Green Chemistry Approaches in Water and Wastewater Treatment: Recent Advances, Sustainability Assessment, and Future Perspectives

Mahdi Yousofian[1,*] - Atefeh Khaleghian[2]
[1] Shiraz university, phd student (mahdi.usefian75@gmail.com)
[2] Shiraz university, phd student (at.khaleghian@gmail.com)

ABSTRACT

The increasing demand for clean water, coupled with rapid industrialization, urbanization, and population growth, has intensified pressure on global water resources and highlighted the need for sustainable wastewater management strategies. Conventional water and wastewater treatment methods are often associated with high energy consumption, the use of hazardous chemicals, and the generation of secondary pollutants. In this context, green chemistry has emerged as a promising framework for developing environmentally friendly and resource-efficient treatment technologies. This review paper examines recent advances in the application of green chemistry principles to water and wastewater treatment systems. Particular attention is given to bio-based adsorbents, green-synthesized nanomaterials, advanced oxidation processes, and sustainable membrane technologies. The environmental and economic benefits of these approaches, including reduced chemical usage, lower sludge production, improved energy efficiency, and enhanced resource recovery, are critically discussed. Furthermore, the study evaluates the major challenges limiting large-scale implementation, such as material costs, process scalability, and regulatory constraints. Future perspectives focusing on smart materials, solar-driven treatment systems, artificial intelligence-assisted process optimization, and circular water economy concepts are also explored. The findings demonstrate that integrating green chemistry principles into water treatment technologies can significantly improve sustainability performance while contributing to long-term water security and environmental protection. This review provides a comprehensive overview of current developments and offers valuable insights for researchers, engineers, and policymakers working toward sustainable water management solutions.

Keywords: **Green Chemistry; Water Treatment; Wastewater Treatment; Sustainable Technologies; Advanced Oxidation Processes; Bio-based Adsorbents; Circular Economy**

1. Introduction

Water is one of the most essential natural resources for human survival, economic development, and ecosystem sustainability. However, increasing population growth, rapid urbanization, industrial expansion, and agricultural activities have significantly intensified pressure on global water resources. According to international environmental reports, water pollution has become one of the most critical environmental challenges of the twenty-first century, affecting both developed and developing countries. Large quantities of untreated or inadequately treated wastewater containing organic pollutants, heavy metals, pharmaceuticals, dyes, pesticides, and pathogenic microorganisms are continuously discharged into aquatic environments, posing serious risks to public health and ecological systems. To address these challenges, a wide range of conventional water and wastewater treatment technologies has been developed, including chemical coagulation, adsorption, biological treatment, membrane filtration, and advanced oxidation processes. Although many of these methods are effective in removing contaminants, they often suffer from several limitations, such as high energy consumption, excessive use of chemical reagents, generation of secondary pollutants, and substantial operational costs(۱) . Furthermore, some treatment processes produce significant amounts of sludge that require additional handling and disposal, thereby increasing environmental and economic burdens. In recent decades, growing concerns regarding environmental sustainability and resource *conservation have stimulated interest in the development of greener and more efficient treatment technologies. Green chemistry, introduced by Anastas and Warner, provides a scientific framework for designing chemical products and processes that minimize or eliminate the use and generation of hazardous substances. The twelve principles of green chemistry emphasize pollution prevention, energy efficiency, renewable feedstocks, safer solvents, waste minimization, and the design of environmentally benign materials. These principles have increasingly been integrated into water and wastewater treatment research to improve process sustainability while maintaining high treatment performance. The application of green chemistry in water treatment has led to the emergence of several innovative approaches, including bio-based adsorbents derived from renewable resources, environmentally friendly nanomaterials synthesized through green methods, sustainable membrane technologies, and energy-efficient advanced oxidation processes. These technologies offer significant advantages over conventional treatment methods by reducing environmental impacts, lowering chemical consumption, enhancing resource recovery, and supporting circular economy strategies. Despite the rapid progress in this field, several challenges remain regarding the large-scale implementation and long-term sustainability of green treatment technologies. Issues such as economic feasibility, process scalability, material stability, regulatory requirements, and technology transfer continue to influence their practical adoption. Therefore, a comprehensive evaluation of recent developments, benefits, limitations, and future opportunities is essential for guiding future research and industrial applications (2, 3). This review aims to critically examine recent advances in green chemistry-based approaches for water and wastewater treatment. The environmental and economic sustainability of major treatment technologies is discussed, with particular emphasis on bio-based adsorbents, green nanotechnology, advanced oxidation processes, and sustainable membrane systems. Additionally, current challenges and future research directions are highlighted to provide a comprehensive perspective on the role of green chemistry in achieving sustainable water management and long-term environmental protection. The remainder of this paper is organized as follows. Section 2 discusses the fundamental principles of green chemistry and their relevance to water treatment applications. Section 3 reviews the major green technologies currently employed in water and wastewater treatment. Section 4 evaluates the sustainability benefits of these technologies, while Section 5 addresses existing challenges and limitations. Finally, Section 6 presents future perspectives, and Section 7 summarizes the main conclusions of the study (4, 5).*

