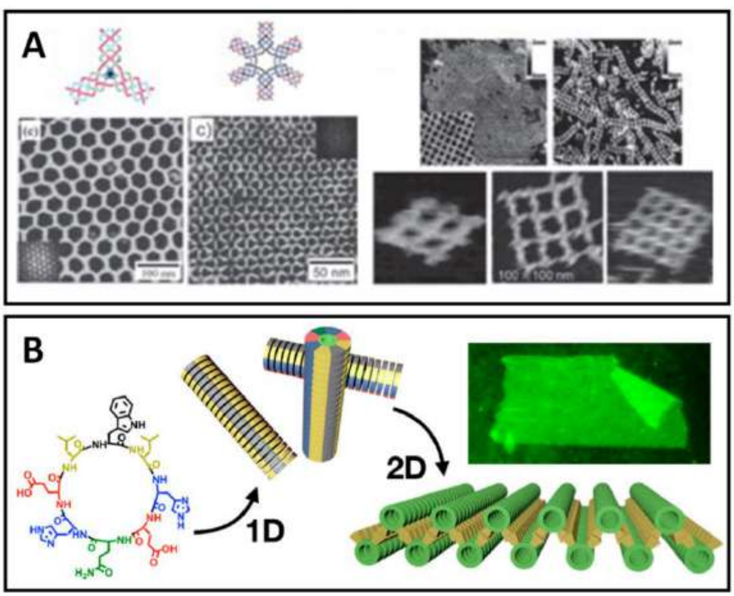
However, several limitations remain unsolved. Even if the colloidal self-assembly process itself does not generate large quantities of hazardous waste, this technique requires the previous synthesis of the colloidal objects. This synthesis normally involves the usage of toxic or hazardous chemicals, which have negative environmental impacts if they are not treated correctly. Additionally, synthesizing monodisperse colloids with uniform size and shape can be challenging, especially for non-spherical or complex structures. Related to this, some of the colloidal synthesis methods presented in the literature are well-suited for lab-scale quantities but may face challenges when scaled up for industrial production. For these reasons, researchers have focused on the development of new bottom-up technologies that involve less hazardous and complex synthetic steps. This strategic shift aims not only to mitigate environmental impacts but also to enhance the applicability of these methodologies.

Biomolecules assembly

Biomolecule-based self-assembly has emerged as a powerful strategy for fabricating nanostructures with precise control over size, shape, and functionality (L. Wang et al., 2019). One of the most prominent biomolecules used for self-assembly is DNA (H. Li et al., 2009). Through techniques such as DNA origami and DNA nanotubes, researchers can program DNA molecules to fold into complex nanostructures with predictable base-pairing interactions (Figure 3A) (Agarwal et al., 2021; He et al., 2005, 2006; Lund et al., 2005). Other biomolecules such as proteins or peptides also offer possibilities for nanofabrication. Thus, while the folding patterns of the proteins have been exploited in the creation of functional nanostructures (Solomonov et al., 2024), the self-assembly of peptides via non-covalent interactions has allowed the creation of structures such as nanofibers, nanotubes, and nanoparticles (Figure 3B) (Levin et al., 2020). Finally, other biomolecules such as lipids and polysaccharides, have been also used in the fabrication of nanostructures such as liposomes, lipid bilayers, or nanofibers respectively (Fan et al., 2021; Mahler et al., 2021).

Figure 3.

Examples of 2D structures fabricated using DNA ***(A).*** *Adapted with permission.(He et al., 2005, 2006; Lund et al., 2005) Copyright 2005-2006 American Chemical Society. Sequential 1D-to-2D self-assembly of cyclic peptides* ***(B)*** *Reprinted with permission.(Insua & Montenegro, 2020) Copyright 2020 American Chemical Society*



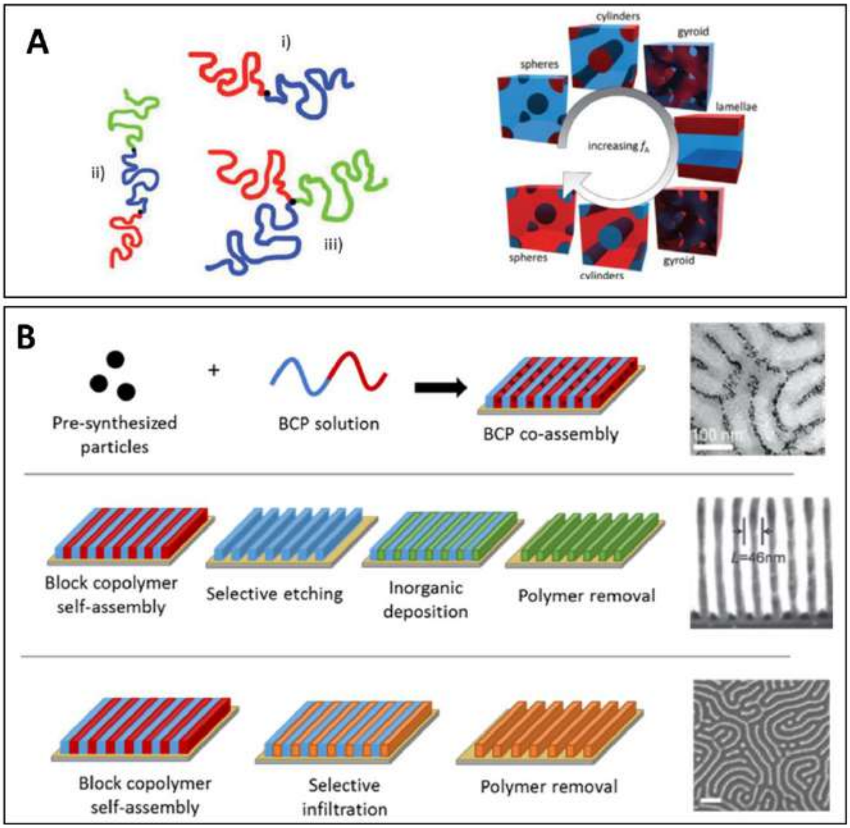
From the environmental point of view, the self-assembly of biomolecules offers a more sustainable approach when compared not only with top-down but also with bottom-up alternative fabrication methods. Thus, by the usage of renewable biomaterials as building blocks, such as proteins, peptides, and DNA, biomolecules self-assembly offers a powerful environmentally friendly fabrication alternative to previously introduced manufacturing methods that rely on non-renewable resources and often lead to the generation of harmful by-products. Moreover, the natural character of the biomolecules makes the generated nanomaterials biodegradable, which can significantly reduce waste accumulation and improve the sustainability of nanoscience. However, despite the remarkable progress in biomolecule-based self-assembly, several challenges remain. These include achieving scalable production methods, ensuring reproducibility of nanostructures, and understanding the interactions between biomolecules and their environments, making necessary the search for new bottom-up nanofabrication methods.

Block copolymers

A block copolymer (BCP) is a macromolecule composed of two or more chemically incompatible polymer segments, known as blocks, which are covalently bonded together. Depending on the arrangement of these blocks, different macromolecular architectures can be formed, including diblock, triblock, star, or graft copolymers (Figure 4A). The self-assembly of these macromolecules gives rise to a diverse range of nanostructured materials over large surface areas. Therefore, BCP self-assembly solves some of the problems previously mentioned for the other bottom-up fabrication technologies focused on their reproducibility, the possibility of obtaining complex nanostructures and scaling up the fabrication process among others.

Figure 4.

*Schematics of the different strategies followed to create inorganic architectures using BCP films as a template: **(A)** BCP co-assembly, **(B)** selective infiltration, and **(C)** Inorganic deposition. Reproduced with permission (Alvarez-Fernandez et al., 2019; Alvarez-Fernandez et al., 2021; Hong et al., 2010; Q. Li et al., 2008). Copyright 2008, 2021 Wiley-VCH; 2019 Royal Society of Chemistry; and 2009 American Chemical Society.*



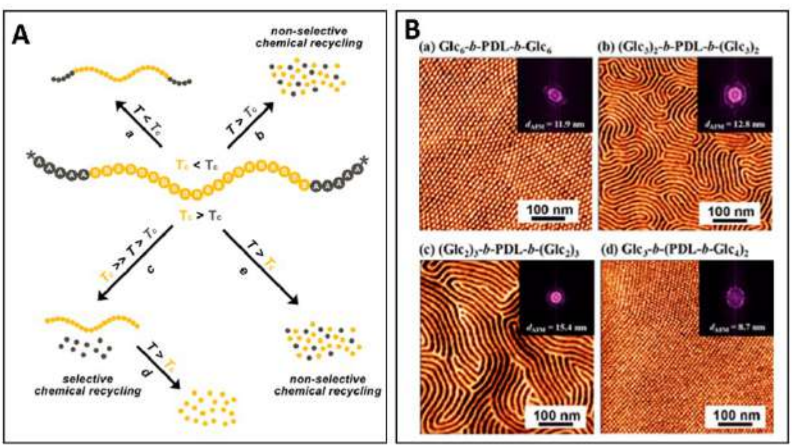
As previously mentioned, the chemical incompatibility between the BCP blocks triggers the formation of microphase-separated structures, offering a versatile platform for thin-film applications. Thus, by precise control over the molecular architecture of the blocks, BCP thin films can adopt various geometries such as spherical, cylindrical, gyroidal, and lamellar configurations with feature sizes and periods typically ranging from 10 to 50 nm. These geometries are largely based on parameters such as the volume fractions of each block (f), the number of repeating units (N), the interaction parameter between the repeating units, referred to as the Flory–Huggins parameter (χ), as well as the thin film process conditions (i.e., thickness and annealing) (Bates & Fredrickson, 1999; Feng et al., 2017; B. H. Kim et al., 2013), While BCPs predominantly consist of organic-based blocks, selective modification of individual blocks allows for the creation of inorganic nanofeatures through techniques such as sequential infiltration synthesis (SIS), aqueous metal reduction (AMR), electrochemical deposition or via the introduction of inorganic nanoparticles into the BCP domains (Figure 4B). Following these methodologies highly ordered and tuneable inorganic replicas have been created, with important applications in optics (Alvarez-Fernandez et al., 2021; X. Wang et al., 2017), energy (C. Li et al., 2020) or sensing (Chung et al., 2011; Suthar et al., 2023), among others.

From an environmental point of view, the impact of the synthesis and usage of block copolymers depends on various factors such as their production methods, chemical composition, or end-of-life disposal. Thus, the synthesis of the most common block copolymers used until now, such as poly(styrene)-block-poly(vinyl pyridine) (PS-b-PVP); poly(styrene)-block-poly(methyl methacrylate) (PS-b-PMMA); poly(styrene)-block-poly(ethylene oxide) (PS-b-PEO) involves the use of petrochemical-derived monomers, making the overall process of fabrication and obtention of the monomers resource intensive and non-renewable. Additionally, block copolymers obtained using these types of monomers are normally not biodegradable, contributing to plastic pollution and ecosystem disruption if waste is not correctly managed.

In response, researchers have developed different methods to reduce the synthetic effort necessary for the obtention of block copolymers with different macromolecular characteristics (e.g., molecular weight, obtained morphology). Thus, methodologies such as supramolecular assembly (Álvarez-Fernández et al., 2018; Alvarez-Fernandez et al., 2019; Reid et al., 2019; Sarkar et al., 2019), solvent vapour annealing, (Alvarez-Fernandez et al., 2022) or size exclusion chromatography (Alvarez-Fernandez et al., 2020; Park et al., 2002), have allowed the fabrication of tuneable nanostructures without the necessity of synthesising a specific block copolymer for each application. Even if following these methodologies, the environmental impact of the usage of block copolymers can be reduced, concerns related to waste production, the non-renewable nature of the monomer production, and the non-biodegradable characteristics of the synthesised block copolymers are still hindering the adoption of block copolymers in industrial environments. Two different strategies focused on two different aspects of the problem have been recently introduced to overcome these challenges. The first one is related to the possibility of recycling and reusing the block copolymers, while the second one verse around the usage of natural molecules as monomers for the synthesis of bio-based block copolymers.

From the perspective of the recycling of block copolymers, researchers have been focused on the design of novel polymers that enable chemical recycling to monomer (CRM) or chemical recycling via upcycling methodologies. In this objective, polymers produced through innovative research approaches such as ring-opening polymerization (ROP) are highly promising due to the equilibrium nature of this polymerization method. This characteristic offers an inherent pathway for recycling through reverse ring-closing depolymerization (Figure 5A) (Cederholm et al., 2023). Other strategies rely for example on the Selective Solvent Extraction strategy.(Y. B. Zhao et al., 2018) This methodology consists of the usage of a solvent that selectively dissolves one block while leaving the other intact. This allows for separation and subsequent recycling of the individual polymer blocks. Parallel to this stands the employ of chemical methods e.g.; amido- or alcohol-lysis or thermal and catalytic methodologies for the cleavage of the polymeric chains at specific sites or bonds, enabling the recovery of the original monomers or shorter polymer segments (oligomers) (Si et al., 2023; Y. Zhao et al., 2023).

Figure 5.
(A) *Chemical recycling via reverse ring-closing depolymerization of an A–B–A block copolymer and how the available recycling scenarios depend on the relationship between the* T_c *of monomer A (grey solid circle) and monomer B (yellow solid circle).* ***(B)*** *AFM phase images of several self-assembled carbohydrates bio-based BCP. Reproduced with permission. (Cederholm et al., 2023; Isono et al., 2020) Copyright 2023 The authors; and 2020 American Chemical Society.*



On the other hand, researchers have also focused on the development of bio-based block copolymers, enabling greener synthetic procedures and avoiding the necessity of petrochemical-derived monomers (Gandini & Lacerda, 2015). One interesting example is the fabrication of the poly(3-hydroxybutyrate)-block-poly(ethylene glycol) (PHB-b-PEG). In this case, the PHB block can be produced by bacteria (such as *Pseudohalocynthiibacter aestuariivivens* P96) from renewable carbon sources (Bonartsev et al., 2013; Esposito et al., 2023; Rai et al., 2011). PHB-b-PEG copolymers have potential applications in drug delivery, tissue engineering, and wound healing due to their biocompatibility and controlled release properties (Bonartsev et al., 2013). Another interesting type of bio BCP, and with important implications in the fabrication of nanostructured surfaces is carbohydrates-based BCP. Thus, for example, maltooligosaccharides such as maltose, maltotriose, maltotetraose, or maltohexaose, and other blocks like poly(δ-decanolactone) have been successfully synthesised and employed in the fabrication of highly ordered and defined nanostructures, with similar results than standard petrochemical-derived BCP like PS-b-PMMA or PS-b-PVP (Figure 5B) (Isono et al., 2020). As previously introduced, the thrive for miniaturization in the microelectronic industry has promoted the search for advanced techniques that allow for a decrease in the feature size obtained. In this objective, bio-based BCP has shown important application with systems achieving sub-10 nm dimensions while keeping a high long-range order and homogeneity (Isono et al., 2013; Otsuka et al., 2012).

Conclusions

The future of nanoscience holds tremendous promise with the advancement of bottom-up nanofabrication methodologies, offering greener and more sustainable approaches to material synthesis and device fabrication. By harnessing the principles of self-assembly and molecular manipulation, we have seen here how bottom-up techniques enable precise control over the design and assembly of nanoscale structures, with minimal material waste and environmental impact. One key aspect of bottom-up nanofabrication is the utilization of bio-inspired and bio-derived materials, such as DNA, proteins, and biopolymers. These materials not only offer inherent biocompatibility but also provide renewable and sustainable alternatives to traditional synthetic polymers and inorganic materials. By mimicking nature's ability to assemble complex structures from simple building blocks, bottom-up approaches can facilitate the development of novel, greener, cheaper, and more advanced nanomaterials.

We have seen here how bottom-up nanofabrication techniques require less energy and fewer harsh chemicals compared to top-down methods, contributing to reduced carbon footprint, environmental pollution, and waste generation. Additionally, the scalability and versatility of bottom-up approaches continue improving, making them already suitable for potential large-scale production. As research in bottom-up nanofabrication continues to evolve, interdisciplinary collaborations between materials scientists, chemists, biologists, and engineers will be essential to explore new design principles, optimize fabrication processes, and unlock the full potential of bottom-up nanotechnology.

References

Agarwal, S., Klocke, M. A., Pungchai, P. E., & Franco, E. (2021). Dynamic self-assembly of compartmentalized DNA nanotubes. *Nature Communications 2021 12:1*, *12*(1), 1–13. https://doi.org/10.1038/s41467-021-23850-1

Alvarez-Fernandez, A., Aissou, K., Pécastaings, G., Hadziioannou, G., Fleury, G., & Ponsinet, V. (2019). High refractive index in low metal content nanoplasmonic surfaces from self-assembled block copolymer thin films. *Nanoscale Advances*, *1*(2), 849–857. https://doi.org/10.1039/C8NA00239H

Alvarez-Fernandez, A., Cummins, C., Saba, M., Steiner, U., Fleury, G., Ponsinet, V., & Guldin, S. (2021). Block Copolymer Directed Metamaterials and Metasurfaces for Novel Optical Devices. *Advanced Optical Materials*, *9*(16), 2100175. https://doi.org/10.1002/adom.202100175

Alvarez-Fernandez, A., Fornerod, M. J., Reid, B., & Guldin, S. (2022). Solvent Vapor Annealing for Controlled Pore Expansion of Block Copolymer-Assembled Inorganic Mesoporous Films. *Langmuir*, *38*(10), 3297–3304. https://doi.org/10.1021/acs.langmuir.2c00074

Alvarez-Fernandez, A., Reid, B., Suthar, J., Choy, S. Y., Jara Fornerod, M., Mac Fhionnlaoich, N., Yang, L., Schmidt-Hansberg, B., & Guldin, S. (2020). Fractionation of block copolymers for pore size control and reduced dispersity in mesoporous inorganic thin films. *Nanoscale*, *12*(35), 18455–18462. https://doi.org/10.1039/d0nr05132b

Álvarez-Fernández, A., Valdés-Bango, F., Losada-Ambrinos, R., Martín, J. I., Vélez, M., Alameda, J. M., & García Alonso, F. J. (2018). Polymer porous thin films obtained by direct spin coating. *Polymer International*, *67*(4), 393–398. https://doi.org/10.1002/pi.5519

Alvarez-Fernandez, A., Valdes-Vango, F., Martín, J. I., Vélez, M., Quirós, C., Hermida-Merino, D., Portale, G., Alameda, J. M., & García Alonso, F. J. (2019). Tailoring block copolymer nanoporous thin films with acetic acid as a small guest molecule. *Polymer International*, *68*(11), 1914–1920. https://doi.org/10.1002/pi.5901

Anderson, A. C., Malinowski, M. E., Rev, P., Cotts, E. J., Miliotis, D. M., Northrop, G. A., Kneezel, G. A., Granato, A. V, Bev, P. B., Binning, G., Rohrer, H., Gerber, C., & Weibel, E. (1982). Surface Studies by Scanning Tunneling Microscopy. *Physical Review Letters*, *49*(1), 57. https://doi.org/10.1103/PhysRevLett.49.57

ASML Annual Report. (2020). Retrieved February 27, 2024, from https://www.asml.com/en/investors/annual-report/2020

Bates, F. S., & Fredrickson, G. H. (1999). Block Copolymers—Designer Soft Materials. *Physics Today*, *52*(2), 32–38. https://doi.org/10.1063/1.882522

Bian, K., Schunk, H., Ye, D., Hwang, A., Luk, T. S., Li, R., Wang, Z., & Fan, H. (2018). Formation of self-assembled gold nanoparticle supercrystals with facet-dependent surface plasmonic coupling. *Nature Communications*, *9*(1), 1–7. https://doi.org/10.1038/s41467-018-04801-9

Binnig, G., & Rohrer, H. (1983). Scanning tunneling microscopy. *Surface Science*, *126*(1–3), 236–244. https://doi.org/10.1016/0039-6028(83)90716-1

Bonartsev, A. P., Yakovlev, S. G., Zharkova, I. I., Boskhomdzhiev, A. P., Bagrov, D. V., Myshkina, V. L., Makhina, T. K., Kharitonova, E. P., Samsonova, O. V., Feofanov, A. V., Voinova, V. V., Zernov, A. L., Efremov, Y. M., Bonartseva, G. A., Shaitan, K. V., & Kirpichnikov, M. P. (2013). Cell attachment on poly(3-hydroxybutyrate)-poly(ethylene glycol) copolymer produced by Azotobacter chroococcum 7B. *BMC Biochemistry*, *14*(1). https://doi.org/10.1186/1471-2091-14-12

Brasse, Y., Müller, M. B., Karg, M., Kuttner, C., König, T. A. F., & Fery, A. (2018). Magnetic and Electric Resonances in Particle-to-Film-Coupled Functional Nanostructures. *ACS Applied Materials and Interfaces*, *10*(3), 3133–3141. https://doi.org/10.1021/acsami.7b16941

Caiger-Smith, A. 1930-2020. (1985). *Lustre pottery: technique, tradition and innovation in Islam and the Western world*. Faber and Faber.

Cederholm, L., Olsén, P., Hakkarainen, M., & Odelius, K. (2023). Design for Recycling: Polyester- and Polycarbonate-Based A-B-A Block Copolymers and Their Recyclability Back to Monomers. *Macromolecules*, *56*(10), 3641–3649. https://doi.org/10.1021/ACS.MACROMOL.3C00274/ASSET/IMAGES/LARGE/MA3C00274_0009.JPEG

Chung, T., Lee, S.-Y., Song, E. Y., Chun, H., & Lee, B. (2011). Plasmonic Nanostructures for Nano-Scale Bio-Sensing. *Sensors*, *11*(11), 10907–10929. https://doi.org/10.3390/s111110907

Dimitrov, A. S., & Nagayama, K. (1996). Continuous convective assembling of fine particles into two-dimensional arrays on solid surfaces. *Langmuir*, *12*(5), 1303–1311. https://doi.org/10.1021/la9502251

Esposito, F. P., Vecchiato, V., Buonocore, C., Tedesco, P., Noble, B., Basnett, P., & de Pascale, D. (2023). Enhanced production of biobased, biodegradable, Poly(3-hydroxybutyrate) using an unexplored marine bacterium Pseudohalocynthiibacter aestuariivivens, isolated from highly polluted coastal environment. *Bioresource Technology*, *368*, 128287. https://doi.org/10.1016/J.BIORTECH.2022.128287

ExtremeTech (2024). Retrieved February 27, 2024, from https://www.extremetech.com/computing/asmls-shows-off-next-generation-380-million-high-na-euv-lithography-machines

Fan, Y., Liu, Y., Wu, Y., Dai, F., Yuan, M., Wang, F., Bai, Y., & Deng, H. (2021). Natural polysaccharides based self-assembled nanoparticles for biomedical applications – A review. *International Journal of Biological Macromolecules*, *192*, 1240–1255. https://doi.org/10.1016/J.IJBIOMAC.2021.10.074

Feng, H., Lu, X., Wang, W., Kang, N.-G., & Mays, J. (2017). Block Copolymers: Synthesis, Self-Assembly, and Applications. *Polymers*, *9*(12), 494. https://doi.org/10.3390/polym9100494

Finlayson, C. E., & Baumberg, J. J. (2013). Polymer opals as novel photonic materials. In *Polymer International* (Vol. 62, Issue 10, pp. 1403–1407). John Wiley & Sons, Ltd. https://doi.org/10.1002/pi.4582

Galisteo-Lõpez, J. F., Ibisate, M., Sapienza, R., Froufe-Pérez, L. S., Blanco, Ú., & Lõpez, C. (2011). Self-assembled photonic structures. In *Advanced Materials* (Vol. 23, Issue 1, pp. 30–69). John Wiley & Sons, Ltd. https://doi.org/10.1002/adma.201000356

Gandini, A., & Lacerda, T. M. (2015). From monomers to polymers from renewable resources: Recent advances. *Progress in Polymer Science*, *48*, 1–39. https://doi.org/10.1016/J.PROGPOLYMSCI.2014.11.002

Heiligtag, F. J., & Niederberger, M. (2013). The fascinating world of nanoparticle research. *Materials Today*, *16*(7–8), 262–271. https://doi.org/10.1016/J.MATTOD.2013.07.004

He, Y., Chen, Y., Liu, H., Ribbe, A. E., & Mao, C. (2005). Self-assembly of hexagonal DNA two-dimensional (2D) arrays. *Journal of the American Chemical Society*, *127*(35), 12202–12203. https://doi.org/10.1021/JA0541938/SUPPL_FILE/JA0541938SI20050722_113354.PDF

He, Y., Tian, Y., Ribbe, A. E., & Mao, C. (2006). Highly connected two-dimensional crystals of DNA six-point-stars. *Journal of the American Chemical Society*, *128*(50), 15978–15979. https://doi.org/10.1021/JA0665141/SUPPL_FILE/JA0665141SI20061026_022502.PDF

Hoang, T. B., Akselrod, G. M., Argyropoulos, C., Huang, J., Smith, D. R., & Mikkelsen, M. H. (2015). Ultrafast spontaneous emission source using plasmonic nanoantennas. *Nature Communications*, *6*(1), 1–7. https://doi.org/10.1038/ncomms8788

Hong, A. J., Liu, C.-C., Wang, Y., Kim, J., Xiu, F., Ji, S., Zou, J., Nealey, P. F., & Wang, K. L. (2010). Metal Nanodot Memory by Self-Assembled Block Copolymer Lift-Off. *Nano Letters*, *10*(1), 224–229. https://doi.org/10.1021/nl903340a

Insua, I., & Montenegro, J. (2020). 1D to 2D Self Assembly of Cyclic Peptides. *Journal of the American Chemical Society*, *142*(1), 300–307. https://doi.org/10.1021/JACS.9B10582/SUPPL_FILE/JA9B10582_SI_002.XYZ

ISO (n.d.). Retrieved February 23, 2024, from https://www.iso.org/standard/79525.html

Isono, T., Nakahira, S., Hsieh, H. C., Katsuhara, S., Mamiya, H., Yamamoto, T., Chen, W. C., Borsali, R., Tajima, K., & Satoh, T. (2020). Carbohydrates as Hard Segments for Sustainable Elastomers: Carbohydrates Direct the Self-Assembly and Mechanical Properties of Fully Bio-Based Block Copolymers. *Macromolecules*, *53*(13), 5408–5417. https://doi.org/10.1021/ACS.MACROMOL.0C00611/ASSET/IMAGES/LARGE/MA0C00611_0006.JPEG

Isono, T., Otsuka, I., Kondo, Y., Halila, S., Fort, S., Rochas, C., Satoh, T., Borsali, R., & Kakuchi, T. (2013). Sub-10 nm nano-organization in AB2- and AB3-type miktoarm star copolymers consisting of maltoheptaose and polycaprolactone. *Macromolecules*, *46*(4), 1461–1469. https://doi.org/10.1021/MA3026578

Jiang, P., Bertone, J. F., Hwang, K. S., & Colvin, V. L. (1999). Single-crystal colloidal multilayers of controlled thickness. *Chemistry of Materials*, *11*(8), 2132–2140. https://doi.org/10.1021/cm990080+

Kim, B. H., Kim, J. Y., & Kim, S. O. (2013). Directed self-assembly of block copolymers for universal nanopatterning. *Soft Matter*, *9*(10), 2780–2786. https://doi.org/10.1039/c2sm27535j

Kim, S. H., Lee, S. Y., Yang, S. M., & Yi, G. R. (2011). Self-assembled colloidal structures for photonics. In *NPG Asia Materials* (Vol. 3, Issue 1, pp. 25–33). Nature Publishing Group. https://doi.org/10.1038/asiamat.2010.192

Kim, S. H., Lim, J. M., Lee, S. K., Heo, C. J., & Yang, S. M. (2010). Biofunctional colloids and their assemblies. *Soft Matter*, *6*(6), 1092–1110. https://doi.org/10.1039/b920611f

König, T. A. F., Ledin, P. A., Kerszulis, J., Mahmoud, M. A., El-Sayed, M. A., Reynolds, J. R., & Tsukruk, V. V. (2014). Electrically tunable plasmonic behavior of nanocube-polymer nanomaterials induced by a redox-active electrochromic polymer. *ACS Nano*, *8*(6), 6182–6192. https://doi.org/10.1021/nn501601e

Kralchevsky, P. A., & Nagayama, K. (1994). Capillary Forces between Colloidal Particles. *Langmuir*, *10*(1), 23–36. https://doi.org/10.1021/la00013a004

Lawson, R. A., & Robinson, A. P. G. (2016). Overview of materials and processes for lithography. *Frontiers of Nanoscience*, *11*, 1–90. https://doi.org/10.1016/B978-0-08-100354-1.00001-6

Levin, A., Hakala, T. A., Schnaider, L., Bernardes, G. J. L., Gazit, E., & Knowles, T. P. J. (2020). Biomimetic peptide self-assembly for functional materials. *Nature Reviews Chemistry 2020 4:11*, *4*(11), 615–634. https://doi.org/10.1038/s41570-020-0215-y

Li, C., Li, Q., Kaneti, Y. V., Hou, D., Yamauchi, Y., & Mai, Y. (2020). Self-assembly of block copolymers towards mesoporous materials for energy storage and conversion systems. *Chemical Society Reviews*, *49*(14), 4681–4736. https://doi.org/10.1039/D0CS00021C

Li, H., Carter, J. D., & LaBean, T. H. (2009). Nanofabrication by DNA self-assembly. *Materials Today*, *12*(5), 24–32. https://doi.org/10.1016/S1369-7021(09)70157-9

Li, Q., He, J., Glogowski, E., Li, X., Wang, J., Emrick, T., & Russell, T. P. (2008). Responsive Assemblies: Gold Nanoparticles with Mixed Ligands in Microphase Separated Block Copolymers. *Advanced Materials*, *20*(8), 1462–1466. https://doi.org/10.1002/adma.200702004

Li, X., & Gilchrist, J. F. (2016a). Large-Area Nanoparticle Films by Continuous Automated Langmuir–Blodgett Assembly and Deposition. *Langmuir*, *32*(5), 1220–1226. https://doi.org/10.1021/acs.langmuir.5b03760

Li, X., & Gilchrist, J. F. (2016b). Large-Area Nanoparticle Films by Continuous Automated Langmuir-Blodgett Assembly and Deposition. *Langmuir*, *32*(5), 1220–1226. https://doi.org/10.1021/acs.langmuir.5b03760

Lund, K., Liu, Y., Lindsay, S., & Yan, H. (2005). Self-assembling a molecular pegboard. *Journal of the American Chemical Society*, *127*(50), 17606–17607. https://doi.org/10.1021/JA0568446/SUPPL_FILE/JA0568446SI20051105_123915.PDF

Mahler, F., Meister, A., Vargas, C., Durand, G., Keller, S., Mahler, F., Vargas, C., Keller, S., Meister, A., & Biophysics, S. K. (2021). Self-Assembly of Protein-Containing Lipid-Bilayer Nanodiscs from Small-Molecule Amphiphiles. *Small*, *17*(49), 2103603. https://doi.org/10.1002/SMLL.202103603

Mishchenko, L., Hatton, B., Kolle, M., & Aizenberg, J. (2012). Patterning hierarchy in direct and inverse opal crystals. *Small*, *8*(12), 1904–1911. https://doi.org/10.1002/smll.201102691

Müller, M. B., Kuttner, C., König, T. A. F., Tsukruk, V. V., Förster, S., Karg, M., & Fery, A. (2014). Plasmonic library based on substrate-supported gradiential plasmonic arrays. *ACS Nano*, *8*(9), 9410–9421. https://doi.org/10.1021/nn503493c

Otsuka, I., Isono, T., Rochas, C., Halila, S., Fort, S., Satoh, T., Kakuchi, T., & Borsali, R. (2012). 10 nm scale cylinder-cubic phase transition induced by caramelization in sugar-based block copolymers. *ACS Macro Letters*, *1*(12), 1379–1382. https://doi.org/10.1021/MZ300543U

Park, S., Cho, D., Ryu, J., Kwon, K., Lee, W., & Chang, T. (2002). Fractionation of block copolymers prepared by anionic polymerization into fractions exhibiting three different morphologies. *Macromolecules*, *35*(15), 5974–5979. https://doi.org/10.1021/ma0205313

Rai, R., Yunos, D. M., Boccaccini, A. R., Knowles, J. C., Barker, I. A., Howdle, S. M., Tredwell, G. D., Keshavarz, T., & Roy, I. (2011). Poly-3-hydroxyoctanoate P(3HO), a medium chain length polyhydroxyalkanoate homopolymer from pseudomonas mendocina. *Biomacromolecules*, *12*(6), 2126–2136. https://doi.org/10.1021/BM2001999

Reid, B., Alvarez-Fernandez, A., Schmidt-Hansberg, B., & Guldin, S. (2019). Tuning Pore Dimensions of Mesoporous Inorganic Films by Homopolymer Swelling. *Langmuir*, *35*(43), 14074–14082. https://doi.org/10.1021/acs.langmuir.9b03059

Sarkar, A., Thyagarajan, A., Cole, A., & Stefik, M. (2019). Widely tunable persistent micelle templates: Via homopolymer swelling. *Soft Matter*, *15*(26), 5193–5203. https://doi.org/10.1039/c9sm00484j

Si, G., Li, C., Chen, M., & Chen, C. (2023). Polymer Multi-Block and Multi-Block+ Strategies for the Upcycling of Mixed Polyolefins and Other Plastics. *Angewandte Chemie International Edition*, *62*(49), e202311733. https://doi.org/10.1002/ANIE.202311733

Solomonov, A., Kozell, A., & Shimanovich, U. (2024). Designing Multifunctional Biomaterials via Protein Self-Assembly. *Angewandte Chemie International Edition*, *2024*, e202318365. https://doi.org/10.1002/ANIE.202318365

Suthar, J., Alvarez-Fernandez, A., Osarfo-Mensah, E., Angioletti-Uberti, S., Williams, G. R., & Guldin, S. (2023). Amplified EQCM-D detection of extracellular vesicles using 2D gold nanostructured arrays fabricated by block copolymer self-assembly. *Nanoscale Horizons*. https://doi.org/10.1039/D2NH00424K

Third IMO GHG Study 2014. (n.d.). Retrieved February 27, 2024, from https://www.imo.org/en/OurWork/Environment/Pages/Greenhouse-Gas-Studies-2014.aspx

Volk, K., Fitzgerald, J. P. S., Retsch, M., & Karg, M. (2015). Time-Controlled Colloidal Superstructures: Long-Range Plasmon Resonance Coupling in Particle Monolayers. *Advanced Materials*, *27*(45), 7332–7337. https://doi.org/10.1002/adma.201503672

Wang, L., Gong, C., Yuan, X., & Wei, G. (2019). Controlling the Self-Assembly of Biomolecules into Functional Nanomaterials through Internal Interactions and External Stimulations: A Review. *Nanomaterials (Basel, Switzerland)*, *9*(2). https://doi.org/10.3390/NANO9020285

Wang, X., Ehrhardt, K., Tallet, C., Warenghem, M., Baron, A., Aradian, A., Kildemo, M., & Ponsinet, V. (2017). Hyperbolic-by-design self-assembled metamaterial based on block copolymers lamellar phases. *Optics and Laser Technology*, *88*, 85–95. https://doi.org/10.1016/j.optlastec.2016.08.005

Wong, S., Kitaev, V., & Ozin, G. A. (2003). Colloidal Crystal Films: Advances in Universality and Perfection. *Journal of the American Chemical Society*, *125*(50), 15589–15598. https://doi.org/10.1021/ja0379969

Xiao, M., Li, Y., Allen, M. C., Deheyn, D. D., Yue, X., Zhao, J., Gianneschi, N. C., Shawkey, M. D., & Dhinojwala, A. (2015). Bio-inspired structural colors produced via self-assembly of synthetic melanin nanoparticles. *ACS Nano*, *9*(5), 5454–5460. https://doi.org/10.1021/acsnano.5b01298

Zhao, Y. B., Lv, X. D., & Ni, H. G. (2018). Solvent-based separation and recycling of waste plastics: A review. *Chemosphere*, *209*, 707–720. https://doi.org/10.1016/J.CHEMOSPHERE.2018.06.095

Zhao, Y., Rettner, E. M., Harry, K. L., Hu, Z., Miscall, J., Rorrer, N. A., & Miyake, G. M. (2023). Chemically recyclable polyolefin-like multiblock polymers. *Science*, *382*(6668), 310–314. https://doi.org/10.1126/SCIENCE.ADH3353/SUPPL_FILE/SCIENCE.ADH3353_SM.PDF

About Author

Dr. Alberto ALVAREZ-FERNANDEZ | Centro de Física de Materiales (CFM) – Materials Physics Center (MPC) |
alberto.alvarez[at]ehu.eus | ORCID: 0000-0002-2607-3035

Alberto Alvarez Fernandez is a Gipuzkoa Fellow researcher at the Materials Physics Center in San Sebastian (Spain). His research interests include the development of complex plasmonic nanostructures and mesoporous architectures based on block copolymer self-assembly for sensing and optical applications. He received his PhD at the University of Bordeaux (France) in 2018, working on the development of new plasmonic metasurfaces using block copolymers. After that, he joined the Adaptive & Responsive Nanomaterials group at the University College London (UK) as a postdoctoral researcher, being promoted to Senior Research Fellow in January 2022. In November 2022, he was granted an ADMIRE MSCA Fellowship to conduct research at Trinity College Dublin (Ireland). In 2021, he received the Young Researcher Award from the European Material Research Society, for his significant work advancing structural characterisation platforms for nanomaterials. Furthermore, in 2023, he was awarded the RSC Materials Chemistry Horizon Prize: Stephanie L Kwolek Prize, for his contributions to the fabrication and characterisation of polymeric porous membranes, particularly in the context of energy applications.

