**Review Article**

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# Sustainable Water Management: Chemical Methods and Green Chemistry Applications

## *Sürdürülebilir Su Yönetimi: Kimyasal Yöntemler ve Yeşil Kimya Uygulamaları*

**Mert SOYSAL**[1]

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**ABSTRACT**:

The sustainable management of water resources has emerged as one of the most pressing global challenges due to increasing water scarcity, rapid population growth, industrialization, climate change, and escalating environmental pollution. Freshwater resources are under severe stress, making it imperative to develop adaptive and sustainable management strategies that ensure both water availability and quality. Within this framework, chemical-based water treatment and management approaches play a crucial role in enhancing water efficiency, reducing pollutant loads, and enabling the safe reuse of water in industrial, agricultural, and domestic applications. Various conventional and advanced chemical techniques, including coagulation–flocculation, ion exchange, adsorption, membrane-based processes, and advanced oxidation processes (AOPs), are extensively utilized to improve the physicochemical characteristics of water. These methods are effective in removing organic contaminants, heavy metals, nutrients, and emerging pollutants such as pharmaceuticals and endocrine-disrupting compounds. Despite their effectiveness, many of these processes rely on hazardous chemicals, generate secondary waste streams, or require high energy inputs, which can limit their long-term sustainability. To address these challenges, the integration of green chemistry principles into water treatment technologies has gained increasing attention. Green chemistry emphasizes the reduction or elimination of toxic reagents, the use of renewable and biodegradable materials, and the design of energy-efficient and environmentally benign processes. In this context, natural and bio-based adsorbents, biodegradable polymers, eco-friendly coagulants, and low-energy chemical treatment methods have emerged as promising alternatives. This review critically examines current chemical approaches for improving water efficiency and highlights recent scientific advancements that incorporate green chemistry principles into sustainable water management strategies.

**KEYWORDS:** *Sustainable water management, Green chemistry, Water efficiency, Eco-friendly treatment technologies*

**ÖZ**:

Su kaynaklarının sürdürülebilir yönetimi; artan küresel su kıtlığı, hızlı nüfus artışı, sanayileşme, iklim değişikliği ve çevresel kirliliğin giderek şiddetlenmesi nedeniyle günümüzde en kritik çevresel sorunlardan biri hâline gelmiştir. Tatlı su kaynakları üzerindeki baskının artması hem suyun niceliğini hem de kalitesini koruyacak uyarlanabilir ve sürdürülebilir yönetim stratejilerinin geliştirilmesini zorunlu kılmaktadır. Bu bağlamda, kimyasal temelli su arıtma ve yönetim yaklaşımları; su verimliliğinin artırılması, kirletici yüklerin azaltılması ve suyun güvenli bir şekilde yeniden kullanımı açısından önemli bir rol oynamaktadır. Koagülasyon-flokülasyon, iyon değişimi, adsorpsiyon, membran prosesleri ve ileri oksidasyon prosesleri (AOP'ler) gibi geleneksel ve ileri kimyasal yöntemler; suyun fizikokimyasal özelliklerini iyileştirmek amacıyla yaygın olarak kullanılmaktadır. Bu yöntemler; ağır metallerin, besin elementlerinin, organik kirleticilerin ve farmasötikler gibi yeni ortaya çıkan kirleticilerin giderilmesinde oldukça etkilidir. Ancak söz konusu tekniklerin bir kısmı toksik kimyasalların kullanımını gerektirmekte, ikincil atık oluşumuna neden olmakta veya yüksek enerji tüketimiyle çalışmaktadır. Bu durum, uzun vadeli sürdürülebilirlik açısından önemli sınırlamalar doğurmaktadır. Bu sorunlara çözüm olarak, yeşil kimya ilkelerinin su arıtma teknolojilerine entegrasyonu, giderek daha fazla

[1] **Mert SOYSAL:** Aydın Vocational School of Health Services, Aydın Adnan Menderes University, 09010 Aydın, Turkiye, msoysal@adu.edu.tr , https://orcid.org/0000-0002-5685-0261