2. Green Chemistry Principles Relevant to Water and Wastewater Treatment

Green chemistry is a preventive and sustainable approach that seeks to reduce environmental impacts throughout the lifecycle of chemical products and processes. Unlike traditional environmental management strategies, which often focus on treating pollution after it has been generated, green chemistry emphasizes pollution prevention at the source. The concept is based on twelve fundamental principles proposed by Anastas and Warner, many of which have direct relevance to water and wastewater treatment technologies (6). The increasing need for sustainable water management has encouraged researchers to integrate green chemistry principles into treatment processes. By reducing the use of hazardous substances, minimizing waste generation, improving energy efficiency, and promoting the utilization of renewable materials, green chemistry provides a framework for developing environmentally responsible treatment technologies (7).

2.1 Waste Prevention and Pollution Reduction

One of the primary principles of green chemistry is the prevention of waste generation rather than its treatment after formation. In conventional wastewater treatment systems, large quantities of sludge and secondary pollutants may be produced during contaminant removal processes. Green treatment technologies aim to minimize such by-products through optimized process design, selective contaminant removal, and resource recovery strategies. For example, bio-based adsorbents and catalytic treatment systems can reduce the production of hazardous residues while maintaining high removal efficiencies. The adoption of waste prevention strategies contributes significantly to reducing environmental burdens and operational costs(8, 9)
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2.2 Use of Safer Chemicals and Materials

Traditional treatment processes frequently rely on chemical coagulants, oxidants, and disinfectants that may introduce secondary environmental risks. Green chemistry promotes the use of safer and less toxic substances capable of achieving comparable or superior treatment performance (10). Natural coagulants derived from plant extracts, biodegradable adsorbents, and green-synthesized nanoparticles are examples of environmentally friendly alternatives that reduce toxicity and improve process sustainability. The replacement *of hazardous chemicals with safer materials is particularly important for protecting aquatic ecosystems and human health (11).*

2.3 Energy Efficiency

Energy consumption represents a major environmental and economic challenge in water treatment facilities. Green chemistry encourages the development of processes that operate under mild conditions and require lower energy inputs. Recent advancements in solar-driven photocatalysis, low-pressure membrane filtration, and energy-efficient oxidation technologies have demonstrated considerable potential for reducing energy demand. Improving energy efficiency not only decreases operating costs but also lowers greenhouse gas emissions associated with treatment processes (12).

2.4 Renewable Feedstocks and Sustainable Resources

The utilization of renewable resources is another key principle of green chemistry. In water treatment applications, renewable feedstocks can replace synthetic and non-renewable materials traditionally used in adsorption and filtration systems. Agricultural residues, forestry by-products, algal biomass, cellulose, chitosan, and biochar have gained significant attention as sustainable treatment materials. These resources are often inexpensive, widely available, and biodegradable, making them attractive alternatives for large-scale applications (13, 14).

2.5 Design for Degradation and Environmental Compatibility

Green chemistry emphasizes the design of materials that can safely degrade into non-toxic products after their intended use. This principle is particularly relevant in water treatment, where residual treatment materials may eventually enter natural ecosystems. Biodegradable polymers, environmentally benign membranes, and naturally derived adsorbents are examples of materials developed according to this principle. Their application reduces the risk of long-term environmental accumulation and secondary contamination (15).