OVERVIEW AND CLASSIFICATION OF SUCCESSFUL SILICON VALLEY START-UPS: STATISTICAL ANALYSIS AND DEVELOPMENT OF RECOMMENDATIONS

Azyk Orozonova

Amangeldi Zhumadilov

Esengeldi Zhumadilov

Aigerim Akmatova

Kashymbekov Aktan

10.53478/TUBA.978-625-6110-22-9.ch12

Overview and Classification of Successful Silicon Valley Start-Ups: Statistical Analysis and Development of Recommendations

Azyk Orozonova
Jusup Balasagyn Kyrgyz National University, Kyrgyzstan
Amangeldi Zhumadilov
Salymbekov University, Kyrgyzstan
Esengeldi Zhumadilov
Salymbekov University, Kyrgyzstan
Aigerim Akmatova
I. Razzakov Kyrgyz State Technical University, Kyrgyzstan
Kashymbekov Aktan
Salymbekov University, Kyrgyzstan

Abstract

The relevance of the study is conditioned by the fact that today's business processes are predisposed to modernisation, which consists in the transition of the economy to an innovative path of development, in connection with which businessmen should identify and solve real consumer problems and resort to innovative activities using start-up projects. In this regard, the purpose of the study is to consider successful Silicon Valley start-ups, their industry classification, statistical analysis, and the development of recommendations. The leading approach to the investigation of this problem is a combination of synthesis and analysis, which, complementing each other, allow for a comprehensive consideration of the process of optimising the innovative activity of enterprises through the successful implementation of start-up projects. The results obtained within the framework of this study are the consideration of the essence of start-ups and the key features of Silicon Valley, the identification of statistics of their failures, familiarisation with the successful start-ups classification, and the development of recommendations for successful creation of similar ones. The results of this study and the formulated conclusions are of practical value both for students studying the features of innovation management, and for entrepreneurs whose sphere of interests covers the innovative and scalable product development, its successful implementation, which besides increase of the start-up creator income, also make a significant contribution to the development of many areas, including the sector of education, medicine, finance, security, communications, ecology, trade, and others, contributing in every possible way to technological progress anywhere in the world.

Keywords

Innovation, Scaling, Start-up projects, Start-up statistics, Silicon Valley's start-up projects

Introduction

Speaking about start-ups, it is important to understand that this is a business that is in the early stages of development. Start-up projects are characterised by two important components (Pacheco-Torgal et al., 2016), namely:

1) innovation, as an entrepreneur embodies new technologies into reality, modernises products or services in a certain market, conducts experiments, tests assumptions, which were not previously implemented by competitors;
2) scalability, since a successful start-up can give exponential growth, not linear, and the faster the project grows, the larger it becomes.

A start-up is a kind of experiment that involves testing assumptions that are not always true (Harmsen, 2019). For this reason, these projects often do not meet expectations and are closed.

According to the U.S. Bureau of labour statistics, regarding the statistics of failures among novice businessmen, it must be noted that almost 90% of new companies fail. Now, there are the following indicators for start-up failures:

1) in 20% of cases, they are rejected in the first year of existence;
2) in 30% are rejected in the period equal to two years;
3) in 50% of cases in the period up to 5 years;
4) in 70% – in the period up to 10 years.

Silicon Valley is a favourable ground for the introduction of start-ups into life. This area is notable for the fact that it combines both opportunities and funding. Businessmen with the necessary skills and abilities believe that getting rich there is a matter of time, but at the same time, it is important to have a business idea suitable for the new realities. It is also a centre where the US government, academia, and the private sector are interconnected. It was this union that gave birth to Silicon Valley, which can be considered unique (Iannarelli & O'Shaughnessy, 2014). Research centres such as Berkeley and Stanford University are in this valley, which provides a constant flow of talented minds in any field.

In modern research, the topic of start-ups is also partially considered. Most of the studies are devoted to the investigation of innovative technologies. Thus, K. Machado and P. Davim (Machado & Davim, 2022) considered the problems of production sustainability, exploring the latest technologies in the field of ecology, and methods by which it is possible to design environmentally friendly products and materials. T. Duening, R. Hisrich, M.

Lechter (Duening et al., 2020) have created a practical guide for potential entrepreneurs, which describes the process of introducing innovations to the market, helping in attracting capital, product development, and intellectual property protection.

Some authors (Phillips & Landahl, 2020) investigated of the issue of scaling, without which start-up projects are impossible, exploring business continuity planning considering many threats, including the COVID-19 pandemic. Importance (Galanakis, 2021) connected with tools considered for the introduction of technological processes and innovations in the food industry. In their book on accelerating transport innovation revolution authors (Giannopoulos & Munro, 2019) insisted on the idea that understanding the nature of revolutionary innovations is as important as creating innovations themselves. Even though in this work more attention is paid to transport innovations, the presented recommendations and concepts can be applied in other areas.

The main problem of earlier research on this topic was the lack of knowledge of successful Silicon Valley start-up projects and general recommendations for optimising the functioning of start-ups. In this regard, the main purpose of this study is to investigate the features of successful start-ups, which are implemented by getting acquainted with successful innovative companies in Silicon Valley and developing recommendations for optimising the activities of start-ups.

Materials and Methods

The basis of the methodological approach is the use of such methods as synthesis and analysis, statistical and graphical methods.

The analysis contributed to the decomposition of the subject matter into its component parts, due to which the features of Silicon Valley and start-up projects were clarified, a review of successful innovative companies was conducted and recommendations that increase the likelihood of success of an innovative product were considered. The synthesis combined the obtained analysis results into a single system, because of which the study comprehensively considered the process of optimising the functioning of start-up projects. Using the statistical method, the negative experiences of entrepreneurs related to failed start-up projects were made known. This method also helped identify the classification of successful start-ups by industry. The graphical method was used to aggregate data and visually demonstrate the results using a diagram of the industry structure of successful start-ups. The tabular method was also used to aggregate the results obtained, due to which data on innovative companies were presented in the form of summary tables.

This study was conducted based on a pre-compiled theoretical basis, which acts as a qualitative foundation for all further research. The theoretical basis of this study is the findings of several foreign researchers who investigated a number of problematic issues related to the introduction of innovative products or services.

The research and experimental base of the study were successful and high-tech start-ups of Silicon Valley, namely: Noname Security, DevRev, FalconX, Luminous Computing, Turing, Athelas, Snorkel AI, Yugabyte, Salt Security, and Medable.

The study included three stages.

At the first stage, a theoretical basis was prepared, which was used as a fundamental factor for the implementation of further research. The key features of start-ups and their failure statistics were identified, and the attractiveness of Silicon Valley for the introduction of start-ups into life was also considered. The characteristic of Silicon Valley gives the entrepreneur and the ordinary citizen an insight into the opportunities in the environment and funding available to them.

At the second stage, the industry classification of successful Silicon Valley start-ups was investigated to determine modern consumer trends, and the leading start-up companies that specialise in various fields, starting with technological progress in the field of medicine, ending with the modernisation of the financial sector of the economy, were reviewed. At this stage, general recommendations have also been developed that can contribute to the successful introduction of a start-up to the market.

At the third stage, based on the data obtained, the final conclusions of the scientific approach were formulated, which act as the final display of the results obtained and determine the main recommendations for optimising the implementation of start-up products or services. In general, the results obtained during the preparation of this paper and the conclusions formulated on their basis can be used by specialists whose sphere of interest includes the introduction of a start-up into life and its successful implementation, which ideally can provide high income.

Results and Discussion

The amount of personal and institutional wealth in the region makes Silicon Valley an ideal place for business development. This area is rich in thousands of investors who can also act as venture capitalists, whose main goal is to monetise their money instead of annual tax payments to the US government. As a result, entrepreneurs are ready to invest in a variety of projects in the hope of high dividends from successful start-ups in the coming years. According to experts (Smelser & Baltes, 2001) Silicon Valley investors will always chase success stories, even though Silicon Valley may see many failed start-ups. In recent years, venture capitalists have poured significant amounts of money into Silicon Valley startups. Hundreds of new startups emerge in Silicon Valley every year. In 2022, according to data book, the investment volume in Silicon Valley startups amounted to over $7 billion, with over 800 new projects registered.

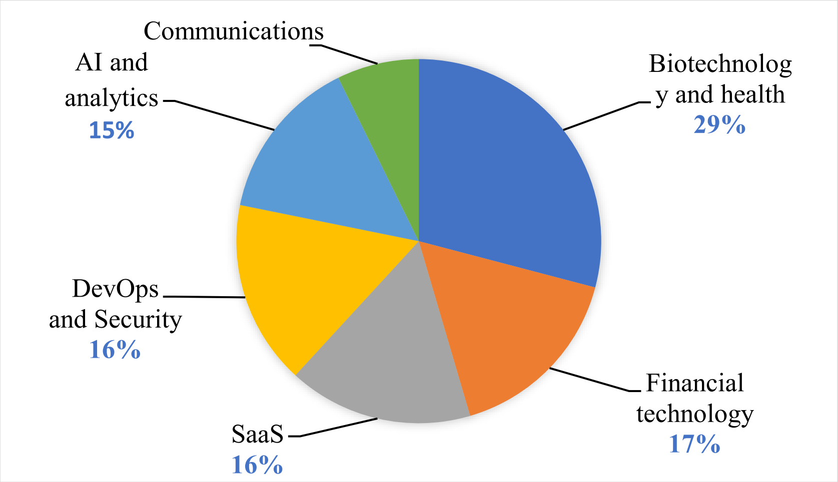
Statistics tells us the most successful industries of Silicon Valley start-ups include the following:

1) biotechnology and health;
2) financial technologies including payments, transfers, lending, blockchain, investments, insurance, etc.;
3) SaaS (software as a service);
4) DevOps (methodology for automating technological processes of software assembly, configuration, and deployment) and security;
5) AI (artificial intelligence) and analytics;
6) Communications.

Out of 55 successful start-up projects according to Growjo: 16 belong to the field of biotechnology and health, 9 – financial technologies, 9 – SaaS, 9 – DevOps and security, 8 companies are engaged in AI and analytics, 4 start-ups belong to the communications industry. This structure is shown in Figure 1.

Figure 1.

Industry structure of successful start-ups among 55 companies



Next, the study considers the 10 fastest-growing Silicon Valley companies in 2023. This rating is provided in Table 1, which is based on the growth of 2022 and on the prediction of future growth. The rating is based on a set of data such as estimates, quality, and quantity of investment, estimated profit growth, hiring announcements, current vacancies, announcements of management staff, comparison of competitors, and many other growth triggers. Silicon Valley represents fast-growing start-ups.

Table 1.

Top 10 successful Silicon Valley start-ups

No.	Name of start-ups	Classification	Financing, USD million	Staff	Staff grows, %	Revenue, USD million	Valuation, USD billion
1	Character.AI	AI	150	73	248	6.5	1
2	Inworld AI	AI	100	89	68	11.5	0.5
3	Lyten	Environmental	360	261	37	60.3	1.4
4	Pinecone	AI	138	121	128	17.5	0.75
5	Skydio	Aviation	570	656	42	196.2	2.2
6	Securly	EdTech	23	316	496	56.2	-
7	Aptos	Fintech	350	246	76	34.4	-
8	Natron Energy	Environmental	50.1	108	3	22.7	-
9	Kodiak Robotics	Transportation	165	195	6	68.8	-
10	Xage Security	IT Security	46	99	57	20.2	-

Source: (growjo.com, 2023).

Next, the study will review each start-up in more detail.

First on the list is AI (Character AI, 2023), which represents an AI chatbot application enabling users to engage in chats with virtual characters inspired by celebrities, gaming personas, and more. Additionally, users can craft and train their own AI characters, defining unique personality traits, interests, and conversational styles, thereby enhancing the realm of fanfiction. While users can develop virtual friends and AI renditions of real-life figures, Character AI implements a NSFW (Not Safe for Work) filter to ensure safe interactions. However, there are strategies available to prompt characters to engage in roleplay across various scenarios. This start-up includes many advantages, which are considered in Table 2.

Table 2.

Advantages of Character AI

Advantages	Characteristics
People-oriented	Character AI prioritizes the development of artificial intelligence that enhances human experiences, focusing on creating technology that is intuitive, empathetic, and beneficial to users.
Interdisciplinary collaboration	Within Character AI, a collaborative environment thrives, emphasizing teamwork and the exchange of knowledge among experts spanning various disciplines. This collective approach aims to develop cutting-edge AI solutions through diverse insights.
Continuous learning	At Character AI, there is a strong emphasis on continuous growth. Employees are encouraged to advance both professionally and personally, with ample opportunities for skill enhancement, research, and career progression in the dynamically evolving landscape of AI.
Innovation for Impact	The core objective of Character AI is to generate AI solutions that generate positive and substantial impacts on society. These solutions are designed to address real-world challenges, utilizing technology to enhance lives and contribute meaningfully to societal betterment.

Source: (Character AI, 2023).

The second start-up in the ranking is Inworld AI (Inworld AI, n.d.). It is tailored for individuals seeking a hassle-free method to create generative AI characters without the need for coding. This platform focuses on responsive storytelling by eliminating repetitive bot dialogues, enhancing narrative depth, and enabling the creation of adaptive AI characters with unique personalities capable of experiencing emotions and formulating responses like human behaviour. The advantages of Inworld AI are listed in Table 3.

Table 3.

Advantages of Inworld AI

Advantages	Characteristics
Highly configurable	Inworld AI offers extensive customization options, allowing users to tailor their character's identity, motivations, roles, hobbies, interests, personalities, moods, knowledge (both personal and general), dialogue styles, and more. This intuitive, no-code character creation process enables users to describe characters in natural language and further refine them using drop-down menus and adjustable sliders.
Production-ready	The platform ensures the seamless integration and immediate deployment of characters into games or other immersive realities. Its comprehensive package for Unity, along with a flexible API, empowers creators to introduce their characters across a range of experiences and platforms.
Flexible and engaging	Inworld AI caters to a variety of applications, making any immersive experience more captivating and interactive. Whether it's for brands or games, Inworld-powered characters significantly contribute to creating engaging user experiences.

Source: (Inworld AI, n.d.).

The third place in the rating is occupied by Lyten (Lyten 3D Graphene, n.d.). A cutting-edge materials company is causing significant changes in the electric vehicle battery sector by unveiling its LytCell EV™ lithium-sulfur (Li-S) battery platform. This recent innovation from Silicon Valley is tailor-made for the electric vehicle (EV) market, aiming to provide a gravimetric energy density three times (3X) higher than that of traditional lithium-ion (Li-ion) batteries. Emerging from its previous stealth mode, Lyten has closely collaborated with the U.S. in this breakthrough.

The products provided by Lyten are described in Table 4.

Table 4.

Lyten Company Products

Products	Characteristics
Batteries	The Lithium-Sulfur battery stands out as the choice for widespread consumer use. It eliminates the need for Nickel, Cobalt, Manganese, and Graphite, resulting in a reduced Bill of Materials. It boasts over twice the energy density (Wh/kg), enabling a significant 60% reduction in the weight of an EV battery pack. What sets it apart is its inherent safety features, rendering it resistant to overcharge and thermal runaway, ensuring a more secure battery system.
Composites	Lightweighting: This strategy aims to reduce materials and weight by up to 50% in polymers, paving the way for more efficient and lighter structures. Enhanced Performance: The objective is to elevate performance by improving characteristics such as strength, conductivity, and stiffness. Promoting Circularity: The emphasis on circularity highlights the efforts to boost the recycled composite materials to approach the properties of virgin materials. Additive Manufacturing Advancements: The focus on high-strength additive manufacturing signifies the drive to make this technology a reality across various sectors such as automotive, aviation, industrial applications, and beyond.
Sensors	Part per Billion Multi-Gas Fingerprinting: These sensors offer the capability to detect multiple gases at concentrations as low as parts per billion. This high level of sensitivity makes them suitable for various applications. Compact and Rugged Design: These sensors are housed in a single, small, and ruggedized unit, making them highly versatile and able to operate in challenging environments. They can be deployed in various locations.

Source: (Lyten 3D Graphene, n.d.).

The fourth company in the ranking is Pinecone (see Pinecone official website). The fundamental objective behind Pinecone's inception was to offer pivotal storage and retrieval infrastructure crucial for constructing and operating cutting-edge AI applications. The founding principle revolved around providing accessibility to engineering teams of all magnitudes and varying levels of AI proficiency. This commitment led start-up to introduce a fully managed service renowned for its user-friendly nature, catering to both small and large teams, regardless of their expertise in AI.

The fifth place is taken by Skydio, which specializing in the development and production of autonomous drones, which have a high degree of self-sufficiency and the ability to fly autonomously without the active participation of an operator. The focus of start-up's work is related to creating drones capable of autonomously detecting and avoiding obstacles in real-time, making them ideal for use in various industries such as security, infrastructure inspection, video and photography, as well as in various professional fields.

The sixth company in the ranking is Securly (see Securly official website), which specializes in developing solutions to ensure digital safety in educational institutions. Securly's primary products and services include software solutions that provide control and filtering of internet content in educational settings. They offer parents and educational institutions tools for monitoring students' internet activity, filtering harmful content, and ensuring a safe online experience for young users. The solutions offered by this start-up cover several key areas, as described in Table 5.

Table 5.

Securly solutions

Solutions	Characteristics
Student Safety	The start-up develops innovative solutions aimed at ensuring student safety in the academic environment. This may include monitoring systems to prevent cyberbullying, campus security alerts, and tools to ensure overall student well-being.
Student Health	The start-up provides technological solutions to support student health. This may include online resources for physical and psychological health, tools for monitoring student health and well-being, as well as platforms for counselling and support.
Student Engagement	The company develops tools and platforms that promote active student participation in the learning process. This may include online forums, platforms for sharing ideas and projects, as well as tools for feedback and collaboration.
Technologies	The start-up uses cutting-edge technologies to achieve these goals. This includes software development, the use of artificial intelligence for data analysis, and the provision of innovative online platforms and applications to enhance the educational process and ensure student safety.

Source: (Securly official website).

The seventh successful start-up is Aptos (Aptos Retail, n.d.). The company is a leading provider of retail business solutions, offering innovative technologies for retail management. Aptos offers a wide range of software products and services that help retail companies improve operational processes and provide a better shopping experience for consumers. Key products by Aptos include software solutions for inventory management, point of sale, order management, analytics, merchandise planning, and other tools that provide comprehensive support for retail companies. Aptos specializes in providing integrated solutions that enable retail companies to efficiently manage their operations, enhance inventory management processes, and improve customer interactions. These solutions cover various aspects of retail business, from sales management to data analysis and merchandise planning.

There are several characteristics of a start-up:

1) Cloud Support with Ironclad Autonomy: The company offers cloud technologies ensuring stable and reliable operation even in autonomous mode. This enables system functionality to be maintained regardless of internet connectivity, ensuring data storage and processing reliability.

2) Mobile Devices: The company's systems are designed for use on mobile devices. This allows operation on mobile technology-based platforms, enhancing flexibility and accessibility from various locations.

3) Reliable POS Capabilities: The company's solutions provide reliable point of sale (POS) features, ensuring stability and efficiency in transactions. This encompasses payment processing, inventory management, and the provision of convenient services for customers.

4) Sell Anywhere Inside Our Store: The company provides tools for selling products and services in any part of the store. This may include mobile platform capabilities, scanning items, or conducting transactions offered in different areas of the store to enhance customer convenience.

The eighth company in the ranking is Natron Energy (Natron, n.d.), which specializing in advanced energy storage solutions. Based in California, the company is dedicated to developing and commercializing innovative batteries based on sodium-ion technology. The key feature of Natron Energy's products is their high performance, safety, and durability. The company aims to address energy storage challenges by offering more reliable and durable energy storage solutions applicable across a wide range of industries. One of Natron Energy's primary achievements is the creation and implementation of a unique sodium-ion battery. It differs from traditional lithium-ion batteries by offering higher levels of safety and stability, with the potential to enhance energy efficiency.

The ninth successful start-up in the ranking is Kodiak Robotics (see Kodiak Robotics official website), which develops autonomous driving systems for trucks. They specialize in autopilot technologies that enable trucks to perform autonomous transportation.

The advantages of the Kodiak Robotics start-up are presented in Table 6.

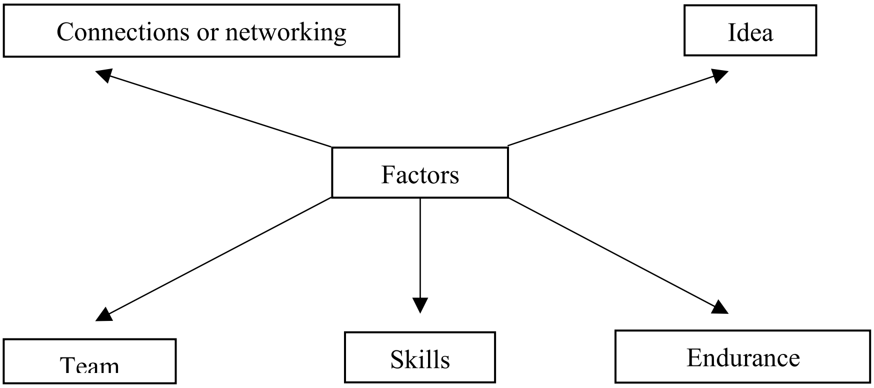
Table 6.
Advantages of Kodiak Robotics company

Advantages	Characteristics
Autonomous Technology	The company integrates cutting-edge autopilot systems, enabling trucks to operate without direct driver involvement. This enhances transportation efficiency and reduces the risks associated with human errors.
Enhanced Safety	Kodiak Robotics' autonomous systems are designed to ensure safe transportation. They can monitor the surrounding environment and react to road changes, reducing the likelihood of accidents.
Improved Efficiency and Cost Savings	Utilizing autonomous technologies can enhance transportation efficiency through more precise route planning and continuous movement, reducing fuel costs and operational expenses.
Innovative Developments in Logistics	Kodiak Robotics presents an innovative approach to cargo transportation, transforming traditional logistics methods and promising efficiency and convenience in cargo delivery.

Source: (Kodiak Robotics official website).

Xage Security (Xage Security, Company Profile, n.d.) closes the top ten successful start-ups. It is a leading provider of cutting-edge cybersecurity solutions that specifically target the protection of both industrial and corporate networks. The company's specialization lies in the proficient and strategic application of blockchain technology, offering robust and innovative security measures that effectively safeguard the integrity and privacy of industrial environments. Through the implementation of blockchain, Xage Security ensures the creation of decentralized, tamper-proof networks that fortify against cyber threats, providing a secure foundation for the intricate systems within industrial settings. This approach not only guarantees protection against external attacks but also ensures the uninterrupted and secure flow of data critical to the operations of various industries, including energy, transportation, manufacturing, and other crucial sectors.

Figure 2.
Start-up success factors



It is important to develop recommendations for the successful creation and implementation of start-ups. Figure 2 suggests the main factors influencing the success of creating such projects.

As for networking, communications and the environment play one of the key roles in creating start-ups. To create a new innovative and scalable product or service, it is important to adopt the experience of people who have already succeeded or are succeeding in this field, therefore, it is important to attend events that are dedicated to the topic of start-ups, entrepreneurship, and innovation. Getting to know more people and sharing ideas at different events can partly bring a start-up closer to success.

The second factor of successful start-up creation is the idea (Reichmuth & Ewald, 2022). It is important to study the market to understand whether this idea has already been implemented by someone. If this product or service has already been implemented in the market, it is possible to modernise the idea and weigh the pros and cons. It is necessary to follow the trends in technology and innovation. Ideas can arise as solutions to any problems. The more competent a person is in a certain area in which they want to create a start-up, the more complete a picture of the list of previously unsolved problems may arise. These are things that can be addressed through the creation of a start-up.

The team also plays a key role in the creation of start-ups (Phillips & Landahl, 2020), because the independent introduction of a product or service to the market can take a lot of time. Start-ups should develop quickly because scalability is one of the main features of such projects. A good team will support the start-up at all stages of the development of the product or service being implemented. The employees in the team should not only be competent, but also acceptable in terms of character and communication.

Another key factor for the successful creation of start-ups is skills. For example, the opening of a start-up offering a new solution in the field of medicine should be associated with expertise and experience in this field. If a start-up relates to the development of an application that can help students in learning, then it is important to be a student with knowledge in the field of programming. Since a start-up includes not only innovation, but also scaling, it is necessary to have basic knowledge about the work of the real market, business, and economy.

A final factor influencing the success of start-up projects is endurance (Reichmuth & Ewald, 2022), as start-ups are mostly about innovation. Before the creators of such projects, there are always risks that a start-up may be hard to perceive by the market. Start-ups may face a huge number of problems in their way of life, which it is important to solve quickly, since modern realities are highly competitive. Active participation in contests, weekends, and events can bring a correct understanding of the product or service being implemented, as well as feedback.

Comparing the modern achievements of scientists with the results of the analysis of the development of recommendations for the successful creation of start-up projects, it is worth noting that in addition to such ways of optimising innovative and scalable activities as networking, idea, team, skills and endurance, the authors have identified others. Some experts (Clayton, et al, 2018) highlighted a recommendation for the creation of start-up projects in university offices, because technology transfer can contribute to their success in every possible way in their work. The main part of the university ecosystem for developers are technology transfer offices that provide support in various fields. To take advantage of the resources that are available at the university, educational institutions encourage and motivate the founders of start-ups to promote science within the university. A strong IP (interconnection protocol) is one of the advantages. The research team also noted that scientists who are in a familiar environment become more productive. Many universities also provide their students with lectures, courses, rich training programmes and other things related to the topic of start-ups. These educational institutions help scientists delve into the topic of commercialisation and provide students with the knowledge necessary to create a start-up at an early stage of the company's development in this ecosystem.

In addition, these scientists investigated the topic of incubators as another recommendation for optimising the work of start-ups. Often firms are placed together with other firms in incubators, the number of which has grown significantly. A group of researchers also identified the concept of "open access incubators", which consist in supporting and developing individual businesses and the market. The economists highlighted other topics in which they showed that the offered training and intensive communication have a positive effect on formal acceleration programmes.

This group of researchers also emphasises the need for a lawyer to contact a venture firm, because now firms are the most studied intermediaries of this ecosystem, providing professional services that include servicing many types of enterprises. An entrepreneur needs a lawyer mainly for reasons related to technology transfer offices. Lawyers act as gatekeepers, business consultants of the ecosystem, and persons helping to conclude transactions, since their position determines the business norms of local entities. Some providers have personal referral networks. Special attention is paid to firms with venture capital. Such firms provide enterprises with trust and accessibility to their own networks, which have proven themselves well as providers of services and knowledge. More specialised firms that provide professional services entail more complex access.

In his dissertation, author studies a large amount of literature devoted to important problems faced by start-ups (Weber, 2017). The researcher highlights overcoming managerial pain points as an important recommendation for optimising the activities of start-ups. These include the obligations of smallness, novelty, and adolescence. The economist summarises studies on problems related to both the distribution of team obligations and the assumption of new roles, emphasising the importance of a high level of trust in the organisation. The scientist also conducted an in-depth investigation on the importance of advisory boards, which include scientific advisory boards and boards of directors that require high managerial skills for growth and navigation.

Comparing the results with the study of success (Verloop, 2013), it is worth noting that the author highlighted not only the factors influencing the success of start-ups, but also the factors leading to failure. According to the economist, most innovative projects fail, but innovation can be managed through the identification of factors that push them to failure. The researcher attributed the lack of risk management and cost reduction to the main factors that negatively affect start-ups. J. Verloop also highlighted positive external and internal factors for the activities of innovative companies. According to the economist, success factors are favourable, supportive circumstances, which are conditions, tools, platforms, or agents. The author attributed to positive factors: patents, investors, strategic partners, subsidies, and the innovation environment.

Discussing the study results with the research of project planning (Melton, 2007), it is important to say that in the recommendation of optimisation of innovation-related activities, the economist highlighted not the factors affecting the activities of start-ups, but the correctness and necessity of planning on specific points:

1) business planning;
2) installation planning;
3) control planning;
4) project implementation plan.

According to the researcher, business planning is what connects the project with the business. This relationship is carried out through the relationship of the project sponsor and the customer, and through the relationship between the project manager and the project sponsor. The business plan should include a reliable methodology that would help realise the business benefits, and whose implementation will prove that the economic justification has been fulfilled. Any project requires a manager who clearly understands the goals of the work, business problems that are important to solve, and a sponsor who owns not only problems, but also successful solutions, end users and customers. It is important for the project manager to build relationships and communicate effectively, putting together a detailed plan for the implementation of all benefits corresponding to the approved economic justification. The manager should use consulting tools and behave like a consultant to facilitate the construction of key relationships that will contribute to the development of all aspects of the business plan.

The installation plan helps in the development and management of the relationship that arises between the project team and the manager. If there are common goals between the manager and the team, then the probability of success of the project increases. In this type of planning, the focus is on the ability to achieve a certain amount by attracting the required capabilities of personnel. Crucial to the success of project installation planning is the choice of a manager that meets the needs of the project, which are usually described in terms of the size, type, importance, and complexity of the project for the business.

Considering the control plan, T. Melton pointed out that this plan supports the management and development of the relationship between the project manager and the project team. It is important that they have common and coordinated management processes, because this is how the team led by the manager optimises the start-up's activities. The management plan acts as a tool for monitoring, planning, and forecasting the activities of an innovative project, which the start-up team will use not only for planning individual workload, but also for the workload of a subgroup. The main purpose of the control plan is to control the project to maximise confidence in its own results. According to the economist, the manager needs to determine a way to manage uncertainty within the project, using a suitable combination of risk management tools for a specific project, developing management strategies for an innovative company.

The last paragraph describes the development of a reliable and comprehensive project implementation plan that defines the way the project is implemented and the achievement of project and entrepreneurial goals. The purpose of the development plan is to ensure that strategies that are implemented, developed, built, and communicated based on best project management practices act as guarantors of compliance with the needs of an innovative company. The PDP (preliminary development plan) defines the purpose and objectives of the project, the implementation strategies, the organisation of the team and the results necessary to ensure success and compliance with business needs. The preliminary development plan must be updated at regular intervals. According to the economist, this will ensure that as strategies are refined and developed, they will be coordinated in achieving benefits for businesses and their goals. The main recommendation of the researcher is the development of the initial PDP, which should be developed and approved before the start of the project implementation phase, and then used by the project manager and the project team throughout the implementation.

Thus, there are many approaches to optimising the activities of companies that are related to innovation and scalability. Every entrepreneur who introduces start-up to the market should be guided not only by own intuition, but also know well the modern basis of economists in this field, namely their recommendations for success.

Conclusions

Start-ups differ from ordinary business projects in scalability and innovation. A statistical review showed that not all start-ups are successful, and investment in such projects decreases with the increase in the life of projects. Now, Silicon Valley belongs to one of the favourable regions for the creation and implementation of start-ups. An analysis of successful Silicon Valley projects has shown that the most successful start-ups are developing in such areas as biotechnology and health, financial technology, SaaS, DevOps and security, AI and analytics, and communications.

The research paper developed recommendations that would favourably influence the creation and implementation of start-ups. Such recommendations included the development and analysis of ideas, the need for communication and networking, the importance of skills and endurance, and the creation of a good team. The lack of risk management and cost reduction were attributed to negative factors for start-ups. The positive factors included patents, investors, strategic partners, subsidies, and the innovation environment. To improve the work of start-ups, it is important to create them in university offices, and the functioning of the company in incubators, which would facilitate technology transfer. The paper emphasised the need for a lawyer to communicate with a venture firm and overcome managerial pain points, which include the obligations of novelty, adolescence, and smallness. Optimisation of business planning, control planning, installation and project implementation were also recommendations for achieving success in innovation.

The materials of this study can be useful for teachers of financial management who are adapting to the new conditions of professional activity in the field of education, for specialists in the field of entrepreneurship who want to launch their start-up, focusing on the positive experience of successful start-up projects in Silicon Valley. The areas of further research may be the investigation of other favourable regions for the creation and implementation of start-ups, the study of their key features and statistics.

References

Aptos Retail: The Leader in Unified Commerce. (n.d.). Retrieved from https://www.aptos.com/.

Character AI: What It Is, Fixing Filters & Repeats, & More. (2023). Retrieved from https://www.wikihow.com/Character-Ai.

Clayton, P., Feldman, M., & Lowe, N. (2018). Behind the scenes: Intermediary organizations that facilitate science commercialization through entrepreneurship. *The Academy of Management*, 32, 104-124.

De Cock, R., Bruneel, J., & Bobelyn, A. (2020). Making the lean start-up method work: The role of prior market knowledge. *Journal of Small Business Management*, 5, 975-1002.

Duening, T., Hisrich, R., & Lechter, M. (2020). *Technology entrepreneurship.* London: Academic Press.

Galanakis, C. (2021). *Innovation strategies in the food industry.* London: Academic Press.

Giannopoulos, G., & Munro, J. (2019). *The accelerating transport innovation revolution*. Oxford: Elsevier.

Harmsen, J. (2019). *Industrial process scale-up*. Oxford: Elsevier.

Iannarelli, J., & O'Shaughnessy, M. (2014). *Information governance and security.* Oxford: Butterworth-Heinemann

Inworld AI Characters & Dialogue for Unity. (n.d.). Retrieved from https://unity.com/partners/verified-solutions/inworld-ai.

Lyten 3D Graphene. (n.d.). Retrieved from https://lyten.com/3d-graphene/.

Machado, C., & Davim, P. (2022). *Innovation and sustainable manufacturing.* Oxford: Woodhead Publishing.

Melton, T. (2007). *Real project planning: Developing a project delivery strategy.* Oxford: Butterworth-Heinemann.

Natron is transforming industrial power. (n.d.). Retrieved from https://natron.energy/.

Pacheco-Torgal, F., Rasmussen, E., Granqvist, C., Ivanov, V., Kaklauskas, H., & Makonin, S. (2016). *Start-up creation* (1st ed.). Sawston: Woodhead Publishing

Pacheco-Torgal, F., Rasmussen, E., Granqvist, C., Ivanov, V., Kaklauskas, H., & Makonin, S. (2020). *Start-Up Creation* (2nd ed.) Sawston: Woodhead Publishing.

Phillips, B., & Landahl, M. (2020). *Business continuity planning.* Oxford: Butterworth-Heinemann.

Reichmuth, T., & Ewald, C.Y. (2022) Ten simple rules for building a successful science start-up. *PLoS Computational Bioljgy*, 18(4), article number e1009982. doi: 10.1371/journal.pcbi.1009982.

Silicon Valley. 2023. https://startupgenome.com/ecosystems/silicon-valley.

Smelser, N.J., & Baltes P.B. (2001). *International encyclopedia of the social & behavioral sciences*. Oxford: Pergamon.

The official website of Kodiak Robotics. (n.d.). Retrieved from https://kodiak.ai/company/.

The official website of Securly (n.d.). Retrieved from https://www.securly.com/solutions/all-solutions.

The official website of Skydio. (n.d.). Retrieved from https://www.skydio.com/about.

The official website of Pinecone. (n.d.). Retrieved from https://www.pinecone.io/company/.

U.S. Bureau of labor statistics. Business employment dynamics by age and size of firms. (2022). Retrieved from https://www.bls.gov/spotlight/2022/business-employment-dynamics-by-age-and-size/home.htm.

Verloop, J. (2013). *Success in innovation.* Oxford: Elsevier.

Weber, E. (2017). *Advisory boards in start-ups*. Wiesbaden: Springer Fachmedien Wiesbaden.

Xage Security – Company Profile. (n.d.). Retrieved from https://tracxn.com/d/companies/xage-security/__Nhb-CPIcq6bjro4F2or0eu5HkrNrDJtHc82MlRRCVS4.

100 fastest growing companies in Silicon Valley 2023: Top start-ups. (2023). Retrieved from https://growjo.com/city/Silicon%20Valley.

About Authors

Dr. Azyk OROZONOVA | Jusup Balasagyn Kyrgyz National University

Dr. Azyk Orozonova holds a PhD in Economics (2006) and has extensive expertise in international economics and external economic relations within the EAEU framework. Dr. Orozonova has authored several articles published in Scopus-indexed journals, focusing on sustainable development and economic theory. With over two decades of academic and practical experience, she has actively participated in international symposia and research initiatives, including those on green economy modeling and climate change adaptation. A recognized expert in economic forecasting and project analysis, she has made significant contributions to Kyrgyzstan's strategic economic development. Married with three children, Dr. Orozonova is committed to advancing interdisciplinary approaches to economic sustainability.

Dr. Amangeldi ZHUMADILOV | Kyrgyzstan Salymbekov University

Dr. Amangeldi Zhumadilov is the President of Salymbekov University and a distinguished expert in higher education reform and economic research. Holding a PhD in Economics from Kyrgyz-Turkish Manas University, he has made significant contributions to the integration of artificial intelligence and digital technologies in education, with a particular focus on IT disciplines. With over a decade of academic and administrative experience, Dr. Zhumadilov is also the General Director of the Askar Salymbekov Foundation, overseeing various scientific, educational, and charitable projects. He is an active participant in international collaborations and a recognized figure in quality assurance and modernization of Kyrgyzstan's educational system. Dr. Zhumadilov's research includes studies on monetary policy transmission in Kyrgyzstan, published in reputable journals. Through his leadership and commitment, he continues to advance education, research, and strategic partnerships both in Kyrgyzstan and globally.

Dr. Esengeldi ZHUMADILOV | Kyrgyzstan Salymbekov University

Dr. Esengeldi Zhumadilov is the Rector of Salymbekov University and a dedicated expert in economic research and educational innovation. Holding a PhD in Economics from Kyrgyz-Turkish Manas University, Dr. Zhumadilov has contributed significantly to advancing regional economic studies and fostering academic excellence in Kyrgyzstan. With extensive experience in leadership and academia, Dr. Zhumadilov plays a pivotal role in shaping Salymbekov University's strategic vision. He also serves as the Executive Director of the Askar Salymbekov Foundation, managing various initiatives focused on education, research, and community development. Dr. Zhumadilov's research interests include economic modeling, the influence of digital economies on regional development, and inflationary processes in Kyrgyzstan. He is actively involved in international collaborations and initiatives aimed at enhancing higher education quality and digital integration in academia.Through his innovative approach and commitment, Dr. Zhumadilov continues to drive progress in Kyrgyzstan's educational and economic landscapes, establishing impactful partnerships and contributing to global academic dialogues.

Aigerim AKMATOVA | I. Razzakov Kyrgyz State Technical University

Aigerim Akmatova is a master's student specializing in logistics and economic management at Kyrgyz Technical University named after I. Razzakov. She has enhanced her academic profile through advanced training in Management Accounting, IFRS, Logistics and Operations Management, and Python programming. Aigerim is proficient in Japanese (A2) and English and German (B1). Aigerim's research interests encompass logistics, regional economic disparities, and state audit issues in Kyrgyzstan. She has published significant work in these areas, including Scopus-indexed articles such as "B2C-Oriented Quality Control of Logistics Services Based on an Economic Perspective" and "Choosing a Mortgage-Lending Model in the Kyrgyz Republic." She has been recognized for her innovative research at the III International Competition of Young Scientists and continues to contribute meaningfully to addressing challenges in logistics and economic systems. Aigerim's dedication to her studies and research reflects her commitment to advancing practical and innovative solutions for Kyrgyzstan's logistics and economic sectors while building a promising academic and professional career.