önem kazanmaktadır. Yeşil kimya; toksik maddelerin kullanımının azaltılmasını, yenilenebilir ve biyobozunur malzemelerin tercih edilmesini ve enerji verimliliği yüksek süreçlerin tasarlanmasını hedeflemektedir. Bu kapsamda doğal adsorbanlar, biyobozunur polimerler, çevre dostu koagülantlar ve düşük enerji tüketimli kimyasal arıtma yöntemleri; sürdürülebilir su yönetimi için umut vadeden alternatifler olarak öne çıkmaktadır. Bu derleme çalışması, su verimliliğini artırmaya yönelik mevcut kimyasal yöntemleri ele almakta ve yeşil kimya yaklaşımlarının su yönetimi stratejilerine entegrasyonuna ilişkin güncel bilimsel gelişmeleri kapsamlı bir şekilde tartışmaktadır.

***Anahtar Kelimeler:*** *Sürdürülebilir su yönetimi, Yeşil kimya, Su verimliliği, Çevre dostu arıtma teknolojileri*

## INTRODUCTION

In an era marked by accelerating climate change impacts globally, the importance of water is increasing day by day. Water is a fundamental resource for human health, agricultural production, and industrial activities, and, at the same time, the global demand for water is steadily increasing. In recent years, increasing concerns about water treatment and reuse have made it essential to implement strict regulations in this field (Kirhensteine, 2016; Mannina et al, 2022; Silva, 2023; Procházková, 2023).

In this context, alternative methods such as water recycling, desalination, and reuse have become priority solutions worldwide (Lazarova et al, 2012; Meena et al, 2019; Yenkie, 2019; Ashraf, 2021; Kumar, 2023; Kumar et al, 2023). Water recovery has been a practice for thousands of years, but its significance has greatly increased in the last century due to climate change and the depletion of water resources (Angelakis et al, 2018; Abou-Shady et al, 2023). This process has been initiated through various techniques and policies in different geographical regions. Under the United Nations' Sustainable Development Goals (SDGs), water recycling and reuse are recognized as vital tools (United Nations, 2025).

The conceptual framework of green chemistry, formally established by Anastas and Warner (1998), is anchored in twelve fundamental principles: waste prevention, atom economy, less hazardous chemical synthesis, designing safer chemicals, safer solvents and auxiliaries, design for energy efficiency, use of renewable feedstocks, reduction of derivatives, catalysis, design for degradation, real-time analysis for pollution prevention, and inherently safer chemistry for accident prevention. While these directives advocate for a "benign by design" ethos in chemical treatment, the universal applicability of green chemistry across diverse water matrices and industrial sectors remains a subject of critical inquiry. The "one size fits all" paradigm often falters when confronted with highly variable contaminant profiles and stringent treatment objectives, requiring a robust evaluation of consistent performance across different environmental contexts.

Moreover, the development of innovative solutions to enhance water efficiency and the improvement of water treatment and reuse technologies are among the critical steps in enhancing global water quality. These efforts contribute significantly to addressing global water scarcity, industrialization, and increasing environmental pollutants. The treatment of industrial and urban wastewater, the preservation of water quality, and the promotion of water reuse are fundamental issues to be addressed in this context (Papiri et al, 2003; Santana et al, 2023; Rinisha Kartheeshwari et al, 2024; Brouillet et al, 2025; Villar et al, 2025; Yue et al, 2025).

Although traditional chemical treatment methods are commonly used to remove pollutants from water, the environmental impacts and operational risks of these methods are increasingly being questioned. Specifically, metal-based coagulants, such as compounds containing iron and aluminum salts, lower the pH of water and necessitate the use of additional chemicals. The application of metal coagulants, often dissolved in acidic solutions, disrupts the pH balance of the environment and requires the addition of bases like sodium hydroxide or calcium hydroxide to restore this balance. This not only increases the necessity for businesses to store and transport strong acids and bases but also poses risks in terms of occupational health and safety (Adamovic et al, 2025; Shehbas et al, 2025; Tan et al, 2025; Wolny et al, 2025; Yu et al, 2025; Zhou et al, 2025).

