

Green Chemistry Approaches for Environmental Pollution Mitigation

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ABSTRACT

The problem of environmental pollution nowadays is one of the most acute issues on the planet in the 21st century, and it considerably poses a threat to the ecosystem, the health of people and economic development. Despite the fact that industrialisation and the development of technology has led to increase in economic growth, it has contributed to the pollution in an increased extent through the heavy exploitation of hazardous chemicals, fossil raw material and also through the energy consuming processes. In the traditional approach, chemical production usually causes toxic by-products, heavy metal, and persistent organic pollutants to enter the atmosphere, water and land, thus causing an irreversible environmental degradation. It is in this environment that Green Chemistry provides a paradigm that attempts to re-innervise chemical processes and products in the effort to avoid pollution at its origin. Green chemistry was pioneered by Paul Anastas and John Warner, who initially proposed green chemistry in the 1990s, emphasizing the use of safer reagents, minimisation of waste, use of renewable resources and ensuring that all aspects of the life cycle of a chemical product are energy-efficient. This is a critical review of the many green chemistry approaches that have resulted in the minimization of pollution such as solvents innovation, catalytic processes, renewable feeds, as well as environmentally friendliness technologies to air, water and soil treatment. The technologies discussed in the paper are nanotechnology-driven green processes, AI-enhanced chemical design, and the models of a circular economy that encourage the efficiency in the use of resources. A number of case studies demonstrate how industries have managed to adopt these practices in order to have less environmental footprint. Also, the review concerns the matters of the policy implementation, cost structure, and scalability. Finally, it gives a prognosis on how green chemistry might be anchored as a pillar of sustainable development, which will result in a healthier planet, and scientific innovation and competitiveness in industries.

Keywords- Green Chemistry, Pollution Mitigation, Sustainable Chemistry, Catalysis, Renewable Resources, Environmental Protection.

I. INTRODUCTION

It has become a matter of concern that environmental pollution is at alarming levels, with dire consequences for the ecosystems, human health, and the sustainability of the world. The industrialisation process, active urbanisation, and uncontrolled extraction and utilisation of natural resources have increased the release of toxic substances into the air, water, and soil. The World Health Organisation notes that air pollution causes approximately 7 million premature deaths each year, and more than 2 billion people have daily access to contaminated drinking water that contains chemical and microbial pollutants. Food insecurity and health risks are additional consequences of soil degradation resulting

from the excessive use of pesticides and heavy metals. Such statistics raise the alarm that proactive, science-based solutions extending beyond traditional pollution control mechanisms are urgently needed (Anjum et al., 2022).

Filtering, scrubbing, or effluent treatment plants, as well as other methods traditionally used to mitigate pollution, are mainly reactive strategies. These systems treat contaminants once they have been created, and in most cases, they move contaminants between one environmental medium and another instead of removing their origin. Air scrubbers could capture particulates and release the pollutants into wastewater streams, for example. The chemical treatment used in water purification can produce a secondary waste that requires

additional disposal. These are merely stopgap measures that are unable to address the systemic inefficiencies in production processes that generate pollution in the first place (Giakoumis et al., 2020).

In comparison, green chemistry provides a radical way of preventing pollution through re-evaluating the processes and structuring of the products of the chemicals. Green chemistry is pegged ideals. It promotes strategies like reduction of waste, maximisation of atom economy, safer reagents, energy-efficient synthesis and renewable feedstocks, catalysis, and biodegradable design. It is a plan which integrates environmental, economic, and social features, and as such, innovation is in line with the long-term sustainability aims (Kharissova et al., 2019). The objective of this review is to critically evaluate how the concept of green chemistry has been used to ensure that the environmental pollution in different sectors and the overall ecosystem is mitigated. It talks of green solvents, where water is used rather than volatile organic compounds (VOCs); ionic liquids or supercritical fluids rather than volatile organic compounds (VOCs); biomass and CO₂ converted to useful chemicals; and reactions that are catalyzed and use less energy and produce less waste. Much attention is paid to their role in the management of air, water, and soil pollution (Pham and Park, 2024). Also, emerging technologies in the form of photocatalysis, enzyme reactions and nanomaterials, which can be used as environmentally friendly alternatives to standard processes are also evaluated in this review. Case studies on industries like pharmaceuticals, agriculture, and energy demonstrate the applied successful cases as well as the challenges of scaling, along with the costs and regulations (Freitas et al., 2021).