2.6 Resource Recovery and Circular Economy Integration

Modern interpretations of green chemistry increasingly incorporate circular economy concepts. Wastewater is no longer viewed solely as a waste stream but also as a potential source of valuable resources, including nutrients, energy, and reusable water. Technologies that enable phosphorus recovery, biogas generation, water reuse, and material recycling align closely with green chemistry objectives. Such approaches contribute to resource conservation while enhancing the overall sustainability of water management systems (16).

Table 1. Relationship Between Green Chemistry Principles and Water Treatment Applications (17-20)

Green Chemistry Principle	Application in Water Treatment	Sustainability Benefit
Waste Prevention	Minimization of sludge production	Reduced environmental burden
Safer Chemicals	Natural coagulants and biodegradable adsorbents	Lower toxicity
Energy Efficiency	Solar-driven and low-energy processes	Reduced carbon footprint
Renewable Feedstocks	Biochar, chitosan, cellulose-based materials	Resource sustainability
Design for Degradation	Biodegradable membranes and polymers	Reduced secondary pollution
Resource Recovery	Water reuse, nutrient recovery, biogas production	Circular economy support

The integration of these principles has transformed water and wastewater treatment from a pollution-control activity into a more sustainable and resource-efficient process. Consequently, green chemistry serves as a *foundation for the development of innovative treatment technologies capable of addressing both environmental and economic challenges associated with water management (20).*

3. Green Technologies in Water and Wastewater Treatment

The application of green chemistry principles has led to the development of innovative technologies that improve pollutant removal efficiency while minimizing environmental impacts. Among the most promising approaches are bio-based adsorbents, green nanotechnology, advanced oxidation processes, and sustainable membrane systems. These technologies not only enhance water treatment performance but also support resource conservation and sustainable development goals (21).

3.1 Bio-based Adsorbents

Adsorption is one of the most widely applied techniques in water and wastewater treatment due to its simplicity, effectiveness, and operational flexibility. Conventional adsorbents, particularly activated carbon, often involve relatively high production and regeneration costs. Consequently, increasing attention has been directed toward the development of bio-based adsorbents derived from renewable and environmentally friendly resources. Bio-based adsorbents are commonly produced from agricultural residues, forestry wastes, algae, and natural biopolymers. Materials such as biochar, cellulose, chitosan, rice husks, coconut shells, and sawdust possess abundant functional groups that facilitate the adsorption of various contaminants, including heavy metals, dyes, pharmaceuticals, and organic compounds. Among these materials, biochar has emerged as one of the most effective sustainable adsorbents. Produced through the pyrolysis of biomass under limited oxygen conditions, biochar exhibits high porosity, large surface area, and excellent adsorption capacity (22, 23). Recent studies have demonstrated its effectiveness in removing lead, cadmium, chromium, and emerging contaminants from wastewater streams. Chitosan, a natural polymer obtained from chitin-rich biomass, has also attracted significant attention because of its biodegradability, biocompatibility, and strong affinity toward metal ions. Similarly, cellulose-based materials and agricultural wastes provide low-cost alternatives for contaminant removal while simultaneously reducing solid waste generation. The major advantages of bio-based adsorbents include low production costs, renewable origin, biodegradability, and reduced environmental impacts. However, limitations such as lower mechanical stability, regeneration difficulties, and variable adsorption performance remain important challenges for large-scale implementation. Overall, bio-based adsorbents represent a sustainable and economically attractive solution for water treatment applications and align closely with the principles of green chemistry and circular resource utilization (24, 25).

3.2 Green Nanotechnology

Nanotechnology has significantly advanced the field of water treatment by introducing materials with exceptional adsorption, catalytic, and antimicrobial properties. However, conventional nanoparticle synthesis often requires toxic chemicals and energy-intensive procedures that may generate environmental concerns. Green nanotechnology addresses these limitations through environmentally benign synthesis methods based on biological resources. Green synthesis approaches utilize plant extracts, microorganisms, enzymes, and natural polymers as reducing and stabilizing agents during nanoparticle production. These methods eliminate or substantially reduce the need for hazardous chemicals while improving process sustainability. Several green-synthesized nanomaterials have demonstrated remarkable performance in water purification (26-28). Iron-based nanoparticles are widely used for heavy metal removal and groundwater remediation. Silver nanoparticles exhibit strong antimicrobial properties and are effective against a broad spectrum of pathogenic microorganisms. In addition, titanium dioxide and zinc oxide nanoparticles are frequently employed as photocatalysts for the degradation of persistent organic pollutants (29).