Considering the disadvantages of traditional treatment methods, the development of sustainable and environmentally friendly alternatives is of utmost importance. In this regard, innovative alternatives such as biopolymer-based coagulants and natural adsorbents are emerging as solutions that reduce chemical consumption and eliminate toxic effects. For instance, biopolymers such as chitosan and starch derivatives enhance coagulation and flocculation efficiency while minimizing waste generation due to their biodegradable nature. Similarly, natural adsorbents like activated carbon, zeolite, and bentonite offer high efficiency in removing heavy metals and organic

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pollutants (Renault et al, 2009; Eberle et al, 2022; Alaoui et al, 2023; Mazumder, 2023; Velarde et al, 2023; Rao et al, 2025).

On the other hand, advanced oxidation processes (AOPs), which are green chemistry approaches, are gaining increasing attention in water treatment technologies. Techniques such as the Fenton reaction, photocatalytic oxidation, electrochemical oxidation, and ozonation generate hydroxyl radicals that effectively decompose organic pollutants. These methods not only reduce chemical usage but also enhance the biodegradability of wastewater, thereby improving the efficiency of the treatment process (Liu et al, 2020; Wu et al, 2014; Yang et al, 2021; Qiao et al, 2021; Zhuo et al, 2022; Aslam et al, 2023; Kaswan & Kaur, 2023; Sarker et al, 2023; Iqbal et al, 2024; Su et al, 2024; Olvera-Vargas et al, 2025; Qiu et al, 2025; Terron et al, 2025).

In recent years, the integration of green chemistry principles into water treatment technologies has emerged as a major component of sustainable water management strategies. Green chemistry primarily focuses on minimizing hazardous chemical consumption, reducing secondary waste generation, improving energy efficiency, and promoting the use of renewable and environmentally compatible materials. Within this framework, water treatment processes are expected not only to achieve effective contaminant removal but also to reduce environmental impacts throughout the entire treatment cycle. Nevertheless, the applicability and performance of green chemistry–based approaches may vary depending on the characteristics of the treated water. Drinking water treatment systems generally require highly controlled processes capable of ensuring microbiological safety and chemical stability, whereas industrial wastewater treatment often involves the removal of complex pollutants with highly variable compositions. Therefore, the selection and implementation of green chemistry applications should be evaluated according to water type, pollutant profile, treatment objectives, and operational requirements.

In conclusion, the optimization of water treatment technologies and the integration of sustainable solutions are not only critical for the preservation of existing water resources but also for the sustainability of the industrial water cycle. In this review, chemical methods to increase water efficiency will be thoroughly discussed, and the current scientific developments on the integration of green chemistry principles into water management will be explored.

## 1. Review Methodology

In this review study, structured literature evaluation of the existing literature was conducted using major academic databases, including Google Scholar, Web of Science, and Scopus. The use of these databases enabled a broad and structured assessment of the literature. The literature search covered a five-year period between 2019 and 2024, during which recent developments, methodological approaches, and application areas related to the subject were critically examined.

To improve the transparency and reproducibility of the review process, predefined inclusion and exclusion criteria were applied during the literature screening stage. Studies published in peer-reviewed journals between 2019 and 2024, written in English, and directly related to sustainable water management, chemical treatment technologies, green chemistry applications, and water reuse strategies were considered eligible for inclusion. Conference abstracts, duplicate records, non-peer-reviewed reports, studies lacking sufficient methodological detail, and publications unrelated to water treatment applications were excluded from the evaluation process. The initial database search yielded a large number of records due to the broad multidisciplinary nature of the topic. Therefore, a stepwise screening procedure based on title relevance, abstract evaluation, methodological adequacy, and thematic compatibility was conducted to refine the dataset. Following this multistage assessment, approximately 200 studies were identified as highly relevant and scientifically appropriate for detailed analysis within the scope of the review.

The literature search strategy was structured using technically focused and non-repetitive keyword combinations to improve search precision and thematic consistency. The primary search terms included “sustainable water management,” “water treatment technologies,” “green chemistry,” “coagulation–flocculation,” “adsorption,” “ion exchange,” “advanced oxidation processes,” “wastewater reuse,” “bio-based adsorbents,” and “eco-friendly treatment systems.” Boolean operators such as AND and OR were systematically employed to establish connections between the main concepts and to optimize database retrieval performance.