Kashymbekov AKTAN | Kyrgyzstan Salymbekov University

Kashymbekov Aktan Iygilikovich is a student at Salymbekov University, Kyrgyz Republic, specializing in "Computer Science" at the IT College. Aktan demonstrates a keen interest in software development and the study of modern artificial intelligence technologies. As part of his education, he actively participates in various projects related to application development and systems aimed at solving current challenges in the IT field. He excels in studying algorithms and the fundamentals of cybersecurity, reflecting his ambition to become a highly sought-after professional in information technology. Aktan is focused on further developing his professional skills through participation in hackathons, internships, and specialized courses. His passion for learning and determination set him apart from his peers, making him a promising young specialist in the IT sector.

GREEN MEMBRANES FOR SUSTAINABILITY

Mustafa Ersöz

10.53478/TUBA.978-625-6110-22-9.ch13

Green Membranes for Sustainability

Mustafa Ersöz
Selcuk University

Abstract

Membranes are inevitable and effectively eliminate a wide range of hazardous substances, both organic and inorganic compounds, including metals, heavy metals, or other pollutants, and the most efficient tools, particularly for water treatment. In the last decade, membrane technology has played a pivotal role in addressing global sustainability challenges by offering efficient solutions for various applications, i.e. water and wastewater treatment, desalination, ion exchange, dairy industry, gas separation, chemical separations and energy applications, and so on. However, this advanced technology faces challenges, including toxicity and fouling of contaminants, posing safety risks in producing environmentally friendly and sustainable from the points of membrane structure and processes. Factors like sustainability, non-toxicity, performance enhancement, and commercial viability are pivotal concerns in green membrane fabrications. Therefore, it is essential to systematically and comprehensively review critical aspects of toxicity, biosafety, and the mechanistic intricacies of green membrane fabrications for sustainability. This review covers various facets of membrane fabrication to perform sustainability, encompassing their fabrication by using green nanoparticles, bio-sourced materials, green solvents, recycled materials, additive manufacturing, and their future perspectives. The evolution of green membrane fabrication presents an exciting avenue for advancing sustainability efforts, reducing environmental impact, and enhancing performance. Elucidating these aspects aims to underscore the importance and potential of green membranes in achieving sustainable development goals.

Keywords
Green membrane fabrication, Water treatment, Sustainability Toxicity and biosafety, Environmental impact

Introduction

Polymer membranes are ubiquitous, and the polymer membrane market is growing quickly and is estimated to reach US$ 7,251.4 million in 2023. Over the assessment period from 2023 to 2033, worldwide product demand is projected to exhibit a 4.4% compound annual growth rate (CAGR), resulting in a market size of US$ 11,153.9 million by the end of 2033 (Polymeric Membrane Market Outlook, 2023 to 2033). Their role in environmental pollution mitigation, water purification, and desalination is expected to grow to meet environmental and climate goals. Polymeric membranes are used in many large-scale and advanced separation processes across water treatment, wastewater treatment, medical (includes separation processes for blood disease treatments and bio-assay), and industrial (gas separation/purification and effluent treatment). There are various types of membranes used in processes such as microfiltration, ultrafiltration, pervaporation and osmosis (used materials such as fluoropolymers, polyarylsulfones, and polyolefins); nanofiltration (NF), reverse osmosis (RO) (materials include cellulose-based and polyamide composites), and ion-exchange; dialysis and filtration membranes (materials include fluoropolymers, polyaryl sulfones, and nonwovens). They are used in a number of domestic products, from electrical appliances to oil and water filters, as well as HVAC and other air treatments. They may be important in CO_2 capture, charge storage (membranes in electrochemical cells), and new molecular sensors.

Nowadays, most of the polymers used for membrane manufacturing are poly(vinylidene fluoride) (PVDF), polysulfone (PSU), poly-(ether sulfone) (PESU), poly(ethylene terephthalate) (PET), polyamide (PA) and poly(ethylene glycol) (PEG), etc. (Razali et al, 2015). All these polymers used for membrane development are fossil-based, non-biodegradable, and harmful to both humans and the environment. In addition, solvents such as N,N-dimethylacetamide (DMAc), dimethylformamide (DMF), or 1-methyl-2-pyrrolidinone (NMP), which are mainly used for membrane fabrications, also highly harmful and toxic to both health and environment concern and they are classified as substances of very high concern (SVHC) (Faggian et al, (2014) by European REACH Regulation (EC, 2006) and all these need to be recycled or reused in circular economy. In other words, many of the polymers used are based on fossil-fuel-derived systems, and many are fluorinated, necessitating the production of ‘forever chemicals’ and by-products of high global warming potential through manufacture or degradation. In order to eliminate these disadvantages and contribute to the European Green Deal (EC, 2020a) and The 2030 Climate target plan (EC, 2020b), the best alternative solution is to use and develop biodegradable membranes that offer a variety of potential uses, however they have a number of challenges and limitations in terms of biocompatibility, mechanical properties and degradability. It is crucial to thoroughly evaluate the biocompatibility, degradability, and mechanical properties of the membranes, including their degradation behavior and rate, to determine their suitability for specific applications (Ehsani et al., 2022). Degradation rate/time depends on the same factors: type of material, enzyme and microorganism concentration, pH, humidity, oxygen, and the conditions of the surrounding environment (Haider et al, 2019). Long-term biodegradation of the polymer membranes also leads to a high risk for environmental problems due to increased waste disposal. Therefore, a thorough understanding of the mechanisms of membrane degradation needs to be evaluated in terms of the membrane's performance in a particular application.

In recent years, there has been a trend towards using more environmentally friendly materials that reduce the use of single-use polymeric membranes. Therefore, the reusability of these biodegradable membranes is also important to minimize waste disposal. Moreover, examining biodegradable membranes' thermal stability, mechanical stability, and swelling rate is essential. To enhance their performance, nanoparticles and cross-linking agents can be added to the membranes, improving the biodegradation rate and making them non-toxic and biodegradable. These environmentally responsible materials can aid in preserving the sustainability of the membranes and enhance their biodegradation rate in the natural environment.

In our global and future perspective, sustainability is a major challenge for us as well as our future generations, demanding a delicate equilibrium between economic priorities and environmental consciousness. In this context, the new, innovative, and more sustainable industrial technologies, characterized by reduced energy consumption and minimized waste and wastewater generation within a circular economy framework, assume paramount importance (Geissdoerfer M. Et al. 2017). Consequently, membrane technology has gained prominence since its inception in previous decades due to its inherently lower energy demands, superior efficiency, and cost-effective points. Membranes have emerged as transformative elements in redefining separation processes, assuming a pivotal role across diverse applications in advanced separation methodologies (Kim and Nunes, 2021; Nunes et al, 2020). Membrane technology applications have also been used in new fields encompassing energy conversion, resource recovery, the production of value-added products, and innovative smart drug delivery systems (Diroli et al., 2021). In all these fields, membrane technology applications have been approved due to their extraordinary properties, including significantly reduced energy consumption, markedly heightened selectivity, diminished carbon footprint, and simplified operational procedures. Despite advancements in membrane technologies over recent decades, there remains a pressing need for further enhancements. This includes requirements for reduced energy consumption, decreased fouling susceptibility, heightened physicochemical durability, enhanced cleanability, superior selectivity, increased permeability, zero waste in manufacturing, cost reduction, and improved membrane module reusability/recyclability (Teodora et al., 2022). Presently, commercial membranes, whether polymeric or inorganic, rely on a limited range of materials that were not originally designed for membrane production for sustainability.

In order to address these challenges, new innovative green membranes are expected to be an alternative solution for conventional membranes for sustainability, produced from renewable materials, including wood-based polymers, or re-use and recycling of biopolymers in terms of flux and antifouling properties. In many cases, biodegradable membranes have shown comparable performance to commercial ones like PES, PVDF, and PTFE. There's a wide scope for creating new eco-friendly membranes and modifying natural or full biomaterials to perform the membrane properties with conventional membranes, expanding their potential uses. However, there are still a number of challenges and limitations with green or biodegradable membranes for application purposes in the market, including their degradation rate and composition with non-biodegradable materials, which can lead to waste disposal and environmental pollution. Further research is needed to understand the degradation mechanisms and how microorganisms and enzymes behave in various environments. Additionally, as green membranes are typically produced on pilot scales, more efficient scale-up models are needed to expand production.

The use of polymer membranes in applications such as CO_2 capture and batteries, as well as healthcare and mitigation, are wholly necessary to meet climate and environmental goals. They will be continually developed in applications such as those detailed above in order to reach net zero 2050 targets. However, their role as largely single-use plastics, their lack of recyclability, their non-biodegradability, and their fossil fuel sources negate their potential benefits, and there is a clear need to develop polymer membranes from materials that themselves have low environmental or climate impact and are based on renewable resources rather than fossil fuels. Therefore, a fully innovative green process desperately needs to be developed for the membrane preparation process, replacing the conventional process, and using green solvents from renewable sources. In addition, used solvents should be efficiently treated or recycled before discharge. In conclusion, all the conventional membrane fabrication processes need to be replaced with the innovative green process, which has to be fully biobased materials for the circular economy.

Green Nanoparticles

Using green chemistry principles in the fabrication of nano-enhanced membranes presents a promising avenue to reduce reliance on petroleum-based, potentially hazardous membranes and their associated costs (Rethinam et al., 2020). Additionally, concerns surrounding the disposal and recyclability of synthetic nano-enhanced membranes, there are still a number of significant challenges for manufacturers (Razmjou et al., 2019a, 2019b; Landaburu-Aguirre, 2016; Lawler, 2012). Recently, increased attention and investment have been directed toward developing green membranes and their components by using different nanomaterials for green membrane fabrication (Wang et al., 2023). Although preparing these green membranes typically involves chemical reactions that may not be entirely sustainable, they demonstrate a superior environmental profile compared to some commercially used chemicals. Despite the rapid advancement in manufacturing green-synthesized nanomaterials and their application in membrane development, a comprehensive review and discussion regarding the mechanisms underlying the properties and performance of green nano-membranes in water treatment are currently lacking.

Nowadays, most green membranes have been prepared using green nanoparticles as mixed matrix membranes (MMM) and thin-film nanocomposite (TFN) membranes. Green nanoparticles have a wide variety of properties, such as size, shape, porosity, and reactivity. In this regard, carefully selecting the source and the green reaction medium is primely important. In recent years, there's been an increasing focus on exploring the synthesis and application of green nanoparticles across various fields, notably in preparing nanocomposite membranes (Hamid et al., 2020 & Nthunya et al., 2019), reported the potential of natural extracts which are incorporation into membrane materials as green nanoparticles.

Green membrane technology encompasses using environmentally friendly nanoparticles and innovative novel fabrication methods in the nanofabrication approach. These nanofabricated membranes possess a high surface-area-to-volume ratio, enhancing their efficiency while reducing the requisite material quantity for specific applications. Notably, nanofiber membranes are designed by using different techniques such as electrospinning, electroblowing, or blown-spinning. These methods significantly curtail the use of polymers and solvents compared to conventional fabrication approaches (Sanaeepur et al., 2022). In the near future, using natural extracts, such as apples or other natural extracts, to synthesize nanoparticles and modify them for various applications might be possible. Researchers have the opportunity to explore how these altered nanoparticles could potentially elevate membrane performance, like boosting salt rejection and bolstering mechanical resilience.

Membrane technology using nanofibers has found extensive applications across multiple sectors encompassing energy, medicine, biology, and environmental domains. Nanofiber-incorporated membranes, known for their high efficacy at low pressure, hold potential in various purification processes such as blood, air, and wastewater purification. Their superior adhesion to biological surfaces makes the membranes particularly suitable for applications in transdermal drug delivery systems (Yoo et al., 2009). Typically exhibiting cross-sectional diameters ranging from 10 to 100 nm, nanofibers boast a significant specific surface area and a high surface area-to-volume ratio. Additionally, their structure allows for creating highly porous fibers with extensive network connectivity.

Furthermore, nanofiber membranes stand out due to their exceptional porosity, high vapour permeability, and interconnected open pore structures, setting them apart from standard membranes. The outstanding qualities of nanofiber membrane-based technology, including flexibility, ease of control and scaling, energy efficiency, and eco-friendliness, have spurred swift advancements in membrane science and technology (Yadav et al., 2021).

Nanofibers fall under two classification criteria: the first pertains to their raw materials—organic, inorganic, carbon, and composite fibres; the second focuses on their structures—nonporous, mesoporous, hollow, and core-shell fibres [Gugulothu et al., 2019). This multifaceted structure grants greater adaptability in tailoring nanofiber properties to meet specific requirements through chemical ingenuity. Traditional methods often necessitate substantial solvent usage, and mismanagement of residual wastes and non-compliance with safety regulations exacerbate environmental concerns. Hence, ensuring the integration of safety measures and green chemistry practices is crucial in mitigating these challenges.

Moreover, in pursuing green strategies for membrane production, several pivotal factors are required to ensure the resulting membranes possess desirable characteristics. These include achieving high membrane packing density and selectivity, effectively managing concentration polarization and membrane fouling, and ensuring efficiency in processing, maintenance, and scalability, all while minimizing expenditure and energy consumption. Accomplishing these objectives without relying on non-green materials and methodologies or generating substantial amounts of toxic and hazardous residual waste represents a significant achievement.

While recognizing the importance of a comprehensive understanding of greener approaches in nanofiber membranes, the current knowledge remains somewhat limited. Hence, this review aims to present a cutting-edge approach encompassing a complete strategy for green nanofiber membranes. It covers aspects ranging from raw materials, solvents, methods, and techniques employed in membrane fabrication to post-treatment processes. Ultimately, this review summarizes key findings and highlights future challenges and prospects in this domain.

Nanofiber membranes have garnered recognition in filtration and separation arenas due to their distinct attributes: adjustable nanoscale diameters and morphology, high porosity, substantial surface area-to-volume ratio, robust internal connectivity, and exceptional mechanical properties. However, prioritizing human health, environmental impact, and expanding applications necessitates developing and integrating a green strategy for nano-enhanced membranes—ones that are safer, non-toxic, sustainable, and eco-friendly. Employing green polymer-based materials, including natural polymers and bio-synthesized and synthesized chemicals, aligns with the ethos of sustainable progress, ensuring eco-friendliness.

Bio sourced materials

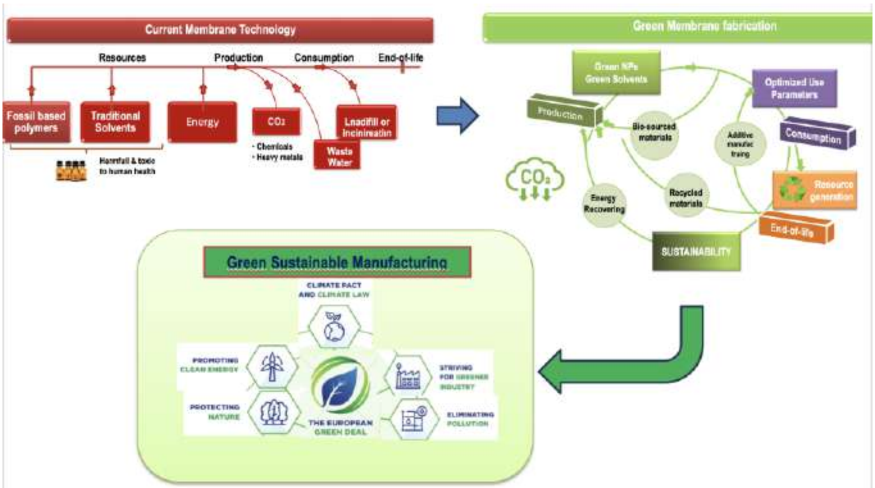
In conventional techniques for membrane production, the primary reliance lies on non-biodegradable polymers and inorganic materials sourced from petroleum-based resources. This association of conventional polymers with membrane fabrication has implications for the global energy crisis. Conversely, green membranes utilize nontoxic, biodegradable polymers, alongside bioinspired or biomimetic materials, offering a more sustainable and environmentally benign alternative to traditional synthetic polymers. The emergence of bioinspired or biomimetic materials, mirroring the structure and functionality of biological membranes, can be crafted from natural or renewable sources and applied across various domains, including water treatment, desalination, and gas separation processes etc. (Lustenberger & Castro-Munoz, 2022; Bandehali et al., 2021).

Various membrane operations like microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO), pervaporation, membrane distillation, and electrodialysis are commonly employed for many applications. However, pore sizes decrease as membrane separation efficiency increases, necessitating higher pressure application. Consequently, mechanically stable, flexible, and thermally resistant synthetic polymers such as PVDF, PAN, PTFE, PS, PES, PEI, and polyethylene are predominantly used. Yet, the adverse environmental and health impacts of these fossil-based polymers have spurred a shift towards biodegradable alternatives like polylactic acid (PLA), polyhydroxyalkanoates (PHA), polybutylene succinate (PBS), cellulose, chitin, chitosan, alginate, collagen, lignin, sporopollenin etc. (Xie et al., 2020; Jiang, 2020).

Over recent decades, membrane technology has emerged as a widely adopted and swiftly expanding separation method, offering numerous advantages over conventional techniques, such as easy setup and operation, minimal energy and chemical usage, cost efficiency, compact space requirements, and decreased environmental impact (Xie et al., 2021). However, certain aspects of membrane production, mainly fossil-based polymers and solvents, lack sustainability. The reliance on fossil-based polymers and extensive use of hazardous organic solvents in membrane fabrication pose severe risks to both health and the environment (Nanda et al., 2022). The membrane market has long been dominated by petroleum-derived nonbiodegradable polymers, extensively utilized across various sectors like water & waste-water treatment, desalination, gas separation, food& beverage, pharmaceutical, and medical industries, despite their notable adverse environmental effects (Bandehali et al., 2022). These polymers, being nonrenewable and resistant to degradation, raise concerns regarding their production and disposal practices, often generating microplastics that negatively impact ecosystems and living organisms (Nguyen Thi et al., 2022). To address these challenges, researchers focus on developing bio-based or biodegradable polymers for membrane manufacturing, aiming to drive a greener transformation in membrane technology. Several strategies, inspired by the 12 principles of green chemistry and green chemical engineering and embracing a cradle-to-grave approach, have been proposed to enhance the environmental sustainability of membrane technology, as illustrated in Figure 1. In the forthcoming decades, the chemical industry is anticipated to transition towards wholly sustainable and environmentally friendly processes. Within the membrane manufacturing phase, five distinct strategies have been suggested to enhance sustainability (Xie et al., 2021). Firstly, replacing entirely or partly the nonbiodegradable fossil-based polymers with renewable bio-based counterparts holds significant promise due to their biodegradability, biocompatibility, versatility, low carbon footprint, reduced toxicity, and societal acceptance (Xie et al., 2021; Nanda et al., 2022). Secondly, substituting toxic traditional solvents, such as 1-methyl-2-pyrrolidinone (NMP), dimethylformamide (DMF), and N,N-dimethylacetamide (DMAc), with greener alternatives (Haque Mizan, et al. 2023). Thirdly, wastewater-primarily composed of organic solvents and polymers generated during membrane manufacturing, as a substantial volume remains untreated, estimated at over 50 billion litres globally annually (Razali et al., 2015). The fourth strategy involves streamlining membrane fabrication steps to reduce the use of toxic solvents, thereby lowering energy consumption and costs. Lastly, considering room temperature for casting solution preparation could minimize energy consumption in the process.

Figure 1.

Green membrane fabrication concept for sustainability



Recyclable Materials

Over millions of membrane modules, mainly reverse osmosis (RO), have been manufactured, and their use time in the process is about 5 years; many of them are discarded and could result in the disposal of hundreds of thousands of tons of intricate composite items, with only approximately 5% by weight comprising direct membrane materials, while the rest comprises spacers and casings. While disassembling these membrane modules is labour-intensive, there might be potential to recover the polymeric materials used in the spacers and main casing components. However, recycling the membrane materials themselves poses significant challenges as they require harsh chemical treatments for valorization. New strategies are urgently required to tackle these challenges and enhance production efficiency while reducing waste. An additional facet of green membranes involves incorporating recycled materials into membrane production. For instance, employing recycled plastic waste as a constituent for polymeric membranes can significantly mitigate the environmental impact associated with conventional manufacturing methods. Recent investigations have also explored the use of waste materials such as animal bones and keratin for membrane fabrication. Consequently, reevaluating waste materials as valuable resources for membrane production presents a viable avenue towards establishing the membrane industry as a sustainable industrial model (Goh et al 2021).

The circular economy, centered on efficient resource management to curb waste generation and foster more sustainable production, revolves around three key principles: reduce, reuse, and recycle (Abou Taleb & Al Farooque, 2021; Lieder & Rashid, 2016), Membrane technology, developed for various applications spanning water treatment, desalination, gas purification, dairy and beverage processing, and energy generation, owes its widespread adoption to its potential for selective separation, ease of configurability, moderate energy consumption, reduced carbon footprint, recovery of valuable substances, and substitution of processes involving harsh and hazardous chemicals (Nunes et al., 2020, Xie et al., 2021). With mounting concerns regarding the adverse effects of conventional fabrication materials and techniques on human health and environmental pollution, a paradigm shift in membrane technology that emphasizes new material sources and reduces raw material usage has emerged (Yadav et al., 2021; Ding et al., 2021). Notably, the membrane industry heavily relies on non-degradable materials and highly toxic chemicals and solvents, many of which were developed during periods of lax environmental regulations compared to today's standards (Shi et al., 2014; Zou et al, 2021). Thus, aligning membrane fabrication with sustainability and environmental protection demands a shift towards greener practices.

Recent suggestions aimed at transforming the membrane industry toward sustainability include strategies proposed by Xie et al. (2020), advocating for the adoption of biodegradable polymers, greener solvents, sustainable fabrication processes, the reuse of wastewater-generated ingredients, sustainable module design, and module recycling. These strategies aim to enhance the membrane industry's sustainability and promote sustainable membrane and membrane process development. When assessing materials for membrane fabrication, numerous potentially reusable and recyclable resources emerge within and beyond the membrane industry (Al-Mutwalli et al., 2023). Discarded plastics, waste paper, newspapers, and reusable elements sourced from waste and wastewater generated during membrane production stand as viable candidates for creating new membranes. Notably, the yearly output of wastewater from the membrane industry amounts to 50 million cubic meters, containing polymers, solvents, and additional additives. The focus should be on reclaiming these constituents to enable cost-effective and environmentally sound membrane production. Waste originating from agricultural produce and animal byproducts, alongside postconsumer plastics, represent primary sources for membrane fabrication materials. For instance, animal-derived waste materials such as wool, hair, and poultry feathers (Goh et al., 2021), as well as crop residues like corn husks, maize, rice straws, sunflower, and wheat stalks, exhibit numerous advantages: abundant supply, renewability, and low energy requirements for conversion into new raw materials suited for membrane fabrication (Debnath et al., 2021). Assessments on polymers and postconsumer plastics indicate a staggering production of 6.3 billion tons of plastic waste over the last 70 years, with a mere 9% being recycled (Li et al., 2021). This substantial volume of discarded plastic positions it as a viable and recyclable raw material within the membrane industry. Leveraging these newly identified resources for reusing and recycling discarded materials, both within and beyond the membrane industry, could significantly propel the shift toward more sustainable and environmentally friendly membrane manufacturing processes (Li et al., 2021). This review delves into organic and inorganic recyclable materials pivotal for membrane fabrication within the context of recycled materials. The aim is to establish a comprehensive framework outlining recyclable materials, thus fostering a crucial and leading role in steering the membrane fabrication industry toward a greener and more sustainable transformation.

While the potential of biopolymers is extensive, the bioplastics market encounters several limitations and hurdles it must overcome. Factors like material costs, cost-effective manufacturing, compatibility with existing infrastructure, and waste management significantly influence this market. Conversely, elements such as material availability, end-of-life product management, and waste remediation favor bioplastics, as many raw materials are sourced from nature and are readily biodegradable. However, there's limited understanding of the synthesis of bioplastics for some of these biomaterials, driving the search for more cost-effective extraction methods and exploring their potential for large-scale production. Bioplastics, known for their biodegradability and eco-friendly extraction, offer potential in the current membrane market. Yet, the biodegradability of certain bioplastics remains debatable, requiring proper remediation technologies and sorting facilities for distinct waste types instead of direct landfill deposition. Different membrane fabrication techniques can tailor functional groups of various bioplastic materials, yet more research is needed regarding their stability, simple chemical synthesis, or biosynthesis. These biomaterials can substitute more environmentally hazardous nanomaterials in surface modification of membranes.

Green Solvents

Membranes are widely used and approved as a clean and environmentally friendly separation process with lower energy consumption compared to conventional techniques. However, the utilization of highly toxic chemicals, non-degradable hydrocarbon-based polymers, and harmful solvents, as used for the current membrane materials and fabrication techniques, have been identified as harmful materials for the sustainable development goals of the United Nations. Consequently, the materials used for membrane development are seriously questioned. Furthermore, concerns persist regarding the impact of membrane production, polymers, and chemicals on human health, water source contamination, global warming, and marine ecotoxicity (Yadav et al., 2021; Ding et al., 2021). Therefore, there is a critical need to envision the next iteration of membranes and their fabrication techniques, employing markedly cleaner and more sustainable approaches. Various alternative strategies have been explored and developed thus far, such as methods utilizing greener polymers, fewer chemical solvents (e.g., electrospinning, electroblowing), using eco-friendly solvents (e.g., DMSO) in the fabrication process, solvent-free techniques like 3D printing, and the utilization of bio-sourced, biodegradable, and/or natural polymers. Figure 1 illustrates the primary transformative alternatives in green membrane technology, categorizing these advancements into two main groups: green membranes and green membrane processes (Yusuf et al., 2020). Notably, 'green' membrane technology encompasses various approaches, including the utilization of biodegradable polymers and non-toxic solvents for membrane coating/casting, substituting non-biodegradable petroleum-based products and hazardous solvents. Other strategies involve minimizing preparatory steps to reduce energy consumption and waste generation, recycling useful membrane components, managing waste brine or sludge, reducing fouling tendencies, and harnessing energy from waste (Xie et al., 2020; Jiang and Ladewig, 2020; Aburabie et al., 2020; Carner et al., 2020).

The driving force behind innovation and new discoveries in sustainability and environmental impact mitigation stems from the adoption of the green chemistry approach. This approach is motivated by health concerns and a growing environmental consciousness. Consequently, extensive research and development efforts are channeled toward identifying eco-friendly alternatives in raw materials, methodologies, solvents, and energy usage. The emergence of groundbreaking advancements in green material production, waste reduction, recycling, and energy/cost efficiency signals promising prospects for a more sustainable and environmentally conscious future. Moreover, integrating economic, social, and environmental components is the cornerstone for establishing sustainability (Mohamed & Yousef, S., 2021, Clarke et al., 2018).

Green methodologies, like solvent-free electrospinning, have been focused on their ability to generate ultrafine fibers efficiently, with zero solvent evaporation, minimal toxic waste, and the production of less soluble fibers, yet challenges persist. These challenges encompass high setup requirements, relatively larger fiber diameters, lack of systematic theoretical guidance, and incomplete large-scale production methodologies. Despite recent strides in developing the green strategy for nanofiber membrane technology, achieving widespread utilization in industries demands continued effort. Future research should prioritize the development and adoption of water-soluble polymers, the elimination of harmful organic solvents, and the optimization of solvent-free electrospinning devices. Shifting from expensive, limited material sources to more affordable, non-toxic, and environmentally friendly alternatives is imperative. Furthermore, enhancing mechanical performance and structural design will broaden potential industrial applications. Introducing green materials, using water-based or less toxic solvents, and embracing solvent-free or reduced-solvent methods for fabricating green-based nanofiber membranes are crucial steps in aligning with industrial production practices.

Green membrane fabrication is an essential aspect of sustainable development, aiming to minimize the environmental impact of membrane production. Several studies have highlighted the importance of employing green chemistry and sustainable materials in membrane fabrication and emphasized the significance of green chemistry in minimizing the generation of hazardous compounds during membrane preparation. Furthermore, successfully replaced toxic solvents with a green solvent, PolarClean, during ultrafiltration membrane fabrication, marking a significant step towards sustainable membrane production (Xie et al., 2019).

However, despite the progress that membrane fabrication is yet to be fully green, indicating the need for further advancements in this area (Park et al., 2021), also highlighted that while membrane-based operations are generally considered green and sustainable, the membrane fabrication process itself still lags behind in terms of sustainability (Meringolo et al., 2018). Moreover, emphasized that sustainable membrane fabrication remains an unsolved challenge, essential for overall membrane filtration to be considered truly green (Le Phuong et al., 2019). Several studies have proposed the use of green solvents and eco-friendly materials in membrane fabrication. For instance, emphasized the importance of employing green solvents in membrane fabrication, as highlighted in recent review articles (Park et al., 2021). While some biomaterials display antimicrobial properties against common microorganisms, their effectiveness against the various microorganisms found in feed wastewater remains uncertain. Bio-based cross-linkers like phenalkamine (FA) which is produced through the Mannich reaction of cardanol with certain amines, which results in a partly bio-based polymer (Pirada, 2022) and can replace synthetic ones but might require additional nanomaterials to enhance stability. Despite the functional benefits bio-based polymers and additives offer in membrane fabrication, the process has not yet entirely transitioned to green technology. Green solvents like triethyl phosphate (TEP) and methyl-5-(dimethylamino)-2-methyl-5-oxopentanoate (Rhodiasolv PolarClean) show promise in membrane fabrication, potentially transforming synthetic membranes into greener alternatives by replacing conventional organic solvents (Russo et al., 2023).

Additive Manufacturing

Additive manufacturing (AM) shows potential to reduce environmental impacts in manufacturing by cutting material use and enabling local production (Jung et al., 2023). However, high production costs and increased energy use in mass production limit its viability compared to traditional methods. The economic and environmental preference for AM depends on factors like production volume and part size. Addressing challenges such as material costs and production speed requires advances in material science and technology beyond just scaling up AM operations. Comparative studies show that AM has lower environmental impacts at very low production volumes unless the part geometry is specific. Higher production costs and environmental impacts of AM at large volumes can be balanced by factors like small part size or performance advantages. Future advancements in material production and AM processes could enhance its environmental and economic benefits. Additionally, studies should incorporate lifecycle energy consumption, CO_2 emissions, human toxicity, and lifecycle cost metrics.

Advancements in solvent-free fabrication techniques, such as 3D printing, hold promise in diversifying membrane technology. Employing 3D printing to create different membrane module components presents an avenue for unparalleled customization and process optimization. However, this technology necessitates further exploration and refinement to enable the production of defect-free membranes and modules at larger scales, especially in fabricating membranes featuring nanoscale pores (Tijing et al., 2020). Additive manufacturing, also known as three-dimensional (3D) printing, involves creating numerous nanofibers that are subsequently compressed to shape objects according to specific dimensions, shapes, and porosities. Comparing 3D printing to traditional manufacturing methods reveals several advantages which offer flexibility in integrating diverse designs and geometries with precise control over object porosity, thickness, and structure, layer-wise control of pore density with varied particle sizes, enhanced resolutions, the ability to produce mechanically robust and chemically resistant objects, a swift and scalable process, and reduced reliance on toxic solvents compared to conventional methods (Sreedhar et al., 2023).

The potential of 3D printing is foreseen to address numerous challenges in membrane production. Enhanced designs in membranes could significantly improve performance and durability. Presently, two widely used membrane types are ceramic and polymeric membranes. Additive manufacturing stands to bridge this gap by enabling the fabrication of cost-effective membranes, offering better control over fabrication parameters (Sreedhar et al., 2023). However, limitations exist in the current state of AM-based membranes, particularly in their restricted resolutions and comparatively lower printing speeds. Furthermore, 3D printing presents opportunities for manufacturing other essential components of membrane modules, overcoming various design constraints. However, despite its potential, challenges persist; for instance, commercializing microfluidic-based products encounters limitations in manufacturing, leading to renewed interest in using AM techniques to craft tailor-made microfluidic devices (Sreedhar et al., 2023). Researchers aim to integrate porous materials into 3D-printed nonporous fluidic devices for applications in membrane separations. Yet, this endeavor faces limitations in material choices, printing control within microfluidic environments, and mitigating fouling and undesirable solute-material interactions. Despite its advantages, 3D printing in membrane technology encounters drawbacks compared to conventional manufacturing, such as limitations in printable materials, desired porosities, and object dimensions. Optimization based on the polymer's chemical nature and membrane structure is crucial, considering 3D printing's relative costliness, limited build volume, resolution, and material choices.

Challenges and Outlook

This review focuses on various innovative approaches to green membrane manufacturing, including the utilization of green solvents, bio-sourced polymers, recycled materials, and additive manufacturing strategies. However, these approaches are presently confined to laboratory-scale experiments and necessitate further demonstration to achieve commercial readiness. Nevertheless, the proliferation of industry-linked research projects in this domain underscores the escalating demand for such innovations on a larger scale.

The emergence of eco-friendly approaches and sustainable practices in separation science enables the more environmentally conscious processing and reutilization of membrane materials. Creating a circular economy requires establishing interconnected closed-loop systems that eliminate waste streams and prioritize recycling or repurposing materials to sustain or improve their value. This transformation, crucial in membrane science, engineering, and various industries, calls for innovative engineering solutions that support fresh design perspectives. Developing eco-friendly solutions can streamline material recycling in a circular manner, aiding in the formulation of more efficient strategies from the outset. This approach ultimately reduces environmental impact and energy requirements, marking a significant stride toward sustainability.

Despite advancements made thus far, hurdles persist in the widespread adoption of environmentally friendly membrane technology. The substantial manufacturing costs associated with biodegradable membranes are a formidable challenge, necessitating focused research and development endeavors. Advancements in materials science and engineering offer promise in introducing novel membrane materials with improved selectivity and permeability, driving sustainability efforts forward. Moreover, fine-tuning membrane fabrication techniques and processes themselves could augment the efficiency and longevity of green membrane technologies. The future course of green membrane technology entails synergizing with other eco-friendly technologies, such as leveraging renewable energy sources like hydrogen, solar, wind, or geothermal energy. Additionally, tapping into industrial waste heat to power membrane-based processes represents a pivotal integration (Shirazi et al., 2023). These strategic amalgamations harbor significant potential for substantially reducing the carbon footprint while fortifying overall sustainability initiatives. With continued commitment to advancement and collaboration, green membranes can play a pivotal role in tackling environmental challenges and fostering a more sustainable and resilient future.

A critical area that warrants further attention is the methodical assessment of the life cycle of membrane materials and systems. It's imperative to systematically integrate such tools into the design of membrane materials to ensure viability, scalability, and environmental relevance. Frequently, intriguing material solutions offered at the laboratory level are not commercially feasible due to evident cost and sustainability concerns. Additionally, the exploration of biodegradable membranes needs further evaluation to mitigate waste disposal issues and support the breakdown of materials into non-toxic compounds through natural enzymatic or environmental processes. Biodegradable membranes hold promise as potential alternatives to conventional ones. Moreover, there's a significant call for comprehensive lifecycle assessments that encompass the entire span of existing and newly developed green membranes. These evaluations, covering everything from production and operation to eventual disposal or recycling, would yield a deeper understanding of the environmental impact of these membranes and their processes.

Future perspectives

Membrane technology stands as a cornerstone in the pursuit of sustainable practices across industries. Its versatile applications, spanning from water purification to biomedical fields, highlight its pivotal role in addressing pressing global challenges. While effective, traditional membrane fabrication methods often pose significant environmental concerns due to the use of non-renewable resources and energy-intensive processes. The advent of green membrane fabrication offers a transformative shift towards sustainable practices, minimizing environmental footprints while maintaining or enhancing performance metrics.

The concept of green membranes revolves around the integration of eco-friendly materials and environmentally conscious fabrication techniques. These membranes are designed to harness the principles of sustainability throughout their life cycle, from material selection and fabrication processes to application and disposal/recycling. By embracing biodegradable, renewable, or recycled materials and employing low-energy, solvent-free, or bioinspired fabrication methods, green membranes aim to reduce resource consumption, minimize waste generation, and mitigate environmental impact compared to conventional counterparts.

The rationale for delving into green membrane fabrication stems from the urgent need to address environmental degradation, resource depletion, and the growing demand for sustainable technologies. This exploration is driven by the inherent potential of green membranes to offer solutions that mitigate environmental harm and optimize performance, durability, and cost-effectiveness. Understanding the significance and possibilities of green membranes is paramount in fostering a sustainable future across diverse sectors, ranging from water treatment and energy production to healthcare and beyond. The future of green membrane fabrication rests on its ability to scale sustainably. Innovations will focus on seamlessly transitioning eco-friendly processes from laboratory-scale experimentation to large-scale industrial production. Circular economy principles will drive the adoption of recycling and reuse strategies, minimizing waste and resource consumption throughout the membrane life cycle.

Advancements in fabrication techniques will revolutionize the scalability and precision of green membrane production. Additive manufacturing and 3D printing methodologies will enable intricate membrane designs using eco-friendly materials, fostering unparalleled control over membrane architecture. Integrating artificial intelligence and machine learning algorithms will optimize fabrication processes, ensuring efficiency and reproducibility at industrial scales. Although additive manufacturing (AM) has progressed significantly, its full potential in membrane technology remains untapped. The application of 3D printing in membranes and membrane modules is still at an early stage, necessitating further exploration. To enhance its deployment and applicability, several future perspectives were outlined (Koo et al., 2021). The direct printing of membranes with submicrometer-sized pores faces challenges due to the limited resolution of current 3D printers. Implementing hybrid AM in membrane technology could redirect future studies, enhancing spacer properties, such as chemical and mechanical stability, for broader commercial applications. However, limitations in hybrid AM regarding materials compatibility, process interconnectivity, and interfacial bonding need addressing (Koo et al., 2021). Most current research on 3D printing in membrane technology is confined to lab-scale testing, often under unrealistic conditions (Atkinson, 2018; Nunes et al., 2019). Scaling up and resolving material issues are key to realistically testing these structures/units in larger industrial applications. Addressing upscaling challenges involving build size, printing speed, and manufacturing power is essential to commercialize 3D printing in membrane technology. Moreover, current 3D printing speeds lag significantly behind conventional manufacturing methods, impacting commercial feasibility. Additionally, material issues, such as material selection based on implementation and environmental conditions, are critical for industrial-scale 3D printing realization in membrane technology.