Lastly, the paper makes a future projection of the intersection of green chemistry and global sustainability programs, which requires interdisciplinary partnership, sound policy mechanisms, and technology. Due to the growing pressure of climate change, resource depletion, and population health crises, adopting green chemistry is no longer just a choice but a necessity for a cleaner, safer, and more resilient future (Tickner & Dunham, 2023). In this exploration, the review has the potential to supply researchers, policymakers, and industry leaders with a holistic view of how green chemistry can be utilised in mitigating environmental pollution in the future.

II. PRINCIPLES OF GREEN CHEMISTRY AND POLLUTION MITIGATION

Green chemistry is a scientific field that considers environmental responsibility in the design and operation of chemical processes from a fundamental perspective. Contrary to traditional pollution control measures, which are usually reactive and applicable in treating waste once it is produced (end-of-pipe measures), green chemistry aims to prevent polluting waste at its

origin. It is driven by 12 principles that aim to reduce or eliminate the use and manufacture of harmful materials throughout the chemical life cycle. These are the pillars that can guide the creation of sustainable technologies that will not only mitigate adverse environmental effects but also enhance the efficiency and financial stability of the processes (Zimmerman et al., 2020).

The first principle, Prevention, focuses on preventing waste before it occurs, rather than after production has taken place. Chemical processes will ensure that pollution is handled at the early stages, thereby minimising by-products and alleviating the load on treatment plants, and reducing the amount of waste sent to landfills. The concept encourages innovation, as it prompts chemists to reconsider process designs, rather than relying on expensive treatment technologies (Halim & Srinivasan, 2009).

The second principle, known as Atom Economy, advocates for the maximisation of raw materials in the end product. Optimised material use minimises waste sources and reduces the number of elements that negatively impact the environment, including those involved in disposal and purification. To illustrate, reactions with fewer by-products are simpler to handle and produce less hazardous waste (Fadlallah & Allais, 2023). Less Hazardous Synthesis is the third concept that promotes safer chemicals and reaction conditions. Industries can eliminate toxic emissions and spills into the air and water resources by substituting the toxic reagents and high-energy operations with benign alternatives (Varma, 2014).

The fourth principle, Design Safer Chemicals, applies the notion of safety to the result. Chemicals must work effectively for their intended purpose without being persistent and toxic. The fact that products can be easily broken down into non-toxic materials averts long-term ecological destruction (Lozano & García-Verdugo, 2023). The fifth principle is Safer Solvents and Auxiliaries, which emphasises the importance of using safer solvents and auxiliaries as a means to reduce pollution. Solvents pollute the air and cause respiratory diseases, and volatile organic compounds (VOCs) are usually solvents. Industries can significantly reduce environmental hazards by replacing hazardous solvents with water, supercritical fluids, or recyclable ionic liquids (Häckl & Kunz, 2018).

Principle six: Energy Efficiency aims to reduce the amount of energy used by designing processes that revolve around ambient temperature and pressure. This not only reduces greenhouse gas emissions but also minimises operational costs, making processes more sustainable in the long term (Fantoni et al., 2021). The seventh principle, Renewable Feedstocks, focuses on substituting petroleum-based raw materials, which are finite, with renewable sources of biomass. The use of agricultural waste, forest remnants, or materials of algae origin can help to reduce a carbon footprint and promote circular economies (Clark, 2017).

Principle eight, Reduce Derivatives, encourages the reduction of unnecessary reaction steps, including protection-deprotection sequences that waste reagents and generate waste. Reduction in synthesis pathways leads to simpler processes, which in turn reduce environmental impacts. The ninth principle, called catalysis, recommends the use of catalysts instead of stoichiometric reagents. Catalysts increase the rate of reaction and need only minute traces, thus minimising the use of chemicals, wastage and energy (Náray-Szabó & Mika, 2018).

The tenth principle, Design for Degradation, addresses the structuring of chemicals to enable them to degrade into harmless substances upon use. This avoids environmental persistence and bioaccumulation, a pertinent issue in ecologies subjected to industrial runoff. The principle eleven of Real-time Analysis allows for the continuous tracking of reactions and processes, which is why reactions and pollution can be identified and prevented at the earliest stage. Sensors or spectroscopy can be used to perform an immediate corrective action to reduce unplanned emissions and waste production (Ananikov, 2024). Lastly, Principle Twelve, Inherently Safer Chemistry, encourages the development of processes in ways that minimise risks, such as explosions, spills, and exposures to toxins. A less risky chemical environment means fewer accidents, reduced intervention at the emergency level, and the preservation of people and ecosystems.

