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SUSTAINABLE CHEMICAL STRATEGIES IN ENVIRONMENTAL CHEMISTRY: EMERGING GREEN TECHNOLOGIES AND FUTURE PERSPECTIVES

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ABSTRACT
Sustainable chemical strategies in environmental chemistry emphasize emerging green technologies and future perspectives for pollution prevention, remediation, and circular resource use. Environmental challenges such as persistent pollutants, solvent waste, greenhouse gas emissions, contaminated water, degraded soils, and unsafe industrial residues require approaches that reduce hazards at the source rather than relying only on end-of-pipe treatment. The review synthesizes literature from 2012 to 2025 on green synthesis, process intensification, sustainable solvents, catalysis, water and wastewater treatment, air pollution control, carbon management, soil and sediment remediation, biomass valorization, circular chemical systems, sustainable materials, and green analytical chemistry. Key technologies discussed include continuous-flow processing, ionic liquids, deep eutectic solvents, supercritical carbon dioxide, photocatalysis, electrocatalysis, biochar, nanomaterials, biopolymer composites, membranes, and low-waste monitoring platforms. These strategies collectively improve resource efficiency, lower toxicity, reduce energy consumption, promote waste-to-value conversion, and support safer environmental monitoring. However, implementation remains constrained by scale-up limitations, cost, catalyst recovery, material durability, nanoparticle fate, regeneration efficiency, toxicity uncertainty, and incomplete life-cycle evaluation. Future progress depends on integrating safe-and-sustainable-by-design principles, digital tools, renewable energy, circular economy models, regulatory support, and interdisciplinary collaboration.

KEYWORDS: Green chemistry, Sustainable environmental chemistry, Green catalysis, Waste valorization, Environmental remediation

INTRODUCTION
Environmental chemistry has emerged as a key science in the global shift towards sustainable development to focus on the chemical sources, transformations, impacts, and control of pollutants in the atmosphere, water, soil, and biological systems. While traditional chemistry has played a major role in the progress of industry, it has also produced long-term environmental issues such as the accumulation of toxic waste, emission of greenhouse gases, working with dangerous solvents, use of non-biodegradable materials, and contamination of aquatic and terrestrial habitats. Sustainable chemical strategies aim to redesign chemical processes, products, and technologies to ensure that the protection of the environment is built into the molecular, process, and systems design, rather than being tackled at the end of the process. In this context, green chemistry offers a preventive approach that will help to reduce the use of hazardous substances, the use of resources, and energy consumption, and will help to find safer technologies for remediation [1]. The basic concept of Green Chemistry is to be found in the design of chemical products and processes that minimize or eliminate the use or generation of hazardous substances. Because many environmental issues have a chemical basis, it is particularly relevant to environmental chemistry, as chemical solutions can be found that are cleaner, safer, and more resource-efficient. In the early literature about green chemistry, representative examples of these aspects included the use of safer synthesis methods, alternative solvents, renewable feedstocks, catalysis, energy-efficient reactions, and/or minimization of waste. Because these applications are not just about treating pollutants, but also preventing pollution, the applications are still relevant and important because they lead the way towards pollution prevention and long-term environmental sustainability for chemical innovation [2]. Solvents are one of the largest materials that can be targeted for sustainable chemical change due to their use in synthesis, extraction, separation, cleaning, and analysis. The traditional organic solvents may have problems with volatility, flammability, toxicity, persistence, and a high amount of waste produced. Alternatives to traditional green solvents, such as water-based, supercritical fluids, ionic liquids, deep eutectic solvents, and bio-derived solvents, provide opportunities to decrease environmental impacts while ensuring chemical effectiveness. The creation of

eco-friendly solvent systems is thus an important feature of the new green technologies, and it is quite important to evaluate each class of solvents in terms of toxicity, recyclability, biodegradability, cost, and practical application [3].

New developments have also shown the progress of sustainable environmental chemistry towards integrated frameworks that integrate safe and sustainable by design aspects with digital innovation, circular materials policy, and pollution mitigation strategies. It is crucial to this convergence because if these technologies are used independently, they are not sufficient to solve the complex problems of the environment unless coupled with predictive design technologies, regulatory integration, circular economy models, and life-cycle evaluation. AI and computational screening, data-driven toxicity prediction, virtual testing, and other digital solutions can speed up the development of safer chemicals and materials, and minimize trial-and-error testing [4]. The green chemistry/ecotoxicology interface further emphasises the necessity of considering the state of environmental quality on the basis of both removal efficiency and process yield, in addition to biological safety. The sustainability claims of marketable chemicals can remain "green" despite their unintentional ecological effects from degradation products, transformation pathways, or chronic toxicity that have not been sufficiently evaluated. An environmentally-friendly chemistry, therefore, needs to incorporate ecotoxicological information into the design of chemicals, their monitoring, risk assessment, and application. This strategy enables the solidification of the scientific considerations for conserving ecosystem health and fosters innovation for safer chemical systems [5]. As a practical solution to mitigate pollution, scarcity of resources, climate-related challenges, and industrial wastes, green chemistry has emerged as a popular approach in current literature on environmental sustainability. Green chemistry approaches are catalytic degradation of pollutants, use of renewable resources, cleaner production, sustainable materials, green analytical methods, and low-energy remediation systems. Although some progress has been made, there are still issues to be addressed in scale-up, cost competitiveness, process durability, regulatory acceptance, and performance in complex environmental conditions [6].