The emergence of four-dimensional (4D) printing holds promise for membrane technology's future. This technology adds a fourth dimension to 3D printing, utilizing intelligent materials that respond to specific stimuli. Intelligent materials offer self-repair, multifunctionality, and self-assembly properties. Yet, their exploration of membrane technology, including spacers, membranes, and modules, remains unexplored. Future studies in 4D printing could transform 3D-printed membranes into commercial reality, fabricating optimized fouling-resistant and self-cleaning spacers, smart membranes with varying properties under different conditions, and components responsive to stimuli like concentration, pH, and charge (Koo et al., 2021).

Surface modification and coating of polymer membranes serve to either create new or enhance existing properties by altering the surface chemistry, a process known as functionalization. This modification aims to elevate separation performance while preserving the inherent properties of the membrane. These approaches can occur during the membrane fabrication phase or as post-treatment methods after membrane production. In water purification applications, treating the membrane surface plays a pivotal role in combating fouling, which typically falls into five primary categories: biofouling, protein fouling, antifoam fouling, colloidal fouling, and scaling fouling.

Acknowledgment

The author thanks financial support from the Turkish Academy of Sciences (TUBA) and the “Reinforcing the Scientific Excellence of Selcuk University in Engineered Surfaces and Films for Emerging Technologies” project (GA: 952289), European Union’s Horizon 2020 Research and Innovation program.

References

Abou Taleb, M., & Al Farooque, O. (2021). Towards a circular economy for sustainable development: An application of full cost accounting to municipal waste recyclables. *J. Clean. Prod.* 280(124047), 1-3.

Aburabie, J.H., Puspasari, T., & Peinemann, K.-V., (2020). Alginate-based membranes: paving the way for green organic solvent nanofiltration. *J. Membr. Sci.,* 596(117615).

Al-Mutwalli S.A., Taher, M.N., Koseoglu-Imer, D.Y., Sanaeepur, H. and Shiraz, M.M.A. (2023). Recycled materials for membrane fabrication. In L. F. Dumee, M. Sadrzadeh, M. M. A. Shirazi (Eds), *Green Membrane Technologies towards Environmental Sustainability,* (pp.75-112). Elsevier

Atkinson, S. (2018). NanoSun, Nano Sun launches 3D-print plant for water filtration membranes. *Membrane Technology,* 10, 10-11, http://doi:10.1016/S0958-2118(18)30208-8

Bandehali, S., Sanaeepur, H., Ebadi Amooghin, A., Shirazian, S., & Ramakrishna, S. (2021). *Biodegradable polymers for membrane separation. Sep. and Purif. Technol.,* 269, https://doi.org/10.1016/j.seppur.2021.118731

Carner, C.A., Croft, C.F., Kolev, S.D., & Almeida, M.I.G. (2020). Green solvents for the fabrication of polymer inclusion membranes (PIMs). *Separ. Purif. Technol. 239.* https://doi.org/10.1016/j.seppur.2019.116486

Clarke, C.J., Tu, W.C., Levers, O., Brohl, A., & Hallett, J.P. (2018). *Green and sustainable solvents in chemical processes. Chem. Rev. 118,* 747-800. https://doi.org/10.1021/acs.chemrev.7b00571

Debnath, B, Haldar, D., & Purkait, M.K. (2021). A critical review on the techniques used for the synthesis and applications of crystalline cellulose derived from agricultural wastes and forest residues. *Carbohydr. Polym. 273.*

Ding, H., Zhang, J, He, H., Zhu, Y., Dionysiou, D.D., Liu, Z., & Zahoo, C. (2021). Do membrane filtration systems in drinking water treatment plants release nano/microplastics? *Sci. Total. Environ.* 755, 142658.

Drioli,E., Macedonio, F., & Tocci,E., (2021) Membrane science and membrane engineering for a sustainable industrial development. *Sep. Purif. Technol. 275,* 119196. https://doi.org/10.1016/J.SEPPUR.2021.119196

EC. (2006). Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH)1907/2006, Latest update: 27/04/2021, https://echa.europa.eu/regulations/reach/understanding-reach EC, 2020, European Green Deal Report, https://www.esdn.eu/fileadmin/ESDN_Reports/ESDN_Report_2_2020.pdf.

EC. (2020b). The 2030 Climate target plan, COM(2020) 562 final, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0562&from=EN

Ehsani, M., Kalugin, D., Doan, H., Lohi, A. & Abdelrasoul, A. (2022). Bio-Sourced and Biodegradable Membranes. *Appl. Sci.,* 12, 12837. https://doi.org/10.3390/ app122412837

Faggian, V., Scanferla, P., Paulussen S., & Zuin, S. (2014). Combining the European chemicals regulation and an (eco) toxicological screening for a safer membrane development. *J. Cleaner Prod.,* 83, 404–412.

Geissdoerfer, M., Savaget, P., Bocken, N. M. P. & Hultink, E. J. (2017). The circular economy a new sustainability paradigm? *J. Clean. Prod.,* 143, 757-768. https://doi.org/10.1016/J.JCLEPRO.2016.12.048

Goh, P. S., Othman, M. H. D., & Matsuura, T. (2021). Waste Reutilization in Polymeric Membrane Fabrication: A New Direction in Membranes for Separation. *Membranes, 11*(10), 782. https://doi.org/10.3390/membranes11100782

Gugulothu, D., Barhoum, A., Afzal, S.M., Venkateshwarlu, B., & Uludag, H. (2019). Structural Multifunctional Nanofibers and Their Emerging Applications. In A. Barhoum, M. Bechelany, & A. Makhlouf (Eds.) *Handbook of Nanofibers* (pp. 693–732). Springer, Cham.

Haider, T.P., Völker, C., Kramm, J. Landfester, K., & Wurm, F.R. (2019). Plastics of the Future? The Impact of Biodegradable Polymers on the Environment and on Society. *Angew Chem Int Ed Engl, 58*(1), 50-62. doi: 10.1002/anie.201805766.

Hamid, A., Khan, M., Hayat, A., Raza, J., Zada, A., Ullah, A., Raziq, F., Li, T., & Hussain, F. (2020). Probing the physio-chemical appraisal of green synthesized PbO nanoparticles in PbO-PVC nanocomposite polymer membranes. *Spectrochim. Acta Mol. Biomol. Spectrosc., 235*(118303). doi: 10.1016/j.saa.2020.118303.

Haque Mizan, M. M., Rastgar, M., Aktij, S.A. , Asad, A., Karami, P. Rahimpour, A., & Sadrzadeh, M. (2023). Organic solvent-free polyelectrolyte complex membrane preparation: effect of monomer mixing ratio and casting solution temperature. *J. Membr. Sci.* 668(121197), https://doi.org/10.1016/j.memsci.2022.121197

Jiang, S., & Ladewig, B.P. (2020). Green synthesis of polymeric membranes: recent advances and future prospects. *Current Opinion in Green and Sustainable Chemistry, 21*, 1–8.

Jung S., Kara L.B., Nie, Z., Simpson T.W., & Whitefoot, K. S. (2023). Is Additive Manufacturing an Environmentally and Economically Preferred Alternative for Mass Production? *Environ. Sci. Technol., 57*, 6373−6386. https://doi.org/10.1021/acs.est.2c04927

Kim, D., & Nunes,S.P. (2021). Green solvents for membrane manufacture: recent trends and perspectives. *Curr. Opin. Green. Sustain. Chem. 28*, 100427. https://doi.org/10.1016/J.COGSC.2020.100427

Koo, J.W. Ho, J.S., An, J., Zhang, Y., Chua, C.K., & Chong, T.H. (2021). A review on spacers and membranes: Conventional or hybrid additive manufacturing? *Water Res. 188,* 116497. https://doi.org/10.1016/j.watres.2020.116497.

Landaburu-Aguirre, J., García-Pacheco, R., Molina, S., Rodríguez-S´aez, L., Rabad´an, J., & García-Calvo, E. (2016). Fouling prevention, preparing for re-use and membrane recycling. Towards circular economy in RO desalination. *Desalination, 393,* 16–30.

Lawler, W., Bradford-Hartke, Z., Cran, M.J., Duke, M., Leslie, G., Ladewig, B.P., & Le- Clech, P. (2012). Towards new opportunities for reuse, recycling and disposal of used reverse osmosis membranes. *Desalination, 299*, 103–112.

Le Phuong, H.A., Izzati Ayob, N.A., Blanford, C.F., Mohammad Rawi, N.F., & Szekely, G. (2019). Nonwoven membrane supports from renewable resources: bamboo fiber reinforced poly (lactic acid) composites. ACS Sustain. *Chem. Eng., 7*(13), 11885–11893.

Li, L., Zuo, J., Duan, X., Wang, S., Hu, K., & Chang, R. (2021). Impacts and mitigation measures of plastic waste: a critical review. *Environ. Impact Assess. Rev., 90*, 106642.

Lieder, M., & Rashid, A. (2016). Towards circular economy implementation: a comprehensive review in context of manufacturing industry. *J. Clean. Prod.,* 115, 36-51.

Lustenberger, S., & Castro-Munoz, R. (2022). Advanced biomaterials and alternatives tailored as membranes for w ater treatment and the latest innovative european water remediation projects: a review. *Case Stud. Chem. Environ. Eng., 5,* 100205. https://doi.org/10.1016/j.cscee.2022.100205.

Meringolo, C., Mastropietro, T. F., Poerio, T., Fontananova, E., De Filpo, G, Curcio, E., & Di Profio, G. (2018) Tailoring PVDF Membranes Surface Topography and Hydrophobicity by a Sustainable Two-Steps Phase Separation Process. *ACS Sustainable Chem. Eng. 6*(8),10069–10077.

Mohamed, A. & Yousef, S. (2021). Green and sustainable membrane fabrication development. Sustain. *Technol. Green. Economy, 1*(1), 14-23. https://doi.org/10.21595/ stge.2021.22126

Nanda, S., Patra, B. R., Patel, R. Bakos, J., & Dalai, A.K. (2022). Innovations in applications and prospects of bioplastics and biopolymers: a review. *Environ. Chem. Lett. 20(*1), 379-395. https://doi.org/10.1007/s10311-021-01334-4

Nguyen Thi, H.Y., Kim, S., Duy Nguyen, B.T., Lim, D., Kumar, S., Lee, H., Szekely, G., & Kim, J. F. (2022). Closing the sustainable life cycle loop of membrane technology via a cellulose biomass platform. *ACS Sustain. Chem. Eng. 10*(7), 2532-2544. https://doi.org/10.1021/acssuschemeng.1c08554

Nunes, S. P., Culfaz-Emecen, P. Z., Ramon, G. Z., Visser, T., Koops, G. Z., & Jin, W. (2020) Thinking the future of membranes: perspectives for advanced and new membrane materials and manufacturing processes. *J. Membr. Sci.,* 598, 117761. https://doi.org/10.1016/J.MEMSCI.2019.117761

Park, S. H., Alammar, A., Fulop, Z., Pulido, B. A., Nunes, S. P., Szekely, G. (2021). Hydrophobic thin film composite nanofiltration membranes derived solely from sustainable sources. *Green. Chem.* 23, 1175 1184. https://doi.org/10.1039/D0GC03226C.

Pirada, S. (2022). Development of novel environmentally-friendly bio-based polymers derived from natural cardanol [Unpublished PhD Thesis], Tokyo University of Agriculture and Technology.

Polymeric Membrane Market Outlook (n.d.) Received from https://www.futuremarketinsights.com/reports/polymericmembrane-market

Razali, M. Kim, J.F. Attfield, M., Budd, P.M., Drioli, E., Lee, Y.M., & Szekely, G. (2015). Sustainable wastewater treatment and recycling in membrane manufacturing. *Green Chem., 17*(12), 5196-5205. https://doi.org/10.1039/c5gc01937k

Razmjou, A., Eshaghi, G., Orooji, Y., Hosseini, E., Korayem, A.H., Mohagheghian, F., Boroumand, Y., Noorbakhsh, A., Asadnia, M., & Chen, V. (2019b). Lithium ion-selective membrane with 2D subnanometer channels. *Water Res., 159,* 313–323.

Razmjou, A., Hosseini,M.A., Asadnia M., Ehsan, A., Korayem, A., & Vicki, C. (2019a). Design principles of ion selective nanostructured membranes for the extraction of lithium ions. *Nat. Commun. 10*(1), 5793.

Rethinam, S., Basaran, B., Vijayan, S., Mert, A., Bayraktar, O., & Aruni, A.W., (2020). Electrospun nano-bio membrane for bone tissue engineering application-a new approach. *Mater. Chem. Phys. 249,* 123010.

Russo, F., Vigile, M.F., Galiano, F., & Figoli, A. (2023). Green solvents for membrane fabrication. In L. F. Dumee, M. Sadrzadeh, M. M. A. Shirazi (Eds.), *Green Membrane Technologies towards Environmental Sustainability,* (pp. 9-36). Elsevier.

Sanaeepur, H., Amooghin, A. E., Shirazi, M. M. A., Pishnamazi, M., & Shirazian, S. (2022). Water desalination and ion removal using mixed matrix electrospun nanofibrous membranes: a critical review. *Desalination, 521,* 115350. https://doi.org/10.1016/j.desal.2021.115350

Zou, D., Nunes, S.P., Vankelecom, I.F.J. , Figoli, A., & Lee, Y.M., (2021). Recent advances in polymer membranes employing non-toxic solvents and materials. *Green. Chem. 23*(24), 9815-9843.

Shi, K, Ren, M., & Zhitomirsky, I., (2014). Activated carbon-coated carbon nanotubes for energy storage in supercapacitors and capacitive water purification. *ACS Sustain. Chem. Eng., (2)*5, 1289-1298.

Shirazi, M. M. A.; Dumee L. F., & Sadrzadeh, M. (2023). An introduction to green membrane technology. In L. F. Dumee, M. Sadrzadeh, M. M. A. Shirazi (Eds.), *Green Membrane Technologies towards Environmental Sustainability,* (pp. 1-18). Elsevier.

Sreedhar, N, Mavukkandy, M.O., Kharraz, J. A, Liu, Y., & Arafat, H.A. (2023). 3D printing in membrane Technology. In L. F. Dumee, M. Sadrzadeh, M. M. A. Shirazi (Eds.), *Green Membrane Technologies towards Environmental Sustainability,* (pp. 45-74). Elsevier.

Sudprasert, P. (2022). *Development of Novel Environmentally-Friendly Biobased Polymers Derived from Natural Cardanol.* [Unpublished Doctoral Dissertation]. Tokyo University of Agriculture and Technology.

Teodoro,A., Giordana, D.A. , Proner, M.C. , Verruck, S., & Rezzadori, K. (2022). A review on membrane separation processes focusing on food industry environment-friendly processes. *Crit. Rev. Food Sci. Nutr.,* 25, 1-15. https://doi.org/10.1080/10408398.2022.2092057

Tijing, L.D., Dizon, J.R.C. , Ibrahim, I., Nisay, A.R.N., Shon, H.K., & Advincula, R.C. (2020) 3D printing for membrane separation, desalination and water treatment. *Appl. Mater. Today,* 100486. https://doi.org/10.1016/J.APMT.2019.100486

Wang, Y., Wang, S., Wang, T., Song, T., Wu, X., Guo, L., Xie, W., Qiu, P., Dong, Q., Li, Q. (2023). A green nanocomposite membrane for concrete moisturizing, with excellent barrier properties and aging resistance. *Mater. Today Commun.,* 35, 105553.

Xie, W., Li, T., Chen, C., Wu, H., Liang, S., Chang, H., Liu, B., Drioli, E., Wang, Q., & Crittenden, J.C. (2019). Using the green solvent dimethyl sulfoxide to replace traditional solvents partly and fabricating PVC/PVC-g-PEGMA blended ultrafiltration membranes. *Ind. Eng. Chem. Res., 58*(16), 6413–6423.

Xie, W., Li, T., Tiraferri, A., Drioli, E., Figoli, A., Crittenden, J.C., & Liu, B., (2020). Toward the next generation of sustainable membranes from green chemistry principles. *ACS Sustain. Chem. Eng., 9*(1), 50-75. https://doi.org/10.1021/acssuschemeng.0c07119

Yadav, P., Ismail, N., Essalhi, M., Tysklind. M., Athanassiadis, D., & Tavajohi, N. (2021) Assessment of the environmental impact of polymeric membrane production. *J. Membr. Sci. 622*(118987), 1-8.

Yoo, H.S., Kim, T.G., & Park, T.G. (2009). Surface-functionalized electrospun nanofibers for tissue engineering and drug delivery. *Adv. Drug. Deliv. Rev. 61,* 1033-1042. https://doi.org/10.1016/j.addr.2009.07.007.

Yusuf, A. Sodiq, A. Giwa, A., Eke, J., Pikuda, O., Luca, G.D., Salvo, J.L.D., & Chakraborty, S. (2020). A review of emerging trends in membrane science and technology for sustainable water treatment. *J. Clean. Prod., 266*(121867). https://doi.org/10.1016/J.JCLEPRO.2020.121867

About Author

Prof. Mustafa ERSÖZ | Selçuk University |
mersoz[at]selcuk.edu.tr | ORCID:0000-0002-9409-9157

Mustafa Ersoz received his PhD. Chemistry from Glasgow University, UK in 1994, Postgraduate fellow in GKSS Research Center, Germany in 1997, Visiting Professor at Department of Chemistry, Hull University, 2001-2002. Professor at Department of Chemistry since 2004. Awarded "Junior Scientists Award" in Natural Sciences in 1998, and "Scientists Award". He has been administrative positions at different levels at Selcuk University and founder and director for Advanced Technology Research and Application Center, Selcuk University, Natural Products Research Center, Consultant of Konya Chamber of Industry. He was researcher for Establishment of Science Center in Konya "TUBITAK-Konya Metropolitan Municipality, Project coordinator for "Establishment of Research and Development infrastructure of Selcuk University" and "Scientific Human Resources Development Program" State Planning Organization, Türkiye and Joint PhD program "liquid/liquid interfaces" with EPFL (Laboratorie d'Electrochimie Physique et Analytique), Switzerland SU. involved FP7 projects (LAMAND, ChitoClaen, EU-SOLARIS, LignoFood, and leader of Nanometrology WP in LAMAND; H2020 projects; His is coordinator of EngSurf-Twin, and Waste2Fresh projects, Regeneu amd Bio-Acouis projects as researcher and Consultant positions. involved as core-STSM-MC member for COST CM1101, COSTMP1106, COST 637 and COSTD43, COST D36, projects and running COST projects are CA22131 and CA22154. Scientific Committee Member of COST between 2015 and 2021 and vice chair of COST SC (2017-2019). Full member of Turkish Academy of Sciences (TUBA) and also Council member of TUBA since 2018. Invited publications, author of more than 140 publications in leading scholarly journals. His research areas, physical chemistry, membrane technology, nanochemistry, energy, surface chemistry.

USING FLEXIBLE SHEAR STRESS SENSORS FOR ROBOTIC MANIPULATION IMPROVEMENT

Inci Rüya Temel

Andrea Adami

Leandro Lorenzelli FBK

10.53478/TUBA.978-625-6110-22-9.ch14

Using Flexible Shear Stress Sensors for Robotic Manipulation Improvement

Inci Rüya Temel
Fondazione Bruno Kessler (FBK)

Andrea Adami
Fondazione Bruno Kessler (FBK)

Leandro Lorenzelli
Fondazione Bruno Kessler (FBK)

Abstract

Mimicking the human ability to dexterously manipulate objects requires sensor arrays to measure the normal and shear force distributions and orientations. This chapter discusses the use of flexible shear stress sensors in medical robotics to improve manipulation. Shear force sensors are critical for enhancing robotic manipulation because they provide tactile perception, which is essential for robots to interact with their environment and handle objects with precision (Jiang et al., 2024). These sensors enable robots to detect and measure the lateral forces applied to their grippers or end effectors, which is crucial for tasks that require delicate handling or fine motor skills. The ability to perceive shear forces allows robots to adjust their grip strength and manipulate objects without slipping or causing damage, thereby improving the dexterity and versatility of robotic systems (Howe, 1993). Therefore, shear force sensors have potential applications in medical-assisting devices, minimally invasive surgeries, and other areas of medical robotics. The use of non-invasive diagnostic and intervention techniques is increasing in modern medicine, and future electronic skins aim to improve the sensitivity, dynamic range, response time, relaxation time, and detection limit (Dahiya, 2019; Navaraj et al., 2019; Soni & Dahiya, 2020; Yeo et al., 2016). This chapter presents the gap between the human sense of touch and the tactile sensors reported in the literature.

Keywords

Flexible electronics, Tactile sensing, Shear stress sensor, Medical assisting devices, Minimally invasive surgery

Introduction

The rapid progress in AI-powered robotics involving the integration of advanced technologies has provided new horizons for healthcare and medical applications. In fact, modern medicine is taking a route towards non-invasive diagnostic and intervention techniques. Emergent technologies are being utilised to enhance the quality, efficiency, and precision of medical procedures, diagnosis, and treatment. Medical robotics holds great potential for transforming healthcare by improving patient outcomes, enhancing the efficiency of medical procedures, and helping surgeons improve their accuracy. Robotic technology is being used to develop and improve a wide range of medical applications, from surgical robots to rehabilitation robots, and from diagnostic tools to drug delivery systems.

Surgical robots are a well-known application of medical robotics and are designed to assist surgeons during minimally invasive procedures such as laparoscopic surgery and robotic-assisted surgery. The minimally invasive surgical approach allows the surgeon to reach the internal organs of the patient through two or three small incisions of the skin using specifically designed low-profile surgical instruments or flexible catheters (Seibold et al., 2005). Reduced incision size has the advantage of not only reducing intraoperative blood loss, postoperative infection, complications, and trauma, but also offers a better cosmesis as the surgeon leaves less visible scars associated with the operation (Nisky et al., 2012; Zhou et al., 2023). Non-invasive methods have the advantage of improving patient comfort by reducing pain, shortening recovery time, and reducing hospitalisation time (Okamura, 2009). Additionally, robotic technologies offer enhanced precision, dexterity, and control, thereby allowing surgeons to perform complex procedures with greater accuracy and less tissue damage. The DA VINCI robotic surgical system (Intuitive Surgical) is among the most popular state-of-the-art medical devices used for minimally invasive surgical procedures. Despite the advancements in robotic technology, the absence of haptic feedback remains a significant limitation. Haptic feedback is crucial in surgical procedures because it enables surgeons to accurately perceive tissue properties and manipulate delicate structures. Lack of tactile feedback can lead to complications and suboptimal outcomes, emphasising the need for the development of technologies that enhance the effectiveness and safety of minimally invasive surgical procedures.

Advancements in medical robotics have extended beyond surgery and revolutionised various aspects of healthcare delivery. For instance, automation in pharmacies and healthcare facilities enhances medication management accuracy and efficiency, while minimising the risk of errors through automated medication- dispensing and drug-delivery processes. Moreover, medical robotics enables telemedicine and remote surgery, thereby allowing healthcare professionals to provide care from a distance. Telepresence robots equipped with cameras and screens enable doctors to interact remotely with patients and provide real-time assistance during consultation from remote locations. However, the lack of tactile feedback poses a significant challenge to remote healthcare delivery. To address this issue, interactive screens with tactile feedback capabilities are required. These screens enable doctors to assess patient injuries or physical conditions remotely by providing sensory information, thereby improving healthcare providers' ability to diagnose and treat patients remotely and enhance access to quality healthcare services.

Technological advancements have revolutionised healthcare training by providing simulation-based platforms that enable medical professionals to enhance their skills and expertise. Medical robotics, such as simulators, offer realistic responses to external stimuli, allowing for the practise of procedures in safe and realistic settings. The integration of soft materials, contractile actuators, and flexible sensors in soft robotics, as well as artificial intelligence and augmented reality in software development, has created opportunities for the development of sophisticated body-part simulators that can replicate the mechanical properties, motion, and function of human tissues (Maglio et al., 2021). These simulations can minimise the need for animal or patient tests and standardise medical procedures. However, haptic feedback is often lacking or limited in these simulations, making the use of actual body mimics for training purposes more effective.

Assistive robots have been created to aid individuals with physical or cognitive limitations in performing daily tasks, such as mobility, personal care, and household chores. These robots provide repetitive, task-specific training to help patients improve their motor skills and enhance their independence. For instance, robots are utilized in rehabilitation to provide therapy and restore motor abilities (Tefertiller et al., 2011). Rehabilitation robots are designed to assist patients in regaining mobility and function after an injury or illness (Kang et al., 2016). Soft robotic gloves with embedded sensors can be used for hand rehabilitation, and soft robotic prosthetics require portability and controllability similar to assistive and rehabilitation devices (Mutlu et al., 2016). Assistive robots also offer a solution for various needs, such as tremor suppression (Manto et al., 2003) and personal care for elderly individuals (Sawik et al., 2023).

As technology continues to advance, we anticipate even more innovative applications of robotics in the medical field. Despite the usefulness of rigid components in everyday tasks, a more precise approach to medical devices is essential for safe surgery, endoscopy, and drug delivery. Laparoscopic surgery presents various challenges due to mechanical constraints at the incision point. Cable-based systems experience friction and interference with the wearer’s body, hindering effective force transmission. Pneumatic actuators offer an alternative solution to overcome this issue (Connelly et al., 2010; Ilievski et al., 2011). Furthermore, the directional movements of the surgeon's hand result in opposite deflections of the working end of the laparoscopic instrument, causing a discrepancy between visual and proprioceptive feedback (Smith et al., 2001). This phenomenon, known as the "*fulcrum effect*", leads to altered force sensations due to mechanical advantage and friction at the incision point (Nisky et al., 2012). Flexible instruments, although highly manoeuvrable, are often used in conjunction with minimally invasive surgical procedures. However, they are lengthy and have a swiveling tip, reducing dexterity once they reach the surgical site. Additionally, these instruments have limited force application capabilities and lack stability.

Rapid advancements in AI-powered robotics have ushered in a new era for healthcare and medical applications, leading to the development of innovative non-invasive diagnostic and intervention techniques. This progress has significantly enhanced the quality, efficiency, and precision of medical procedures, diagnosis, and treatment. With these advancements, there is a growing need for tactile sensors that emulate the human skin to augment robotic manipulation and interaction with the environment. These sensors are crucial for robots to safely and effectively engage with their surroundings, particularly in dynamic settings where precise modelling is challenging (Cirillo et al., 2017). They enable the detection of various stimuli such as force, texture, and temperature, which are essential for tasks ranging from personal healthcare monitoring to advanced robotic manipulation (G et al., 2022; Pang et al., 2022).

Soft robotics hold a vital position in the discipline of biomedical engineering, and biocompatibility and biomimicry are key aspects to be considered in this field. It is of paramount importance that the materials utilised in the development of soft robotics be compatible with the human body and tissues, in order to guarantee the proper functioning and acceptance by the body of the entire system. Nonetheless, the extent of compatibility is contingent upon the particular biomedical application, as evidenced by Cianchetti et al. (2018). Currently, biocompatibility is achieved by using inert materials that do not trigger an immune response, such as silicones or hydrogels. Nevertheless, to achieve biocompatibility, biomimicry, portability, and functionality, advanced active materials and novel actuation and sensing principles are needed. A significant advancement in this field would be the combination of materials science for implants and surgical tools with tissue-engineering approaches.

Interestingly, while the development of tactile sensors is inspired by the human sense of touch, achieving the complexity and sensitivity of the human skin remains a significant challenge. The multifunctionality of tactile sensors, as demonstrated by Pang et al. (2022), can recognise voice and monitor physiological signals, in contrast to the more focused applications of sensors designed for specific tasks, such as object manipulation or human-robot interaction (Cirillo et al., 2017; G et al., 2022). This highlights diverse approaches and potential contradictions in the design and application of tactile sensors. Integrating tactile sensors into robotic systems is crucial for the development of human-like interaction capabilities. These sensors are essential for enhancing perception in various applications such as healthcare and manufacturing (Jamone, 2020; Pang et al., 2022).

Inspirations from the human skin

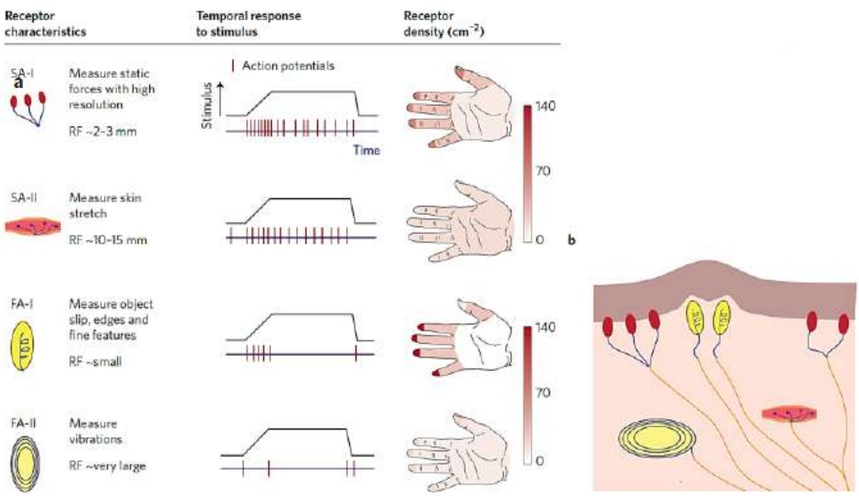
Touch is one of the five fundamental senses through which living organisms detect and interpret their physical surroundings. It involves the detection and perception of pressure, temperature, and texture by making physical contact with objects or surfaces. To perform a precise manipulation task, a person needs not only information about their body's current state, but also details about the object's physical properties, such as shape, weight, location, and temperature. The human brain can detect the resistance of objects, including their stiffness, damping, and inertia, by combining motion and force signals (Jones & Hunter, 1993; Kuschel et al., 2010; Nisky et al., 2008, 2010). Touch is a multifaceted sensory experience that involves physical sensations as well as the cognitive and emotional responses associated with it. On the other hand, tactile sensing refers to an organism or system's capacity to detect and process tactile information. Tactile sensors are devices or structures designed to imitate the human sense of touch, allowing machines or robots to perceive and interact with their surroundings. Touch pertains to the sensory experience of physical contact with objects, whereas tactile sensing refers to the ability to detect and process tactile information. Tactile sensing is crucial for enabling machines and robots to simulate the sense of touch and engage in effective interactions with the surrounding world.

The hands serve as a critical interface between humans and the world around them; their hands allowed them to craft tools for millions of years, play musical instruments and produce art, and now serves as an interface for most of the computing technology. This reflects the high density of sensory receptors (such as mechanoreceptors) in the hands, which allow for detailed tactile discrimination and fine motor control. Therefore, the representation of the hands and fingers in the somatosensory cortex is proportionally larger compared to other body regions in the sensory homunculus. The rich sensory feedback provided by the hands allows for precise tactile discrimination and intricate motor control. This importance is not only reflected in our daily activities but also in our physiology: 54 bones of the 206 bones of human skeleton are dedicated to the hands. Therefore, it's no surprise that the representation of the hands and fingers in the somatosensory cortex is particularly pronounced, underscoring their paramount role in our sensory perception and motor skills.

A substantial amount of research on the framework and features of the skin has been undertaken by Johansson and his team at the University of Umea, Sweden. Their studies in the 1970s and the 1980s focused on mechanoreceptors, including their receptive field characteristics (Johansson, 1978), densities (Johansson & Vallbo, 1979), and spatiotemporal properties (Johansson & Lamotte, 1983a; Johansson & Vallbo, 1979a, 1980). Their work contributed to the understanding of precision gripping when lifting objects (Gordon et al., 1991; Johansson & Westling, 1984; Westling & Johansson, 1984, 1987).

The skin, which is the interface between the word and body, is composed of seven types of sensory receptors: temperature, humidity, pain, and four types of mechanoreceptors (Gerardo Rocha & Lanceros-Mendez, 2008). Mechanoreceptors in the hand can be classified based on their receptive field and response time to a stimulus. Type I receptors have small and well-defined receptive fields and are located in superficial layers of the skin. Type II receptors have large, ill-defined, and roughly uniform receptive fields and terminate deeper in the dermis and epidermis (Johansson, 1978). Each type includes both fast- and slow-adapting receptors. Fast adapting (FA) receptors are sensitive to dynamic skin indentation as long as the stimulus is in motion and stops firing when the stimulus becomes stationary. Slowly adapting (SA) receptors are also sensitive to moving stimuli but respond to sustained skin indentation during static pressure with sustained discharge. Figure 1 shows the different mechanoreceptors located in the skin and their temporal responses to the stimuli.

Figure 1.
Skin receptors and transduction process. ***a,*** *Types of mechanoreceptors, their function, temporal response and density in the hand.* ***b.*** *Schematic of the location of mechanoreceptors in the skin. Adapted from (Chortos et al., 2016)*



SA-I receptors are sensitive to low-frequency (<5 Hz (Johansson & Flanagan, 2009)) dynamic skin deformations and are involved in transmitting high-resolution force information that is useful for object shape and texture representation and recognition (Weber et al., 2013). Their highest density is found in sensitive areas of the skin, such as the fingertips, where they can measure normal force distributions with a resolution of ~0.5mm (Dahiya et al., 2010; Hammock et al., 2013). The limit of detection for SA-I receptors is as low as 1 mN (Johansson & Lamotte, 1983), with a sensitivity range of 2–10 $Hz.kPa^{-1}$ (Ge & Khalsa, 2002), or a sensitivity to skin indentation of 30–160 $Hz.mm^{-1}$ (Burgess et al., 1983). SA-II receptors, on the other hand, measure tangential shear strain of the skin and respond to lateral stretching that occurs during object manipulation (Johansson & Flanagan, 2009).

FA-I receptors are responsible for measuring high-frequency (5–50 Hz (Johansson & Flanagan, 2009)) dynamic skin deformations and are insensitive to static force. They are essential for detecting changes in the position of objects in one's hand and adjusting grip force to prevent slippage. FA-II receptors are sensitive to mechanically transient and high-frequency vibrations (40–400 Hz (Johansson & Flanagan, 2009)) that propagate over largeareas through tissues and are also insensitive to static force. They play a crucial role in detecting slippage and discriminating textures.

Figure 2.

Sensory events during lifting task. ***(a)*** *Identification of goals and measurement of forces applied to reach the goal;* ***(b)*** *measurement of signals recorded from the four mechanoreceptors. Adapted from (Johansson & Flanagan, 2009)*

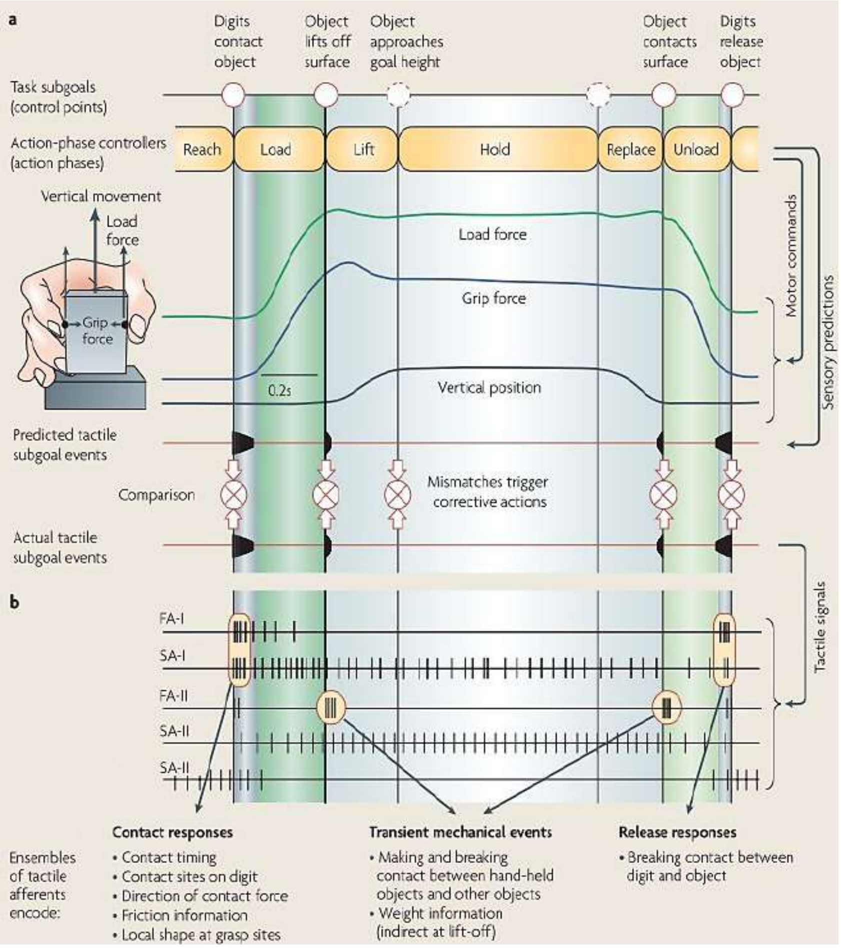


Figure 2 shows the different steps involved in sensing the contact and adapting the grip according to the physical properties of the object. Tactile afferent signals were recorded during lifting tasks. These recordings show that all four types of mechanoreceptors participate in the task, allowing the brain to monitor the progression of the task and correct any errors that can occur before the end of the lifting task. Primarily, when the fingers enter in contact with the object, the FA-I afferents fire, giving information about the contact, along with FA-II afferents responding to transient mechanical events when the object is lifted and then replaced. Second, at all times, a static force is applied to hold the object, and slow adapting afferents fire continuously.

This study shows that both static and dynamic force transductions are required to detect shear stress and strain. Mimicking the humans' ability to dexterously manipulate objects requires sensors arrays to measure normal and shear force distributions and orientations. In addition, the number and diversity of different sensors are important parameters to be included to build an electronic skin capable of detecting slip and allowing efficient grip. To meet these requirements, future electronic skin aims to improve the following key performance parameters: sensitivity, dynamic range, response time, relaxation time, and detection limit.

Recreating sensation of slip

Mimicking the intricate sense of slip allows users to interact more effectively with objects in their environment, thereby improving their overall dexterity and control. Numerous studies have reported sensors that demonstrate sensitivities equal to or better than those of the human skin. Notably, both capacitive and resistive sensors offer improved detection thresholds compared to the skin. While the skin's detection threshold stands at 1 mN, those of the capacitive and resistive sensors are respectively smaller than 0.05 mN and 0.08 mN. Furthermore, both capacitive and resistive sensors achieved significantly enhanced response times. It can reach less than 10 ms and less than 20 ms for devices based on capacitance (Schwartz et al., 2013) and resistance (Lee et al., 2016), respectively. In comparison, the response time of the skin is approximately 15 ms (Chortos et al., 2016).