Table 1: The 12 Principles of Green Chemistry and their Relevance in Pollution Mitigation

Principle	Description	Environmental Relevance
Prevention	Avoid waste rather than treat it	Minimises waste disposal issues
Atom Economy	Maximise the incorporation of materials	Reduces by-products and residues
Less Hazardous Synthesis	Use safe chemicals and processes	Prevents toxic emissions
Design Safer Chemicals	Create effective yet non-toxic products	Prevents environmental persistence
Safer Solvents & Auxiliaries	Avoid VOCs and harmful solvents	Reduces air and water pollution
Energy Efficiency	Conduct reactions at ambient temperature	Cuts greenhouse gas emissions
Renewable Feedstocks	Use biomass and non-depleting resources	Lowers carbon footprint

Reduce Derivatives	Minimise unnecessary modifications	Prevents extra waste streams
Catalysis	Prefer catalysts over stoichiometric reagents	Reduces waste and energy demand
Design for Degradation	Ensure products break down safely	Prevents long-term accumulation
Real-time Analysis	Monitor processes to prevent pollution	Prevents accidental emissions
Inherently Safer Chemistry	Minimise accident potential	Reduces risk of environmental disasters

These principles collectively contribute to the sustainability of pollution in various fields, including air, water, soil, and biodiversity. In one example, less toxic solvents emit fewer smog-causing VOCs, and renewable feedstocks will reduce dependency on fossil fuels, thereby reducing greenhouse gas emissions. Equally, a chemical formulation that degrades means there is no accumulation of intractable gases, such as endocrine disruptors and heavy metals (Ismael, 2020).

Practically, industries that apply these principles experience lower costs in waste management, reduced regulatory compliance pressure, and a better relationship with the community. Moreover, monitoring the process in real-time and utilising safer chemical design units can also help ensure the safety of the workplace, thereby eliminating environmental disasters and occupational hazards (Ujaczki et al., 2022). As shown in the table above, each principle not only informs sustainable practices but also supports the broader environmental goals. Green chemistry can be used as an overall approach to preventing and mitigating pollution by integrating these principles into research, product development and industrial processes.

III. GREEN SOLVENTS:
ALTERNATIVES TO TOXIC
CHEMICALS

Green chemistry has made and continues to make one of the most significant contributions in reducing environmental pollution through the development and use of green solvents as safer and more sustainable alternatives to the traditional organic solvents. More conventional solvents, such as benzene, toluene, chloroform, and dichloromethane, have long been associated with adverse effects on both human health and the environment. These organic volatile substances (VOCs) not only pollute the air and contribute to smog formation, but also pose occupational risks, and their improper disposal can lead to soil and water pollution.

Being aware of such perils, green champions have been calling for the substitution of toxic solvents with less toxic substitutes, which reduce toxicity, emissions, and other waste without affecting or increasing process efficiency.

3.1 Types of Green Solvents

Water is one of the most common green solvent alternatives, and is possibly the most sustainable. It is not only safe, but also cheap and easily accessible. Aqueous processes, such as aqueous-phase catalysis and biocatalysis, are being applied in chemical synthesis and pharmaceutical manufacturing as alternatives to organic solvents, without compromising product yield or reaction rate (Sheldon, 2018). Another potential green solvent is supercritical carbon dioxide (scCO₂). High pressure and temperature are used to obtain the supercritical properties of CO₂, which enable the solubility of non-polar substances. It has found widespread use in processes such as decaffeination of coffee, dry cleaning, and polymer synthesis, where it has replaced the use of hazardous organic solvents, is considered safe, and can be easily recycled (Villacis-Chiriboga et al., 2021).

The low-melting salts are Ionic liquids (ILs) which offer non-volatile thermally stable alternatives to catalysis, electrochemical reactions and separations. They have low vapour pressure, enabling less polluted air, and customised chemical structures are selectable, allowing solvent capabilities to be tailored to special applications. One of the most promising, versatile and biodegradable alternatives is deep eutectic solvents (DES). DESs are very solvent-powered, low impact products manufactured using cheap and renewable raw materials, such as choline chloride and urea. Their biodegradability and lower toxicity make them highly suitable in different applications with respect to the disposal issues of conventional solvents.