Recent advances have focused on combining nanoparticles with natural support materials to improve stability, facilitate recovery, and minimize environmental risks. Such hybrid systems integrate the benefits of nanotechnology with the sustainability objectives of green chemistry. Despite their considerable potential, concerns regarding nanoparticle toxicity, environmental fate, and long-term ecological impacts remain unresolved. Therefore, further studies are required to establish safe implementation strategies and comprehensive regulatory frameworks. Green nanotechnology is expected to play an increasingly important role in future water treatment systems due to its high efficiency, adaptability, and compatibility with sustainable development objectives (30, 31).

3.3 Advanced Oxidation Processes (AOPs)

Advanced oxidation processes (AOPs) constitute a group of highly effective treatment technologies that rely on the generation of reactive oxygen species, particularly hydroxyl radicals, to degrade complex organic *contaminants. These radicals possess extremely high oxidation potential and are capable of mineralizing pollutants into simpler and less harmful compounds (32). AOPs are particularly effective for the removal of pharmaceuticals, pesticides, dyes, endocrine-disrupting chemicals, and other recalcitrant pollutants that are difficult to eliminate through conventional biological treatment methods. Common AOPs include ozonation, photocatalysis, Fenton oxidation, photo-Fenton processes, UV-based oxidation, and electrochemical oxidation. Among these technologies, photocatalytic systems have gained substantial attention because they can utilize solar energy as a sustainable energy source (33, 34). Semiconductor materials such as titanium dioxide and zinc oxide generate reactive species under light irradiation, enabling efficient degradation of organic contaminants without excessive chemical consumption. The primary environmental advantages of AOPs include high treatment efficiency, reduced formation of secondary pollutants, and the ability to address emerging contaminants. Furthermore, solar-assisted systems contribute to lower energy consumption and reduced greenhouse gas emissions. Nevertheless, challenges related to catalyst recovery, operational complexity, and energy requirements continue to limit widespread adoption. To overcome these limitations, researchers are increasingly exploring integrated treatment systems that combine AOPs with adsorption, membrane filtration, and biological treatment processes. As concerns regarding emerging contaminants continue to grow, advanced oxidation processes are expected to remain among the most important green technologies for future wastewater treatment applications (35, 36).*

3.4 Green Membrane Technologies

Membrane-based treatment technologies have become indispensable components of modern water purification systems. Processes such as microfiltration, ultrafiltration, nanofiltration, reverse osmosis, and membrane bioreactors provide high separation efficiency and excellent treated-water quality. Despite these advantages, conventional membrane production frequently relies on petroleum-based polymers and toxic organic solvents. Such manufacturing practices raise concerns regarding environmental sustainability and resource consumption. Green membrane technologies have therefore emerged as a promising alternative. Green membranes are commonly fabricated using renewable biopolymers such as cellulose, chitosan, alginate, and polylactic acid. These materials offer improved biodegradability and reduced environmental impacts compared with conventional synthetic polymers (37, 38). Additionally, environmentally friendly fabrication techniques have been developed to reduce solvent consumption and waste generation. Recent studies have demonstrated that incorporating sustainable nanomaterials into membrane structures can significantly enhance permeability, selectivity, and fouling resistance. Ceramic membranes have also attracted considerable attention because of their excellent durability, thermal stability, and long operational lifespan.
Membrane fouling remains one of the most significant operational challenges affecting treatment efficiency and maintenance costs. Consequently, current research focuses on surface modification techniques and antifouling materials to improve long-term membrane performance. The future development of membrane technologies is expected to emphasize sustainable manufacturing, renewable materials, energy efficiency, and circular economy principles. These advancements will contribute significantly to the development of environmentally responsible water treatment systems capable of meeting increasing global water demands (39, 40).

Table 2. Comparison of Major Green Water Treatment Technologies (41-43)

Technology	Primary Mechanism	Main Advantages	Main Limitations
Bio-based Adsorbents	Adsorption	Renewable, biodegradable, low cost	Regeneration and stability issues
Green Nanotechnology	Adsorption, catalysis, antimicrobial action	High efficiency and selectivity	Toxicity and environmental concerns
Advanced Oxidation Processes	Oxidative degradation	Effective for refractory pollutants	Energy demand and operational costs
Green Membrane Technologies	Physical separation	High water quality and recovery rates	Fouling and high capital costs

The rapid development of these technologies demonstrates the transformative role of green chemistry in modern water and wastewater treatment. By integrating sustainability principles with technological innovation, these approaches provide viable pathways toward environmentally responsible and resource-efficient water management systems (43).