Green chemistry is also responsible for ecosystem restoration via technologies that are capable of clean-up of contaminated environments with a minimum of secondary pollution. Applications range from biobased adsorbents to biodegradable materials, to phytochemical-assisted remediation, microbial and enzymatic processes, and safer nanomaterials for pollutant removal. These strategies are particularly applicable to the restoration of degraded water bodies, agricultural soils, and industrially affected ecosystems [7]. In addition to protecting the environment, green and sustainable chemistry has the additional significance of enabling the production of cleaner consumer goods, safer pharmaceuticals, better agricultural chemicals, sustainable packaging, renewable energy systems, and minimizing exposure to hazardous substances in the workplace. It has a social value in the link between the innovation of the chemical and public health and environmental justice, and responsible industrial development [8]. Strong chemical knowledge is needed for sustainable technologies, as solutions like renewable fuels, carbon capture, advanced materials, green manufacturing, and circular resource recovery rely on molecular design and process optimization. Chemistry is thus a contributor to environmental issues and a basis for transitions towards sustainable technology solutions [9]. New green chemistry/nanotechnology combinations have potential applications in environmental remediation, sensing, catalysis, water treatment, and resource recovery. Despite these potential advantages, the environmental fate and toxicity of nanomaterials are important considerations to evaluate before their use in enhancing pollutant adsorption, photocatalytic degradation, antimicrobial activity, membrane performance, etc. The present review highlights the development of new green technologies and their applications in sustainable chemical strategies for environmental chemistry, along with their challenges and prospects to enable environmentally safer and circular systems [10].

Objectives of the Review

1. To examine green chemistry principles in environmental chemistry.
2. To review emerging green technologies for pollution control.
3. To identify challenges, gaps, and future directions.

METHODOLOGY

The Review was carried out in a narrative synthesis manner to review the sustainable chemical approaches in the field of environmental chemistry, with special emphasis on the emerging green technologies and perspectives for the future. Significantly important scholarly sources were used to search the relevant literature, such as Scopus, Web of Science, PubMed, ScienceDirect, SpringerLink, Wiley Online Library, Taylor & Francis, Google Scholar, and official databases of the publishers. Among the search terms were the following concepts: green chemistry, sustainable chemistry, environmental chemistry, green synthesis, sustainable solvents, catalysis, nanotechnology, waste valorization, circular economy, water treatment, soil remediation, air pollution control, ecosystem restoration, and safe-and-sustainable-by-design. Literature search was performed for the publications in the range 2012–2025 to include the basics as well as recent technological advancements. Peer-reviewed review articles, original research articles, edited books, book chapters, and policy-relevant scientific reports were given priority in the scope of the conference, focusing on chemical sustainability, pollution prevention, remediation, and environmental applications. Sources were included if they discussed directly green chemical principles, sustainable materials, cleaner processes, or environmental risk reduction, or future pathways of implementation. They were withheld from publication if they were not related to environmental chemistry, lacked scientific relevance, lacked sufficient methodological and conceptual detail, were duplicated, there was no full-text information available, or they only included conventional chemical processes without any relevance to sustainability. English-language publications that were relevant to the review objectives were reviewed, synthesized, and interpreted.

Green Synthesis and Sustainable Chemical Production

Green synthesis and sustainable chemical production are key processes for decreasing the environmental footprint of chemical industries. Typical manufacturing processes rely on toxic solvents, high temperatures, stoichiometric reagents, and energy-intensive separation processes, which generate waste streams that need to be treated. These drawbacks can be overcome by optimizing reactions for selectivity, reducing reaction time, minimizing auxiliary materials, and incorporating cleaner energy inputs, as is done in green process intensification [11]. These methods are in line with the overall principle of remediation, which is to stop polluting sources rather than treating contaminants after they're released [1]. Intensified systems such as microwave, ultrasound, mechanochemical, and flow-assisted systems can provide higher mass and heat transfer efficiency with reduced solvents consumption and less generation of by-products [12]. These strategies are in line with sustainable chemistry as they link reaction engineering with safer process design, conservation of resources, and minimisation of ecological risk [6]. In the industrial production of organic compounds, green chemistry has been demonstrated to improve the catalytic efficiency, use of renewable resources, avoid atom economy sacrificing, and replace toxic reagents with safer alternatives [13]. This transition is crucial for ecosystem restoration and the long-term environmental quality, especially if the chemical production involves the generation of long-lasting pollutants or toxic residues [7]. The continuous-flow processing is another benefit for green manufacturing as it allows for a precise control of residence time, temperature, mixing, and hazardous intermediates, which is beneficial for pharmaceuticals, specialty chemicals, and fine chemicals production [14]. Green synthesis can go beyond optimization in the laboratory to large-scale production, if combined with sustainable solvents, greener catalysts, and life-cycle assessment [3]. Thus, sustainable chemistry should be defined as the sum of a cleaner synthesis, process safety, economic viability, and environmental improvement, as measured by results [9]. Key pathways of green production and their sustainability impacts are presented in Figure 1.