The Google Scholar database initially retrieved more than 445000 academic publications related to the topic, of which 200 studies were selected for inclusion based on predefined eligibility criteria. The full texts of the selected articles were thoroughly examined to ensure a nuanced understanding of their methodologies, experimental designs, and key findings. Only primary literature sources published in peer-reviewed journals were considered in this review, thereby enhancing the scientific rigor and reliability of the study.

Following the systematic evaluation of the relevant literature, the need arises to briefly present fundamental information on the principal methods used to enhance water efficiency. Establishing a general framework for these methods is important for a clearer understanding of the mechanisms, advantages, and limitations that will be discussed in subsequent sections. Accordingly, the next section provides an overview of the water efficiency–oriented methods that are widely applied within the scope of sustainable water management.

Despite the systematic structure of the review process, several limitations should be acknowledged. The analysis was restricted to studies indexed in major academic databases and published in English between 2019 and 2024. Consequently, relevant studies published in other languages or outside the selected databases may not have been captured. In addition, variations in experimental conditions, pollutant compositions, operational parameters, and performance evaluation criteria among the reviewed studies may limit the direct comparability of treatment efficiencies. Nevertheless, the selected literature provides a comprehensive and up-to-date overview of recent developments in sustainable water treatment and green chemistry applications.

## 2. Chemical Treatment Approaches in Sustainable Water Management

Chemical treatment approaches applied in sustainable water management may differ considerably according to the intended application area and the physicochemical properties of the water source. In drinking water treatment, the primary objective is to obtain water that is safe for human consumption by controlling turbidity, microorganisms, taste, odor, and dissolved contaminants. In contrast, industrial wastewater treatment processes are generally designed to remove sector-specific pollutants such as dyes, oils, heavy metals, refractory organic compounds, and high-strength chemical loads. As a result, treatment efficiency, operational conditions, and sustainability considerations may vary substantially between drinking water systems and industrial wastewater applications. This distinction becomes particularly important when evaluating the applicability of environmentally friendly and green chemistry–based treatment technologies.

### 2.1 Coagulation-Flocculation Processes

Coagulation–flocculation processes constitute one of the most established chemical treatment methods in water and wastewater treatment, particularly for the removal of turbidity, color, and suspended solids. Conventional applications commonly rely on metal-based coagulants such as aluminum sulfate and ferric chloride due to their high removal efficiencies. Nevertheless, the excessive generation of sludge and disturbances in system pH caused by these chemicals represent significant operational drawbacks, leading to increased treatment costs and additional handling requirements (Ameta et al., 2018; Arzate et al., 2020; Machado et al., 2023). To address these limitations, recent research has increasingly focused on biopolymer-based coagulants. However, their large-scale operational stability and long-term economic feasibility remain insufficiently explored. Natural materials such as chitosan, starch derivatives, and plant-based mucilages (e.g., okra mucilage) have attracted attention owing to their biodegradability and lower environmental impact. Al-Gethami et al. (2024) reported that chitosan-based coagulants achieve turbidity removal efficiencies comparable to those of metal salts, while simultaneously simplifying sludge management. In addition, biopolymers obtained from food industry residues, including soybean proteins and polysaccharides extracted from orange peels, have been identified as cost-effective materials compatible with circular economy principles (Iqbal et al., 2021). Despite their rapid floc formation and high removal performance, coagulation–flocculation processes remain constrained by chemical consumption, sludge disposal requirements, and potential occupational health risks.

### 2.2 Adsortion Technologies

Adsorption represents a versatile treatment approach based on the attachment of contaminants onto solid surfaces through physical or chemical interactions. Owing to its adaptability across different scales, adsorption has been widely applied in water treatment systems. Although activated carbon remains the most commonly used adsorbent, its high production cost and regeneration limitations have prompted the exploration of alternative materials (Mansouri et al., 2021). Studies conducted after 2019 highlight the increasing relevance of biochar and nanostructured composite adsorbents. Biochars derived from agricultural residues such as rice husks and corn cobs have demonstrated effective adsorption of heavy metals and dye pollutants (Dutta et al., 2020). Furthermore, the incorporation of magnetic properties into biochar materials has been shown to enhance operational efficiency by facilitating post-treatment recovery of the adsorbent (Zhang et al., 2021). While adsorption offers advantages such as broad contaminant applicability and relatively low operational costs, challenges related to adsorbent regeneration and material longevity persist.