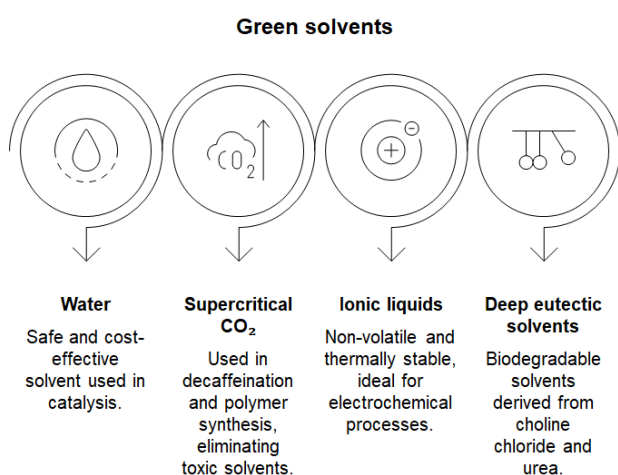


Figure 1: Types of green solvents

3.2 Applications in Pollution Mitigation

The use of green solvents has been proven to provide a measurable advantage in preventing environmental pollution. For example, chlorinated

solvents, which had long been used in industrial cleaning and extraction, have been successfully replaced with water or ionic liquids, thereby reducing hazardous emissions and enhancing workplace safety. Likewise, water-based paints and coatings are also being introduced into the construction and manufacturing industries to facilitate the release of VOCs, thereby improving air quality within both internal and external environments (Athappan et al., 2013). Deep eutectic solvents have been primarily used in the cleanup of contaminated water containing heavy metals. Their peculiar chemical structure allows complexing with metal ions such as lead, cadmium, and arsenic, and is extractable without contributing additional pollutants to the ecosystems.

IV. CATALYSIS AND ENERGY-EFFICIENT REACTIONS

Green chemistry is based on catalysis, which offers long-term solutions to most environmental issues associated with traditional chemical reactions. The classic responses typically involve high temperatures, high pressures, and excessive amounts of stoichiometric reagents, resulting in unnecessary energy consumption and significant waste. Conversely, catalytic processes enhance the effectiveness of reactions by reducing the activation energy barriers, improving selectivity, and utilising safer reagents. In this regard, catalysis is a crucial element in developing energy-efficient reactions that minimise environmental impact while meeting industrial needs (Orupattur et al., 2020).

4.1 Types of Green Catalysis

A variety of catalytic methods have been developed that align with the principles of green chemistry. The benefit of easy separation and reuse of the catalyst, since the catalyst is in a different phase than the reactants, is that heterogeneous catalysis decreases waste and improves the sustainability of the process. A typical example is the refining of petrochemicals using zeolites, in which the porous nature of these materials enables the efficient cracking and conversion of hydrocarbons with minimal byproducts. The ability of green chemistry to work at mild conditions, i.e. at ambient temperature and pressure is also shown by biocatalysis, which involves the use of enzymes or microorganisms. They are predisposed to use water as a solvent, and produce biodegradable by-products. One of such is the enzymatic digestion of cellulose into bioethanol which relies on the use of cellulase enzymes to digest plant biomass, a renewable fuel source with little environmental impact.

Photocatalysis is a reaction in which solar energy is used to drive chemical reactions to cause changes that in turn drive environmental remediation; hence it is one of the most promising methods of environmental remediation. Substances such as titanium dioxide (TiO₂) are extensively used in water treatment systems to break down organic pollutants, including nitrogen oxides (NO₂) and volatile organic compounds (VOCs), thereby

effectively enhancing air and water quality without the use of secondary pollutants (Li, 2023). Electrocatalysis, which utilises electrical power to catalyse reactions, has a significant capacity in handling carbon. Electrocatalytic systems can utilise renewable electricity to convert carbon dioxide (CO₂) into valuable products, such as fuels and chemicals, thereby addressing the issue of greenhouse gas emissions and producing sustainable products. The strategy aligns with international efforts to mitigate climate change and transition to a low-carbon economy.