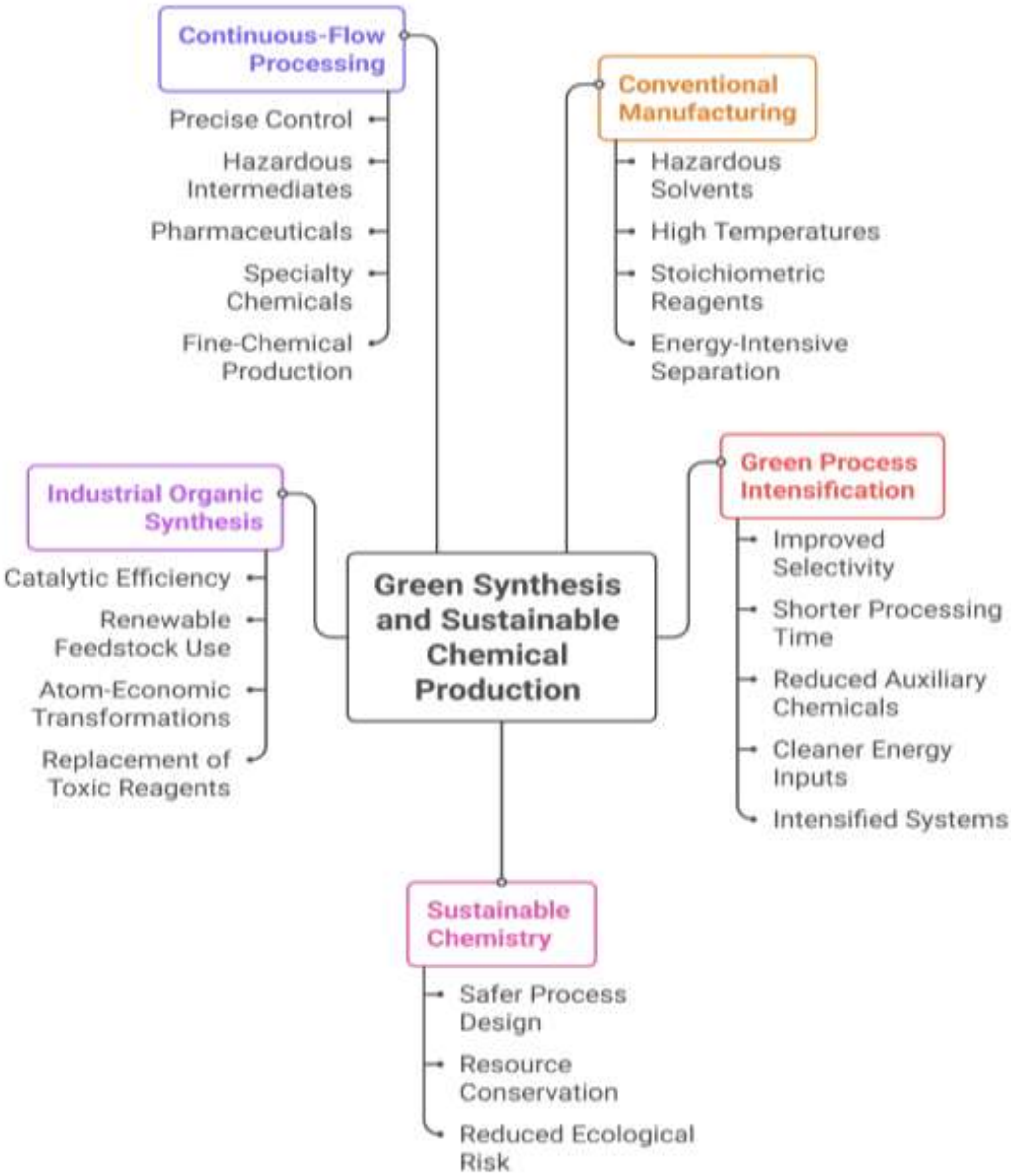

Figure 1. Green synthesis and sustainable chemical production framework

Sustainable Solvents and Alternative Reaction Media

The use of sustainable solvents and alternative reaction media is crucial for green environmental chemistry since solvents may be a major component regarding material intensity, toxicity, and waste of chemical processes. Normal volatile organic solvents pose issues of worker exposure, flammability, persistence, difficult recovery, and atmospheric emissions. Ionic liquids and supercritical carbon dioxide are also highly investigated green reaction media, which can enhance the selectivity, decrease the emission of volatile substances, and allow for efficient extraction, separation, and catalytic processing, if properly designed [15]. These systems are used to facilitate pollution prevention measures, to minimize the use of hazardous auxiliary substances, and to reduce the need to clean up downstream [1]. Recent studies on sustainable processes also highlight the use of bio-based solvents, water, low-toxicity solvent blends, and recycled media as viable solutions for cleaner synthesis and environmental applications [16]. These alternatives should be based on performance, toxicity, cost, biodegradability, and life cycle rather than being taken on their word as green alternatives [5]. The use of green solvents for organic synthesis, pharmaceutical production, analytical chemistry, and waste treatment technologies, therefore, has become a strategic part of organic synthesis [17]. This can be coupled with the green process intensification approach that involves the reduction of solvents, continuous operation, and better energy efficiency to decrease chemical footprints [11]. Another extension of the solvent family is the use of deep eutectic solvents (DESs) and related mixtures with low melting points that can be used in extraction, catalysis, biomass processing, and pollutant removal, among other applications, and are tunable and relatively easy to prepare [18]. The use of these also relates to circular chemistry, as it facilitates the valorisation of renewable feedstocks and reduces the need for petroleum-based solvents. In general, the development of sustainable solvents needs to focus on closed-loop recovery, degradation products that are non-toxic or less toxic, regulation, and proven environmental benefits throughout the chemical's life cycle [4]. The information in Table 1 indicates that overall, the use of sustainable chemical methods decreases waste, toxicity, and energy usage in environmental applications.

Table 1. Major Sustainable Chemical Strategies in Environmental Chemistry

Strategy	Main Purpose	Key Applications	Sustainability Benefit	Reference
Green synthesis	Cleaner chemical production	Organic synthesis, pharmaceuticals, specialty chemicals	Reduces waste, solvents, and hazardous reagents	[11]
Sustainable solvents	Safer reaction media	Extraction, synthesis, separation, analysis	Lowers toxicity, volatility, and solvent waste	[15]