All four mechanoreceptors are involved in tasks such as gripping. While slow adapting receptors transduce static force, fast adapting receptors are engaged in order to transduce dynamic force. Therefore, both static and dynamic force transduction are required to detect shear stress and strain. In addition, the number and diversity of different sensors are important parameters to be included to build an electronic skin capable of detecting slip and allowing efficient grip. Sensors capable of detecting multidirectional forces have also been reported; however, they all present a decrease in the sensitivity of sensors to shear when subjected to normal pressure (Boutry et al., 2018; Park, Lee, Hong, Ha, et al., 2014).

Recent advancements in shear force sensors, such as the development of microcolumn array dielectric layers, have addressed previous limitations, such as direction sensitivity and integration challenges, leading to sensors with high sensitivity and linearity (Jiang et al., 2024). This progress is significant given that current robotic systems often lack the flexibility and robustness needed for complex manipulation tasks and require extensive programming for specific tasks. The integration of these sensors into robotic systems can lead to significant advancements in the field, allowing robots to perform tasks with human-like dexterity and adaptability (Howe, 1993; Jiang et al., 2024). The ongoing development of these sensors and their integration with other sensory modalities are crucial for the evolution of robotic manipulation capabilities (Howe, 1993; Li et al., 2018). In this section, we discuss the various methods and technologies employed to recreate the slip sensation during robotic manipulation.

Dynamic sensing capabilities

Dynamic force transduction involves the detection and response to changes in force over time. Dynamic force sensing is essential for detecting slip events and adjusting the grip force of the artificial limbs (Rossi et al., 2017). Piezoelectric and triboelectric sensors are ideal for this application because they are sensitive to changes in force rather than the force's absolute value, which mimics the properties of fast-adapting mechanoreceptors found in human skin (Dahiya et al., 2010). Piezoelectric and triboelectric sensors produce voltage when they are mechanically deformed, causing a change in the magnitude of the dipoles in the active layer and inducing charging of the electrodes (Chortos et al., 2016). The difference between piezoelectric and triboelectric materials resides in the mechanism leading the dipole to charge. In piezoelectric materials, applying strain can alter the magnitude of the dipole in the unit cell or the number of dipoles per unit volume of the material. In contrast, triboelectric devices induce dipoles through contact electrification, where charges are separated due to differences in work function between the two materials. Ultimately, the operation of piezoelectric and triboelectric sensors allows them to generate energy autonomously through mechanical stimulation, which is known as self-powering (L. Wang et al., 2015).

Triboelectric sensors have emerged as a promising technology for dynamic force transduction in robotic manipulation, offering a high sensitivity and low energy consumption (Xiang et al., 2022). Specifically, triboelectric nanogenerators (TENGs) have been utilised in electronic skin (E-skin) sensors to detect multidimensional forces, such as normal pressure and shear force, which are crucial for robotic manipulation and human-robot interactions (Z.Wang et al., 2021). The integration of flexible, multilayer piezoelectric-based tactile sensors has shown promise in real-time dynamic force measurement, with applications in robotic grasping and tactile feedback (Xiang et al., 2022).

Piezoelectric sensors are popular because of their low cost, linear response, and high sensitivity (Alea et al., 2022; Ha et al., 2015, 2018; Parida et al., 2019; Park et al., 2015; Tao et al., 2019; Yi et al., 2019). However, their use in static force measurements is limited owing to the neutralisation of the surface charge. Interestingly, while piezoelectric sensors are typically associated with dynamic force measurements owing to their high sensitivity and fast response times (Xiang et al., 2022), advancements have been made to extend their capabilities to static force applications. This was achieved by leveraging different aspects of piezoelectricity beyond the direct piezoelectric effect (K.Kim et al., 2021). Moreover, the development of multimodal tactile sensors that combine different transduction mechanisms, such as those based on elastomers and optics, can offer a wide dynamic range and the ability to sense static forces (Wettels & Pletner, 2012). By exploring various parameters and combining different sensing technologies, tactile sensors can be adapted to accurately measure static forces, thereby expanding their utility in numerous applications (K.Kim et al., 2021; Wettels & Pletner, 2012).

Static force sensing

Static force transduction in robotic manipulation involves the measurement and interpretation of the forces exerted by objects in a stationary state. These forces typically include compression, tension, or shear forces acting on the end effector or gripper of the robot. Static force sensors are used to detect and quantify these forces, providing feedback to the robot's control system to ensure the precise and stable manipulation of objects. Various types of sensors, including strain gauges, load cells, piezoelectric sensors, and capacitive sensors, can be used for static force transduction in robotic manipulations. These sensors can be integrated into the robot's end- effector or gripper to provide real-time feedback on the forces exerted during manipulation tasks.

In resistive sensors, the output signal can originate from two different mechanisms: the measurement of the intrinsic material piezoresistivity or the change in contact resistance between a conductor and an electrode (Khalili et al., 2018). Piezoresistive sensors are integral to providing feedback for the control of robotic hands, as they can be optimised to achieve precise grasp kinematics through impedance control (Hou & Sucahyo, 1990). Their simple structure also has a simple working principle which is based on the variation in the resistivity of the conductive material in response to different magnitudes of applied pressure. They generate an output signal by either measuring the intrinsic material resistivity or by detecting changes in the contact resistance between a conductor and an electrode. In general, the resistance decreases as a given pressure is applied. Additionally, resistive sensors have been developed using materials such as graphite and polydimethylsiloxane to create thin-film layers, which are useful for localising force applications and are applicable in both industrial and healthcare settings (Sapra et al., 2019). Despite challenges, such as hysteresis and nonlinear electromechanical response, which can affect their accuracy and reliability (Ozioko & Dahiya, 2022), advancements in sensor technology and materials continue to enhance their performance and application scope (Hou & Sucahyo, 1990; Sapra et al., 2019).

The properties of resistive-type devices can be improved by inducing geometrical changes (Chossat et al., 2013) or by improving the resistivity of the material. There are two ways to modify ρ: if the material is a semiconductor, then changing its band structure will change its resistivity (Kanda, 1991); if it is a composite material, then adding conductive particles will change its percolation pathways (N. Hu et al., 2008), and thus, its resistivity (Chortos et al., 2016). Despite the fact that piezoresistive polymer composites possess a relatively low operating voltage and are highly sensitive, they are characterized by a significant amount of hysteresis and a substantial temperature sensitivity that can complicate measurements. Additionally, their pressure sensitivity is relatively poor compared to other materials.Resistive sensors capable of detecting normal force, shear force, lateral stretch, and bending have been successfully reported in the literature (N. Hu et al., 2008; Khalili et al., 2018; C. Pang et al., 2012; Y. Pang et al., 2018; Park et al., 2018; Park, Lee, Hong, Lee, et al., 2014; Su et al., 2015; Yamada et al., 2011).

On the other hand, capacitive-type sensors depend only on electrode displacement and less on changes in material properties. In capacitive sensors, the output signal is a measure of the variations in capacitance due to the movements of two electrodes separated by a dielectric layer. Its working principle remains on the change in capacitance due to the applied force (Puers, 1993). A change in capacitance will be observed either when the distance between the electrodes changes, when the overlapping area between the two electrodes is modified, or when the relative permittivity of the dielectric changes. (Mishra et al., 2021). Capacitive sensors are integral to robotic manipulation, particularly for static force transduction, owing to their high sensitivity, resolution, robustness, and stability (Ştefănescu, 2011). For instance, the development of soft capacitive sensors for soft robotics demonstrates the potential of these sensors to withstand large deformations without significant changes in sensitivity, which is crucial for static force measurements in applications where large strains occur (Alshawabkeh et al., 2023). Additionally, the use of curved electrodes in capacitive transducers has been shown to provide higher sensitivity and a wider linear dynamic range, which could be beneficial for static force measurements in robotic manipulations (McIntosh et al., 2006).

Capacitive sensors have the advantage of being able to detect both static pressure and strain, making them very suitable for electronic skin ((Boutry et al., 2018; W. Hu et al., 2013; Lipomi et al., 2011; X. Wang et al., 2013; Xu & Zhu, 2012). In addition, they demonstrate excellent sensitivity and linearity, making their response fast while requiring low power consumption and free from temperature dependency. However, they must be shielded to reduce their susceptibility to external noise sources from electromagnetic waves. Advancements in sensor design, such as the use of soft capacitive sensors and curved electrode transducers, have enhanced their capabilities, allowing accurate static force measurements even under substantial deformation (Alshawabkeh et al., 2023; Mcintosh et al., 2006). These developments highlight the potential of capacitive sensors to play a pivotal role in the evolution of robotic manipulation technologies.

In theory, for the same amount of deformation due to the applied pressure, the output signal demonstrates a greater change in resistive-type sensors than in capacitive sensors, leading to a wider dynamic range in the former. In addition, resistive-type sensors seem to be more interesting owing to their simple readout mechanisms. However, their cost efficiency is low owing to their constant and high-power consumption, and they are more difficult to fabricate because novel materials have to be considered in order to observe a wide range of conductivity changes. Compared with resistive-type sensors, capacitive sensors are much easier to fabricate and consume less power (Khalili et al., 2018).

In general, flexible sensors may be subject to hysteresis owing to the viscoelastic nature of rubber dielectrics, which represents one of the major disadvantages of flexible capacitive pressure sensors. To address this challenge, researchers have introduced air voids inside thin films of elastomers to alleviate problems associated with their viscoelastic behaviour (Mannsfeld et al., 2010; Ruth, Beker, et al., 2020; Ruth, Feig, et al., 2020; Ruth & Bao, 2020). Microengineering of the dielectric layer presents many advantages, including an increase in the effective dielectric constant owing to the collapse of the pores (Ruth & Bao, 2020) and, therefore, a higher sensitivity and a decrease in the Young's modulus and viscoelastic properties of the elastomer (J.O. Kim et al., 2019). Park et al. developed in 2014 (Park, Lee, Hong, Lee, et al., 2014) their simple bioinspired interlocked microstructures using only PDMS and carbon nanotubes. For instance, Bao et al. (Boutry et al., 2018) successfully designed a capacitive sensor with a high resolution and sensitivity using microstructures.

Towards the integration of both static and dynamic force transduction

The integration of both static and dynamic force transduction in robotic manipulation is an area of active research with various approaches being explored. This integration is crucial for enhancing the performance, accuracy, and robustness of robotic systems in various applications including industrial automation, assembly, and logistics. Tripicchio et al. and Xiang et al. (Tripicchio et al., 2023; Xiang et al., 2022) highlighted advancements in tactile sensing technologies for robotic grippers and tactile sensors, respectively, which are crucial for dynamic force measurement during object manipulation. Tripicchio et al. discussed the integration of fibre sensing elements for the real-time classification of gripper-object interactions, whereas Xiang et al. focused on a piezoelectric-based tactile sensor capable of real-time force measurements, including dynamic forces.

The integration of both static and dynamic force-sensing technologies into a single robotic system presents several technical challenges. These challenges include the development of sensor fusion algorithms and data processing techniques, as well as hardware design considerations, communication and coordination overhead, cost and maintenance issues, system scalability, and a limited workspace. Effective cooperation among multiple robot arms requires robust communication and coordination, which can lead to communication overheads and latency. Additionally, implementing and maintaining a multirobot arm system can be costly, with each extra robot arm adding to the hardware and maintenance expenses.

There are also challenges associated with accurately measuring the dynamic forces. (Ammar et al., 2022) addressed the complexities of dynamic force measurement in aerodynamic and robotic systems, noting that system dynamics can affect the sensitivity of force transducers and that static stiffness is typically greater than dynamic stiffness. (Chen et al., 2023) presented a strategy for compensating for charge leakage in piezoelectric force sensors, enabling a wide spectrum of force measurements from static to dynamic.

Adaptive control strategies have been developed to compensate for uncertainties related to an object's weight, shape, friction, or the robot's physical parameters. These strategies allow the system to adapt and adjust the control parameters in real time, thereby ensuring accurate and stable manipulation. This is particularly important for tasks requiring precise positioning and force regulation. Moreover, adaptive control can improve the accuracy of task execution by continuously adjusting the control inputs based on feedback from the sensors and the state of the system. This is crucial in cooperative manipulation scenarios that often involve complex and dynamic environments. Adaptive control strategies can make a system more robust by adapting to changes in the environment or disturbances that may affect the robots' ability to carry and manipulate an object. Additionally, ensuring compatibility and interoperability between different sensor types and robotic platforms is essential for achieving robust and reliable force sensing capabilities in robotic manipulation.

Despite these challenges, the integration of static and dynamic force transduction, with several innovative sensor technologies and compensation strategies being developed (Chen et al., 2023; Tripicchio et al., 2023; Xiang et al., 2022), is a promising area of research with ongoing efforts to improve the performance and efficiency of cooperative robotic systems. Despite these advancements, the accurate measurement of dynamic forces remains a complex issue because of the system dynamics and inherent properties of force transducers (Ammar et al., 2022). Ongoing research efforts are indicative of the potential for further improvements in robotic manipulation capabilities through enhanced force transduction.

Conclusion

Flexible shear stress sensors are essential for robots to accurately interact with their surroundings and manipulate objects. These sensors provide tactile perception, which enables robots to adjust their grip strength and prevent slipping or damage. Electronic skins have been developed for non-invasive diagnostic and intervention techniques in modern medicine, enhancing sensitivity, dynamic range, response time, relaxation time, and detection limit. Medical robotics have the potential to transform healthcare by improving patient outcomes, medical procedure efficiency, and assisting surgeons in enhancing their accuracy. Haptic feedback is vital during surgical procedures, allowing surgeons to accurately perceive tissue properties and manipulate delicate structures. Shear force sensors are necessary for enhancing robotic manipulation as they provide tactile perception, which enables robots to detect and measure lateral forces applied to their grippers or end effectors. This is crucial for tasks requiring delicate handling or fine motor skills. Recent advancements in shear force sensors, such as the development of microcolumn array dielectric layers, have addressed previous limitations, such as direction sensitivity and integration challenges, leading to sensors with high sensitivity and linearity. Integrating these sensors into robotic systems can lead to significant advancements in the field, allowing robots to perform tasks with human-like dexterity and adaptability. The ongoing development of these sensors and their integration with other sensory modalities are crucial for the evolution of robotic manipulation capabilities. One of the primary difficulties is the need to create sensors that are small, consume low power, and are resistant to interference from motion artifacts and electromagnetic fields. Additionally, these sensors must be capable of measuring both the intensity and direction of forces, which is less mature in current technologies compared to other sensing modalities like vision. The integration of sensors onto robotic platforms also presents challenges, particularly in terms of direction sensitivity and the ability to maintain performance over repeated use.

Acknowledgments

This work has received funding from the European Union's Horizon 2020 Research and Innovation Programme under the Marie Sklodowska-Curie Grant Agreement number 861166 (INTUITIVE) and partially from the European Union's Horizon 2020 Research and Innovation Programme, under Grant Agreement number 952289 (EngSurf Twin). The authors would like to thank R. Hall-Wilton of *Fondazione Bruno Kessler*, and M. Ersöz of *Selçuk University* for the opportunity to extend my research

References

Alea, M. D., Safa, A., Assche, J. Van, & Gielen, G. G. E. (2022). Power-Efficient and Accurate Texture Sensing Using Spiking Readouts for High-Density e-Skins. *BioCAS 2022 - IEEE Biomedical Circuits and Systems Conference: Intelligent Biomedical Systems for a Better Future, Proceedings*, 359–363. https://doi.org/10.1109/BioCAS54905.2022.9948546

Alshawabkeh, M., Alagi, H., Navarro, S. E., Duriez, C., Hein, B., Zangl, H., & Faller, L. M. (2023). Highly Stretchable Additively Manufactured Capacitive Proximity and Tactile Sensors for Soft Robotic Systems. *IEEE Transactions on Instrumentation and Measurement*, *72*. https://doi.org/10.1109/TIM.2023.3250232

Ammar, M. M., Mohamed, M. I., Mahmoud, G. M., Hassan, S. R., Kumme, R., Zakaria, H. M., & Gaafer, A. M. (2022). A comparison between static and dynamic stiffness of force transducers for dynamic force calibrations. *Measurement: Journal of the International Measurement Confederation*, *203*. https://doi.org/10.1016/j.measurement.2022.111945

Boutry, C. M., Negre, M., Jorda, M., Vardoulis, O., Chortos, A., Khatib, O., & Bao, Z. (2018). A hierarchically patterned, bioinspired e-skin able to detect the direction of applied pressure for robotics. *Science Robotics*, *3*(24), 1–10. https://doi.org/10.1126/scirobotics.aau6914

Burgess, P. R., Mei, J., Tuckett, R. P., Horch, K. W., Ballinger, C. M., & Poulos, D. A. (1983). The neural signal for skin identation depth. I. Changing identations. *Journal of Neuroscience*, *3*(8), 1572–1585. https://doi.org/10.1523/jneurosci.03-08-01572.1983

Chen, F., Lin, H., Li, Z., Ju, B. F., & Chen, Y. L. (2023). Development of a novel strategy based on in-process compensation of charge leakage for static force measurement by piezoelectric force sensors. *Smart Materials and Structures*, *32*(7). https://doi.org/10.1088/1361-665X/acd7b5

Chortos, A., Liu, J., & Bao, Z. (2016). Pursuing prosthetic electronic skin. *Nature Materials*, *15*(9), 937–950. https://doi.org/10.1038/nmat4671

Chossat, J. B., Park, Y. L., Wood, R. J., & Duchaine, V. (2013). A soft strain sensor based on ionic and metal liquids. *IEEE Sensors Journal*, *13*(9), 3405–3414. https://doi.org/10.1109/JSEN.2013.2263797

Connelly, L., Jia, Y., Toro, M. L., Stoykov, M. E., Kenyon, R. V., & Kamper, D. G. (2010). A pneumatic glove and immersive virtual reality environment for hand rehabilitative training after stroke. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *18*(5), 551–559. https://doi.org/10.1109/TNSRE.2010.2047588

Dahiya, R. (2019). E-Skin: From Humanoids to Humans [Point of View]. *Proceedings of the IEEE*, *107*(2), 247–252. https://doi.org/10.1109/JPROC.2018.2890729

Dahiya, R., Metta, G., Valle, M., & Sandini, G. (2010). Tactile Sensing—From Humans to Humanoids. *IEEE Transactions on Robotics*, *26*(1), 1–20. https://doi.org/10.1109/TRO.2009.2033627

Ge, W., & Khalsa, P. S. (2002). Encoding of compressive stress during indentation by slowly adapting type I mechanoreceptors in rat hairy skin. *Journal of Neurophysiology*, *87*(4), 1686–1693. https://doi.org/10.1152/jn.00414.2001

Gerardo Rocha, J., & Lanceros-Mendez, S. (2008). *Sensors: Focus on Tactile Force and Stress Sensors* (J. Gerardo Rocha & S. Lanceros-Mendez, Eds.).

Gordon, A. M., Forssberg, H., Johansson, R. S., & Westling, G. (1991). Integration of sensory information during the programming of precision grip: comments on the contributions of size cues. *Experimental Brain Research*, *85*(1), 226–229. https://doi.org/10.1007/BF00230004

Ha, M., Lim, S., Cho, S., Lee, Y., Na, S., Baig, C., & Ko, H. (2018). Skin-Inspired Hierarchical Polymer Architectures with Gradient Stiffness for Spacer-Free, Ultrathin, and Highly Sensitive Triboelectric Sensors. *ACS Nano*, *12*(4), 3964–3974. https://doi.org/10.1021/acsnano.8b01557

Ha, M., Lim, S., Park, J., Um, D. S., Lee, Y., & Ko, H. (2015). Bioinspired interlocked and hierarchical design of zno nanowire arrays for static and dynamic pressure-sensitive electronic skins. *Advanced Functional Materials*, *25*(19), 2841–2849. https://doi.org/10.1002/adfm.201500453

Hammock, M. L., Chortos, A., Tee, B. C.-K., Tok, J. B.-H., & Bao, Z. (2013). 25th Anniversary Article: The Evolution of Electronic Skin (E-Skin): A Brief History, Design Considerations, and Recent Progress. *Advanced Materials*, *25*(42), 5997–6038. https://doi.org/10.1002/adma.201302240

Hou, E. S. H., & Sucahyo, N. (1990). Multi-sensor system for an articulated robotic hand. *[Proceedings] IECON '90: 16th Annual Conference of IEEE Industrial Electronics Society*, 627–630. https://doi.org/10.1109/IECON.1990.149214

Howe, R. D. (1993). Tactile sensing and control of robotic manipulation. *Advanced Robotics*, *8*(3), 245–261. https://doi.org/10.1163/156855394X00356

Hu, N., Karube, Y., Yan, C., Masuda, Z., & Fukunaga, H. (2008). Tunneling effect in a polymer/carbon nanotube nanocomposite strain sensor. *Acta*

Materialia, *56*(13), 2929–2936. https://doi.org/10.1016/j.actamat.2008.02.030

Hu, W., Niu, X., Zhao, R., & Pei, Q. (2013). Elastomeric transparent capacitive sensors based on an interpenetrating composite of silver nanowires and polyurethane. *Applied Physics Letters*, *102*(8). https://doi.org/10.1063/1.4794143

Ilievski, F., Mazzeo, A. D., Shepherd, R. F., Chen, X., & Whitesides, G. M. (2011). Soft robotics for chemists. *Angewandte Chemie - International Edition*, *50*(8), 1890–1895. https://doi.org/10.1002/anie.201006464

Intuitive Surgical. (n.d.). Retrieved April 2, 2024, from https://www.intuitive.com/en-us

Jiang, J., Lv, C., Lv, T., Lu, Y., Wang, X., Li, Q., Chen, X., & Xie, M. (2024). An Angle-Sensitive Microcolumn- Based Capacitive Shear Force Sensor for Robot Grasping. *Advanced Materials Technologies*, *9*(6). https://doi.org/10.1002/admt.202302113

Johansson, R. S. (1978). Tactile sensibility in the human hand: Receptive field characteristics of mechanoreceptive units in the glabrous skin area. *The Journal of Physiology*, *281*, 101–123. https://doi.org/10.1113/jphysiol.1978.sp012411

Johansson, R. S., & Flanagan, J. R. (2009). Coding and use of tactile signals from the fingertips in object manipulation tasks. In *Nature Reviews Neuroscience* (Vol. 10, Issue 5, pp. 345–359). Nature Publishing Group. https://doi.org/10.1038/nrn2621

Johansson, R. S., & Lamotte, R. H. (1983). Tactile detection thresholds for a single asperity on an otherwise smooth surface. *Somatosensory & Motor Research*, *1*(1), 21–31. https://doi.org/10.3109/07367228309144538

Johansson, R. S., & Vallbo, A. B. (1979). Tactile sensibility in the human hand: relative and absolute densities of four types of mechanoreceptive units in glabrous skin. *The Journal of Physiology*, *286*, 283–300. https://doi.org/10.1113/jphysiol.1979.sp012619

Johansson, R. S., & Westling, G. (1984). Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects. *Experimental Brain Research*, *56*(3), 550–564. https://doi.org/10.1007/BF00237997

Jones, L. A., & Hunter, I. W. (1993). A perceptual analysis of viscosity. *Experimental Brain Research*, *94*(2), 343–351. https://doi.org/10.1007/BF00230304

Kanda, Y. (1991). Piezoresistance effect of silicon. *Sensors and Actuators: A. Physical*, *28*(2), 83–91. https://doi.org/10.1016/0924-4247(91)85017-I

Kang, B. B., Lee, H., In, H., Jeong, U., Chung, J., & Cho, K.-J. (2016). Development of a polymer-based tendon-driven wearable robotic hand. *2016 IEEE International Conference on Robotics and Automation (ICRA)*, 3750–3755. https://doi.org/10.1109/ICRA.2016.7487562

Khalili, N., Shen, X., & Naguib, H. E. (2018). An interlocked flexible piezoresistive sensor with 3D micropyramidal structures for electronic skin applications. *Soft Matter*, *14*(33), 6912–6920. https://doi.org/10.1039/c8sm00897c

Kim, J. O., Kwon, S. Y., Kim, Y., Choi, H. B., Yang, J. C., Oh, J., Lee, H. S., Sim, J. Y., Ryu, S., & Park, S. (2019). Highly Ordered 3D Microstructure-Based Electronic Skin Capable of Differentiating Pressure, Temperature, and Proximity. *ACS Applied Materials and Interfaces*, *11*(1), 1503–1511. https://doi.org/10.1021/acsami.8b19214

Kim, K., Kim, J., Jiang, X., & Kim, T. (2021). Static Force Measurement Using Piezoelectric Sensors. In *Journal of Sensors* (Vol. 2021). Hindawi Limited. https://doi.org/10.1155/2021/6664200

Kuschel, M., Di Luca, M., Buss, M., & Klatzky, R. L. (2010). Combination and integration in the perception of visual-haptic compliance information. *IEEE Transactions on Haptics*, *3*(4), 234–244. https://doi.org/10.1109/TOH.2010.9

Lee, S., Reuveny, A., Reeder, J., Lee, S., Jin, H., Liu, Q., Yokota, T., Sekitani, T., Isoyama, T., Abe, Y., Suo, Z., & Someya, T. (2016). A transparent bending-insensitive pressure sensor. *Nature Nanotechnology*, *11*(5), 472–478. https://doi.org/10.1038/nnano.2015.324

Li, Q., Natale, L., Haschke, R., Cherubini, A., Ho, A.-V., & Ritter, H. (2018). Tactile Sensing for Manipulation. *International Journal of Humanoid Robotics*, *15*(01), 1802001. https://doi.org/10.1142/S0219843618020012

Lipomi, D. J., Vosgueritchian, M., Tee, B. C. K., Hellstrom, S. L., Lee, J. A., Fox, C. H., & Bao, Z. (2011). Skin- like pressure and strain sensors based on transparent elastic films of carbon nanotubes. *Nature Nanotechnology*, *6*(12), 788–792. https://doi.org/10.1038/nnano.2011.184

Maglio, S., Park, C., Tognarelli, S., Menciassi, A., & Roche, E. T. (2021). High-Fidelity Physical Organ Simulators: From Artificial to Bio-Hybrid Solutions. *IEEE Transactions on Medical Robotics and Bionics*, *3*(2), 349–361. https://doi.org/10.1109/TMRB.2021.3063808

Mannsfeld, S. C. B., Tee, B. C. K., Stoltenberg, R. M., Chen, C. V. H. H., Barman, S., Muir, B. V. O., Sokolov, A. N., Reese, C., & Bao, Z. (2010). Highly sensitive flexible pressure sensors with microstructured rubber dielectric layers. *Nature Materials*, *9*(10), 859–864. https://doi.org/10.1038/nmat2834

Manto, M., Topping, M., Soede, M., Sanchez-Lacuesta, J., Harwin, W., Pons, J., Williams, J., Skaarup, S., & Normie, L. (2003). Dynamically responsive intervention for tremor suppression. *IEEE Engineering in Medicine and Biology Magazine*, *22*(3), 120–132. https://doi.org/10.1109/MEMB.2003.1213635

McIntosh, R. B., Mauger, P. E., & Patterson, S. R. (2006). Capacitive transducers with curved electrodes. *IEEE Sensors Journal*, *6*(1), 125–138. https://doi.org/10.1109/JSEN.2005.854137

Mishra, R. B., El-Atab, N., Hussain, A. M., & Hussain, M. M. (2021). Recent Progress on Flexible Capacitive Pressure Sensors: From Design and Materials to Applications. *Advanced Materials Technologies*, *2001023*, 1–34. https://doi.org/10.1002/admt.202001023

Mutlu, R., Alici, G., in het Panhuis, M., & Spinks, G. M. (2016). 3D Printed Flexure Hinges for Soft Monolithic Prosthetic Fingers. *Soft Robotics*, *3*(3), 120–133. https://doi.org/10.1089/soro.2016.0026

Navaraj, W., Smith, C., & Dahiya, R. (2019). E-skin and wearable systems for health care. In *Wearable Bioelectronics* (pp. 133–178). Elsevier. https://doi.org/10.1016/B978-0-08-102407-2.00006-0

Nisky, I., Baraduc, P., & Karniel, A. (2010). Proximodistal gradient in the perception of delayed stiffness. *Journal of Neurophysiology*, *103*(6), 3017–3026. https://doi.org/10.1152/jn.00939.2009

Nisky, I., Huang, F., Milstein, A., Pugh, C. M., Mussa-Ivaldi, F. A., & Karniel, A. (2012). Perception of stiffness in laparoscopy - the fulcrum effect. *Studies in Health Technology and Informatics*, *173*, 313–319. http://www.ncbi.nlm.nih.gov/pubmed/22357009

Nisky, I., Mussa-Ivaldi, F. A., & Karniel, A. (2008). A regression and boundary-crossing-based model for the perception of delayed stiffness. *IEEE Transactions on Haptics*, *1*(2), 73–83. https://doi.org/10.1109/TOH.2008.17

Okamura, A. M. (2009). Haptic feedback in robot-assisted minimally invasive surgery. In *Current Opinion in Urology* (Vol. 19, Issue 1, pp. 102–107). https://doi.org/10.1097/MOU.0b013e32831a478c

Ozioko, O., & Dahiya, R. (2022). Strain sensors for soft robotic applications. In *Sensory Systems for Robotic Applications* (pp. 75–90). Institution of Engineering and Technology. https://doi.org/10.1049/PBCE097E_ch4

Pang, C., Lee, G. Y., Kim, T. Il, Kim, S. M., Kim, H. N., Ahn, S. H., & Suh, K. Y.

(2012). A flexible and highly sensitive strain-gauge sensor using reversible interlocking of nanofibres. *Nature Materials*, *11*(9), 795–801. https://doi.org/10.1038/nmat3380

Pang, Y., Zhang, K., Yang, Z., Jiang, S., Ju, Z., Li, Y., Wang, X., Wang, D., Jian, M., Zhang, Y., Liang, R., Tian, H., Yang, Y., & Ren, T. L. (2018). Epidermis Microstructure Inspired Graphene Pressure Sensor with Random Distributed Spinosum for High Sensitivity and Large Linearity. *ACS Nano*, *12*(3), 2346–2354. https://doi.org/10.1021/acsnano.7b07613

Parida, K., Xiong, J., Zhou, X., & See, P. (2019). Nano Energy Progress on triboelectric nanogenerator with stretchability , self-healability and bio-compatibility. *Nano Energy*, *59*(January), 237–257. https://doi.org/10.1016/j.nanoen.2019.01.077

Park, J., Kim, J., Hong, J., Lee, H., Lee, Y., Cho, S., Kim, S. W., Kim, J. J., Kim, S. Y., & Ko, H. (2018). Tailoring force sensitivity and selectivity by microstructure engineering of multidirectional electronic skins. *NPG Asia Materials*, *10*(4), 163–176. https://doi.org/10.1038/s41427-018-0031-8

Park, J., Kim, M., Lee, Y., Lee, H. S., & Ko, H. (2015). Nanomaterials: Fingertip skin-inspired microstructured ferroelectric skins discriminate static/dynamic pressure and temperature stimuli. *Science Advances*, *1*(9). https://doi.org/10.1126/sciadv.1500661

Park, J., Lee, Y., Hong, J., Ha, M., Jung, Y. Do, Lim, H., Kim, S. Y., & Ko, H. (2014). Giant tunneling piezoresistance of composite elastomers with interlocked microdome arrays for ultrasensitive and multimodal electronic skins. *ACS Nano*, *8*(5), 4689–4697. https://doi.org/10.1021/nn500441k

Park, J., Lee, Y., Hong, J., Lee, Y., Ha, M., Jung, Y., Lim, H., Kim, S. Y., & Ko, H. (2014). Tactile-direction- sensitive and stretchable electronic skins based on human-skin-inspired interlocked microstructures. *ACS Nano*, *8*(12), 12020–12029. https://doi.org/10.1021/nn505953t

Puers, R. (1993). Capacitive sensors: When and how to use them. *Sensors and Actuators: A. Physical*, *37– 38*(C), 93–105. https://doi.org/10.1016/0924-4247(93)80019-D

Rossi, M., Nardello, M., Lorenzelli, L., & Brunelli, D. (2017). *Dual Mode Pressure Sensing for Lower-Limb Prosthetic Interface*. 593. https://doi.org/10.3390/proceedings1040593

Ruth, S. R. A., & Bao, Z. (2020). Designing Tunable Capacitive Pressure Sensors Based on Material Properties and Microstructure Geometry. *ACS Applied Materials and Interfaces*, *12*(52), 58301–58316. https://doi.org/10.1021/acsami.0c19196

Ruth, S. R. A., Beker, L., Tran, H., Feig, V. R., Matsuhisa, N., & Bao, Z. (2020). Rational Design of Capacitive Pressure Sensors Based on Pyramidal Microstructures for Specialized Monitoring of Biosignals. *Advanced Functional Materials*, *30*(29), 1–12. https://doi.org/10.1002/adfm.201903100

Ruth, S. R. A., Feig, V. R., Tran, H., & Bao, Z. (2020). Microengineering Pressure Sensor Active Layers for Improved Performance. *Advanced Functiona Materials*, *30*(39), 1–31. https://doi.org/10.1002/adfm.202003491

Sapra, S., Nag, A., Han, T., & Gooneratne, C. P. (2019). Localisation of thin- film resistive sensors for force sensing applications. *2019 13th International Conference on Sensing Technology (ICST)*, 1–6. https://doi.org/10.1109/ICST46873.2019.9047720

Sawik, B., Tobis, S., Baum, E., Suwalska, A., Kropińska, S., Stachnik, K., Pérez-Bernabeu, E., Cildoz, M., Agustin, A., & Wieczorowska-Tobis, K. (2023). Robots for Elderly Care: Review, Multi-Criteria Optimization Model and Qualitative Case Study. *Healthcare (Switzerland)*, *11*(9). https://doi.org/10.3390/healthcare11091286

Schwartz, G., Tee, B. C. K., Mei, J., Appleton, A. L., Kim, D. H., Wang, H., & Bao, Z. (2013). Flexible polymer transistors with high pressure sensitivity for application in electronic skin and health monitoring. *Nature Communications*, *4*(May). https://doi.org/10.1038/ncomms2832

Seibold, U., Kübler, B., & Hirzinger, G. (2005). Prototype of instrument for minimally invasive surgery with 6- axis force sensing capability. *Proceedings - IEEE International Conference on Robotics and Automation*, *2005*, 496–501. https://doi.org/10.1109/ROBOT.2005.1570167

Smith, C. D., Farrell, T. M., McNatt, S. S., & Metreveli, R. E. (2001). Assessing laparoscopic manipulative skills. *American Journal of Surgery*, *181*(6), 547–550. https://doi.org/10.1016/s0002-9610(01)00639-0

Soni, M., & Dahiya, R. (2020). Soft Eskin: Distributed touch sensing with harmonized energy and computing. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *378*(2164). https://doi.org/10.1098/rsta.2019.0156

Ştefănescu, D. M. (2011). Capacitive Force Transducers. In *Handbook of Force Transducers* (pp. 87–108).

Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-18296-9_5

Su, B., Gong, S., Ma, Z., Yap, L. W., & Cheng, W. (2015). Mimosa-Inspired Design of a Flexible Pressure Sensor with Touch Sensitivity. *Small*, *11*(16), 1886–1891. https://doi.org/10.1002/smll.201403036

Tao, J., Bao, R., Wang, X., Peng, Y., Li, J., Fu, S., Pan, C., & Wang, Z. L. (2019). *Self-Powered Tactile Sensor Array Systems Based on the Triboelectric Effect*. *1806379*, 1–23. https://doi.org/10.1002/adfm.201806379

Tefertiller, C., Pharo, B., Evans, N., & Winchester, P. (2011). Efficacy of rehabilitation robotics for walking training in neurological disorders:A review. *Journal of Rehabilitation Research and Development*, *48*(4), 387–416. https://doi.org/10.1682/JRRD.2010.04.0055

Tripicchio, P., D'Avella, S., Avizzano, C. A., & Velha, P. (2023). Towards robust grasping: An analysis of in- hand object motion with FBG optical fibers as force sensing technology. *Mechatronics*, *93*. https://doi.org/10.1016/j.mechatronics.2023.102990

Wang, X., Li, T., Adams, J., & Yang, J. (2013). Transparent, stretchable, carbon-nanotube-inlaid conductors enabled by standard replication technology for capacitive pressure, strain and touch sensors. *Journal of Materials Chemistry A*, *1*(11), 3580–3586. https://doi.org/10.1039/c3ta00079f

Wang, Z., Bu, T., Li, Y., Wei, D., Tao, B., Yin, Z., Zhang, C., & Wu, H. (2021). Multidimensional Force Sensors Based on Triboelectric Nanogenerators for Electronic Skin. *ACS Applied Materials and Interfaces*, *13*(47), 56320–56328. https://doi.org/10.1021/acsami.1c17506

Wang, Z. L., Chen, J., & Lin, L. (2015). Progress in triboelectric nanogenerators as a new energy technology and self-powered sensors. *Energy and Environmental Science*, *8*(8), 2250–2282. https://doi.org/10.1039/c5ee01532d

Weber, A. I., Saal, H. P., Lieber, J. D., Cheng, J. W., Manfredi, L. R., Dammann, J. F., & Bensmaia, S. J. (2013). Spatial and temporal codes mediate the tactile perception of natural textures. *Proceedings of the National Academy of Sciences of the United States of America*, *110*(42), 17107–17112. https://doi.org/10.1073/pnas.1305509110

Westling, G., & Johansson, R. S. (1984). Factors influencing the force control during precision grip. *Experimental Brain Research*, *53*(2), 277–284. https://doi.org/10.1007/BF00238156

Westling, G., & Johansson, R. S. (1987). Responses in glabrous skin mechanoreceptors during precision grip in humans. *Experimental Brain Research*, *66*(1), 128–140. https://doi.org/10.1007/BF00236209

Wettels, N., & Pletner, B. (2012). Integrated dynamic and static tactile sensor: focus on static force sensing. *Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2012*, *8345*, 83454H. https://doi.org/10.1117/12.917391

Xiang, G., Wang, X., Cheng, N., Hu, L., Zhang, H., & Liu, H. (2022). A Flexible Piezoelectric-based Tactile Sensor for Dynamic Force Measurement. *2022 International Conference on High Performance Big Data and Intelligent Systems, HDIS 2022*, 207–211. https://doi.org/10.1109/HDIS56859.2022.9991654

Xu, F., & Zhu, Y. (2012). Highly conductive and stretchable silver nanowire conductors. *Advanced Materials*, *24*(37), 5117–5122. https://doi.org/10.1002/adma.201201886

Yamada, T., Hayamizu, Y., Yamamoto, Y., Yomogida, Y., Izadi-Najafabadi, A., Futaba, D. N., & Hata, K. (2011). A stretchable carbon nanotube strain sensor for human-motion detection. *Nature Nanotechnology*, *6*(5), 296–301. https://doi.org/10.1038/nnano.2011.36

Yeo, J. C., Yu, J., Koh, Z. M., Wang, Z., & Lim, C. T. (2016). Wearable tactile sensor based on flexible microfluidics. *Lab on a Chip*, *16*(17), 3244–3250. https://doi.org/10.1039/C6LC00579A

Yi, F., Zhang, Z., Kang, Z., Liao, Q., & Zhang, Y. (2019). *Recent Advances in Triboelectric Nanogenerator- Based Health Monitoring*. *1808849*, 1–16. https://doi.org/10.1002/adfm.201808849

Zhou, Y., Tang, Y., & Yu, Y. (2023). Technological trends in medical robotic sensing with soft electronic skin. In

Sensors and Diagnostics. Royal Society of Chemistry. https://doi.org/10.1039/d3sd00284e

About Authors

Inci Rüya TEMEL | Fondazione Bruno Kessler (FBK) |
ORCID: 0009-0001-9279-0411

Received the B.Sc degree in Life Sciences from Sorbonne University, Paris, and the M.Sc degree in Biomedical engineering from University of Montpellier. Since 2020, she is working on the MSCA ITN INTUITIVE project in the Bruno Kessler Foundation, Italy as a Marie Curie Early-Stage Researcher and pursuing her Ph.D. in the University of Glasgow, UK. She is working on flexible shear force sensors to be integrated in an electronic skin.