4.2 Pollution Mitigation Examples

The process of catalysis has already proven helpful in practical applications, such as reducing pollution. A good example is the catalytic converters, which are used in vehicles to convert harmful gases into less harmful ones (carbon monoxide (CO), nitrogen oxides (NO_x), hydrocarbons) to air-toxic substances (carbon dioxide, nitrogen), thereby leading to better air quality and better human health. Another innovative use is the application of photocatalytic surfaces on building exteriors, where TiO₂ surfaces can effectively disable NO_x and VOCs in urban settings, resulting in cleaner air without requiring additional energy. Moreover, the textile industry's enzyme-based operations offer viable alternatives to traditional chemical processes. Enzymes like laccases and peroxidases, which are used to degrade dyes, have been shown to considerably lower the emission of harmful effluents that are otherwise very hazardous to aquatic life and human health (Zdarta et al., 2018).

V. RENEWABLE FEEDSTOCKS AND BIOMASS UTILISATION

Renewable biomass, rather than fossil-based feedstocks, is a fundamental pillar of sustainable chemistry and critical in reducing environmental pollution. Fossil fuels are non-renewable and lead to the emission of greenhouse gases, climate change, and the depletion of resources. By contrast, biomass-based resources are generally carbon-neutral because the carbon dioxide they release during processing or combustion is offset by the carbon sequestration that occurs during their growth and development. Additionally, biomass is biodegradable, which minimises waste buildup and reduces the long-term risks of pollution. That is why biomass is a viable alternative, aligning with the concept of green chemistry, which emphasises reducing environmental impacts while ensuring the efficiency and functionality of chemical operations (Marzorati et al., 2018).

5.1 Sources of Renewable Feedstocks

Natural and waste materials form a variety of renewable feedstocks that are both versatile and accessible. Agricultural residues, such as corn stover and sugarcane bagasse, are considered by-products of farming and some of the most widely used sources. These waste materials are typically disposed of or incinerated, resulting in air pollution and the generation of additional

waste. Their environmental impact is reduced when they are converted into bio-based chemicals and fuels. Forestry biomass and lignocellulosic biomass are other rich sources, encompassing wood chips, sawdust, and bark. These materials contain a significant amount of cellulose, hemicellulose, and lignin, which can serve as a starting point for producing biofuels, solvents, and other industrial chemicals. Also, algal biomass has become an attractive feedstock, especially in the production of biofuels. Algae multiply rapidly, require less land, and can be grown in wastewater or salty water, among other places. Hence, it is a viable option to diminish competition with food crops (Gomez et al., 2015).

5.2 Applications

There are many applications of renewable biomass feedstocks. Two of the most important contributions in the production of bioplastics are polylactic acid (PLA) and polyhydroxyalkanoates (PHA). The materials present biodegradable substitutes to the traditional plastics, which are intractable pollutants in the oceans and landfills. Bio plastics can play a role in alleviating the issue of plastic waste build up in the world by substituting petroleum based plastics. The biofuels, like ethanol and the bio-diesel, are used as vehicles of renewable energy within the energy sector to curb the consumption of fossil fuels. A substitute that can be implemented with ethanol is sugarcane bagasse or corn stover, which can replace gasoline and a substitute that can be implemented with bio-diesel is vegetable oils or algal biomass which can be used instead of diesel to reduce carbon dioxide emissions and better the air quality. Moreover, renewable biomass is also a source of platform chemicals (such as furfural and succinic acid) that are very important intermediates in the green synthesis process. Such chemicals are used in production of solvents, resins and other industrial products as substitute to those made using petroleum and therefore helping in the implementation of sustainable supply chain. New feedstocks such as renewable ones in industrial processes do not only cause less environmental pollution, but also enhance efficiency in resources utilization, create new economic opportunities and are components of circular bioeconomies. However, scaling, processing expenses, and variability of feedstock are still a concern that needs to be explored and enhanced by conducting additional studies and innovation (Gupta et al., 2020).

Table 2: Comparison of Conventional Plastics vs Bioplastics

Property	Conventional Plastics	Bioplastics
Source	Petroleum	Renewable biomass
Biodegradability	Non-biodegradable	Biodegradable
CO ₂ Emissions	High	Low
Cost	Lower (currently)	Slightly higher