Green catalysis	Efficient pollutant transformation	Photocatalysis, electrocatalysis, biocatalysis	Improves selectivity and reduces energy demand	[19]
Waste valorization	Resource recovery	Biochar, adsorbents, catalysts, membranes	Converts waste into functional materials	[35]
Green analytical chemistry	Low-impact monitoring	Pollutant detection, sample preparation, sensors	Reduces reagent use and laboratory waste	[39]

Catalysis for Sustainable Environmental Chemistry

Catalysis is an important method for sustainable environmental chemistry as it enhances the efficiency of a reaction with a reduction in waste, energy consumption, and use of harmful chemicals. The application of green catalytic systems is gaining importance in environmental remediation, in which the catalysts catalyse the degradation, transformation, or immobilization of pollutants at milder and safer conditions [19]. This strategy helps to prevent pollution by minimising the use of unnecessary chemical additives and allows polluted water, soil, and air to be treated more cleanly [1]. Nonetheless, sustainable catalysts involve heterogeneous catalysts, photocatalysts, electrocatalysts, organocatalysts, enzymes, and nanostructured (catalytic) materials, which improve the selectivity, recyclability, and operation stability [20]. These systems are in accordance with green chemistry since they provide atom economy, reduce solvent consumption, and secondary pollution in the chemical processes [2]. Recent studies have pointed out both opportunities and challenges, such as catalyst deactivation, recovery, metal leaching, high preparation cost, and uncertainty for the environmental fate of the catalyst upon use [21]. The concerns demonstrate that, besides catalytic performance, toxic, durable, regenerative, and life-cycle effects are the properties that are required for evaluating catalysts [5]. In recent development of sustainable catalysis, there is a focus on using renewable feedstock, bio-derived catalyst supports, non-toxic metal catalysts, low energy activation, and coupling with intensified or continuous flow processes [22]. These developments go hand-in-hand with green manufacturing, and tie catalytic efficiency with more environmentally friendly industrial applications and larger-scale environmental applications [14]. The photocatalytic and electrocatalytic platforms are especially promising for remediation systems, since they would be able to break down recalcitrant organic contaminants with solar or renewable electricity and also facilitate chemical conversion in a way that is carbon-efficient [10]. Sustainable catalysis is a transition step between cleaner chemical production and environmental protection, which is possible if it is conceived by integrating the concepts of efficiency, safety, circularity, and field applicability [6]. Based on the above, the various types of catalysts, their uses, and challenges are summarized in Fig. 2.