**2.3 Ion Exchange Applications**

Ion exchange technology operates on the selective substitution of dissolved ions in water with functional groups immobilized on solid resin matrices. This method is widely employed in water softening as well as in the removal of nitrate, ammonium, and heavy metal ions (Fu et al, 2022). Conventional ion exchange resins are primarily synthesized from polystyrene-based polymers; however, their regeneration requires concentrated saline solutions, resulting in high operational costs and environmentally problematic brine effluents. Consequently, recent studies have emphasized the development of bio-based ion exchange materials. Zhang et al. (2021b) demonstrated that cellulose-derived resins provide high ion selectivity while offering improved environmental compatibility. Despite their advantages in terms of selectivity and reusability, ion exchange processes remain limited by regeneration expenses and the environmental burden associated with saline wastewater discharge.

**2.4 Advanced Oxidation Processes**

Advanced oxidation processes (AOPs) were first introduced in the 1980s for drinking water treatment and are defined by their ability to generate highly reactive oxidizing species, primarily hydroxyl radicals ($^{\cdot}OH^{-}$). Over time, the concept has expanded to include other reactive species, such as sulfate radicals ($^{\cdot}SO_4^{2-}$), broadening the applicability of these systems. Unlike conventional oxidants such as chlorine and ozone, which are frequently employed for disinfection, AOPs are mainly utilized for the degradation of recalcitrant organic and inorganic pollutants. In wastewater treatment applications, these processes aim to transform persistent contaminants into less toxic or fully mineralized products. Common AOP techniques include Fenton and photo-Fenton reactions, ozonation, photocatalysis, and electrochemical oxidation (Wang et al, 2019; Ferreira et al, 2020). Martins et al. (2022) reported that photo-Fenton and ozonation processes are particularly effective in degrading pharmaceutical residues, while recent studies have emphasized the energy efficiency of solar-driven photocatalytic systems. Although AOPs offer high oxidation potential and improved biodegradability of pollutants, their application is often limited by high energy demands, operational costs, and the formation of secondary by-products. To overcome these challenges, current research increasingly explores hybrid systems that integrate AOPs with biological treatment processes (Silva, 2025).

**2.5 Green Chemistry-Based Treatment Approaches**

Green chemistry principles in water treatment technologies aim not only to minimize adverse environmental impacts but also to promote the efficient use of resources through waste valorization and circular economy strategies. Rather than focusing solely on pollutant removal efficiency, this approach emphasizes the reduction of hazardous chemical consumption, energy demand, and secondary waste generation throughout the treatment process. In recent years, green chemistry–oriented water treatment strategies have gained increasing attention as sustainable alternatives to conventional physicochemical methods, particularly in response to stricter environmental regulations and growing concerns over climate change and resource scarcity. One of the most prominent applications of green chemistry in water treatment is the development and implementation of bio-based coagulants. Biopolymers such as chitosan, starch derivatives, guar gum, and cellulose-based materials have emerged as viable substitutes for traditional metal-based coagulants. These materials are derived from renewable resources and are characterized by their biodegradability, low toxicity, and reduced sludge production. Unlike aluminum- or iron-based coagulants, biopolymer coagulants typically do not induce significant pH changes or generate hazardous residuals. Agricultural and food industry residues, including orange peels, banana fibers, coffee grounds, eggshells, and various lignocellulosic wastes, have been successfully modified and applied for the removal of heavy metals, nutrients, and dye pollutants (Ali et al., 2020; Bilal et al., 2022). These materials offer significant advantages in terms of availability, low cost, and reduced environmental footprint when compared to conventional adsorbents such as activated carbon. Notably, biochar produced from coffee grounds has been reported to exhibit adsorption capacities for cadmium and lead that are comparable to those of commercial activated carbon (Nguyen et al., 2021). Beyond pollutant removal, the utilization of such waste-derived adsorbents contributes to sustainable waste management practices and reduces the dependence on non-renewable raw materials. Green chemistry approaches in water treatment are not limited to coagulation and adsorption processes. Enzymatic and biocatalytic systems have also been increasingly explored as environmentally benign alternatives for the degradation of organic contaminants. Enzymes such as laccase, peroxidase, and tyrosinase are capable of selectively oxidizing a wide range of organic pollutants under mild operating conditions, thereby reducing energy consumption and avoiding the formation of toxic by-products. For instance, Arshad et al. (2020) reported successful degradation of textile dyes using laccase-based systems, demonstrating that enzymatic treatment can achieve high removal efficiencies while maintaining a lower environmental impact compared to conventional advanced oxidation processes. The integration of renewable energy sources into water treatment technologies further strengthens the green chemistry framework. Recent studies have shown that photocatalytic systems activated by solar irradiation can achieve high degradation efficiencies for pharmaceutical residues and emerging contaminants, while significantly reducing energy-related operational costs (Xiong et al., 2022). Similarly, electrochemical oxidation systems operated at low temperatures and powered by renewable energy sources such as solar or wind energy have been proposed as promising solutions for minimizing the carbon footprint of water treatment facilities (Silva, 2025). These approaches align closely with the principles of green chemistry by coupling pollutant removal with sustainable energy utilization. Finally, the valorization of waste materials plays a central role in achieving sustainable water treatment within a green chemistry and circular economy framework. Biopolymers derived from food industry by-products, including sugar beet pulp and brewery wastes, have been shown to function not only as coagulants but also as adsorbents and ion exchange materials (Iqbal et al., 2021). By transforming waste streams into functional treatment materials, these strategies reduce disposal burdens while creating value-added products.