VI. GREEN CHEMISTRY IN AIR POLLUTION MITIGATION

Air pollution is among the most pressing ecological issues, contributing to respiratory diseases, climate change, and ecosystem degradation. Green chemistry offers a novel solution to air pollution through the development of cleaner technologies and more sustainable processes that do not compromise efficiency to reduce harmful emissions. The design and application of non-noble green catalysts as catalytic converters are among the most essential applications of green chemistry in controlling air pollution. Conventional catalytic converters utilise costly and limited noble gases, including platinum, palladium, and rhodium. In contrast, green catalysts (including transition metal oxides, bio-inspired catalysts, and earth-abundant metal composites) offer cost-efficient and environmentally friendly alternatives, without compromising high conversion efficiency in carbon monoxide, hydrocarbons, and nitrogen oxide (NO_x) reduction (Iliopoulou et al., 2022). The photocatalytic destruction of volatile organic compounds (VOCs) and NO_x is another potential opportunity, where a semiconductor catalyst, such as titanium dioxide or zinc oxide, is activated by sunlight or artificial light. These photo catalysts catalyze oxidation reactions which may change the toxic pollutants into less toxic elements, e.g. water and carbon dioxide. It is especially useful in the industrial areas and urban centers where smog is formed due to high levels of VOCs and NO_x and presents respiratory hazards. Besides, green solvents, in particular, amine-functionalized ionic liquids (ILs) have become a major momentum in carbon capture technologies. These ILs are highly capable of trapping CO₂, thermal resistant and less volatile; therefore, they are the ideal to capture carbon dioxide in the flue gases without the process of creating secondary pollutants. Such green solvents demand low energy in the regeneration process and reduce the chances of solvent degradation relative to the conventional aqueous amine solutions (Li et al., 2019).

VII. GREEN CHEMISTRY IN WATER POLLUTION MITIGATION

One of the most pressing problems of the environment has been water pollution caused by industrial discharges, agricultural run-offs and urban effluents which are heavy metals, dyes, pharmaceuticals and other toxic wastes. Green chemistry provides new, sustainable remedies to water remediation, with a focus on environment-friendly, less toxic, and efficient materials and processes. Biochar and nanocomposites are also one of the potential methods of heavy metal removal. Agricultural waste produced through pyrolysis produces biochar, a high-surface-area, porous adsorbent that is an efficient adsorbent of metals, and can effectively adsorb

lead, cadmium and arsenic. The use of nanocomposites, in particular the use of magnetic nanoparticles, improves the speed of adsorption and the possibility of recovering and reusing the adsorbents to prevent secondary pollution (Ateş et al., 2020). The second method is called photocatalysis, and it operates light-mediated reactions to break down a contaminant, such as dyes and pharmaceuticals. Nanoparticles like titanium dioxide (TiO₂) and zinc oxide (ZnO) generate reactive species when excited by sunlight or UV light and subsequently oxidise and mineralise organic contaminants. The reason why photocatalysis is an energetically efficient process is that reactions can be conducted at ambient temperature and no harsh chemicals are required among other energy sources.

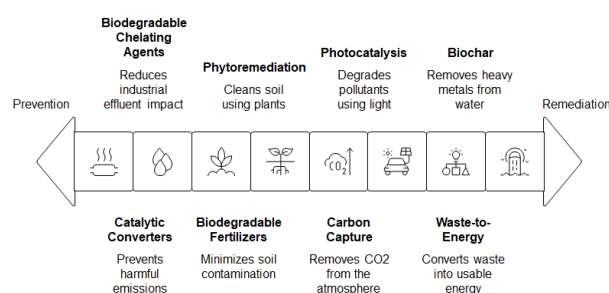


Figure 2: Green chemistry solutions range from prevention to remediation.

In addition, biodegradable chelating agents are gaining popularity in the treatment of industrial effluents that contain metal ions. Traditional agents of chelation, such as EDTA, remain in the environment, which leads to secondary pollution. In place of petrochemicals, green alternatives made from natural amino acids and polysaccharides have a binding capacity that is just as effective, and they are easily degraded by microorganisms, thereby reducing ecological hazards. Such green chemistry methods not only provide effective means of removing pollutants but also align with the objectives of sustainable development by utilising renewable resources, reducing energy consumption, and minimising waste. Coupled with process optimisation and monitoring technologies, these solutions provide scalable solutions to industries and municipalities, enabling them to reduce their environmental impact and provide safe, clean water supplies (Badhoutiya et al., 2023).

VIII. GREEN CHEMISTRY FOR SOIL POLLUTION AND WASTE MANAGEMENT

Pollution and waste management of soil are serious environmental concerns, and green chemistry offers sustainable and environmentally friendly solutions. The creation and use of biodegradable fertilisers and pesticides is one of the most promising methods because such products are designed to break down into non-toxic

components when their service is over. These products increase the buildup of harmful substances in the soil, which helps prevent soil contamination of water and reduces the negative impact on healthy soil organisms. An example is controlled-release fertilisers, which are made of natural polymers, thereby enabling the slow release of nutrients and minimising nutrient runoff, shielding ecosystems against eutrophication.