4. Sustainability Assessment

4.1 Environmental Sustainability

Environmental sustainability has become one of the primary driving forces behind the development of green chemistry approaches for water and wastewater treatment. Conventional treatment technologies often rely on intensive chemical consumption, generate considerable quantities of sludge, and require substantial energy input, all of which contribute to environmental degradation. In contrast, green chemistry emphasizes pollution prevention at the source by promoting environmentally benign reagents, renewable materials, and energy-efficient treatment processes. This transition has encouraged the development of innovative technologies that simultaneously achieve effective contaminant removal while minimizing adverse environmental impacts throughout the treatment process (44, 45).

Among the most significant environmental benefits of green chemistry is the reduction of secondary pollution generated during wastewater treatment. The use of biodegradable adsorbents, naturally derived coagulants, photocatalysts activated by visible light, and bio-based catalytic systems significantly decreases the release of hazardous residues into aquatic ecosystems. Furthermore, many green treatment technologies require lower energy consumption and produce smaller amounts of sludge compared with conventional physicochemical methods. The incorporation of renewable energy sources, particularly solar-driven treatment systems, further reduces greenhouse gas emissions and contributes to a lower environmental footprint. Collectively, these advances support the development of environmentally sustainable water treatment systems that protect natural resources while maintaining high purification efficiency (46, 47).

4.2 Economic Sustainability

Besides their environmental advantages, green chemistry technologies have attracted increasing attention because of their long-term economic benefits. Although some advanced materials involve relatively high initial production costs, many green treatment systems substantially reduce operating expenses through lower energy demand, reduced chemical consumption, and simplified waste management. Reusable adsorbents and recyclable catalytic materials further enhance economic performance by extending material lifetime and decreasing replacement frequency. As operational efficiency improves, the overall treatment cost becomes increasingly competitive with conventional technologies, making green chemistry an attractive option for both municipal and industrial wastewater treatment facilities (48).

Another important aspect of economic sustainability is the ability of green treatment technologies to generate additional value from wastewater streams. Rather than considering wastewater solely as a waste product, modern treatment strategies recognize it as a potential source of reusable water, nutrients, metals, and renewable energy. Recovering these valuable resources can offset treatment costs while simultaneously reducing the demand for virgin raw materials. This value-added approach transforms wastewater management from a cost-intensive environmental obligation into a resource-efficient process that supports sustainable industrial development. As technologies continue to mature and become more economically accessible, green chemistry is expected to play a key role in improving both environmental performance and financial viability across the water sector (49, 50).

4.3 Circular Economy and Resource Recovery

The concept of the circular economy has significantly reshaped modern wastewater management by promoting the continuous use of resources rather than their disposal after a single application. Within this framework, wastewater is no longer viewed as an unwanted by-product but as a valuable reservoir of water, nutrients, energy, and recoverable materials. Green chemistry provides the scientific foundation for implementing this concept by developing environmentally compatible treatment processes capable of recovering valuable resources while minimizing waste generation. Such approaches contribute to reducing dependence on finite natural resources and improving the overall sustainability of water management systems (51, 52).

Resource recovery technologies have expanded rapidly in recent years, enabling the extraction of phosphorus, nitrogen, valuable metals, and organic matter from municipal and industrial wastewater. In parallel, reclaimed *water has become an increasingly important alternative water source for agricultural irrigation, industrial cooling, and various non-potable applications. These practices reduce freshwater consumption while mitigating environmental pollution associated with wastewater discharge. The integration of green chemistry with circular economy principles creates opportunities for developing closed-loop treatment systems in which water, energy, and materials are continuously recovered and reused. Such integrated strategies not only improve environmental protection but also strengthen economic resilience and support the transition toward more sustainable and resource-efficient water infrastructure (53, 54).*

Figure 1: Circular Economy and Resource Recovery(55)

5. Current Challenges

5.1 Scale-Up and Industrial Implementation

Despite the remarkable progress achieved in laboratory-scale research, the transition of green chemistry technologies to full-scale industrial applications remains one of the greatest challenges in sustainable water and wastewater treatment. Most innovative materials and treatment processes are evaluated under carefully controlled laboratory conditions using synthetic wastewater and relatively low pollutant concentrations. However, industrial and municipal wastewaters are considerably more complex, containing mixtures of organic compounds, heavy metals, suspended solids, microorganisms, and fluctuating physicochemical properties that can significantly influence treatment efficiency. Consequently, technologies that demonstrate excellent performance under laboratory conditions may experience reduced effectiveness, lower stability, or operational difficulties when exposed to real wastewater matrices (56).