Although green chemistry applications provide important environmental advantages in water treatment processes, these approaches may not be equally suitable for all water matrices or industrial sectors. Natural coagulants, biodegradable adsorbents, and bio-based treatment materials are generally more effective in waters containing moderate pollutant loads and biodegradable contaminants. Such approaches are particularly promising for agricultural wastewaters, food industry effluents, and certain municipal wastewater streams. However, industrial wastewaters characterized by high salinity, toxic metal concentrations, persistent organic pollutants, or complex chemical compositions may require more advanced or combined treatment strategies to achieve the desired treatment performance. Similarly, some green chemistry–based processes may require additional treatment or disinfection stages before direct application in drinking water production systems. Therefore, the practical applicability of green chemistry technologies should be assessed according to the nature of the pollutant load, treatment targets, operational stability, and sector-specific process requirements.

Overall, the reviewed treatment technologies exhibit distinct advantages and limitations in terms of treatment efficiency, operational complexity, environmental impact, and sustainability potential. Conventional physicochemical methods generally provide robust and reliable pollutant removal performance, whereas green chemistry–based approaches offer significant environmental benefits through reduced chemical consumption, renewable material utilization, and lower secondary waste generation. However, the applicability of these technologies may vary depending on water characteristics, pollutant composition, and treatment objectives. To provide a clearer comparative perspective on the major treatment approaches discussed in this review, the principal advantages, limitations, application areas, and sustainability potential of these methods are summarized in Table 1.

Table 1. Comparison of Conventional and Green Chemistry-Based Water Treatment Approaches

| **Treatment Method** | **Main Advantages** | **Main Limitations** | **Suitable Water Types** | **Sustainability Potential** |
| --- | --- | --- | --- | --- |
| Coagulation-Flocculation | High turbidity removal | Sludge generation | Drinking water, municipal wastewater | Moderate |
| Adsorption | Broad pollutant removal | Regeneration issues | Industrial wastewater | Moderate-high |
| Ion Exchange | High selectivity | Saline waste generation | Heavy metal containing waters | Moderate |
| AOPs | Effective for persistent pollutants | High energy demand | Industrial wastewater | High |
| Green Chemistry Approaches | Low toxicity, renewable materials | Variable performance | Agricultural and biodegradable wastewater | Very high |

**DISCUSSION AND RESULTS**

Rapid global population growth, increasingly pronounced impacts of climate change, expansion of industrial activities, and the intensification of agricultural production are exerting growing pressure on freshwater resources worldwide. Under contemporary conditions, water is no longer regarded solely as a basic natural resource but has emerged as a strategic element essential for ecosystem sustainability, food security, protection of public health, and the continuity of economic development. In this context, the efficient, effective, and sustainable management of water resources has become a priority that encompasses environmental as well as social and economic dimensions. This review study examines chemical treatment methods aimed at enhancing water efficiency and discusses recent approaches that reconsider these methods in line with green chemistry principles from a holistic perspective. The reviewed studies collectively indicate that coagulation–flocculation, adsorption, ion exchange, and advanced oxidation processes remain widely applied and fundamental techniques in water and wastewater treatment; however, these methods require renewed evaluation in terms of environmental impacts, energy requirements, and secondary waste generation.