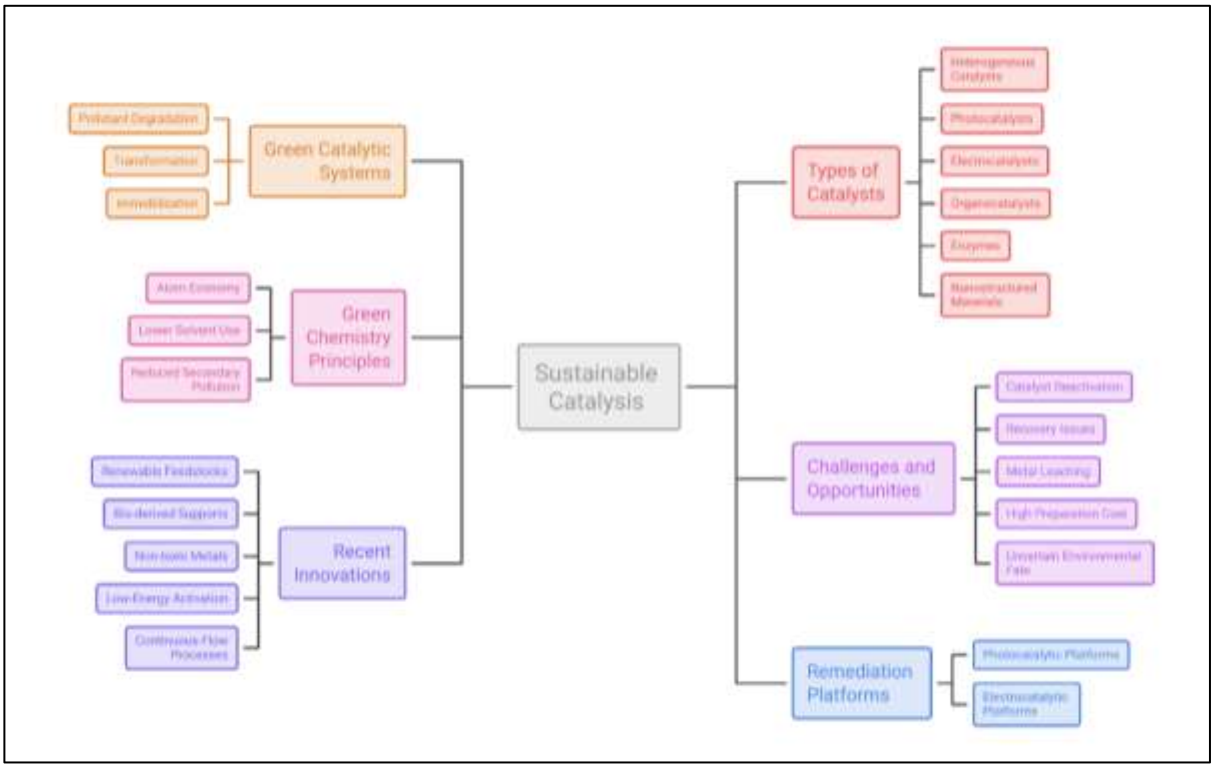

Figure 2. Sustainable catalysis in environmental chemistry

Green Strategies for Air Pollution Control and Carbon Management

Both the field of air pollution control and carbon management need to effectively capture, transform, and recover contaminants under sustainable operating conditions, like what industrial wastewater treatment technologies are achieving. Green strategies in environmental chemistry for air pollution control emphasize the minimization of volatile organic compounds, NOx, SOx, PMs, and GHG emissions and the minimization of the secondary waste production [6]. The strategies are an extension of the green chemistry preventive logic, which is focused on cleaner production, safer materials, and low-energy control systems, instead of relying solely on end-of-pipe treatment [1]. The use of adsorbents, catalysts, membranes, and processes powered by renewable energy to capture, utilize, and convert CO2 falls under sustainable carbon management [14]. Technologies for green adsorption from wastewater streams, especially sewage sludge, are promising as they link the remediation of wastewater, the reuse of resources in a circular manner, and the valorisation of the wastewater residues [30]. These strategies are in line with the principles of circular chemistry, in which residues are used to minimize pollution, rather than as a burden to be discarded. [9] New air cleaning systems are also being developed to remove the gaseous pollutants or convert them to less harmful forms with the help of biochar, activated carbon, biopolymer composites, photocatalysts, or nanostructured materials [10]. Although these systems are easy to operate, there are several challenges with their use, such as low efficiency in the regeneration process, low selectivity, low moisture tolerance, and handling of the spent material [5]. Integration with process intensification, renewable energy, and sustainable design of solvents/catalysts is also necessary to achieve green chemistry solutions for air pollution, which minimize overall environmental impact [11]. Overall, a comprehensive air pollution control and carbon management should be designed as an integrated sustainability approach that integrates emission prevention, circular material design, carbon-efficient conversion, and stringent life cycle assessment [4]. Table 2 emphasizes the key technologies in the field of green technologies that are emerging and their advantages in the process of controlling and removing pollution.