Andrea ADAMI | Fondazione Bruno Kessler (FBK) |
ORCID: 0000-0003-2833-7564

Received the Italian Master degree in materials engineering and the Ph.D. degree in information and communications technologies from the University of Trento, Italy, in 2003 and 2010, respectively. He is currently a Researcher with the Fondazione Bruno Kessler (FBK), where he is involved in sensors and microsystems. Since 2003, he acquired good experience on device design and development, especially on chemical sensors, micromechanical sensors, and microfluidics for several applications. His current main research interest is the development of microsystems and microfluidics, in particular for sample preparation in analytical systems. He is the author of more than 70 articles in international conferences and scientific journals.

Leandro LORENZELLI | Fondazione Bruno Kessler (FBK) |
ORCID: 0000-0003-4624-170X

(Member, IEEE) received the degree in electronic engineering from the University of Genova in 1994, and the Ph.D. degree in electronics materials and technologies from the University of Trento in 1998. In 1998, he joined the Staff of the ITC-irst Microsystems Division, and he was involved in the realization of microsystems for biomedical, environmental, and agro-food applications. Since 2005, he has been directing the BioMEMS research area at Bruno Kessler Foundation. His research interests include biosensors, nanobiotechnology, and lab-on-chip.

THE ROLE OF BASIC SCIENCES IN BUILDING SUSTAINABLE SMART CITIES

Musab Talha Akpınar

Cem Korkut

10.53478/TUBA.978-625-6110-22-9.ch15

The Role of Basic Sciences in Building Sustainable Smart Cities

Musab Talha Akpınar, Cem Korkut
Ankara Yıldırım Beyazıt University

Abstract

This chapter explores the integral role of basic sciences—physics, chemistry, biology, and mathematics—in developing Sustainable Smart Cities, which aim to enhance urban living through environmental sustainability and technological advancement. By examining how each of these scientific disciplines contributes to urban sustainability, the chapter provides a comprehensive overview of their application to smart city infrastructure, resource management, and environmental health. Physics underpins energy efficiency and structural integrity in building designs, while chemistry drives innovations in sustainable materials, waste management, and pollution control. Biological sciences support the development of green spaces, biodiversity conservation, and urban agriculture, promoting ecosystem services like carbon sequestration and natural cooling. Meanwhile, mathematics and data science enable real-time monitoring, predictive modeling, and optimized resource allocation, ensuring that cities can respond to dynamic urban challenges with agility and foresight. The chapter also discusses the interconnectedness of these sciences and highlights the need for continued investment in research and education to sustain progress in this field. Through interdisciplinary collaboration and a commitment to scientific innovation, Sustainable Smart Cities can address the pressing issues of climate change and urbanization, paving the way for resilient, efficient, and inclusive urban environments.

Keywords
Sustainable Development, Smart Cities, Basic Sciences, Urban Sustainability, Environmental Technology Integration

Introduction

Sustainable smart cities are urban environments that seamlessly blend cutting-edge technologies with environmentally conscious practices to create spaces that are efficient, livable, and ecologically sustainable (Hui and et al, 2023). These cities rely on technological innovations, such as the Internet of Things (IoT), big data analytics, and artificial intelligence (AI), to enhance the management and optimization of urban services (Allam & Dhunny, 2019). By leveraging these technologies, cities can improve the efficiency of transportation, energy usage, waste management, and public services, all while minimizing resource consumption and reducing environmental impact. The overarching goal of sustainable smart cities is not only to elevate the quality of life for their residents but also to foster economic growth in a way that is harmonious with ecological sustainability (Kutty and et al, 2020). This holistic approach ensures that urban development aligns with the principles of long-term environmental stewardship, thereby creating cities that are not only responsive to the needs of today but also resilient and adaptable to future challenges, all while keeping their ecological footprints to a minimum.

The significance of integrating sustainability with advanced technology lies in the capacity to optimize resource utilization and minimize waste (Dao and et al., 2011). For instance, the implementation of smart grids, which are integral to many smart city frameworks, enables real-time monitoring and dynamic adjustment of energy distribution according to demand. This capability not only reduces energy waste but also promotes the integration of renewable energy sources such as solar and wind power—critical for sustainable development in highly populated urban areas. By increasing the efficiency of resource usage, smart technologies contribute to the development of urban systems that are both resilient and capable of adapting to environmental fluctuations (Ramirez Lopez & Grijalba Castro, 2020).

Moreover, sustainable smart cities significantly enhance the quality of life by enabling more responsive, efficient urban services (Belli and et al., 2020). For example, smart traffic management systems leverage IoT sensors and real-time data analytics to alleviate congestion, resulting in reduced emissions and improved air quality. This is particularly crucial as cities are responsible for a substantial portion of global carbon dioxide emissions. Similarly, advanced technologies are vital in the fields of healthcare and emergency services, where real-time data can optimize resource allocation, thereby increasing the effectiveness and responsiveness of these services, ultimately safeguarding the health and well-being of urban populations (Damaševičius and et al., 2023; Mohammadzadeh and et al., 2023).

In addition to optimizing urban services, the integration of sustainability and technology within smart cities plays a pivotal role in environmental conservation and protection (Li and et al., 2019). Through the deployment of sensor networks (Channi & Kumar, 2021) and advanced data analytics, smart cities monitor and regulate pollution, water quality, and waste management processes (Arshi & Mondal, 2023). These measures are essential for mitigating the environmental impact of urbanization on natural ecosystems and for fostering urban biodiversity. Furthermore, green infrastructure—such as parks, green roofs, and other eco-friendly designs—combined with real-time environmental monitoring technologies, creates urban environments that promote ecosystem vitality and mitigate challenges like the urban heat island effect (Singh and et al., 2024). Through these initiatives, sustainable smart cities contribute to the creation of urban landscapes that are not only technologically advanced but also ecologically balanced.

Another crucial element of sustainable smart cities is their resilience to the impacts of climate change (Ramirez Lopez & Grijalba Castro, 2020). Through the use of predictive analytics and advanced technological systems, these cities can anticipate and proactively respond to extreme weather events, enhancing their ability to withstand environmental stressors. As climate change continues to present increasingly complex challenges, this adaptability becomes vital for the sustainability of urban areas. For example, smart water management systems can continuously monitor water levels and distribution networks, enabling cities to more effectively manage and mitigate the risks associated with droughts, floods, and other climate-induced events.

In addition to fostering resilience, the integration of sustainability with advanced technology in smart cities drives economic growth and innovation (Blasi and et al., 2022). These cities become magnets for investment in green industries, promoting job creation and stimulating local economies. Moreover, they serve as innovation hubs where businesses and entrepreneurs develop cutting-edge solutions to address urban challenges. By prioritizing technology-driven sustainability, smart cities not only enhance their economic competitiveness but also position themselves at the forefront of the global movement toward sustainable urban development (Yigitcanlar & Cugurullo, 2020).

The sustainable smart cities harness advanced technologies to optimize resource usage, improve the efficiency of urban services, protect the environment, strengthen climate resilience, and stimulate economic growth (Hui and et al. 2023). By aligning their development with sustainability objectives, these cities are better equipped to meet the challenges of rapid urbanization and climate change, while simultaneously promoting a higher quality of life for their residents.

Basic sciences play a foundational role in understanding and addressing the complex challenges associated with sustainability and urbanization, particularly within the context of Sustainable Smart Cities (Bibri, 2018; De Jong and et al., 2015). By applying principles from physics, chemistry, biology, and mathematics, these sciences enable a deeper comprehension of urban systems and facilitate the development of technologies and strategies that promote sustainability. The integration of basic sciences into urban planning and management is essential for creating cities that can sustain their growing populations while minimizing their environmental impact (Wu, 2014).

Mathematics serves as the underlying foundation for various aspects of software engineering, offering a structured approach to problem-solving that is essential for analyzing and optimizing algorithms, data structures, and system designs (Braha & Maimon, 2013; Martins & Ning, 2021). In the context of smart cities, this mathematical framework is indispensable, as it enables the development of advanced technologies to manage the complexities of urban environments (Javed and et al., 2022). For instance, linear algebra is crucial for processing large datasets in applications such as machine learning and real-time analytics, both of which are pivotal for optimizing traffic systems and managing energy consumption (Sun and et al., 2023; Elgohary and et al., 2018). Mathematical models allow for the simulation, prediction, and enhancement of urban systems, ensuring they function efficiently and sustainably (Bibri and Bibri, 2020; Chang and et al., 2020).

Beyond its computational applications, mathematics fosters a logical methodology for solving technical challenges, a necessity in smart city infrastructure. Optimization techniques derived from mathematical theories are employed to ensure algorithms perform efficiently, minimizing resource consumption while maintaining high levels of accuracy. This is especially important in systems like smart grids or IoT-based urban monitoring networks, where large-scale data must be processed in real time to facilitate decision-making that affects millions of city residents (Ahmad & Zhang, 2021).

Mathematics also plays a critical role in the design and verification of software systems (Alagar & Periyasamy, 2011). Formal methods, based on mathematical logic, are used to verify the correctness, reliability, and security of software—particularly in essential systems such as energy management or emergency response frameworks. The rigor provided by mathematical principles ensures that these systems are functional, scalable, secure, and capable of operating under a variety of environmental and operational conditions.

In addition to mathematics, the basic sciences, including physics, chemistry, and biology, are fundamental in shaping the sustainability and functionality of smart cities (Batty and et al., 2012). Physics plays a significant role in the development of resilient infrastructure and energy systems. The principles of thermodynamics and material science inform the design of energy-efficient buildings and renewable energy technologies, reducing reliance on fossil fuels and minimizing greenhouse gas emissions. Understanding the physical properties of materials enables engineers to select those that can withstand environmental stressors, contributing to resource conservation and climate resilience (Grifoni and et al., 2012). Additionally, geosciences, closely related to physics, offer critical insights into land use, resource distribution, and natural hazard management. Geospatial data and geoinformatics, which analyze spatial data, are instrumental in monitoring land changes and informing sustainable urban growth.

Chemistry, likewise, is pivotal in addressing urban sustainability challenges, particularly through advancements in pollution control and resource management (Shi and et al., 2021). By understanding chemical processes, scientists develop methods for treating wastewater, managing air quality, and recycling materials effectively. Chemical engineering, for example, plays a key role in water treatment facilities, ensuring clean water supplies for growing urban populations. Additionally, chemistry supports the development of eco-friendly materials, such as biodegradable plastics and sustainable building components, which reduce waste and reliance on non-renewable resources—particularly important in densely populated cities facing sustainability pressures.

Biology also contributes significantly to urban sustainability by promoting ecosystem health and biodiversity within city environments (Marselle and et al., 2021). The study of ecological interactions helps urban planners design green spaces that support local flora and fauna, contributing to biodiversity conservation even in densely built areas. Biophilic design, which integrates natural elements into urban architecture, enhances the physical and mental well-being of residents while improving urban ecosystems. Moreover, biology informs urban agricultural initiatives that provide locally sourced food, reduce the carbon footprint of food transport, and improve food security. These ecological insights are integral to creating urban environments that are both sustainable and conducive to a higher quality of life for residents.

Mathematics, coupled with data science, is indispensable in addressing the dynamic challenges of urban sustainability. Mathematical models enable urban planners to simulate the impacts of sustainability initiatives—such as energy efficiency programs and waste reduction strategies—allowing for data-driven decision-making. Data science, supported by big data analytics, plays a critical role in managing the vast volumes of information generated by smart city technologies like IoT sensors and urban monitoring systems. These data analytics tools allow cities to respond swiftly to real-time issues such as traffic congestion, pollution spikes, or resource shortages. By providing insights into urban patterns and trends, mathematics and data science optimize city operations and ensure that sustainability goals are met efficiently.

In conclusion, mathematics provides the foundational framework upon which software engineering and technological advancements in smart cities are built. When combined with insights from physics, chemistry, and biology, smart cities can develop systems that are resilient, efficient, and environmentally sustainable. These basic sciences collectively form the backbone of smart cities, each contributing unique insights and technologies that ensure urban environments are technologically advanced, ecologically sound, and socially inclusive. This multidisciplinary approach helps cities address immediate sustainability challenges while also preparing for future demands driven by rapid urban growth and environmental change.

Method

This study employs an interdisciplinary, empirical approach to explore the role of four core scientific disciplines—physics, chemistry, biology, and mathematics—in shaping the sustainability and functionality of smart cities (Bettencourt, 2021; Zhao and et al., 2019). Each branch of science is examined individually to illustrate its contribution to urban resilience, efficiency, and ecological balance. Case-based analysis will be applied to highlight real-world applications of scientific principles, offering a holistic understanding of how these disciplines intersect with urban planning and smart city technologies.

By integrating qualitative and quantitative data from existing literature, technical reports, and smart city initiatives, the study systematically examines how each scientific discipline underpins sustainable urban development. Physics will be analyzed for its role in energy systems and infrastructure; chemistry for its innovations in materials and pollution control; biology for enhancing green spaces and biodiversity; and mathematics for its role in data-driven decision-making and resource optimization.

The empirical nature of the study ensures that each discipline's contribution is not only conceptualized but demonstrated through practical, real-world examples. This approach allows for a comprehensive understanding of how smart cities can leverage the basic sciences to achieve long-term sustainability and resilience.

The Role of Physics in Sustainable Infrastructure

Physics plays a critical role in shaping sustainable building designs within smart cities by enhancing energy efficiency, structural integrity, and materials science. Through the principles of thermodynamics, engineers can design energy-efficient buildings that minimize heat loss, using insulation and optimizing thermal conductivity to reduce energy consumption for heating and cooling (Kheiri and et al., 2018). This not only lowers the energy demand of individual buildings but also integrates them into renewable energy networks, contributing to the city's overall sustainability.

Structural integrity, guided by mechanics and materials science, ensures buildings are resilient against environmental stressors like earthquakes and extreme weather. By applying physics-based models, engineers can distribute loads effectively within structures, preventing material fatigue and enhancing durability. These designs are especially crucial in dense urban areas where safety and flexibility are paramount.

Materials science, rooted in physics, also contributes to the development of sustainable materials. Innovations in composites and nanomaterials provide lighter, stronger alternatives to traditional materials like steel and concrete, reducing environmental impact. Advanced materials, such as phase-change materials, further enhance energy efficiency by regulating indoor temperatures, thus supporting the broader sustainability goals of smart cities.

Renewable energy technologies, including solar, wind, and geothermal, are central to reducing the environmental impact of smart cities. Improvements in solar panel efficiency and compactness allow for widespread integration into buildings, enabling on-site clean energy generation and reducing reliance on centralized grids. Wind energy, with quieter and more efficient turbines, is harnessed even in urban environments, contributing to a diversified and stable energy portfolio. Geothermal energy, though less visible, offers consistent heating and cooling solutions, reducing dependence on conventional energy sources.

The impact of these renewable technologies extends beyond environmental benefits—they also promote energy independence, reduce vulnerability to energy disruptions, and foster economic growth by creating jobs in green industries. By integrating renewable energy into their infrastructure, smart cities are not only reducing carbon footprints but also enhancing their resilience against future challenges.

Case studies like Masdar City, Stockholm, and Copenhagen illustrate the real-world application of physics-based solutions in smart urban planning (Jafari and et al., 2023). Masdar's use of advanced aerodynamics for natural cooling and its extensive solar power infrastructure demonstrate how physics can reduce energy reliance. Stockholm's district heating system, driven by geothermal energy and waste heat recovery, showcases thermodynamic efficiency, while Copenhagen's wind energy infrastructure highlights the potential of physics-optimized turbines to power cities sustainably.

In conclusion, the application of physics—whether through building design, materials science, or renewable energy technologies—serves as a foundational element in the development of sustainable smart cities. These principles enable cities to optimize resource use, minimize environmental impact, and enhance resilience, paving the way for a more sustainable and adaptable urban future.

The Contribution of Chemistry to Urban Sustainability

Chemistry is pivotal in developing sustainable materials and addressing urban environmental challenges. Innovations like biodegradable plastics and eco-friendly building materials help reduce the environmental footprint of urban areas (Muthusamy & Pramasivam, 2019). Biodegradable plastics, crafted through polymer chemistry, break down naturally under specific conditions, unlike conventional plastics that persist for centuries. These materials help alleviate waste issues, particularly in cities where waste management systems are strained. Eco-friendly building materials, such as green concrete and lightweight composites, also reduce resource consumption and carbon emissions by incorporating renewable or industrial by-products like fly ash, helping cities decrease their reliance on energy-intensive materials.

Chemistry also enhances energy efficiency in buildings through advanced materials such as phase-change materials and insulative coatings, which regulate indoor temperatures by absorbing and releasing energy. These innovations contribute to lower heating and cooling demands, further reducing energy consumption in smart cities.

Waste management, recycling, and pollution control are other critical areas where chemistry plays a central role. Chemical processes break down hazardous waste and convert it into safer substances, while technologies like anaerobic digestion transform organic waste into renewable biogas (Holm-Nielsen and et al., 2009). Chemical recycling allows materials like plastics and metals to be reconstituted at a molecular level, maintaining their quality and reducing the need for virgin resources. Moreover, urban recycling efforts benefit from the chemical recovery of valuable elements, like gold and copper, from electronic waste, making recycling more efficient and sustainable.

In pollution control, chemical processes are fundamental for treating air and water pollutants. Catalytic converters in vehicles and industrial facilities use chemical reactions to neutralize harmful emissions, while advanced water treatment processes, such as coagulation and disinfection, remove contaminants from wastewater. These solutions help cities mitigate the negative impacts of urbanization on the environment and public health.

In terms of air quality and soil remediation, chemical engineering has introduced catalytic systems and innovative filtration technologies. These systems neutralize airborne pollutants and detoxify contaminated soils, making urban environments healthier and more sustainable. For example, photocatalytic materials applied to buildings and roads can break down pollutants using sunlight, while chemical additives enhance soil remediation processes like phytoremediation.

The chemistry provides essential tools for creating sustainable urban environments. From developing biodegradable materials to improving waste management, recycling, and pollution control, the contributions of chemistry are integral to reducing cities' environmental impact and supporting broader sustainability goals (Chen and et al., 2020). Through these innovations, chemistry plays a key role in transforming urban areas into more resilient, eco-friendly spaces that meet the needs of future generations.

Biological Sciences and Ecosystem Integration in Smart Cities

Biological sciences are fundamental to the development of sustainable and resilient smart cities by enhancing green spaces, promoting biodiversity, and supporting urban agriculture. These contributions not only improve ecological health but also directly impact residents' quality of life. Urban planners, informed by principles from ecology and environmental biology, can design green spaces such as parks, urban forests, and community gardens that function as habitats for native species, contribute to carbon sequestration, and improve air quality (Lovell & Taylor, 2013). Green spaces serve multiple ecological functions—providing shade, cooling urban areas, and acting as carbon sinks—all of which are essential for mitigating the environmental pressures associated with urbanization. By understanding the physiological and ecological needs of plants and wildlife, cities can create self-sustaining ecosystems that thrive in urban settings, enhancing biodiversity even in densely developed environments.

In addition to green spaces, biological sciences significantly contribute to urban agriculture initiatives, which are becoming increasingly important as cities strive to improve food security and reduce their environmental impact. Urban agriculture leverages insights from plant biology and agricultural science to incorporate innovative solutions like vertical farms, rooftop gardens, and community gardens into the urban fabric. These urban farming systems allow cities to produce fresh, locally sourced food, reducing the need for transportation and minimizing the carbon emissions associated with traditional agricultural supply chains. Moreover, urban agriculture supports sustainable farming practices, such as organic pest control and soil enhancement techniques, which help maintain soil fertility and improve crop resilience (Lin and et al., 2015). These projects not only provide food but also contribute to urban biodiversity and offer recreational, educational, and social benefits for city residents.

Biological sciences also play a critical role in promoting biodiversity within cities, which is essential for creating resilient urban ecosystems. The study of species interactions, habitat requirements, and ecological processes enables urban planners and environmental scientists to design urban landscapes that support a diversity of species. For example, incorporating pollinator-friendly plants into green spaces supports the populations of insects crucial for pollination and natural pest control. This, in turn, helps maintain ecological balance and sustains the ecosystem services that cities rely on, such as water filtration, erosion control, and air purification. By preserving and enhancing biodiversity, smart cities create environments that are not only functional but also rich in ecological value and natural beauty.

Ecosystem services, such as carbon sequestration and natural cooling, are indispensable components of sustainable urban planning. Carbon sequestration is the process by which trees and plants absorb carbon dioxide and store it in their biomass, a critical function in mitigating climate change (Demuzere and et al., 2014). By incorporating extensive green spaces and vegetation into urban landscapes, smart cities can reduce atmospheric carbon levels and offset emissions from vehicles, industries, and buildings. This natural process is vital in helping cities meet their carbon reduction goals, improve air quality, and contribute to global climate action.

Natural cooling, another essential ecosystem service, is equally important for cities facing rising temperatures and frequent heatwaves. The urban heat island effect—caused by heat retention in materials like concrete and asphalt—can be mitigated by green spaces, which provide shade and lower temperatures through evapotranspiration. Strategically placed vegetation, green roofs, and urban forests can significantly reduce the need for energy-intensive air conditioning, lowering overall energy consumption and reducing the strain on urban power grids. These cooling benefits not only improve the comfort and well-being of city residents but also enhance the energy resilience of smart cities.

Furthermore, ecosystem services such as carbon sequestration and natural cooling contribute to the overall resilience of cities by helping to buffer against environmental stressors. Green infrastructure, including parks and urban forests, acts as a natural defense against extreme weather events like heatwaves and air pollution episodes. These services offer numerous co-benefits, such as providing recreational spaces, supporting biodiversity, and offering educational opportunities, while being cost-effective solutions for enhancing urban sustainability.

Bio-inspired technologies, also known as biomimicry, have become integral to smart city infrastructure, offering innovative solutions that emulate natural processes to address urban challenges. Green roofs, for example, replicate the natural functions of ecosystems by using layers of vegetation to absorb rainwater, regulate temperature, and provide insulation for buildings. This not only helps reduce the urban heat island effect but also minimizes energy consumption for heating and cooling. Green roofs also create habitats for pollinators and other wildlife, integrating biodiversity into urban environments and enhancing the aesthetic and ecological value of cities.

Vertical gardens, or green walls, are another bio-inspired solution widely adopted in smart cities. These structures mimic natural vertical ecosystems by incorporating vegetation into building facades, where they help filter air, improve insulation, and create visually appealing urban spaces. Vertical gardens contribute to air purification by removing pollutants, producing oxygen, and providing natural cooling through evapotranspiration. Additionally, they help regulate building temperatures, reducing energy needs and enhancing urban sustainability. These systems offer a practical and aesthetically pleasing way to integrate nature into dense urban environments, contributing to healthier and more livable cities.

Further examples of biomimicry in smart cities include materials and technologies inspired by natural organisms. For instance, engineers have developed building materials that mimic the light-capturing efficiency of leaves, optimizing solar energy absorption for more effective renewable energy generation. Other designs are inspired by desert plants that capture water from the air, providing sustainable water solutions for green spaces in urban areas. These bio-inspired innovations demonstrate how natural mechanisms can be adapted to solve urban challenges, contributing to the sustainability and resilience of smart cities.

The biological sciences are crucial to the success of smart cities, providing the knowledge and innovations needed to integrate nature into urban environments (Chourabi et al., 2012). By fostering green spaces, promoting biodiversity, and supporting urban agriculture, biological sciences help create cities that are more sustainable, resilient, and livable. Ecosystem services such as carbon sequestration and natural cooling are key to mitigating climate change and improving urban health, while biomimicry offers innovative solutions for sustainable infrastructure. In sum, the integration of biological sciences into urban planning ensures that smart cities not only meet the needs of their residents but also protect and enhance the natural environment for future generations.

Mathematics and Data Science: The Backbone of Smart City Analytics

Mathematical modeling and data science are essential tools for efficient urban planning, traffic management, and resource allocation in smart cities. Mathematical models allow urban planners to simulate various scenarios, such as population growth or infrastructure changes, to predict their impact on the city (Wegener, 2004). These models, powered by algorithms and statistical techniques, enable planners to optimize land use, forecast population density patterns, and strategically place new residential areas and public amenities to minimize environmental impact and enhance accessibility. This data-driven approach ensures that urban expansion is both sustainable and well-organized, reducing congestion and resource overuse.

In traffic management, data science enables real-time analysis of data from sensors, GPS systems, and traffic cameras, allowing cities to monitor and manage traffic flow efficiently. Adaptive traffic signal control systems adjust in response to real-time conditions, reducing bottlenecks, travel times, and vehicle emissions. Predictive models can anticipate peak traffic periods and recommend alternative routes, while integrated transportation networks combine buses, trains, and bike-sharing systems for seamless urban mobility. These data-driven insights optimize traffic patterns, reduce congestion, and improve urban transportation efficiency.

Resource allocation in smart cities also benefits greatly from mathematical modeling and data science. By analyzing vast datasets on energy use, water consumption, and waste production, cities can predict future resource demands and identify inefficiencies. Energy consumption models inform the placement of renewable energy sources to maximize efficiency, while water distribution models ensure effective resource allocation during peak usage times. These predictive models help cities conserve resources and align their operations with sustainability goals.

Algorithms and machine learning are revolutionizing energy optimization, environmental monitoring, and urban growth prediction (Tien and et al., 2022). Machine learning models analyze large datasets on energy consumption and weather patterns to make real-time adjustments, ensuring energy is used efficiently. These models are particularly valuable for balancing the fluctuating supply of renewable energy sources like solar and wind. By predicting peak demand and optimizing energy storage, machine learning enhances energy resilience and reduces costs.

Machine learning also plays a crucial role in monitoring environmental factors such as air quality and water pollution. Sensor data is analyzed to detect pollution spikes and recommend immediate actions, such as adjusting traffic flow or issuing public health warnings. Predictive analytics allow city managers to anticipate environmental changes and take preventive measures, contributing to the long-term sustainability and health of urban ecosystems.

In predicting urban growth, machine learning analyzes historical data on population trends and economic indicators to forecast how cities will expand. These predictions help planners allocate resources and upgrade infrastructure to accommodate growth without overextending resources. By simulating various development scenarios, machine learning models support proactive urban planning, ensuring cities remain adaptable and resilient.

Big data initiatives are central to smart city sustainability efforts. In Barcelona, an extensive network of IoT sensors collects real-time data on air quality, noise, and energy consumption, allowing the city to optimize resource efficiency and reduce its carbon footprint. Data insights from energy use patterns have led to more efficient street lighting and public transit routes, contributing to lower emissions and improved sustainability.

Singapore's "Virtual Singapore" platform integrates data from various sources to create a digital twin of the city, allowing planners to simulate the impact of infrastructure projects on energy use and air quality. This real-time data analysis supports better resource management and ensures the city's efficiency and resilience.

In Amsterdam, the Open Data portal promotes transparency and collaboration between the government, businesses, and citizens to address sustainability issues. Data from energy meters and environmental sensors helps optimize building regulations and transportation schedules, reducing emissions and improving the city's overall sustainability.

Mathematics, data science, algorithms, and machine learning form the analytical backbone of smart cities, enabling efficient urban planning, resource management, and sustainability. Through the use of big data, smart cities can optimize operations, enhance environmental health, and make informed decisions to meet the challenges of urbanization and climate change.

Conclusion

This study underscores the critical role of basic sciences—physics, chemistry, biology, and mathematics—in the development and sustainability of smart cities (Bibri and et al., 2024). By providing foundational knowledge and practical applications, these scientific disciplines collectively form the backbone of sustainable urban development. The integration of these fields into urban planning and infrastructure design enables cities to create systems that are resilient, efficient, and environmentally conscious, addressing the multifaceted challenges posed by rapid urbanization and climate change. Table 1 encapsulates how each basic science plays a vital role in building smart, sustainable cities, emphasizing their interconnected contributions to urban development and sustainability.

Table 1.

Role of basic sciences in building sustainable smart cities.

Basic Science	Role in Sustainable Smart Cities	Example
Physics	Physics principles help optimize energy efficiency, structural integrity, and the development of renewable energy technologies in urban settings. These principles guide the design of energy-efficient buildings, support renewable energy systems, and ensure the safety and resilience of infrastructure.	In Masdar City, principles of aerodynamics and thermodynamics are applied to reduce energy usage for cooling, while renewable energy sources, such as solar power, provide a clean energy solution for urban sustainability.
Chemistry	Chemistry contributes to sustainable urban environments by developing biodegradable materials, eco-friendly construction materials, and waste management solutions. Chemical processes are also essential in water purification, air quality improvement, and the recycling of urban waste.	Photocatalytic materials used on buildings in smart cities break down pollutants in the air through chemical reactions, helping to control urban pollution and improve air quality.
Biology	Biological sciences aid in enhancing biodiversity, integrating green spaces into urban areas, and promoting urban agriculture. These elements contribute to the resilience of urban ecosystems, supporting carbon sequestration and providing natural cooling effects to mitigate the urban heat island effect.	Green roofs in urban areas emulate natural ecosystems, absorbing rainwater and regulating temperature, while providing habitats for pollinators and reducing energy consumption in buildings.
Mathematics	Mathematics and data science enable efficient urban planning and resource allocation by providing models for real-time data analysis. These models optimize traffic management, energy use, and resource distribution in smart cities, ensuring sustainability and minimizing resource wastage.	In Singapore, the “Virtual Singapore” platform integrates real-time data from various sectors, allowing planners to simulate infrastructure projects' impacts on energy use, air quality, and resource management for optimized planning.
Geosciences	Geosciences provide essential data on land use, natural hazards, and resource distribution, informing sustainable urban development. This science helps cities manage natural resources efficiently, mitigate environmental risks, and plan for long-term sustainability.	Geospatial data is used to monitor land changes in cities like Stockholm, where advanced data collection informs district heating systems, contributing to energy efficiency and sustainable resource use.

Physics contributes significantly to the structural and energy efficiency of urban environments. The application of thermodynamics and materials science allows for the design of energy-efficient buildings and renewable energy systems, reducing the carbon footprint of cities while enhancing their capacity to withstand environmental stressors. These principles provide a framework for optimizing resource use, a crucial factor in sustainable city management.

Chemistry plays a vital role in advancing waste management, pollution control, and the development of sustainable materials. Innovations such as biodegradable plastics and eco-friendly building materials demonstrate chemistry's potential to reduce the environmental impact of urbanization. Chemical processes are central to water purification and air quality improvements, both of which are essential in maintaining public health and environmental sustainability in densely populated urban areas.

Biology fosters urban resilience through the promotion of biodiversity, the design of green spaces, and the advancement of urban agriculture. Ecological principles inform the integration of nature into the urban landscape, contributing to carbon sequestration, natural cooling, and enhanced air quality. Moreover, urban agriculture initiatives supported by biological sciences offer a sustainable solution to food security challenges, reducing cities' reliance on external food supplies and minimizing transportation-related emissions.

Mathematics and Data Science provide the analytical tools necessary for optimizing urban systems. Through the use of predictive models, data-driven decision-making becomes possible in areas such as traffic management, resource allocation, and environmental monitoring (Sarker, 2021). The integration of IoT technologies with data science enables real-time analysis of vast datasets, allowing cities to adapt to changing conditions quickly and efficiently. These technologies are essential for ensuring the flexibility and responsiveness required for sustainable smart cities.

The findings of this study highlight the interconnectedness of these scientific disciplines in creating a holistic framework for sustainable smart cities. However, the integration of basic sciences into urban systems also presents challenges that must be addressed to ensure long-term success.

One significant challenge is **scalability**. While many innovations in materials science, renewable energy, and ecological conservation are promising, implementing them across entire cities requires substantial investment, infrastructure development, and policy support (Hepburn and et al., 2021). For instance, widespread adoption of green infrastructure and renewable energy systems will necessitate not only technological advancements but also political commitment and financial resources. Cities with limited budgets may struggle to scale these solutions without external support or public-private partnerships.

Another challenge lies in the **equitable distribution of benefits**. Smart city innovations often disproportionately benefit affluent areas, leaving underserved communities with fewer resources and less access to sustainability initiatives (Sovacool and et al., 2022). This raises important questions about **social equity** in urban development. To address these disparities, future research and policymaking must focus on ensuring that the environmental and economic benefits of smart city technologies are accessible to all residents, regardless of socio-economic status. This will require inclusive planning processes, community engagement, and targeted investments in disadvantaged neighborhoods.

Moreover, as cities increasingly rely on data science and machine learning for decision-making, concerns regarding **data privacy** and **cybersecurity** become more prominent (Habibzadeh and et al., 2019). While data-driven systems offer significant advantages in optimizing urban operations, they also raise the potential for misuse of personal information and vulnerabilities in city infrastructure. Developing robust legal and regulatory frameworks will be essential to protect citizens' privacy while enabling cities to harness the full potential of big data for sustainability insights.

The role of **biology and biodiversity** in urban planning also faces challenges as cities expand. The pressure to balance green infrastructure with economic growth and housing demands is a key issue in urban planning (Aronson and et al., 2017). Furthermore, climate change presents additional challenges, as cities will need to continuously adapt their green infrastructure to withstand more extreme weather events, such as floods and heatwaves. These pressures demand ongoing innovation and research in the application of biological sciences to urban sustainability.

Lastly, **mathematics and data science** face the challenge of integrating vast and varied datasets from sectors such as transportation, energy, and environmental monitoring (Molina-Solana and et al., 2017). Achieving interoperability between these systems requires collaboration across government agencies, private companies, and civil society. Additionally, as technological advancements continue at a rapid pace, cities will need to invest in continuous upgrades to their systems and workforce training to manage and interpret increasingly complex data.

The findings of this study suggest several avenues for future research and policy development. First, there is a need for more empirical studies that evaluate the long-term impacts of integrating basic sciences into urban systems, particularly in diverse geographic and socio-economic contexts. Comparative studies across different cities would provide valuable insights into the scalability and transferability of smart city innovations. Second, interdisciplinary collaboration between scientists, urban planners, policymakers, and technologists is essential to address the challenges of sustainability in cities. Future research should explore how different sectors can work together more effectively to integrate scientific innovations into urban infrastructure. Third, public engagement and education are key to ensuring the success of smart city initiatives. As cities increasingly adopt high-tech solutions, fostering a deeper understanding of these technologies among residents will be critical for gaining public support and ensuring that sustainability goals are achieved (Appio and et al., 2019).

The integration of physics, chemistry, biology, and mathematics into urban sustainability offers a powerful framework for creating cities that are resilient, efficient, and environmentally responsible. However, overcoming the challenges of scalability, equity, and adaptability will require continued investment in research, innovation, and education. By addressing these challenges, cities can evolve into smart urban environments that meet the needs of current and future generations, fostering a more sustainable and equitable future.

References

Ahmad, T., & Zhang, D. (2021). Using the internet of things in smart energy systems and networks. Sustainable Cities and Society, 68, 102783.

Alagar, V. S., & Periyasamy, K. (2011). Specification of software systems. Springer Science & Business Media.

Allam, Z., & Dhunny, Z. A. (2019). On big data, artificial intelligence and smart cities. Cities, 89, 80-91.

Appio, F. P., Lima, M., & Paroutis, S. (2019). Understanding Smart Cities: Innovation ecosystems, technological advancements, and societal challenges. Technological Forecasting and Social Change, 142, 1-14.

Aronson, M. F., Lepczyk, C. A., Evans, K. L., Goddard, M. A., Lerman, S. B., MacIvor, J. S., ... & Vargo, T. (2017). Biodiversity in the city: key challenges for urban green space management. Frontiers in Ecology and the Environment, 15(4), 189-196.

Arshi, O., & Mondal, S. (2023). Advancements in sensors and actuators technologies for smart cities: a comprehensive review. Smart Construction and Sustainable Cities, 1(1), 18.

Batty, M., Axhausen, K. W., Giannotti, F., Pozdnoukhov, A., Bazzani, A., Wachowicz, M., ... & Portugali, Y. (2012). Smart cities of the future. The European Physical Journal Special Topics, 214, 481-518.

Belli, L., Cilfone, A., Davoli, L., Ferrari, G., Adorni, P., Di Nocera, F., ... & Bertolotti, E. (2020). IoT-enabled smart sustainable cities: Challenges and approaches. Smart Cities, 3(3), 1039-1071.

Bettencourt, L. M. (2021). Introduction to urban science: evidence and theory of cities as complex systems.

Bibri, S. E. (2018). A foundational framework for smart sustainable city development: Theoretical, disciplinary, and discursive dimensions and their synergies. Sustainable Cities and Society, 38, 758-794.