Although conventional chemical treatment methods often provide high removal efficiencies, they involve significant sustainability-related limitations associated with the use of metal salts, high production and operational costs of activated carbon, regeneration requirements of adsorbents and resins, and the energy-intensive nature of advanced oxidation processes. In this regard, recent scientific studies demonstrate that bio-based coagulants, waste-derived adsorbents, biodegradable ion exchange materials, and low-energy oxidation systems offer considerable potential to overcome these limitations. In particular, the utilization of biopolymers and biochars obtained from agricultural and food industry wastes contributes to effective waste management while offering value-added solutions consistent with circular economy principles.

A comparative evaluation of the reviewed treatment methods indicates that no single technology can simultaneously maximize treatment efficiency, economic feasibility, operational simplicity, and environmental sustainability under all conditions. Conventional coagulation and adsorption methods remain advantageous in terms of operational reliability and large-scale applicability; however, they often generate secondary sludge and require significant chemical consumption. In contrast, green chemistry–based systems provide important environmental benefits through lower toxicity, renewable material utilization, and reduced waste generation, although their treatment performance may vary depending on pollutant complexity and wastewater composition. Similarly, advanced oxidation processes demonstrate superior efficiency in degrading persistent contaminants, yet their high energy demand and operational costs may limit large-scale implementation. These findings highlight the importance of integrated and hybrid treatment strategies that combine the advantages of multiple technologies while minimizing their individual limitations.

The integration of green chemistry principles into water treatment technologies extends beyond the adoption of alternative and environmentally benign materials and also involves the redesign of treatment processes, optimization of energy sources, and holistic improvement of system performance. Solar-driven photocatalytic systems, renewable energy–supported electrochemical methods, and hybrid treatment configurations combining chemical and biological processes have emerged as prominent applications for reducing the environmental footprint of water treatment systems. Evidence reported in the literature suggests that these approaches are especially promising for the removal of persistent, toxic, and biologically recalcitrant contaminants. In conclusion, the future of chemical treatment methods aimed at improving water efficiency relies on green chemistry–based solutions that balance high treatment performance with environmental sustainability.

The findings evaluated within the scope of this review indicate that the effectiveness of green chemistry–based treatment technologies is closely associated with the characteristics of the target water source and the composition of the pollutant load. While environmentally friendly coagulants, natural adsorbents, and renewable-energy-supported treatment systems offer considerable advantages in terms of sustainability, their direct application may not always be sufficient for highly contaminated industrial wastewaters. Industrial sectors such as mining, petrochemical processing, textile manufacturing, and pharmaceutical production often generate wastewater streams containing persistent and complex pollutants that may require integrated or hybrid treatment systems. In contrast, green chemistry approaches may provide more practical and sustainable solutions for wastewater streams with lower toxicity and more biodegradable contaminant profiles. Consequently, future sustainable water management strategies should prioritize the development of sector-specific and water-specific treatment models rather than assuming the universal applicability of a single treatment approach.

Future research is needed to transfer laboratory-scale achievements to pilot and full-scale applications, quantitatively assessing environmental impacts through life-cycle analysis, and strengthening economic feasibility. Within this framework, the green chemistry perspective stands out as a fundamental guiding principle for the development of sustainable water management strategies.

***Ethical Standards***

***Conflict of Interest***
The author declares that there is no conflict of interest.

**Ethics Committee Approval**
Ethics committee approval is not required for this study. A wet-signed declaration confirming this has been included in the manuscript submission file.

**Declaration on the Use of Generative Artificial Intelligence (AI)**
No generative artificial intelligence tools were used in any part of this study.

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