Table 2. Emerging Green Technologies and Environmental Applications

Technology	Environmental Target	Advantages	Key Limitation	Reference
Photocatalysis	Organic pollutants, dyes, and pharmaceuticals	Solar-driven degradation potential	Catalyst recovery and efficiency issues	[19]
Electrocatalysis	Pollutant conversion, CO_2 reduction	Compatible with renewable electricity	High material and operational cost	[20]
Biochar adsorbents	Metals, nutrients, and organic pollutants	Low-cost, waste-derived, regenerative	Variable performance by feedstock	[30]
Biopolymer composites	Wastewater and soil pollutants	Renewable and biodegradable	Stability and durability concerns	[33]
Membrane systems	Desalination, wastewater reuse	Selective separation and low chemical use	Fouling and energy demand	[25]

Nanomaterials	Emerging contaminants	High reactivity and surface area	Toxicity and environmental fate concerns	[26]

Sustainable Soil and Sediment Remediation

Sustainable soil and sediment remediation aims to minimize risk from contaminants while maintaining the ecological structure, fertility, and future functioning of the ecosystem. The broad applicability of selective capture materials is illustrated by the use of adsorbent materials for air systems, in which the ability to capture pollutants, as well as to regenerate and safely dispose of these pollutants, is responsible for the environmental performance [31]. Green Remediation is used to remediate contaminated soils and sediments similarly by using biochar, biodegradable polymers, mineral amendments, plant-based systems, microbial degradation, and low-toxicity chelating agents [7]. These are better choices than vigorously excavating or chemically washing when they help to save energy, limit habitat fragmentation, and save secondary waste [1]. The literature on industrial air pollution control also cautions that the type of treatment technology to be used should be based on the class of contaminant, feasibility in operation, and the environmental impact of that technology, which also applies to soil and sediment treatment systems [32]. Efficient removal and environmental acceptability, low cost, and long-term stability of post-remediation products are, therefore, important factors in sustainable remediation [6]. Eco-friendly biopolymers and composites have been attracting interest as pollutant adsorbents since they are made from renewable sources, can be chemically modified to bind a specific pollutant, and can be used in aqueous or solid phase contaminated areas [33]. These materials are used for circular chemistry, that is, to replace sorbents based on petroleum and persistent synthetic residues [9]. The ability of bio-resourced adsorbent frameworks and biodegradable polymer systems to remove phosphate and remediate wastewater selectively also suggests their potential transferability to nutrient-contaminated soils and sediments [34]. The efficiency of their use depends on the sorption capacity, mechanical properties, biodegradability, and lack of harmful transformation products (TP) [5]. In conclusion, sustainable soil and sediment remediation must involve integrating pollutant immobilization, degradation, bioavailability reduction, ecosystem recovery, material safety, and durability at the field scale [4]. Table 4 summarizes key remediation components, sustainability benefits, requirements, and supporting references for soil and sediment treatment.

Table 3. Sustainable remediation components for soil and sediment treatment

Component	Main Role	Sustainability Benefit	Key Requirement	Reference
Selective adsorbent materials	Capture pollutants from contaminated systems	Supports pollutant retention, regeneration, and safer disposal	High capture efficiency and reusability	[31]
Biochar	Immobilizes pollutants in soils and sediments	Reduces contaminant mobility and improves remediation efficiency	Stable sorption capacity	[7]
Biodegradable polymers	Adsorbs or stabilizes contaminants	Replaces persistent synthetic sorbents	Safe degradation behavior	[33]
Plant-based and microbial systems	Supports biological remediation	Reduces energy use and habitat disturbance	Field adaptability	[1]
Bio-resourced adsorbent frameworks	Removes nutrients such as phosphate	Enables transfer to nutrient-contaminated soils and sediments	Mechanical stability and selectivity	[34]
Sustainable remediation assessment	Evaluates overall treatment suitability	Balances efficiency, cost, ecological safety, and durability	Field-scale validation	[4]

Biomass, Waste Valorization, and Circular Chemical Systems

Pollution control and recovery of resources from low-value residues are key areas in sustainable environmental chemistry, which include biomass, waste valorization, and circular chemical systems. The developments of porous biopolymer composites in recent years demonstrate the possibility to modify renewable polymers for use as adsorbents and remediators of organic contaminants, which represents a step towards the substitution of synthetic polymers with biodegradable ones [35]. This is in line with the overall objective of green chemistry to minimize waste and enhance the safety and environmental compatibility of the materials [2]. Incorporating the waste material or the renewable materials into the biopolymer fibrous membranes can also increase their mechanical strength, surface area, and pollutant removal efficiency in the field of sustainable water treatment when the materials are used in combination [36]. These hybrid systems are in line with principles of the circular economy, which integrate the use of biomass, material regeneration, and wastewater remediation [6]. Green analytical chemistry helps in circular systems by providing reduced solvent, reduced waste, monitoring of contaminants, process streams, and treatment efficiency [37]. Such monitoring is needed because, before large-scale deployment, it is necessary to evaluate valorized materials for the leaching, degradation products, and their real-world performance [5]. Environmental assessment itself uses a green method of sample preparation, which decreases the amount of solvents used and analytical waste in the monitoring of aquatic organic pollutants [38]. The wastes that may be subjected to waste valorization are agricultural residues, forestry by-products, sewage sludge, food waste, industrial biomass, and polymeric wastes that are converted to adsorbents, catalysts, membranes, biochar, and platform chemicals [30]. Pollution prevention is combined with sustainable solvents and catalysis, along with process intensification, in these strategies [15]. In general, the design of circular chemical systems must be integrated, considering the renewability of feedstock, conversion efficiency, function of the product, its recyclability, toxicity, and benefits of the life cycle, all at once [4]. Figure 3 illustrates the conversion of low-value residues into sustainable materials through circular design, green monitoring, and valorization pathways.

