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

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

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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.

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