Another good measure is phytoremediation that entails using plants to eliminate or sequester contaminants in the earth. Recent advances in genetic engineering have seen the development of new types of plants that have the ability to absorb heavy metals, e.g. cadmium, lead, arsenic, which are in contaminated soils. Such modified plants can accumulate the pollutants as biomass to be removed safely or change them to less toxic products. Using this technique, which adheres to the ideas of green chemistry, can be combined so that the remediation process becomes cost-efficient and non-toxic (Singh and Pant, 2023). Also, there are waste-to-energy techniques, including anaerobic digestion, a sustainable way of handling organic waste and creates renewable energy. Biodegradable waste is broken down by microorganisms in this process in the absence of oxygen and converted to biogas rich in methane which can be utilized as a fuel. The resulting by-product is an amendment of fertilisers called digestate, which is safe and can be used to amend soil, an aspect that enhances soil fertility but not pollution. Such a strategy to decrease the use of landfills and greenhouse gases is in line with the goals of green chemistry in general.

IX. EMERGING TECHNOLOGIES IN GREEN CHEMISTRY

The sphere of green chemistry has been actively evolving over the last couple of years as there has been a rise of new technologies that assist in making the processes of environmental pollution less harmful and more reasonable. The nanogreen chemistry is one of the most active ones, and its purpose is to synthesize nanoparticles with means of greener synthesis, using plant extracts, microbial cultures, and biodegradable reducing reagents. These green nanoparticles are applicable in environmental cleaning, e.g. in wastewater treatment, pollutant adsorption and extraction of heavy metals. Unlike most other conventional methods of nanoparticle synthesis that often involve the utilisation of harmful solvents and harsh conditions, nanogreen chemistry uses the renewable materials, minimises the amount of dangerous by-products and works at room temperature, which is in line with green chemistry concepts (Jeong et al., 2021).

The use of artificial intelligence (AI) and machine learning (ML) into chemical design and process optimisation is the other disruptive innovation. By analysing large datasets, it is possible to predict the reaction pathways, enhance the solvent selection process,

and identify safer alternatives that have a less harmful impact on the environment using the AI-based models. Such computational tools do not only speed up research, but as well reduce the labour of trial and error that would be used in the laboratory and save chemical wastes as well as energy. The predictive nature of AI also allows scientists to come up with effective and biodegradable molecules, thus, sustainability and environmental responsibility. Besides, the idea of a circular economy emerges in green chemistry. The aim of this strategy is to have waste material removed through promotion of recycling, reuse and regeneration of chemical material. The circular processes are less reliant in virgin materials, less wasteful and encourage sustainable consumption tendencies. Applying the concepts of the circular economy to an industrial context, one can execute the principles of this model by designing products in such a way that would facilitate their easy recycling and by creating systems that would make it possible to reuse valuable resources present in waste flows (Ananikov, 2024).

X. CASE STUDIES

Green chemistry can be best understood by real-world case studies on how industries have applied sustainable chemical practices with a view to reducing environmental pollution. These case studies emphasise technological development, but also show the positive impact of implementing environmentally friendly procedures into the manufacturing processes. The following three examples are discussed to illustrate how green chemistry can improve the reduction of hazardous waste, consumption of energy, and pollution, and the fact that, in addition, the quality of the product remains or is improved: the application of supercritical carbon dioxide (SC-CO₂) extraction in the coffee industry, biodegradable packaging with the help of polylactic acid (PLA), and the introduction of green catalysis to the manufacturing process of propylene oxide, in which case, by BASF (Bennett et al., 2021).

SC-CO₂ Extraction in the Coffee Industry

Conventionally, flavours and caffeine in coffee had to be extracted using chlorinated solvents, including methylene chloride or ethyl acetate, which are inherently toxic and persistent in the environment and very harmful to health. The transition of the coffee industry to the use of supercritical carbon dioxide (SC-CO₂) as an extraction medium represents an innovative breakthrough in sustainable processing. By pressurising and heating carbon dioxide above its critical point, SC-CO₂ is obtained —a solvent-like substance that can be useful in dissolving target compounds without the use of harmful chemicals. The system allows solvent leftovers to be eliminated, the generation of hazardous waste to be reduced, and energy consumption decreases by recover and reuse of CO₂ within the system. Moreover, the CO₂ that is obtained as a result of industrial waste flows is used

in the decrease of greenhouse gases. By using SC-CO₂ extraction by the coffee producers they attain the purification of the flavour, and high safety of the products, and large reductions in the solvent-related emissions. This is in line with the goals of green chemistry that are directed at minimizing the effects on the environment (Lianza et al., 2022).