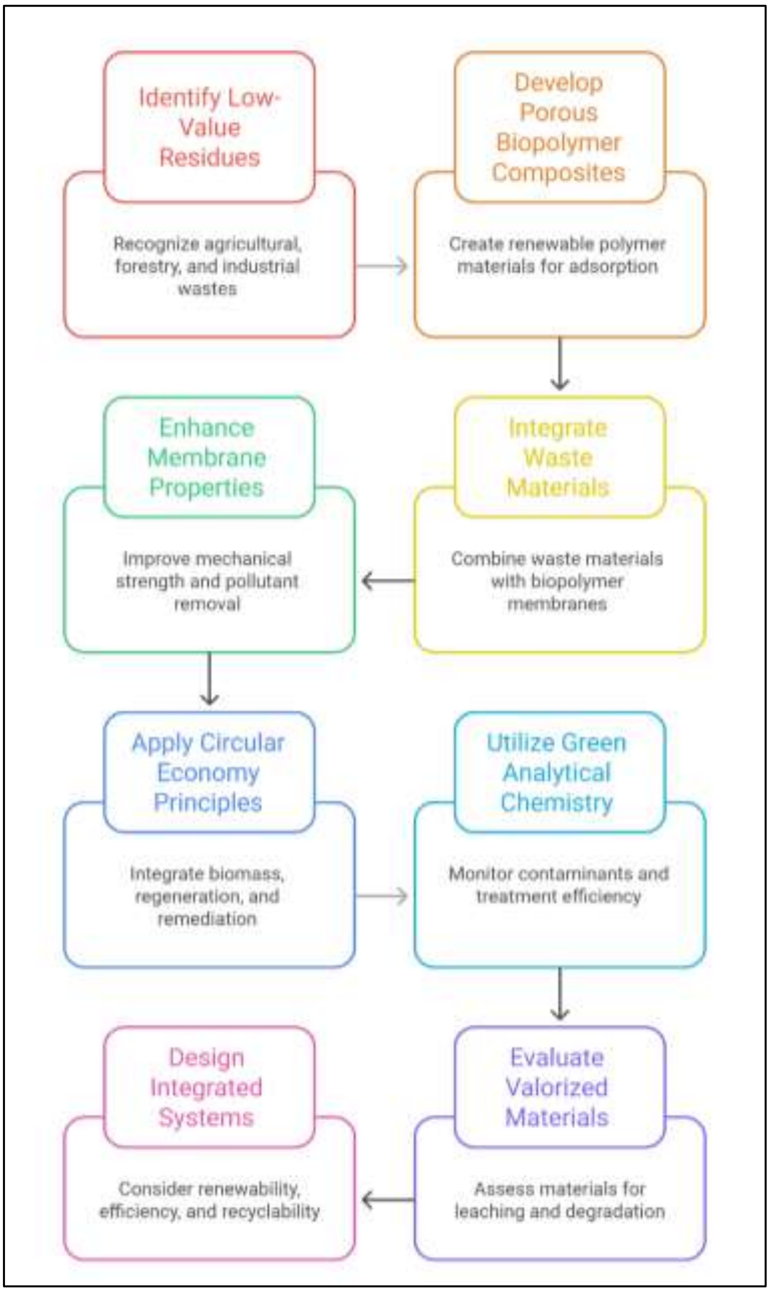

Figure 3. Biomass, waste valorization, and circular chemical systems framework

Analytical Green Chemistry and Environmental Monitoring

The analytical green chemistry has the potential to help strengthen environmental monitoring by minimizing the ecological impact of pollutant detection, sample preparation, and laboratory analysis. The key characteristics of green analytical methods are to use less sample, less solvent, less toxic reagents, to miniaturize methods, use energy-efficient instrumentation, and to handle waste more safely [39]. The method not only includes green chemistry in the synthesis, but also in the environmental assessment process, which does not add unnecessary burden to the environment [2]. In the field of environmental monitoring, food safety analysis, and pharmaceutical analysis, the need for rapid, selective, and low-waste measurement has gained attention, and several sustainable analytical platforms are increasingly adopted [37]. Some of the key elements of green environmental chemical analysis are the use of sustainable materials, less polluting extraction processes, portable sensors, and processes that can detect trace levels of pollutants in complex matrices [40]. These are significant for water, air, soil, sediment, and biological monitoring impacted by industrial chemicals, pesticides, pharmaceuticals, metals, and emerging contaminants [24]. The Green analytical method development involves reducing the use of hazardous solvents, the number of preparation steps, and the amount of waste generated, and at the same time, the method developed must be accurate, precise, sensitive, and reproducible [41]. These enhancements are crucial for supporting safe and sustainable by design approaches, as data will be required to assess exposure, toxicity, degradation, and life-cycle impacts [4]. Other contributions to green analytical chemistry encompass new approaches to green extraction, such as solvent-free extraction, microextraction, flow-based analysis, direct sensing, chemometrics, and portable field detection systems [42]. These enable less reliance on centralized high-waste laboratories and help to make quicker environmental decisions [38]. Overall, analytical green chemistry offers the measurement foundation for sustainable environmental chemistry as it facilitates cleaner monitoring, pollutant control, circular material assessment, remediation validation, and evidence-based environmental policy [5]. Table 4 shows how green chemistry concepts can be applied to the various parts of the environment to achieve sustainable protection of the environment.