Another critical limitation is the lack of long-term pilot-scale demonstrations that bridge the gap between laboratory research and commercial implementation. Industrial facilities require treatment technologies that operate continuously under variable environmental conditions while maintaining stable performance, minimal maintenance requirements, and predictable operational costs. Scaling up also introduces engineering challenges related to reactor design, hydraulic performance, mass transfer limitations, material durability, and process integration with existing treatment infrastructure. Addressing these issues requires multidisciplinary collaboration among researchers, engineers, industries, and policymakers to develop scalable systems that maintain both environmental sustainability and economic feasibility under real operating conditions (56, 57).

5.2 Cost of Advanced Green Materials

The development of advanced green materials has significantly improved the efficiency of contaminant removal; however, their production cost continues to limit widespread commercial adoption. Many high-performance materials, including engineered nanomaterials, metal-organic frameworks, advanced photocatalysts, and functionalized carbon-based composites, require sophisticated synthesis procedures, expensive precursors, and specialized equipment. These factors increase manufacturing costs and reduce the economic competitiveness of such materials, particularly for large-scale wastewater treatment plants operating under strict budget constraints. Consequently, balancing high treatment performance with affordable production remains a major objective in green chemistry research (58).

In recent years, considerable attention has shifted toward the utilization of renewable biomass, agricultural residues, industrial by-products, and naturally abundant minerals as alternative raw materials for green adsorbents and catalysts. These sustainable feedstocks not only reduce production costs but also contribute to *waste valorization and environmental protection. Nevertheless, challenges remain regarding material consistency, regeneration efficiency, long-term durability, and large-scale manufacturing. Future research should therefore focus on developing low-cost materials that combine excellent adsorption capacity, structural stability, and multiple regeneration cycles while minimizing environmental impacts throughout their life cycle (59).*

5.3 Regulatory and Technology Transfer Barriers

In addition to technical and economic limitations, regulatory frameworks and technology transfer processes play a decisive role in determining the successful implementation of green chemistry technologies. Environmental regulations often differ considerably among countries and regions, creating uncertainty regarding the approval and commercialization of newly developed treatment systems. In many cases, innovative materials must undergo extensive environmental risk assessments, toxicity evaluations, and long-term performance verification before receiving regulatory acceptance. Although these requirements are essential for protecting public health and ecosystems, they may significantly delay the introduction of promising technologies into practical applications (60-62).

Another important challenge is the limited transfer of scientific innovations from academic research to industrial practice. Universities and research institutions continue to produce a large number of high-quality laboratory studies; however, only a small proportion progress toward commercialization or full-scale implementation. This gap is frequently associated with insufficient industrial collaboration, limited financial investment, inadequate pilot-scale validation, and the absence of clear commercialization strategies. Strengthening partnerships among academia, industry, governmental agencies, and technology developers will be essential for accelerating innovation, facilitating knowledge transfer, and promoting the widespread adoption of sustainable water treatment technologies in the coming years (63, 64).

Table 3. Major challenges limiting the large-scale implementation of green chemistry technologies in water and wastewater treatment.(62-64)

Challenge	Main limitation	Potential impact	Possible mitigation strategy
Scale-up and industrial implementation	Limited pilot-scale validation and process optimization	Reduced industrial adoption	Pilot demonstrations, process optimization, interdisciplinary collaboration
High cost of advanced green materials	Expensive synthesis routes and precursor materials	Increased operational and capital costs	Development of biomass-derived and recyclable materials
Material durability	Performance degradation during repeated use	Reduced long-term efficiency	Improved regeneration methods and structural stabilization
Regulatory barriers	Lengthy approval procedures and inconsistent environmental regulations	Delayed commercialization	Harmonized regulatory frameworks and standardized evaluation protocols
Technology transfer	Weak collaboration between academia and industry	Limited practical implementation	Public–private partnerships, industrial investment, and innovation platforms