Biodegradable Packaging in the Beverage Industry

Plastic pollution has remained one of the most widespread environmental problems globally, primarily driven by the packaging of consumer products. Other beverage companies have responded by using a renewable polymer, polylactic acid (PLA), made from fermented plant starch (such as corn or sugarcane) in biodegradable packaging. PLA presents a viable alternative to petroleum-based plastics, as it can decompose in industrial composting conditions to produce water, carbon dioxide, and biomass, thereby reducing the accumulation of landfill waste and marine pollution. The use of PLA bottles in the beverage sector adheres to the principles of green chemistry, utilising renewable feedstocks that are designed to degrade and no longer rely on fossil fuels. In addition to being eco-friendly, PLA packaging has also received favourable acceptance from consumers, enhancing its marketability and corporate sustainability. Nevertheless, there are issues with the provision of large-scale composting infrastructure and preservation of such performance characteristics as barrier property and shelf life. Ongoing research and development are expected to increase the formulations of PLA and also enhance the lifecycle assessment to maximise the benefits to the environment.

Green Catalysis in BASF's Propylene Oxide Production

A good example of how green chemistry is employed is in the case of propylene oxide production by BASF, which has switched from traditional chlorohydrin-based processes to green catalysis using hydrogen peroxide as the oxidant. Propylene oxide is one of the central intermediates used in the manufacture of polyurethane foams, coatings, and adhesives. Its production has long been carried out using chlorine-based chemicals, which generate corrosive waste and pose a risk to workers and ecosystems. According to a hydrogen peroxide-based epoxidation process, BASF managed to reduce the number of hazardous by-products significantly, waste consumption was lowered by 80 per cent, and water consumption was also cut in half. Not only does the process enhance the efficiency of resource use, but it also improves worker safety, as exposure to toxic intermediates is reduced. The transformation proves to be the use of the green chemistry principle, such as energy efficiency, removal of auxiliary substances, and catalysis to develop cleaner transformations. This process has reached industry standards that have been described as an example of a sustainable chemical production (Dubey et al., 2017).

These case studies put into consideration that the application of the principle of green chemistry is not only

a theoretical concept but also it is transforming the manner in which industries are conducted. They prove that pollution of the environment can be reduced through the replacement of solvents, the design of biodegradable materials as well as optimisation of catalytic processes whilst retaining a commercial profit. Besides, it is possible to discuss the importance of cross-disciplinary collaboration between chemists, engineers, environmental scientists and policymakers in such cases to provide the execution of green solutions.

XI. CONCLUSION

Green chemistry is a revolution and visionary response to the currently growing problem of environmental pollution. Green chemistry is also focused on prevention at the source, rather than dealing with waste or remediation of pollution after it has occurred, which is a common treatment approach in traditional chemical practices. This approach addresses pollution at its source by incorporating values such as waste reduction, atom economy, utilisation of renewable resources, and designing safer chemical processes. Green solvents, such as water and supercritical CO₂, as well as biomass-based renewable feedstocks and new catalytic systems, are not only substitutes but also building blocks for developing sustainable industrial practices, as noted throughout this review. Besides, green chemistry drives innovation and science by challenging researchers and industrial users to reconsider traditional approaches, seek energy-saving reactions, and develop biodegradable and non-toxic materials. Practices in the pharmaceutical, agricultural, and energy industries have demonstrated that sustainability and economic profitability are not mutually exclusive when grounded in sound chemical principles. However, to fully realise the potential of green chemistry, it requires more than just technology. The institutional structures that would attract environmentally friendly activities, investments to fund research and infrastructure, as well as awareness campaigns to the population, are needed to expedite the adoption process at both the industrial and community levels. It is also imperative to train the coming generation of scientists and engineers to accept green concepts. Conclusively, green chemistry is not only an environmental policy but a scientific movement that balances economic development, technology, and environmental accountability. Through government-industry-academic-civil society initiatives, it provides a viable way forward in reducing pollution to protect the planet for the coming generations.

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