Bibri, S. E., & Bibri, S. E. (2020). Data-driven smart sustainable cities: A conceptual framework for urban intelligence functions and related processes, systems, and sciences. Advances in the Leading Paradigms of Urbanism and their Amalgamation: Compact Cities, Eco–Cities, and Data–Driven Smart Cities, 143-173.

Bibri, S. E., Krogstie, J., Kaboli, A., & Alahi, A. (2024). Smarter eco-cities and their leading-edge artificial intelligence of things solutions for environmental sustainability: A comprehensive systematic review. Environmental Science and Ecotechnology, 19, 100330.

Blasi, S., Ganzaroli, A., & De Noni, I. (2022). Smartening sustainable development in cities: Strengthening the theoretical linkage between smart cities and SDGs. Sustainable Cities and Society, 80, 103793.

Braha, D., & Maimon, O. (2013). A mathematical theory of design: foundations, algorithms and applications (Vol. 17). Springer Science & Business Media.

Chang, N. B., Hossain, U., Valencia, A., Qiu, J., & Kapucu, N. (2020). The role of food-energy-water nexus analyses in urban growth models for urban sustainability: A review of synergistic framework. Sustainable Cities and Society, 63, 102486.

Channi, H. K., & Kumar, R. (2021). The role of smart sensors in smart city. In Smart Sensor Networks: Analytics, Sharing and Control (pp. 27-48). Cham: Springer International Publishing.

Chen, T. L., Kim, H., Pan, S. Y., Tseng, P. C., Lin, Y. P., & Chiang, P. C. (2020). Implementation of green chemistry principles in circular economy system towards sustainable development goals: Challenges and perspectives. Science of the Total Environment, 716, 136998.

Chourabi, H., Nam, T., Walker, S., Gil-Garcia, J. R., Mellouli, S., Nahon, K., ... & Scholl, H. J. (2012, January). Understanding smart cities: An integrative framework. In 2012 45th Hawaii international conference on system sciences (pp. 2289-2297). IEEE.

Damaševičius, R., Bacanin, N., & Misra, S. (2023). From sensors to safety: Internet of Emergency Services (IoES) for emergency response and disaster management. Journal of Sensor and Actuator Networks, 12(3), 41.

Dao, V., Langella, I., & Carbo, J. (2011). From green to sustainability: Information Technology and an integrated sustainability framework. The Journal of Strategic Information Systems, 20(1), 63-79.

De Jong, M., Joss, S., Schraven, D., Zhan, C., & Weijnen, M. (2015). Sustainable–smart–resilient–low carbon–eco–knowledge cities making sense of a multitude of concepts promoting sustainable urbanization. Journal of Cleaner production, 109, 25-38.

Demuzere, M., Orru, K., Heidrich, O., Olazabal, E., Geneletti, D., Orru, H., ... & Faehnle, M. (2014). Mitigating and adapting to climate change: Multi-functional and multi-scale assessment of green urban infrastructure. Journal of environmental management, 146, 107-115.

Elgohary, A., Boehm, M., Haas, P. J., Reiss, F. R., & Reinwald, B. (2018). Compressed linear algebra for large-scale machine learning. The VLDB Journal, 27(5), 719-744.

Grifoni, M., Franchi, E., Fusini, D., Vocciante, M., Barbafieri, M., Pedron, F., ... & Petruzzelli, G. (2022). Soil remediation: Towards a resilient and adaptive approach to deal with the ever-changing environmental challenges. Environments, 9(2), 18.

Habibzadeh, H., Nussbaum, B. H., Anjomshoa, F., Kantarci, B., & Soyata, T. (2019). A survey on cybersecurity, data privacy, and policy issues in cyber-physical system deployments in smart cities. Sustainable Cities and Society, 50, 101660.

Hepburn, C., Qi, Y., Stern, N., Ward, B., Xie, C., & Zenghelis, D. (2021). Towards carbon neutrality and China's 14th Five-Year Plan: Clean energy transition, sustainable urban development, and investment priorities. Environmental Science and Ecotechnology, 8, 100130.

Holm-Nielsen, J. B., Al Seadi, T., & Oleskowicz-Popiel, P. (2009). The future of anaerobic digestion and biogas utilization. Bioresource technology, 100(22), 5478-5484.

Hui, C. X., Dan, G., Alamri, S., & Toghraie, D. (2023). Greening smart cities: An investigation of the integration of urban natural resources and smart city technologies for promoting environmental sustainability. Sustainable Cities and Society, 99, 104985.

Jafari, M., Kavousi-Fard, A., Chen, T., & Karimi, M. (2023). A review on digital twin technology in smart grid, transportation system and smart city: Challenges and future. IEEE Access, 11, 17471-17484.

Javed, A. R., Shahzad, F., ur Rehman, S., Zikria, Y. B., Razzak, I., Jalil, Z., & Xu, G. (2022). Future smart cities: Requirements, emerging technologies, applications, challenges, and future aspects. Cities, 129, 103794.

Kheiri, F. (2018). A review on optimization methods applied in energy-efficient building geometry and envelope design. Renewable and Sustainable Energy Reviews, 92, 897-920.

Kutty, A. A., Abdella, G. M., Kucukvar, M., Onat, N. C., & Bulu, M. (2020). A system thinking approach for harmonizing smart and sustainable city initiatives with United Nations sustainable development goals. Sustainable Development, 28(5), 1347-1365.

Li, X., Fong, P. S., Dai, S., & Li, Y. (2019). Towards sustainable smart cities: An empirical comparative assessment and development pattern optimization in China. Journal of Cleaner Production, 215, 730-743.

Lin, B. B., Philpott, S. M., & Jha, S. (2015). The future of urban agriculture and biodiversity-ecosystem services: challenges and next steps. Basic and applied ecology, 16(3), 189-201.

Lovell, S. T., & Taylor, J. R. (2013). Supplying urban ecosystem services through multifunctional green infrastructure in the United States. Landscape ecology, 28, 1447-1463.

Marselle, M. R., Lindley, S. J., Cook, P. A., & Bonn, A. (2021). Biodiversity and health in the urban environment. Current environmental health reports, 8(2), 146-156.

Martins, J. R., & Ning, A. (2021). Engineering design optimization. Cambridge University Press.

Mohammadzadeh, Z., Saeidnia, H. R., Lotfata, A., Hassanzadeh, M., & Ghiasi, N. (2023). Smart city healthcare delivery innovations: a systematic review of essential technologies and indicators for developing nations. BMC Health Services Research, 23(1), 1180.

Molina-Solana, M., Ros, M., Ruiz, M. D., Gómez-Romero, J., & Martín-Bautista, M. J. (2017). Data science for building energy management: A review. Renewable and Sustainable Energy Reviews, 70, 598-609.

Muthusamy, M. S., & Pramasivam, S. (2019). Bioplastics–an eco-friendly alternative to petrochemical plastics. Current world environment, 14(1), 49.

Ramirez Lopez, L. J., & Grijalba Castro, A. I. (2020). Sustainability and resilience in smart city planning: A review. Sustainability, 13(1), 181.

Sarker, I. H. (2021). Data science and analytics: an overview from data-driven smart computing, decision-making and applications perspective. SN Computer Science, 2(5), 377.

Shi, J., Huang, W., Han, H., & Xu, C. (2021). Pollution control of wastewater from the coal chemical industry in China: Environmental management policy and technical standards. Renewable and Sustainable Energy Reviews, 143, 110883.

Singh, M., Arora, V., & Kulshreshta, K. (2024). Towards Sustainable Cities: Exploring the Fundamentals of Urban Sustainability. In AI Applications for Clean Energy and Sustainability (pp. 212-233). IGI Global.

Sovacool, B. K., Newell, P., Carley, S., & Fanzo, J. (2022). Equity, technological innovation and sustainable behaviour in a low-carbon future. Nature human behaviour, 6(3), 326-337.

Sun, W., Katsifodimos, A., & Hai, R. (2023, July). Accelerating Machine Learning Queries with Linear Algebra Query Processing. In Proceedings of the 35th International Conference on Scientific and Statistical Database Management (pp. 1-12).

Tien, P. W., Wei, S., Darkwa, J., Wood, C., & Calautit, J. K. (2022). Machine learning and deep learning methods for enhancing building energy efficiency and indoor environmental quality–a review. Energy and AI, 10, 100198.

Wegener, M. (2004). Overview of land use transport models. In Handbook of transport geography and spatial systems (pp. 127-146). Emerald Group Publishing Limited.

Wu, J. (2014). Urban ecology and sustainability: The state-of-the-science and future directions. Landscape and urban planning, 125, 209-221.

Yigitcanlar, T., & Cugurullo, F. (2020). The sustainability of artificial intelligence: An urbanistic viewpoint from the lens of smart and sustainable cities. Sustainability, 12(20), 8548.

Zhao, L., Tang, Z. Y., & Zou, X. (2019). Mapping the knowledge domain of smart-city research: A bibliometric and scientometric analysis. Sustainability, 11(23), 6648.

About Authors

Asst. Prof. Musab Talha AKPINAR | Ankara Yıldırım Beyazıt University | musabtakpinar[at]gmail.com | ORCID: 0000-0003-4651-7788

Dr. Musab Talha Akpınar is a highly accomplished academician in the field of Management Information Systems, currently holding assistant professorship at Ankara Yıldırım Beyazıt University. He earned his undergraduate degree in Business Administration from Bahcesehir University and his law degree from Gazi University. Additionally, he holds a master's degree in MIS and a Ph.D. in artificial intelligence technology and smart systems demonstrating his commitment to rigorous academic pursuits. Dr. Akpınar has extensive industry experience, having previously worked as a Data Scientist at Turkish Airlines. His proficiency and notable contributions to his domain led to his appointment as the Executive Assistant to the President of the Turkish Academy of Sciences in 2022. In this role, he persistently shapes the course of his field, specifically focusing on areas such as Artificial Intelligence, Smart City, Data Science, and GDPR. With his wealth of expertise and significant academic achievements, he has established himself as a frontrunner in the field, becoming an invaluable resource for any organization.

Assoc. Prof. Cem KORKUT | Ankara Yıldırım Beyazıt University | ckorkut[at]aybu.edu.tr | ORCID: 0000-0002-1104-5330

Cem Korkut, Ph.D. is Associate Professor at the Department of Economics of Ankara Yıldırım Beyazıt University (AYBU). He is also the advisor to the President at the Turkish Academy of Sciences (TÜBA). He took his Bs degree at economics from TOBB University of Economics and Technology. He completed his MA in Economics at AYBU in 2014, and his Ph.D. in Islamic Economics and International Finance at Istanbul Sabahattin Zaim University (IZU) in 2018. Having national and international papers and book chapters on topics such as Islamic economics, Islamic banking and finance, and cash waqfs, Dr. Korkut is an active member of the Ankara Center for Thought and Research (ADAM) and executive of Islamic Economics School. His main academic interests are Islamic economics, Islamic banking and finance, macroeconomic policies, world economy in the longue durée, Ottoman economic history and economic development paradigms of different societies.

GEOTHERMAL ENERGY FROM BASIC SCIENCES PERSPECTIVE: TÜRKİYE'S POTENTIAL AND CONTRIBUTION TO THE ECONOMY

Mehmet Furkan Şener

Abdulkadir Hızıroğlu

10.53478/TUBA.978-625-6110-22-9.ch16

Geothermal Energy From Basic Sciences Perspective: Türkiye's Potential and Contribution to the Economy

Mehmet Furkan Şener
İzmir Bakırçay University

Abdulkadir Hızıroğlu
İzmir Bakırçay University

Abstract

Science begins with physics from the moment of the Big Bang, and then with chemistry and geology. Geology science is closely interested in the tectonic and volcanic activities that occur on the planet Earth and its products. In the process that started with the big bang, geology science is extremely important in the formation and understanding of the earth. However, population growth on a global scale, rising living standards with modernization, and ongoing industrialization directly increases the energy demand and triggers the search for alternative energy sources. Fossil fuels meet the majority of energy needs worldwide. The fact that fossil fuels pose a risk to the environment and will run out soon has shown that renewable energy sources should replace fossil fuels in the future. In addition, as stated in the Paris Agreement, we need to avoid carbon-based energy sources to keep the global temperature rise below 2°C. If it is evaluated in terms of both regional and national development, one of the most important products of tectonism and volcanism is geothermal. Geothermal energy is one of the renewable energy sources and is a natural resource that can be utilized directly or by converting to other types of energy. The use of geothermal energy for different purposes such as electricity, home heating, greenhouse cultivation, thermal tourism, fishing, and road heating has become common in many countries, as of 2022, the direct contribution of geothermal applications to the Turkish economy is around 4 billion USD annually. the economic size can reach 15 billion USD annually if the potential is used after new geothermal applications and investments. In addition, the direct and indirect employment to be created by geothermal energy will be approximately 450,000 people. In summary, this study embodies the relationship between basic sciences and geothermal energy and reveals how to benefit from basic sciences in order to reach geothermal energy resources and make them sustainable.

Keywords
Basic science, Geology, Geothermal, Türkiye, Economy

Introduction

Science is a widely used and highly esteemed concept in modern times. It serves as the most influential reference point in contemporary life. Science has always been present as an endeavor to uncover the truth about humanity, the universe, and the societies in which we live. In this regard, science is an activity that exists in all societies. Both the scientific understanding of the historical process and modern science cannot be separated from their social context. When analyzing the development of modern scientific understanding, the 16th century appears to be a significant turning point. Following the Enlightenment, reason, and observation gained prominence, and induction was accepted as a valid method of acquiring knowledge (Köroğlu and Köroğlu, 2016). Basic science, often referred to as "pure" or "fundamental" science, plays a crucial role in helping researchers understand living systems and life processes. Given the vastness of fields such as physics, chemistry, geology, biology, etc., pure scientists must choose to specialize in order to excel in their chosen scientific disciplines (Karcher, 1938).

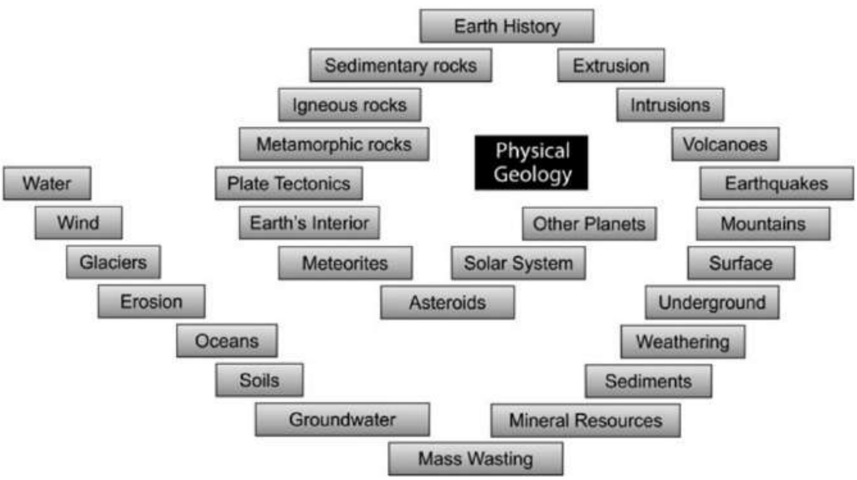
Geology encompasses the comprehensive study of the Earth, including its materials, the processes that influence them, the resulting products, and the Earth's history dating back to its birth approximately 4.54 billion years ago (±0.5 billion years). This estimation is inferred from the impact of the Canyon Diablo iron meteorite on the Barringer Crater in Arizona, USA (Warwick et al., 2007; Dalrymple 2001). Geology not only encompasses the investigation of processes that have shaped the Earth's surface but also includes the study of the ocean floor and the Earth's interior. To gain a profound understanding of the Earth and its mechanisms, it is essential to examine contemporary processes and structures and interpret them in relation to past occurrences. This objective is accomplished through the discipline of Geology. Geology is the scientific field dedicated to the comprehensive study of the Earth, focusing on its composition, structure, and geological history. It involves the examination of the origins, properties, and compositions of rocks and minerals. Describing the Earth's geological development and processes necessitates an interdisciplinary approach, incorporating fundamental sciences such as physics, chemistry, biology, and mathematics.

Physics-Geology Relationship

The term "Physical Geology" was coined by William Hopkins, an English mathematician and geologist, in 1883. This field of study focuses on the physical forces and processes that result in changes in the Earth's crust or on its surface due to their prolonged existence and impact (Fig. 1). On the other hand, "Geophysics" refers to the scientific discipline that utilizes the methods and principles of physics to investigate various aspects of the Earth. The scope of geophysics encompasses a wide range of subjects within geology, including investigations into the conditions within the Earth's deep interior, characterized by temperatures reaching several thousand degrees Celsius and pressures in the millions of atmospheres. Geophysics also extends to the Earth's exterior, encompassing its atmosphere and hydrosphere.

Figure 1.

The relationship between physics and geology (Jain, 2014)

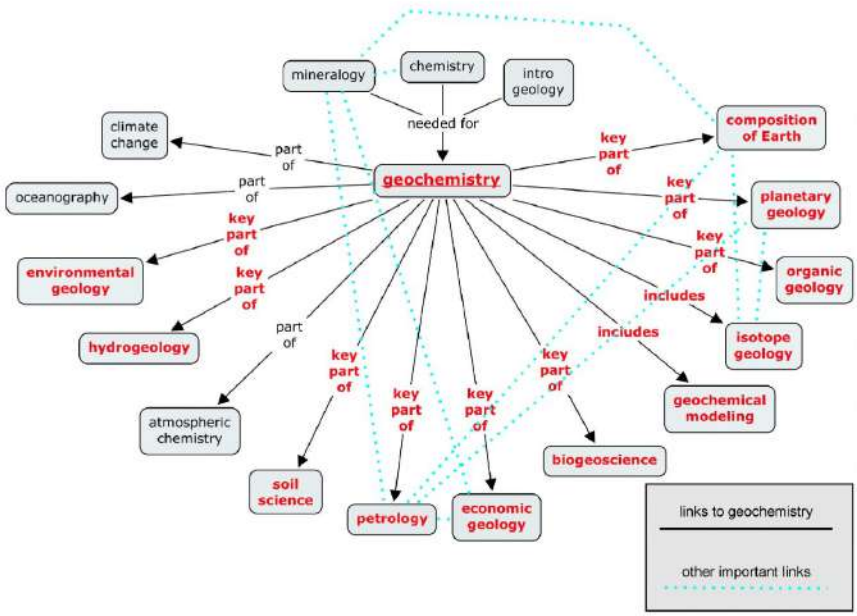


Chemistry-Geology Relationship

Geochemistry encompasses the broad application of chemistry to nearly all aspects of geology (Fig. 2). Since the Earth is composed of chemical elements, it is possible to consider all geological materials and processes from a chemical perspective. Geochemistry addresses various significant problems, including the origin and abundance of elements in the solar system, galaxy, and universe (known as cosmochemistry). It also investigates the distribution of elements in the major components of the Earth, such as the core, mantle, crust, hydrosphere, and atmosphere. Additionally, geochemistry explores the behavior of ions within crystal structures, the chemical reactions occurring during the cooling of magmas, and the origin and evolution of deeply buried intrusive igneous rocks. Furthermore, it investigates the chemistry of volcanic (extrusive) igneous rocks and phenomena closely associated with volcanic activity, including hot-spring activity, emission of volcanic gases, and the formation of ore deposits through hot waters derived from the late stages of igneous magma cooling. Geochemistry also explores the chemical reactions involved in rock weathering, which lead to the decay of previously formed minerals and the creation of new minerals. It examines the transportation of weathering products in solution by natural waters in groundwater, streams, lakes, and the ocean. Moreover, it investigates the chemical changes that occur during the compaction and cementation of unconsolidated sediments, leading to the formation of sedimentary rocks. Finally, geochemistry studies the progressive chemical and mineralogical transformations that occur during the process of rock metamorphism (Fig. 2).

Figure 2.

The consensus view of a geochemistry-centric world by workshop participants.



Math-Geology Relationship

Science inherently relies on numerical data and measurements. In the field of geology, various aspects can be quantified using numerical values. For instance, minerals can be quantified based on specific gravity, hardness, Miller index, and abundance. Geologic structures can be quantified using parameters such as strike and dip, and even abundance when assessing the integrity of rock masses. Economic geologists and geochemists construct intricate databases consisting of samples, each associated with multiple elements. Analyzing these elements provides valuable insights into ore genesis, the origin of water, environmental stresses, and rock classification, among other applications. Geophysics and remote sensing generate vast datasets represented as digital images, comprising large sets of numerical values. Mathematical geology encompasses the application of theoretical and applied mathematics to assess geologic data, aiding in the interpretation of the Earth's evolution (Carr, 2018). Consequently, this study employs a comprehensive approach that incorporates all fundamental sciences to evaluate and interpret geothermal phenomena, which falls within the realm of geology.

Basic Sciences and Geothermal Energy Exploration

Geothermal energy refers to the heat energy contained within the Earth's interior. The origin of this heat is associated with the internal structure of our planet and the physical processes occurring therein. While the Earth's crust and deeper regions contain vast and practically limitless quantities of heat, its distribution is uneven, concentration is rare, and often it exists at depths too great for industrial exploitation (Barbier, 2002). A geothermal system comprises several crucial components, as outlined below:

1. Heat Source: This refers to the source that provides heat to the geothermal system (Fig. 3). There are two primary heat sources.

- Geothermal Gradient: The geothermal gradient represents the rate at which the ground temperature increases with depth. Under normal crustal conditions, the temperature rises by approximately 1°C for every 33 meters. The geothermal gradient tends to be low in regions with a thick Earth's crust (compression-orogeny) and high in areas exhibiting an extensional regime (graben basins).

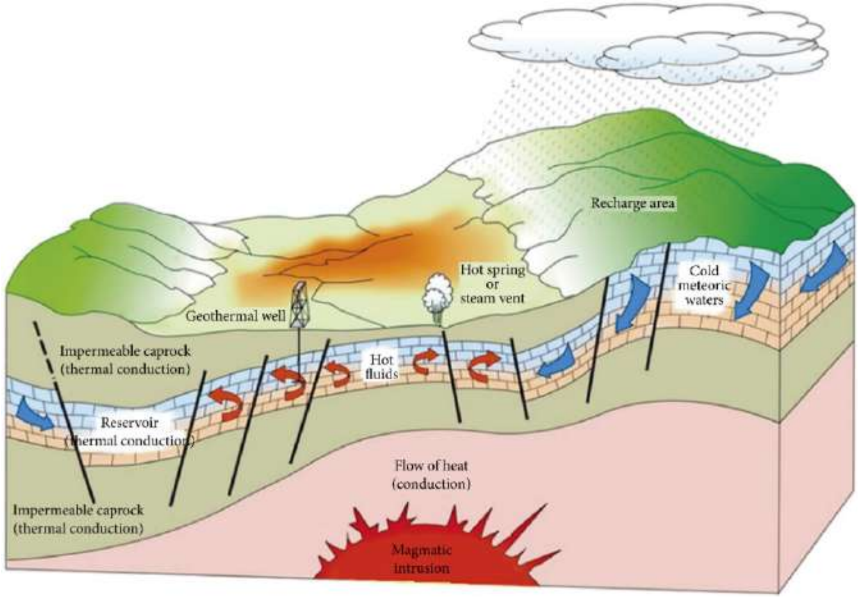
- Igneous Activity: This involves the cooling of underground magma (not necessarily volcanic in nature at the surface). The cooling of magma underground occurs over a period ranging from tens of thousands of years to several million years. High-temperature minerals cool earlier, while those formed during the late stages of magma crystallization cool at lower temperatures.

2. Reservoir Rock: This refers to a type of rock that possesses sufficient permeability to store or accumulate heated fluid. Reservoir rocks can be of various types, including sedimentary, igneous, or metamorphic rocks (Fig. 3).

3. Fluid: The fluid within the geothermal system can consist of liquid, steam (gas), or a mixture of both. It facilitates the transfer of underground heat to the surface (Fig. 3).

4. Cap Rock: The cap rock is a lithological unit comprised of impermeable materials located above the reservoir rock. It serves as insulation, preventing the escape of heat stored underground within the reservoir rock (Fig. 3).

Figure 3.
Schematic diagram of an ideal geothermal system (Huenges, 2016).



Results and Discussions

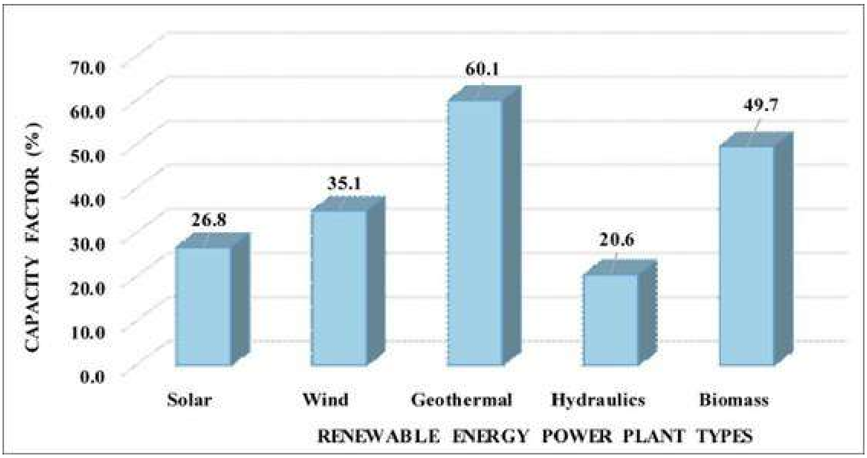
The Contribution of Geothermal Energy Discovered with Basic Sciences to The Country's Economy

In the last century, industries have experienced rapid development, populations have witnessed significant growth, and standards of living have improved considerably. As a consequence, there has been an ever-increasing demand for energy and mineral resources. Geologists, geochemists, and geophysicists have played a pivotal role in the exploration of fossil fuels such as coal, oil, and natural gas, as well as the identification of geothermal energy reservoirs. In recent years, the applications of geothermal energy have expanded, further driving the interest and research in this field.

Geothermal energy has witnessed the development of a variety of applications, encompassing public buildings, residential heating, and greenhouses. The global total energy supply (TES) experienced an approximately 2.6-fold increase between 1971 and 2018, as reported by REN21 (2021). Despite the slight growth in geothermal power capacity in comparison to recent years (partly due to disruptions caused by the Covid-19 pandemic), most new facilities were established in Türkiye, as indicated by REN21 (2021). Despite challenges faced by the industry due to the pandemic, a total of 246 MW of additional capacity has been installed worldwide, including countries such as Colombia (with small-scale ORC units from co-produced oil) and Taiwan (with a 4.2 MW power plant) (Thinkgeoenergy, 2022).

Between 2010 and 2020, a total of $40 billion was invested in new geothermal energy developments worldwide. As of the end of 2021, the global installed geothermal power generation capacity reached 15,854 MW, reflecting an increase of 246 MW compared to the previous year (Thinkgeoenergy, 2022). Presently, the United States leads in installed geothermal capacity with approximately 3,722 MWe, followed by Indonesia, the Philippines, Türkiye, and New Zealand. Türkiye's share in electricity generation from geothermal sources amounts to around 11% (Şener et al., 2022). Geothermal power generation plants play a crucial role in Türkiye. Additionally, solar, wind, and hydroelectric power plants have also been impacted by climate-related events and regional meteorological variations, resulting in fluctuations in their production levels (EPDK, 2019; 2021). Capacity factor data for power plants in Türkiye reveals that wind power, solar power, hydroelectric power, biomass, and geothermal power plants (GPP) have capacity factors of 35.1%, 26.8%, 20.6%, 49.7%, and 60.1%, respectively. The significant variation in capacity factors among different power plant types emphasizes the crucial role of geothermal power plants as base load providers in Türkiye's power generation system (Fig. 4).

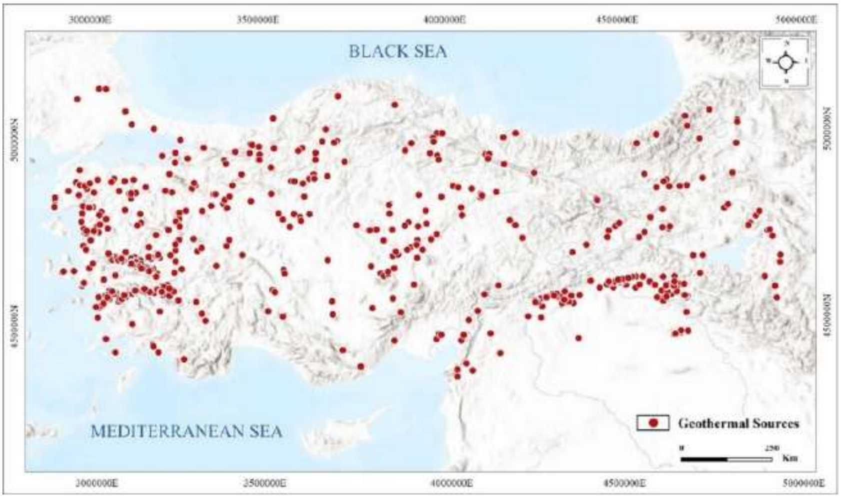
Figure 4.
Renewable energy sources and capacity factors (Selenka, 2021).



Türkiye boasts over 2,000 wells and 415 geothermal fields, where the accepted lower temperature limit is 30°C. In 2022, the electricity generation capacity in Türkiye reached 1,663 MWe, while the total installed thermal power for direct heat use reached 5,113 MWt. Due to the diverse geological structure of the country, geothermal systems have flourished primarily in regions characterized by young tectonic and volcanic activity. Notably, Western and Central Anatolia stand out as particularly rich in geothermal resources (Fig. 5). The geothermal well with the highest recorded well-bottom temperature was drilled in Niğde, located in Central Anatolia, reaching a temperature of 341°C at a depth of 3,845 meters. Other regions in the country, such as Nevşehir, Sivas, Yozgat, Erzurum, Ankara, Batman, Van, and Şırnak, also possess medium-high temperature springs (Şener et al., 2023).

Figure 5.

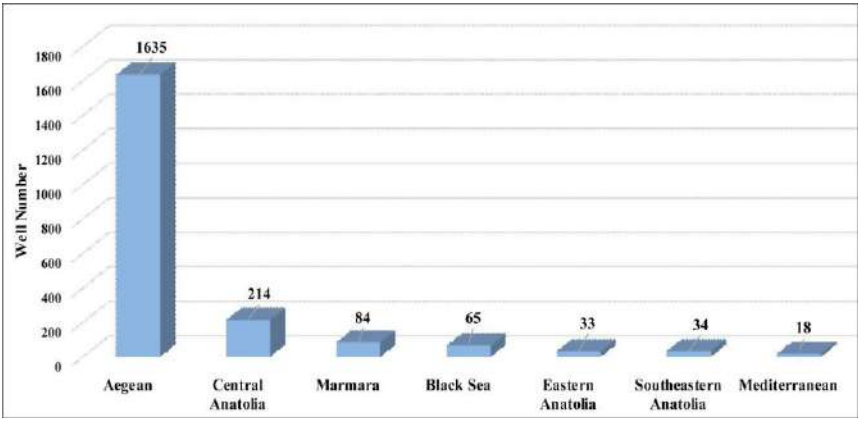
Geothermal sources of the Türkiye (Updated from Akkuş et al., 2005; Baba et al., 2019; Şener, 2019; Şener and Baba, 2019; EBRD, 2020a).



Regarding the distribution of wells by region, the Aegean Region takes the lead with 1,635 wells, followed by Central Anatolia and Marmara (Fig. 6). However, in terms of capacity, the Aegean Region significantly surpasses others, boasting a capacity of 34,920 MWt. The presence of 673 wells in Aydın, 384 in Manisa, 228 in Denizli, and 209 in İzmir underscores the high geothermal potential in the Aegean Region.

Figure 6.

Distribution of the number of wells by region (Akkuş et al., 2005; Şener et al., 2017; Baba et al., 2019; EBRD, 2020b; Şener et al., 2021).



In recent years, the Central Anatolia Region, particularly in Nevşehir, Aksaray, and Niğde, has witnessed a growing potential, whereas other regions are still awaiting investment. The current utilization areas and capacities of geothermal energy in Türkiye are outlined in the Türkiye Geothermal Strategy Report, which was prepared in 2022. According to the report, the total installed heat power for direct use amounts to 5,113 MWt (Lund and Torth, 2020).

Support Mechanisms and Investment Costs

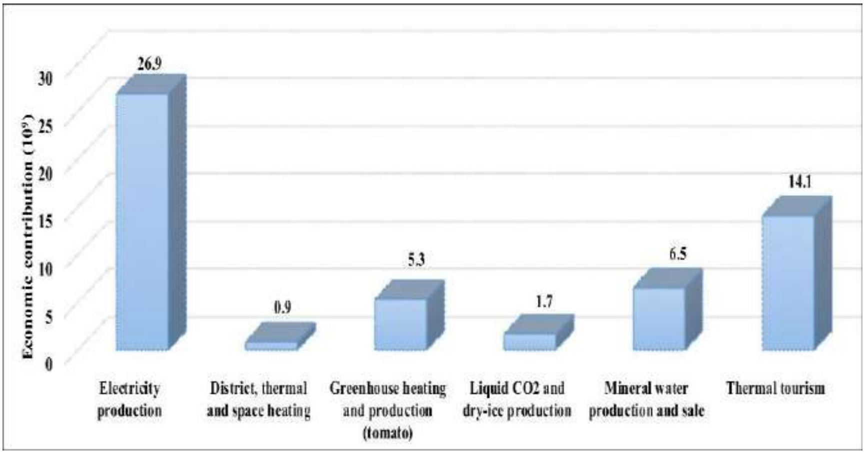
One of the key economic advantages of geothermal energy is its ability to reduce dependence on imported energy by utilizing domestic resources. As a result, domestic investments in geothermal energy can contribute to reducing trade deficits and retaining capital within the country.

Presently, geothermal heat is approximately 70% cheaper than natural gas in many locations based on local household tariffs. When considering the subsidies provided by the government for natural gas used in residential heating, the substantial contribution of geothermal energy to the country's economy becomes evident. In comparison to the current actual cost of natural gas at 9.135 TL/m3 (6.3 TL/m3 x 1.45, accounting for the 45% increase by BOTAŞ as of 01.04.2022), the highly economical price of geothermal energy at approximately 1/8th of the cost is advantageous for both the state and the population. Data on the economic contribution of geothermal energy for electricity generation and direct use are presented in Figure 7 (Şener et al., 2023).

The total direct contribution of geothermal applications to the economy, as calculated above, amounts to 54,857,760,000 TL (excluding the contribution to employment, natural gas savings, and CO_2 emission reduction). Additionally, when accounting for an estimated 5% for unknown and unregistered factors, the direct contribution of geothermal applications to the economy can be considered to be approximately 58 billion TL per year.

Figure 7.

The annual contribution of geothermal energy to the Turkish economy in terms of electricity and direct use (TL/year).



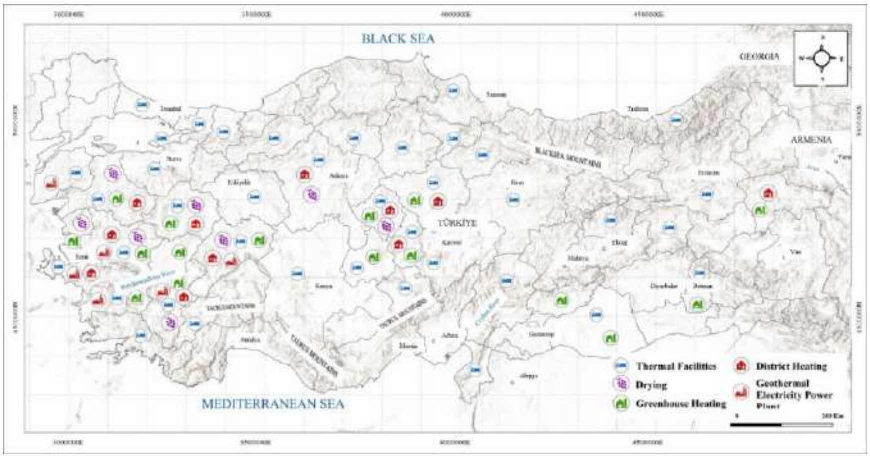
Recommendations and Strategies

If systematically and technically explored, operated, and regulated within legal frameworks, geothermal resources hold significant importance as a renewable energy source for Türkiye's economy. Presently, geothermal resources are extensively utilized both directly and indirectly in the country. Indirect utilization refers to the production of electricity in geothermal power plants from geothermal fluids, while direct utilization includes applications such as urban heating and cooling, greenhouse heating, agricultural drying, thermal and health tourism, CO_2 production, and dry ice production (Fig. 8).

In view of the geological data obtained, an evaluation of which applications can be made in which provinces in Türkiye is presented in Figure 8. Geothermal energy power plants and electricity production, as well as integrated production, can be implemented in numerous cities in Western Anatolia. Agricultural applications, thermal tourism, and heating are becoming increasingly prevalent in Western and Central Anatolia. Thermal tourism and integrated facilities, along with heating and cooling applications, can be observed in different regions across Türkiye. Furthermore, it is recommended to explore the geothermal potential in select provinces of the Mediterranean and Black Sea regions.

Figure 8.

Current direct and indirect use of geothermal energy sources in Türkiye (Şener et al., 2023).



While not included in the short and medium-term projections, hot dry rock (HDR) and Enhanced Geothermal Systems (EDGS) hold significant potential in geothermal energy applications. In the calculations conducted in this study, when the value of EDGS is taken into account, Türkiye's total potential is predicted to reach at least 400,000 MWe. Furthermore, with the realization of potential targets and estimated investments, it is anticipated that geothermal energy will contribute approximately 210 billion TL per year to the economy, generating direct and indirect employment opportunities for approximately 450,000 individuals (Table 1).

Table 1.

Potential targets and estimated investment amounts for geothermal applications.