6. Future Perspectives

6.1 AI-Assisted Water Treatment

The integration of artificial intelligence (AI) into water and wastewater treatment is expected to redefine the design, operation, and management of future treatment systems. AI-based algorithms can analyze large volumes of operational data, identify complex relationships among treatment variables, and optimize process performance in real time. Machine learning models have already demonstrated considerable potential for predicting contaminant removal efficiency, forecasting equipment failures, optimizing chemical dosage, and reducing energy consumption. By continuously learning from operational data, these intelligent systems enable *treatment facilities to respond rapidly to changing wastewater characteristics and improve overall process stability (65, 66).*

Beyond operational optimization, AI is expected to accelerate the development of new green treatment materials and integrated treatment technologies. Data-driven approaches can rapidly screen thousands of potential adsorbents, catalysts, and membrane materials before laboratory synthesis, significantly reducing research time and development costs. The combination of AI with digital twins, Internet of Things (IoT) sensors, and automated monitoring platforms will further enable autonomous wastewater treatment systems capable of self-adjustment and predictive maintenance. Such intelligent infrastructures are anticipated to enhance treatment efficiency, improve resource utilization, and support more resilient and sustainable water management in the coming decades (67, 68).

6.2 Smart and Solar-Driven Technologie*s*

The next generation of green water treatment technologies is expected to rely increasingly on smart materials capable of responding dynamically to environmental changes. These advanced materials can alter their physicochemical properties in response to external stimuli such as pH, temperature, light intensity, magnetic fields, or pollutant concentration. Such adaptive behavior improves contaminant selectivity, enhances regeneration efficiency, and prolongs material lifetime. Responsive adsorbents, self-cleaning membranes, multifunctional photocatalysts, and hybrid nanocomposites represent promising examples of smart materials that may overcome many of the limitations associated with conventional treatment technologies (69).

At the same time, solar-driven treatment processes have emerged as one of the most promising strategies for reducing the energy demand of water purification systems. Solar photocatalysis, solar evaporation, and photoelectrochemical technologies utilize abundant renewable solar energy to degrade organic contaminants, inactivate microorganisms, and produce clean water with minimal environmental impact. Continued advances in visible-light-responsive photocatalysts, efficient solar collectors, and hybrid renewable energy systems are expected to improve treatment performance while lowering operational costs. The integration of solar energy with smart functional materials offers a promising pathway toward low-carbon, energy-efficient, and environmentally sustainable water treatment technologies (70).

6.3 Circular Water Economy

The concept of a circular water economy is expected to become a central principle in future water resource management by promoting the continuous reuse of water and the recovery of valuable resources from wastewater. Rather than treating wastewater solely as a waste stream requiring disposal, future treatment systems will increasingly function as resource recovery facilities capable of producing reclaimed water, renewable energy, nutrients, and valuable raw materials. This transition supports more efficient resource utilization while reducing pressure on freshwater supplies and minimizing environmental pollution. Green chemistry provides the technological foundation for this transformation by developing environmentally compatible processes that maximize recovery efficiency while minimizing waste generation (71, 72).

Achieving a fully circular water economy will require the integration of advanced treatment technologies, supportive policy frameworks, digital monitoring systems, and sustainable industrial practices. Collaboration among governments, researchers, industries, and local communities will be essential for establishing effective water reuse strategies and encouraging investment in innovative recovery technologies. As global concerns regarding water scarcity, climate change, and resource depletion continue to intensify, circular water management is expected to become a key component of sustainable development. Future research should therefore focus on integrated treatment systems that simultaneously enhance water quality, recover valuable resources, reduce energy consumption, and promote long-term environmental resilience (73).

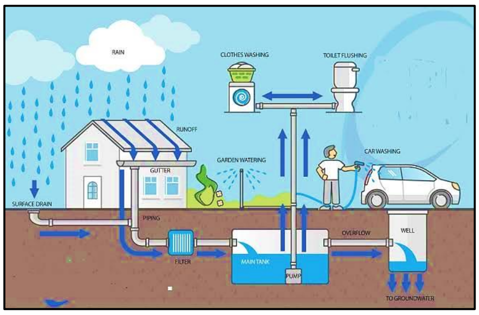

Figure 2: Circular Water Economy(74)

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