Table 4. Green Chemistry Approaches Across Environmental Compartments

Environmental Compartment	Major Pollution Concerns	Green Chemistry Approach	Expected Outcome	Reference
Water and wastewater	Dyes, pharmaceuticals, pesticides, heavy metals, microplastics	Photocatalysis, membranes, biochar, nanoadsorbents, biopolymer composites	Cleaner effluent, contaminant removal, water reuse	[23]
Soil and sediment	Heavy metals, petroleum residues, agrochemicals, nutrients	Biochar amendment, phytoremediation, bioremediation, green chelating agents	Reduced toxicity, restored soil function, and lowered contaminant mobility	[31]
Air	VOCs, particulate matter, greenhouse gases, and industrial emissions	Green adsorbents, catalytic oxidation, carbon capture materials, low-emission processes	Improved air quality and reduced carbon burden	[29]
Industrial systems	Solvent waste, hazardous reagents, and high energy demand	Green synthesis, process intensification, continuous flow, sustainable solvents	Lower waste generation and cleaner production	[11]
Analytical monitoring	Solvent-intensive sample preparation, laboratory waste	Green analytical methods, miniaturized sensors, microextraction	Low-waste detection and sustainable environmental assessment	[39]

Limitations and Future Directions

Despite strong progress, sustainable chemical strategies still face several limitations that restrict their large-scale environmental application. Many green technologies remain laboratory-based and lack sufficient pilot-scale or field-scale validation under complex real-world conditions. The high cost of advanced catalysts, membranes, nanomaterials, and specialized solvents can limit industrial adoption, especially in low-resource settings. Some alternatives described as green may still present concerns related to toxicity, persistence, transformation products, regeneration difficulty, or uncertain environmental fate. Performance can also vary depending on pollutant type, matrix complexity, pH, temperature, competing ions, and operational conditions. In addition, the absence of standardized sustainability metrics makes comparison between technologies difficult.

Future research should prioritize scalable, low-cost, and safe technologies supported by life-cycle assessment, techno-economic analysis, and long-term ecological evaluation. Greater attention is needed toward safe-and-sustainable-by-design materials, renewable feedstocks, recyclable catalysts, biodegradable adsorbents, and closed-loop solvent systems. Digital tools, artificial intelligence, and predictive modeling can accelerate the discovery of safer chemicals and optimize treatment processes. Integration of green chemistry with circular economy models, renewable energy, regulatory frameworks, and interdisciplinary collaboration will be essential for practical implementation.

CONCLUSION

Sustainable chemical strategies in environmental chemistry underscore the importance of shifting from reactive pollution control to a preventive, circular, and safer environmental model. The collection of these technologies in green synthesis, sustainable solvents, catalytic processes, water and wastewater treatment technologies, air pollution control, carbon management, soil remediation, waste valorization, sustainable materials, and green analytical methods offers an integrated solution to minimize environmental impact. These methods are designed to reduce harmful materials, increase resource efficiency, decrease energy consumption, and facilitate the transformation of wastes into valuable resources. Technologies under development – including photocatalysis, electrocatalysis, nanomaterials, biochar, bio-polymer adsorbents, and membrane systems – have significant promise to deal with legacy pollutants and emerging contaminants. Technology innovations that are emerging, such as photocatalysis, electrocatalysis, nanomaterials, bio-polymer adsorbents, biochar, membrane systems, and low-waste analytical platforms, hold promise to tackle persistent pollutants and emerging contaminants. But, they need to be scalable, cost-effective, stable, non-toxic, regenerate easily, and have proven life-cycle benefits to be practically successful. Emphasis needs to be placed on further embedding the principles of safe-and-sustainable-by-design, digital tools, circular economy models, renewable energy, regulatory support, and interdisciplinary cooperation into future progress. In conclusion, sustainable environmental chemistry can play an important role in pollution prevention, ecosystem repair, climate change mitigation, and industrial transformation, provided that it is based on innovation and real-world environmental applications, which can be assessed and implemented in a responsible manner.

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