Geothermal Application	Estimated Goals for 2030	Additional Investment (USD) (from 2022 to 2030)
Electricity Generation (Hydrothermal)	3000 MWe (24 billion kWh)	5,4 billion USD
Heating (housing, hotel, thermal facilities, etc.)	5000 MWt (500,000 Housing equivalent)	1,2 billion USD
Greenhouse Heating	2800 MWt (12,000 Acres)	1,3 billion USD
Drying, etc.	80 MWt (300,000 tons/year)	30 billion USD
Thermal Tourism	2000 MWt Total of 520 thermal springs, Health Tourism Facilities, ect.	1 billion USD
Cooling	350 MWt (20,550 residences equivalent)	140 million USD
Fishing+Other Uses (Mineral extraction, etc.)	400 MWt	100 million USD
Total Investment		9,170,000,000 USD

The natural gas equivalent of all geothermal uses above	6 billion USD /Year
Amount of economic growth created by applications such as geothermal electricity production, heating (housing, thermal facilities, etc.), thermal tourism (spa), greenhouse cultivation, drying, fishing, etc. if goals in 2030 are reached	210 billion USD /Year
Direct and Indirect Employment	450,000 people

Geothermal energy implementation, both on the supply and demand sides, should be prioritized in the short and long term through collaboration between national and local authorities. The private sector, universities, institutes, and research centers needs to develop short-term, medium-term, and long-term strategies for the effective utilization and development of geothermal resources. In the geothermal sector, there are still areas where wells have not been drilled despite the studies conducted thus far. Therefore, it is anticipated that Türkiye's future capacity will significantly increase with the inclusion of drilling research and development studies, as well as the discovery of new fields. This capacity is expected to surpass 100,000 MWt levels in the medium term, particularly with the incorporation of Hot Dry Rock (HDR) technology.

Conclusion

Basic sciences form a fundamental element of a country's technological and economic development system. The proper utilization of basic sciences plays a crucial role in a country's progress, while their incorrect application can result in irreparable damage. Geology, as a scientific field, combines essential disciplines such as physics, chemistry, and mathematics. Geothermal energy represents one of the most prominent applications of basic sciences within the realm of geology. It is a natural resource that can be directly harnessed or converted into other forms of energy. Türkiye, with its diverse geological structure, has witnessed the development of geothermal systems associated with young tectonic and volcanic activity. Geothermal energy is now extensively employed for various purposes in Türkiye, including power generation, residential heating, thermal tourism, and greenhouse cultivation. Particularly, Western and Central Anatolia boast abundant geothermal resources. Notably, the hottest geothermal well was drilled in Central Anatolia, reaching a well-bottom temperature of 341°C at a depth of 3845 meters. As of 2022, Türkiye's electricity generation capacity and total installed direct heat use have reached 1663 MWe and 5113 MWt, respectively. Considering the Curie depth and heat flux in Anatolia, it is estimated that the batholith's probable thickness is approximately 10 km. Türkiye occupies a geologically strategic position to harness geothermal energy from hot and radiogenic granitoids using Hot Dry Rock (HDR) technology. With further drilling research, development studies, and the discovery of new fields, Türkiye's future geothermal capacity is expected to surpass 100,000 MWt in the medium term, particularly with the integration of HDRs. Effectively and appropriately utilizing geothermal resources can significantly mitigate Türkiye's energy challenges in a short timeframe. Therefore, increasing and supporting geothermal research in Türkiye is of utmost importance.

Acknowledgments: This study was funded by the General Directorate of Mining and Petroleum Affairs and the Republic of Türkiye Ministry of Energy and Natural Resources.

References

Akkuş, I., Akıllı, H., Ceyhan, S., Dilemre, A., & Tekin, Z. (2005). Türkiye Jeotermal Kaynaklar Envanteri. MTA Genel Müdürlüğü Envanter Serisi, 201, Ankara

Baba, A., Şaroğlu, F., Akkuş, I., Özel, N., Yeşilnacar, M. İ., Nalbantçılar, M. T., Demir, M. M., Gökçen, G., Arslan, Ş., Dursun, N., Uzelli, T., &Yazdani, H. (2019). Geological and hydrogeochemical properties of geothermal systems in the southeastern region of Türkiye. Geothermics 78, 255-271. https://doi.org/10.1016/j.geothermics.2018.12.010

Barbier, E. (2002). Geothermal energy technology and current status: an overview. Renewable and sustainable energy reviews, 6(1-2), 3-65. https://doi.org/10.1016/S1364-0321(02)00002-3

Carr, J.R. (2018). Mathematical Geology by Example: Teaching and Learning Perspectives. In: Daya Sagar, B., Cheng, Q., Agterberg, F. (eds) Handbook of Mathematical Geosciences. Springer, Cham. https://doi.org/10.1007/978-3-319-78999-6_41

Dalrymple, G.B. (2001). The age of the Earth in the twentieth century: a problem (mostly) solved. Geological Society, London, Special Publications, 190, 205-221. https://doi.org/10.1144/GSL.SP.2001.190.01.14

Huenges, E. (2016). Enhanced geothermal systems: Review and status of research and development. Geothermal power generation, 743-761. https://doi.org/10.1016/B978-0-08-100337-4.00025-5

EBRD. (2020a). Early Stage Geothermal Support Framework: (PLUTO)-Cumulative Impact Assessment Report of Cumulative Impact Assessment of Geothermal Resources in Türkiye. European Bank for Reconstruction and Development.

EBRD. (2020b). European Bank for Reconstruction and Development, Türkiye: Feasibility Study On The Potential For Geothermal District Heating And Cooling Systems.

EPDK. (2019). 2019 yılı Elektrik Piyasası Sektör Raporları, T.C. Enerji Piyasası Düzenleme Kurumu.

EPDK. (2022). Elektrik Piyasası Üretim Lisansları. T.C. Enerji Piyasası Düzenleme Kurumu.

Jain, S. (2014). Fundamentals of physical geology. New Delhi, India: Springer India. https://doi.org/10.1007/978-81-322-1539-4

Karcher, J. C. (1938). A Review of The Relation Between Physics and Geology In Petroleum Exploration, Geophysics, 3, 69-77 https://doi.org/10.1190/1.1439483

Köroğlu, C. Z., & Köroğlu, M. A. (2016). Bilim Kavramının Gelişimi Ve Günümüz Sosyal Bilimleri Üzerine. Pamukkale Üniversitesi Sosyal Bilimler Enstitüsü Dergisi (25), 115. https://dergipark.org.tr/tr/pub/pausbed/issue/34751/384330

Lund, J., & Tóth, A. N. (2020). Direct utilization of geothermal energy 2020 worldwide review, Geothermics 90, 101915.

REN21. (2021). Renewables 2020 Global Status Report. (Paris: REN21 Secretariat). Global Overview.

Selenka. (2021). https://selenkaenerji.com/blog/ulkemizdeki-yenilenebilir-kaynakli-santrallerin-kapasitefaktoru-agustos-2021-17.html

Şener, M. F., Şener, M., & Uysal, I. T. (2017). The evolution of the Cappadocia Geothermal Province, Anatolia (Türkiye): geochemical and geochronological evidence. Hydrogeology Journal 25(8), 2323-2345. https://doi.org/10.1007/s10040-017-1613-1

Şener, M. F. (2019). A new approach to Kırşehir (Türkiye) geothermal waters using REY, major elements and isotope geochemistry. Environmental Earth Sciences 78, 75. https://doi.org/10.1007/s12665-019-8068-8

Şener, M. F., & Baba, A. (2019). Geochemical and hydrogeochemical characteristics and evolution of Kozaklı geothermal fluids, Central Anatolia, Türkiye, Geothermics 80, 69-77. https://doi.org/10.1016/j.geothermics.2019.02.012

Şener, M. F., Yiğit, B., & Şener, M. (2021). Geochemical proxies and formation mechanism of Hatay (Başlamış) travertine and relation with Dead Sea Fault Zone (S-Türkiye). Journal of African Earth Sciences 177, 104126. https://doi.org/10.1016/j.jafrearsci.2021.104126

Şener, M. F., Baba, A., Uzelli, T., Akkuş, İ., & Mertoğlu, O. (2022). Türkiye Jeotermal Kaynaklar Strateji Raporu. Maden ve Petrol İşleri Genel Müdürlüğü

Şener, M. F., Uzelli, T., Akkuş, İ., Mertoğlu, O., & Baba, A. (2023). The potential, utilization, and development of geothermal energy in Türkiye. Bulletin of the Mineral Research and Exploration, 171, 69-90. https://doi.org/10.19111/bulletinofmre.1229381

Thinkgeoenergy. (2022). https://www.thinkgeoenergy.com/thinkgeoenergys-top-10-geothermal-countries2021-installed-power-generation-capacity-mwe

USGS (2007) Divisions of geologic time - Major chronostratigraphic and geochronologic units: U.S. Geological Survey Fact Sheet, 3015. https://pubs.usgs.gov/fs/2007/3015/fs2007-3015.pdf

Warwick, P.D., Coleman, J.L., Hackley, P.C., Hayba, D.O., Karlsen, A.W., Rowan, E.L. & Swanson, S.M. (2007). USGS assessment of undiscovered oil and gas resources in Paleogene strata of the US Gulf of Mexico Coastal Plain and state waters. (eds) Kennan, L., Pindell, J., Rosen, N.C. The Paleogene of the Gulf of Mexico and Caribbean Basins: Processes, Events and Petroleum Systems https://doi.org/10.5724/gcs.07.27.0002

About Authors

Assoc Prof. Mehmet Furkan ŞENER | İzmir Bakırçay University | furkan.sener[at]bakircay.edu.tr | ORCID: 0000-0003-0865-0852

He started his academic life as a research assistant at Niğde University in 2010. After receiving his B.Sc. and M.Sc. degrees in Geological Engineering from Niğde University in 2008 and 2011, respectively. At the same time, He did his master's research at Friedrich Schiller University Jena in Germany in 2009-2010 and his Ph.D. research at the University of Queensland in Australia in 2013-2015. He worked as a research assistant in the Department of Geological Engineering at Niğde University in 2010-2015 and as an assistant professor in the Department of Geography at Niğde Ömer Halisdemir University in 2015-2020. Since 2020, he has been working as an Assoc. Prof. in the Geography Department at İzmir Bakırçay University. He has published 31 articles, 8 projects and more than 30 symposium proceedings. His research is mainly focused on geothermal energy, hydrogeochemical and isotopic properties of water, Hot Dry Rock (HDR) and recovery of elements such as lithium (Li) from geothermal fields. In addition, I am researching the geothermal systems of Central, Western, Eastern and Southeastern Anatolia, the Enhanced Geothermal System (EGS) potentials of Türkiye and the Rare Earth Element (REE) potentials of geothermal fields.

Prof. Abdulkadir HIZIROĞLU | İzmir Bakırçay University | kadir.hiziroglu[at]bakircay.edu.tr | ORCID: 0000-0003-4582-3732

He started his academic life as a research assistant at Sakarya University in 2001. After receiving his B.Sc. and M.Sc. degrees in Industrial Engineering from Sakarya University in 2001 and 2003, respectively, he worked as a research assistant at the same university for many years in various departments such as the head of the Computer Science Department and the Distance Education Application and Research Centre. Later, he expanded his areas of expertise by obtaining his Ph.D. in Business Management from the University of Manchester in England in 2009. After receiving his Ph.D., he continued his academic life as an Assistant Professor and worked in the fields of Industrial Engineering and Management Information Systems at Sakarya University. Between 2016 and 2018, he worked as an associate professor at Ankara Social Sciences University, Faculty of Business Administration. Hızıroğlu, who started his duties as the secretary general of Izmir Bakırçay University on 2018, continued this duty until 2020 and has so far conducted many scientific researches and projects on a national and international basis. As of 2019, he received the title of Professor in the field of Management Information Systems. Since this date, he has been working as the Vice Rector of Izmir Bakırçay University.

A PLATFORM FOR BASIC SCIENCE AND INNOVATION IN SUSTAINABLE DEVELOPMENT

Arif Hashimov

Rustam B. Rustamov

10.53478/TUBA.978-625-6110-22-9.ch17

A Platform for Basic Science and Innovation in Sustainable Development

Arif Hashimov
Azerbaijan National Academy of Sciences

Rustam B. Rustamov
Azerbaijan National Academy of Sciences

Abstract

The UNESCO between July 2022 and July 2023 with collaboration global partners has celebrated International Year of Basic Sciences for Sustainable Development where recognizes that basic sciences are vital to achieving sustainable development and improving the quality of life for people around the World. In this regard, it was considered by the National Academy of Sciences of Azerbaijan reform in the system of innovative economy and organization of science: transition from classical projects to system projects. In this chapter is considered options of approach how basic science can be play important place in the future science development [1]. In the meantime, it is necessary to create appropriate environment for enhancement capacity building in basic science which has to be undertaken for future science jumping for achievement of high results.

Keywords

Basic science, development, capacity building, science and education, scientific commercialization

Introduction

The Azerbaijan National Academy of Sciences today contains:

- Department of Physical and Mathematical and Technical Sciences;
- Department of Chemical Sciences;
- Department of Earth Sciences;
- Department of Biological and Medical Sciences;
- Department of Humanities; and
- Department of Social Sciences.

Within the framework of such an infrastructure, it is intended to implement five main areas: the integration of fundamental science and other scientific fields:

Physical-mathematical and engineering sciences:

- development and implementation of functional materials with high efficiency;
- development of artificial intelligence technologies, cybersecurity and the sustainability of society in the context of digital transformations;
- development of scientific and theoretical foundations of energy security and energy conversion processes;
- development of methods and algorithms; and
- expansion of research in the field of nuclear physics and high energy.

Chemical sciences:

- increasing an efficiency of oil refining and petrochemical processes;
- development and production of low-tonnage chemical products, including specialized products;
- synthesis of physiologically active substances; and
- new topological materials, a sneak property for the creation of high-tech polymers.

Earth Science:

- monitoring of geophysical and geodynamic processes;
- global and regional environmental changes; and
- formation of global and regional environmental changes, mineral deposits.

Biology and Medicine:

- application of digital, bio-, nano- and postgenomic technologies;
- genomic, proteomic and metabolomic studies;
- problem solution in food and food security;
- human health and biodiversity;
- molecular genetic research of the population of Azerbaijan;
- biomedicine, neurobiological and gerontological research;
- methods of mechanization and artificial use intelligence in biology; and
- agriculture and medicine, green energy.

Humanities and social sciences:

- study of ethnogenesis, archelogy, ethnography, language, folklore, literature, ancient manuscripts, culture, art, national architectural schools, the history of the Azerbaijani people based on modern challenges, modern theoretical and methodological views, including Azerbaijani principles;
- writing the history of Azerbaijani literature on the concept of a new transformation, Azerbaijan's study of the scientific and theoretical foundations of the idea of Azerbaijanism; and
- concept of multiculturalism, studying various problems of philosophy of the world, conducting research in the field of oriental studies and Caucasian studies, sociology.

The report submitted by the Presidium of Azerbaijan National Academy of Sciences (ANAS), in particular, where the main scientific results reflected in the report, show once again that in the reporting period of the year fundamental scientific research was carried out, which laid the foundation for the continuous development of science in all fields. These results reflect the goal of UNESCO's decision to declare the Year of Basic Sciences for the 2022 International Progress for Sustainable Development at the Main Conference.

Achievements

The main goal of this solution is to demonstrate the decisive role of basic scientific research in the sustainable development of the World. Taking this approach into consideration Institute of Physics of the Ministry of Science and Education, the leading center for basic research in the field of physics, invited scientific and educational institutions to integrate efforts in this area. The purpose of joint activity is to support basic research projects that are important for the country. It has been identified development of semiconductor heterostructures used in high-frequency cycles and optoelectronics as a new direction of the Institute.

The concept of sustainable development consists of three main components:

- ecology;
- social; and
- economic.

Currently, ecological direction is considered one of the most important. This direction is based on the principle of harmonizing the natural needs of mankind with the natural capabilities of the biosphere. Ignoring this principle could lead to the situation described in the documents of the 1992 Rio de Janeiro Conference. It noted that "we can be the last generation to have a chance to save our planet." As a result, sustainable development is possible only when economic activity does not go beyond the ecological sustainability of the ecosystem.

Today, the technological environment is an extraordinary energy user. Thus, according to the international energy agency, in order to form a digital economy in 2025, the need for energy of the info-communication network will amount to 30% of the electricity produced in the world. Taking into account this fact an emergence of new energy technologies can only occur on the basis of fundamental research and based on this AMEA degree dated May 20, 2021 on the creation of Scientific Councils on "Alternative and Renewable Energy Sources." It contains:

- current scientific and technological problems;
- provision of flexible and professional discussions on scientific and organizational issues;
- problems of science and technology; and
- in order to provide scientific support for issues related to energy supply within the country, especially in territories liberated from occupation.

Along with the fundamental studies defined by the internal logic of the country's development, which create the possibility of timely assessment of the risks causing scientific and technological development, joint applied studies, which are their main organizers, should also be noted [2]. It should be indicated an opinion of famous scientists that there is no fundamental and applied science. All real science is applied. The difference is that some scientific results are applied immediately, and some - after 10 years or more.

The scientific environment is an exceptional area of activity, largely determined by the purpose of science related to the acquisition of new knowledge about the laws of nature and the laws of development of society. Nobel laureate Richard Feynman considered "the most important requirement for true fundamental science the need for integrity. This is a very difficult term to translate. Translations from the dictionary: integrity – wholes, safety, reliability and correctness of data, observance of ethical principles, honesty, high moral qualities. " These criteria are difficult to meet but grants and funding tend to get better minds. In addition, in modern science, serious scientific results can be obtained most often at the junctions of scientific areas by teams of specialists who represent different scientific disciplines.

Today we sometimes meet such thoughts that it is difficult to afford to invest in science, that supporting research is somehow a luxury in moments defined by needs. This is a fundamentally flawed approach. Science is more important for the prosperity, safety, health, environment and quality of life of all mankind.

The pandemic as a result of COVID has become a test of all mankind. Obviously, this is a cause for concern and requires increased combat readiness to minimize risks. It is necessary to use all the resources necessary to quickly and effectively respond to events related to the pandemic. Fundamental sciences in the field of medicine play an important role in this matter, which has been achieved in this area. Thanks to such an achievement, humanity will learn the importance and invalidity of the achievements of basic and applied sciences.

It should be indicated that the pandemic has demonstrated the importance of achievements not only in the field of medical science, but also in many scientific areas, requiring the integration of a number of scientific disciplines.

There is one aspect needed to be pointed out: the ability to address public health issues of this magnitude depends heavily on the work of the scientific and medical community. And this is another example of why we cannot allow a slowdown in the development of science.

It is important to consider that US President George Herbert Walker Bush in his speech in the National Academy of Sciences Annual Meeting taken place in April 27, 2009 stressed that the Federal Funding for Physical Sciences as part of Gross Domestic Product has fallen by almost half in the last quarter of a century. As he noted, over and over again we have allowed us to deny a tax loan for research and experiments, which helps businesses grow and innovate. The consequence of this facto is not immediately heard, it finds its non-negative not immediately, but after some time. In certain situations, we miss the fallacy of this approach, which is very difficult to fix and sometimes with tragic consequences.

It should be noted that some of the world's leading countries have committed themselves to leading the world in the field:

scientific and technical innovations;

- invest in education;
- scientific research;
- engineering;
- set a goal to achieve space technology and science; and
- engaging all citizens in this historic mission.

Countries that invest more in the development of fundamental and applied science are growing and growth indicators share of national income. As Bush noted in his speech: I am here today to set this goal: we will allocate more than 3 percent of our GDP for research and development. We will exceed the level achieved at the height of the space race, through policies that invest in basic and applied research, create new incentives for private innovation, promote breakthroughs in energy and medicine, and improve education in mathematics and science [3].

This is the greatest commitment to scientific research and innovation in the world:

- the basic science opens an opportunity to create solar cells as cheap as construction paint;
- green buildings that produce all the energy they consume;
- training software effective as a personal tutor prosthetics are so advanced that you can play the piano again;
- artificial intelligence and machine learning; and
- expanding the boundaries of human knowledge of ourselves and the world around us.

The desire for the development of basic science contributed to prosperity and success. The commitments we make today will contribute to our success in the bugbear. This is how we will ensure that our children and their children look back at the work of our generation as one that has defined progress and ensured the prosperity of future generations. These actions begin with a historical commitment to basic science and applied research, from the laboratories of prominent universities to the implementation of innovative ideas.

It should be considered that the study of a specific physical, chemical or biological process may not pay off within a year, decade or at all. And when this happens, the awards are often widely shared, they are used by those who bear its costs, as well as those who did not contribute to the process at all.

That is why the private sector tends not to invest enough in basic science, and why the public sector should invest in this kind of research - because while the risks can be large, so can the rewards for the economy and society as a whole.

No one can predict which new applications will be born from basic research, such as:

- new treatments in our hospitals;
- new sources of efficient energy;
- new building materials;
- new types of crops that are more resistant to heat and drought;
- new approach of basic studies in the photovoltaic field to develop solar panels;
- new approach of basic research in physics to achieve production of the CAT scans;
- new approach of application of Einstein equations in modern GPS technology for the geo-positioning systems based on satellite technology.

The US views the approach in such a way that it doubles the budget of key institutions, including the National Science Foundation, the main source of funding for academic research; and the National Institute of Standards and Technology, which supports a wide range of activities - from improving health information technology to measuring carbon pollution - from testing smart network designs to developing advanced manufacturing processes.

As the result budget doubles funding for the Department of Energy's Office of Science, which builds and operates accelerators, colliders, supercomputers, high-energy light sources and means to make nanomaterials - because the nation's potential for scientific discovery is determined by the tools it provides to its researchers.

It is necessary to indicate that any country's renewed commitment will depend on more than just public investment. This commitment extends from the lab to the market. So, the state budget makes tax credits for research and experimentation permanent. This is a tax credit that returns two dollars to the economy for every dollar that is subsequently spent, helping companies afford the often high costs of developing new ideas, new technologies and new products.

It should be noted that by making this loan permanent, it enables businesses to plan projects that create jobs and economic growth. This fact plays a significant role in stabilizing society as a whole [4].

Secondly, in no area will innovation be more important than the development of new technologies for the production, use and saving of energy - this is why leading countries tend to commit to developing a clean energy economy of the 21st century.

Our future on this planet depends on our willingness to address carbon pollution. And our future depends on our willingness to accept this challenge as an opportunity to lead the world in striving for new discoveries through the development of the fundamental sciences.

It should be noted that the existing competition between the United States and the former Soviet Union was the source of the development of science and technology in the world as a whole. It should be noted that the launch of the first satellite by the Soviet Union was a stunning factor for the Americans. They accepted that challenge. And just a few years later, a month after his speech at the 1961 Annual Meeting of the National Academy of Sciences, President Kennedy boldly declared before a joint session of Congress that the United States would send a man to the moon and return him safe and sound to Earth. The ambition of the United States presented by the President of the country was realized. This was achieved thanks to a successful superposition of fundamental and scientific and humid achievements of the United States. The US scientific community rallied behind the implementation of this goal and took up its achievement. And it didn't just lead to the first steps on the moon. This would lead to giant jumps in the development of many branches of science and technology. This Apollo program created technologies that improved:

- sensors for hazardous gas testing;
- energy-saving building materials; and
- fire-resistant fabrics used by firefighters and soldiers.

Considering the requirements of the modern world, the following goals of popularizing science can be distinguished: the presentation of up-to-date proven scientific information adapted for the perception of people with different levels of education and qualifications:

- formation in public opinion of the scientific picture of the world as an integral part of the general culture;
- clarification in society of the role of science in the modern world and its influence on the lives of people and the associated increase in the prestige and social attractiveness of research work; and
- increasing the level of natural science and humanitarian education of graduates of schools and universities, scientific and educational work with schoolchildren and young generation.

Up to date stage of the development of world processes is distinguished by their high dynamism, inconsistency and ambiguity. The transformations taking place are sometimes dual in nature, can be interpreted as both negative and positive. In such conditions, it is tempting to pay more attention to the problems of the current moment, while promising tasks are the lot of time when the country will emerge from the recession. However, this approach is strategically unjustified. The current situation is largely due to the lack of orientation towards long-term goals, a proper assessment of possible risks and threats, the problem of import substitution began to be perceived as relevant only after the introduction of the food embargo. For example, the definition of the perspective of the agro-industrial complex implies the need to create and adopt a strategy for the socio-economic development of the industry.

More broadly, huge investments in this era have been made in science and technology in particular in basic sciences, in education and in funding scientific research. All this gave rise to a huge surge of creativity, the benefits of which were incalculable. Today we are reaping the fruits of the achievements that were achieved in those years of scientific and technological renaissance.

But energy and energy resources are a universal question. Humanity faces a goal of reducing carbon pollution by more than 80 percent by 2050. This could be achieved by doubling the capacity to produce renewable energy over the next few years - expanding the production tax credit, providing credit guarantees and providing grants to spur investment. There must be new efforts to ensure the competitiveness of solar and other clean energy technologies.

There are aspirations to make renewables a lucrative type of energy. It is necessary to create resources so that scientists can focus on this most important area. At the same time, it is necessary to find a source of creative potential that will be used by researchers and entrepreneurs.

But it is important to note that this approach has the potential to offer people the opportunity to be more active participants in the prevention and treatment of their diseases. We must maintain patient control over these records and respect their privacy. At the same time, we have the opportunity to offer billions and billions of anonymous data points to medical researchers who can find evidence in this information that can help us better understand the disease.

History also teaches us that the greatest successes in any field, and in medicine, among other things, were achieved thanks to scientific breakthroughs, whether it is the discovery of antibiotics or the improvement of public health practices, smallpox and polio vaccines and many other infectious diseases, antiretroviral drugs that can bring AIDS patients back to productive lives, pills that can control certain types of blood cancer, and many others.

With recent advances - not just in biology, genetics and medicine, but in physics, chemistry, computer science and engineering - we can make tremendous progress in disease control in the coming decades. That is why states should be interested in the development of science and technology and should intend to increase funding for national research institutes, including industry and private development research centers and centers of excellence.

In terms of environmental science, it will require strengthening our weather forecasting, observing the Earth from space, managing land, water and forest resources and managing our coastal zones and oceanic fisheries. This requires a new approach to the development of fundamental work and scientific research, including the development of new methods, taking into account the challenges of fundamental work. It is necessary to introduce a culture of achievement in the field of artificial intelligence, machine learning, big data etc. Should work reporting around the world. Science has no boundaries. It is obvious that technology and innovation are developing faster and more efficiently in terms of costs when sharing information, costs and risks. Many of the tasks that will help us solve the problems of science and technology are global in nature, which requires the integration of joint efforts.

It is undoubtedly necessary to significantly improve achievements in mathematics and science by raising standards, modernizing scientific laboratories, updating the curriculum and creating partnerships to improve the use of science and technology in our universities. Set a task to improve the training and teaching staff, as well as to attract new and qualified teachers of mathematics and science, so that they better involve students and revive and motivate students to these subjects.

Yes, scientific innovation gives us a chance to prosper. It has given us benefits that have improved our health and our lives - improvements that we take for granted. But it gives us something more. Science makes us reckon with the truth as best we can.

Some truths fill us with awe. Others make us question longstanding views. Science cannot answer every question, and, indeed, sometimes it seems that the more we abandon the secrets of the physical world, the more modest we should be. Science cannot supplant our ethics, our values, our principles, or our faith. But science can inform these things and help lay down these values - these moral feelings that faith - can make these things work - to feed a child or heal the sick to be good stewards of this Earth [5].

We are reminded that with each new discovery and new force, she bears a new responsibility; that fragility, the very specificity of life require us to overcome our differences and solve our common problems, preserve and continue the desire of mankind for a better world.

Patterns for clarification

The Nobel Prize is a prestigious association prize established by Alfred Nobel on November 27, 1895 and announced on December 30, 1896 in Stockholm. It should be noted that this award is considered an advocate of fundamental science of world scale and the most powerful source supporting it.

As you know, the scientific fields covering the Nobel Prize:

- Nobel Prize in Literature;
- Nobel Prize for in Physiology or Medicine;
- Nobel Prize in Physics;
- Nobel Prize in Chemistry; and
- Nobel Peace Prize.

It is interesting to present examples of the results obtained by Nobel Prize winners in scientific fields. Here are examples of the first Nobel Prizes in various fields.

Wilhelm Konrad Roentgen is a German physicist. Known for the discovery of X-rays. The area of research in which he is interested: the connection between piezoelectric and pyroelectric properties, electrical and optical phenomena. Discovered X-rays, created the first X-ray tube. The discovery of X-rays greatly influenced all fields of science. A unit of X-rays and gamma rays was named in his honour.

Jacobus Henricus van't Hoff is a Dutch chemist. Winner of the Nobel Prize in Chemistry. In 1901, the Nobel Committee declared Vant-Goff the first laureate in chemistry. Chemical dynamics, which he discovered as the reason for receiving a diploma award (Chemical dynamics is a science that studies the role of chemical reactions in the development, conduct, speed, equilibrium and its change, electrolytic dissociation, third-party effects. Each of these processes takes place in a certain volume and under pressure. A special area of the science of physical chemistry is called the "foundations of thermodynamics." All of the above chemical areas are based on the laws of chemical thermodynamics) and osmotic pressure in liquids (which means pressure from osmotic to passport, that is, for example, the smell of a plant through this pressure attracts water from the soil to itself). Presenting the Vant-Goff Prize on behalf of the Swish of the Royal Academy of Sciences, Odner called him the founder of stereochemistry and one of those who worked in the field of chemical dynamics, and also stressed that the scientist's research provides extremely important results for the science of physical chemistry.

Emil Adolf von Behring is a German chemist, winner of the 1901 Nobel Prize in Medicine and Physiology. During his military service, Bering began to conduct various experiments with the aim of combating infectious diseases. Disinfectants and antiseptics were underdeveloped at the time. His main experiments were related to tetanus and diphtheria diseases. Bering studied these diseases together with the Japanese scientist Shibasaburo Kitasato. In the course of the study, it turned out that antibodies to bacteria are formed in the blood of those who died from the disease. Then, as a result of the study of mice and rabbits, they discovered the possibility of recovery of other animals with the help of antitoxins formed in the blood of sick animals.

In 1891, the first diphtheria vaccine began in a Berlin hospital. Many of them recovered.

Rene Francois Armand Prude was known for his conservative position in relation to literary forms and genres. In the book "Literary Testament" (1900), he advocated the traditions of classical French poetry, expressed a critical attitude to free art, the search for symbolists and decadence literature. In 1901, he won the first Nobel Prize in Literature.

Jean-Henry Dunant - world famous Swiss benefactor, businessman, first Nobel laureate. In 1863, he, along with his friends, decided to create an organization to help the wounded around the world. These emblems, transported by sanitary workers and their miniature means, indicate that the workers of the Golden Cross and the Golden Bear are not military personnel. Since 1869, the Golden Cross began to help victims of floods, earthquakes, epidemics, famine and other disasters around the world.

Ragnar Anton Kittil Frisch is a Norwegian economist. In 1969, together with Jan Tinbergen, he was first awarded the Nobel Prize in Economy. Ragnar Frisch is one of the economists who played an important role in shaping the modern economy conducted research on mathematical explanation, called new economic concepts. The role of Ragnar Frisch in creating econometric models for social accounting and economic planning of the modern state is great.

Let's pay attention to the Nobel Prizes of our time.

Donna Strickland is a Canadian physicist working in laser physics and nonlinear optics. He together with Gerard, invented a method to increase fine pulses. 2018 Nobel Prize in Physics.

Francis Hamilton Arnold is an American scientist, engineer and scientist who has made a significant contribution to the development of oriented evolution of enzymes. Winner of the 2018 Nobel Prize in Chemistry.

Ōsumi Yoshinori is a Japanese cytologist. The main work is autophagy. This process involves the destruction and repetition of cell components.

Denis Mukengere Mukwege is a congregational gynecologist and pastor. He founded the Pantsi Hospital in Bukhava, where he treated women attacked by armed rebels. In 2018, Mukwege and Iragli were awarded the Nobel Peace Prize for "efforts to end sexual violence as a weapon of war and armed confrontation."

William D. Nordhaus is an American economist. Winner of the 2018 Nobel Prize in Economy. Nordhaus is known for his activities in integrating climate change into long-term macroeconomic analysis, as well as leading contributions to environmental economics.

When considering the activities of the Nobel Prize winners, they were awarded for their contribution to fundamental science. Nobel Prizes, dedicated to peace, literature and the economic sphere, are also scientists awarded fundamental apple results.

When Nobel laureates qualify for the activities of the first and coinciding with our era of laureates, then from time to time there is a tendency to remove results from fundamental science. Here you can see a tendency towards the synthesis of sciences and their relationship, including technologically, to achieve scientific production. This trend makes it difficult to see what results in the future will have a positive or negative impact on scientific activities. It is just obvious that the development of science covering any industry is determined by basic science. This laid the foundation for the future of world science to become uncertain.

Conclusion

What approach of the basic science is needed to be selected and taken into attention in order to achieve expected results? It always takes a vital place to understand and find out pointed out questions “what, when and how” which make possible to put the right way line for problem solution. There is no doubt that basic science is the main platform for maintaining and creating fundamental principles embracing all aspect with coming end for the human life. It is obvious that science is only source impacting for developments and improvement of existing environment of human society in all areas. So, it demands to consider place and importance of the basic science in our life.

An analyse of the current achievements in the basic science is the subject of this chapter. It has been learned and provided arguments where basic science plays significant role in all areas of human life. In the meantime, it has been demonstrated importance of basic science in achievement of expectations for technological developments in the future. At the same time it demonstrates importance of responsibility of decision makers in creation of positive environment for the basic science and science commercialization which directly linked all the spheres of human life.

Today circumstances and conditions demand to take care of the basic science for the future of the.

Reference

Schwab, K. (2016). The Fourth Industrial Revolution (Geneva, World Economic Forum, 2016). Retrieved from www.weforum.org/pages/the-fourthindustrial-revolution-by-klaus-schwab

United Nations. (2014). The Crucial Role of Science for Sustainable Development and the Post-2015 Development Agenda Preliminary Reflection and Commentsby the Scientific Advisory Board of the UN Secretary-General. Retrieved from https://www.leopoldina.org/fileadmin/redaktion/Internationales/2014_The_Crucial_Role_of_Science_for_the_Post-2015_Development_Agenda.pdf

Adenle, A. A., Chertow, M. R., Moors, E. H. M. & Pannell, D. J. (2020). Science, Technology, and Innovation for Sustainable Development Goals. Oxford University Press.

Seiler-Hausmann, J. (2002). Innovation & Sustainable Development. Retrieved from https://www.iges.or.jp/en/publication_documents/pub/discussionpaper/en/86/BE2_3018.pdf

Mani, P. & Ramakrishnan, R. (2018). Science, Technology and Innovation for Sustainable Development. International Journal of Scientific research and Review, 7(7), 127-131.

About Authors

Arif HASHIMOV | Azerbaijan National Academy of Sciences | arif[at]physics.ab.az | ORCID: 0009-0003-8984-7581

Prof. Dr. Arif Hashimov has completed his MS degree at the Azerbaijan State Oil Academy, Baku, Azerbaijan and awarded diploma of Electrical Engineering. His scientific degree diploma of Candidate of Sciences (PhD) is achieved in Kiev, Ukraine, at the Institute of Electrodynamics of Ukrainian Academy of Sciences. In 1993 Arif Hashimov is awarded Diploma of Doctor of Sciences, Kiev, Institute of Electrodynamics of Ukrainian Academy of Sciences. His achievements: Laureate of Government Prize of Azerbaijan, Honored scientist of the Azerbaijan Republic, Academician of the Azerbaijan National Academy of Sciences. Researches area: Power engineering, Wave processes in electric systems, Modeling of electromagnet processes in the electric networks, Electrophysics, High voltage physics and technology, Electrophysical processes in the dielectrics. Currently Arif Hashimntov is the First Vise-President of Azerbaijan National Academy of Sciences and General Director of Institute of Physics Ministry of Science and Education. From 2021 to the present Prof. Dr. Arif Hashimov is the Representative of the Republic of Azerbaijan at the Joint Institute for Nuclear Research in Dubna of the Russian Federation. In 2022 Prof. Dr. Arif Hashimov has elected a full member of the International Association of Academies of Sciences. He is an author of about 400 scientific papers and 23 patents.

Rustam B. RUSTAMOV | Azerbaijan National Academy of Sciences r_rustamov[at]hotmail.com | ORCID ID: 0000-0003-2056-9352

Rustam B. Rustamov has completed his master's degree in semiconductors and insulators at the Azerbaijan Technical University, Baku, Azerbaijan. He has spent two years scientific training at the Physical-Technical Research Institute of National Academy, Sankt-Petersburg with further intake and defence of PhD at the same research Institute of Sankt-Petersburg. He is Assoc. Prof. and currently working in the Institute of Physics Ministry of Science and Education of the Republic of Azerbaijan as a head of department. Rustam B. Rustamov is Cambridge Scholars Publishing International Editorial Advisory Board Member on Astronomy, Astrophysics and Space Science, London, UK and Panel of Experts for the assessment of application/paper of candidate for selection for the post of Professor and Associate Professor in the Department of Institute of Space Science and Technology, University of Karachi. Rustam B. Rustamov is the Corresponding Member of the International Academy of Astronautics, Paris, France. Former Acting Director General of the Azerbaijan National Aerospace Agency. Scientific Publications: more than 145 scientific papers as well as 19 books published in the famous World publication houses.

INDEX

A

B

C

D

E

F

G

H

I

J

M

N

O

P

R

S

T

U

V

W

Z

Foundations of Science for a Sustainable Future: Principles and Innovations is a comprehensive work that highlights the crucial role of basic sciences in addressing global sustainability challenges. This book brings together contributions from 34 authors across 7 countries, presenting insights from diverse scientific fields including chemistry, biology, physics, engineering, and medicine. With 17 chapters, it explores the interdisciplinary approaches needed to drive sustainable innovation and global change. Notably, the book reflects the goals of the United Nations' Sustainable Development Agenda, with a particular focus on climate change, resource depletion, and socio-economic inequalities. The publication also stands out for its unique contributions from Turkish scholars and global experts, bridging local and international perspectives on sustainability. The Turkish Academy of Sciences and the editors have fostered collaboration among leading researchers, making this volume a valuable resource for academics, policymakers, and practitioners. By showcasing cutting-edge research and innovations, this book is a key reference for anyone committed to advancing sustainability through science. Through this collective effort, it offers both theoretical foundations and practical solutions to shape a more sustainable future.

TÜBA

TÜRKİYE BİLİMLER AKADEMİSİ
TURKISH ACADEMY OF SCIENCES

Vedat Dalokay Caddesi No: 112 Çankaya 06670 ANKARA
Telefon : +90 (312) 442 29 03 **Faks :** +90 (312) 442 72 36

www.tuba.gov.tr

www.facebook.com/**TUBAakademi**

www.x.com/**TUBAakademi**

ISBN 978-625-611-022-9
9 786256 110229 >