Review of Recent Sustainable Water Technologies for Heavy Metal Removal

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Abstract. Growing concerns about climate change, global warming, water scarcity and pollution have intensified the search for sustainable water treatment technologies. Among the most pressing challenges is heavy metal contamination, which poses severe risks to ecosystems and human health. This literature review evaluates recent advancements in water recycling, treatment, and purification technologies for heavy metal removal.

The findings suggest that adsorption-based methods, such as activated carbon, nanomaterials, and biochar achieve high removal efficiencies but face limitations related to saturation, regeneration, and cost. Membrane filtration methods provide effective separation yet demand substantial energy inputs. Bioremediation offers an ecologically sound solution, but with limited scalability. Electrochemical approaches, such as electrocoagulation and electrodialysis, demonstrate high efficiency and reduced chemical use; ongoing research focuses on optimizing electrode materials and system design to improve energy efficiency. Green precipitation methods using plant-based coagulants also show promise as sustainable alternatives for decentralized applications.

The review emphasizes the potential of hybrid and thermophysical systems that integrate multiple technologies to enhance performance, reduce operational costs, and strengthen environmental sustainability. Future research should focus on optimizing these hybrid systems, improving energy efficiency and exploring decentralized, modular solutions tailored for developing countries such as Mongolia, where water scarcity, mining activities, and infrastructure limitations make adaptive and low-cost technologies essential for achieving sustainability.

Keywords: Wastewater Treatment, Sustainable Technology, Heavy Metals, Hybrid Systems, Water Sustainability.

1 Introduction

Water is a critical resource for sustaining life, maintaining ecosystem integrity, and supporting socio-economic development [2, 5, 15]. However, global water systems are under increasing strain due to a confluence of challenges, including water scarcity,

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pollution, climate change, and poor governance [15, 31]. Particularly in arid and semi-arid regions, growing populations, urban expansion, and industrial demands have led to over-extraction of freshwater resources and heightened vulnerability to water shortages [2, 24]. In parallel, the quality of available water is deteriorating due to rising levels of pollution, with heavy metals representing some of the most hazardous and persistent contaminants [4, 18, 28].

Common heavy metals of concern in aquatic environments include arsenic (As), cadmium (Cd), lead (Pb), mercury (Hg), chromium (Cr), nickel (Ni), and manganese (Mn) [4, 18]. These elements exhibit high toxicity, even at low concentrations, and pose severe risks due to their potential for bioaccumulation and biomagnification. Toxic elements such as mercury (Hg), lead (Pb), cadmium (Cd), arsenic (As), and chromium (Cr) originate primarily from mining activities, industrial discharges, improper waste disposal, and agricultural runoff [4, 7, 14]. Once released into aquatic environments, heavy metals tend to accumulate in sediments, lakes, rivers, and groundwater systems, posing long-term threats to both ecological and human health [4, 28]. Fish and benthic invertebrates often suffer from growth inhibition, reproductive failure, and mortality. The degradation of aquatic ecosystems also undermines the livelihoods of communities that depend on fisheries and clean water sources [32].

Human exposure to heavy metals, either through the consumption of contaminated water or aquatic food, can lead to serious health issues, including neurological disorders, kidney dysfunction, cardiovascular diseases, and developmental problems in children [4, 18, 37]. Populations living near industrial zones or mining operations are disproportionately affected, exacerbating socio-environmental inequities and raising urgent concerns about environmental justice [33]. Inadequate wastewater infrastructure, limited monitoring capacity, and weak enforcement of environmental regulations exacerbate the problem [17, 31]. Addressing this issue requires the development and scaling of efficient, affordable, and context-appropriate water treatment technologies. In addition to technical solutions, raising public awareness, enforcing environmental standards, and strengthening governance frameworks are crucial to ensuring long-term water quality and sustainability.

The scale and complexity of water pollution by heavy metal contamination underscore the urgent need for innovative and sustainable solutions to treat water. In recent years, green technologies such as nanomaterials, bio-based adsorbents, phytoremediation, and hybrid systems have gained prominence as promising alternatives to conventional treatment methods [7, 10, 35]. These approaches aim to improve the efficiency, cost-effectiveness, and environmental compatibility of wastewater treatment, particularly in low-resource settings. While notable advancements have been made in sustainable water treatment technologies, a critical gap remains in translating innovative, laboratory-scale methods into practical, scalable, and context-sensitive solutions for heavy metal removal.

This literature review explores recent advancements in sustainable water technologies, focusing on their effectiveness in removing heavy metals from wastewater, as well as efforts to bridge the gap between innovation and scalable, real-world applications. It is guided by the following research questions:

- What are the most recent advancements in green technologies, such as nanomaterials, bio-based adsorbents, phytoremediation, and hybrid systems, targeting the removal of heavy metals from contaminated water sources?
- What integrated hybrid technologies have recently emerged, and how do they enhance removal efficiency?
- What are the main technical, economic, and environmental challenges hindering the large-scale implementation and commercialization of sustainable water treatment technologies for heavy metal removal?

2 Methodology

This literature review employs a two-step methodological approach to examine recent advancements in sustainable water treatment technologies for heavy metal removal. The approach includes a comprehensive literature review to explore a wide range of green technologies and a more focused systematic literature review using the PRISMA framework to identify highly relevant studies.

2.1 Literature Search Strategy and Inclusion Criteria

An extensive review of academic literature was conducted using Google Scholar and Web of Science. This phase focused on identifying advancements in green and sustainable wastewater treatment technologies over the past decade. The literature review included peer-reviewed journal articles, conference proceedings and books.
The Inclusion criteria for literature selection were as follows:

- Publication years: 2015–2025
- Language: English
- Content focus: Technologies targeting the removal of heavy metals (e.g., Pb, Cd, Cr, As, Hg) from wastewater
- Source: Peer-reviewed articles, conference proceedings, books and reports from recognized organizations.

2.2 Step 1: Comprehensive Literature Review on Sustainable Wastewater Treatment and Water Recycling Technologies

An extensive review of scholarly and technical literature was conducted using “Google Scholar”. Key words used: sustainable/green water technologies, wastewater treatment, water sustainability.

Screening Criteria. Studies were screened based on the following criteria:

- Technology Focus: The study investigates green technologies: nanomaterials, adsorption, ion exchange, precipitation, phytoremediation, or hybrid systems, for the removal of heavy metals.
- Performance Metrics: The study reports quantitative data on removal efficiency or performance related to heavy metal removal.
- Study Design: The study includes experimental validation through laboratory experiments, pilot-scale trials, or scale-up implementations.
- Economic Analysis: The study includes an assessment of economic feasibility or a cost analysis of the technology.
- Environmental Impact: The environmental impacts of the technology are considered.

Data Extraction Protocol. Efficiency and Adsorption Capacity. From the discussion and results section, the proposed removal mechanisms and quantitative performance metrics were extracted:

- Metal removal efficiency (percentage)
- Adsorption capacity (e.g., mg/g, mmol/g)

Challenges and Limitations. From the discussion and conclusion sections, the following were extracted:

- Barriers to scale-up or commercial application
- Economic and cost-related considerations
- Environmental constraints
- Suggested improvements or future research needs

2.3 Step 2: Systematic Literature Review on Technologies for Heavy Metal Removal

PRISMA Framework Application. A systematic literature review was conducted using the PRISMA approach (Fig. 1). The search was restricted to the Web of Science database, applying strict filters based on predefined inclusion criteria (publication date, language, peer-review status, and thematic relevance to heavy metal removal technologies). After using the filters, only four articles met all criteria for inclusion, highlighting a significant narrowing of the literature under strict methodological controls.

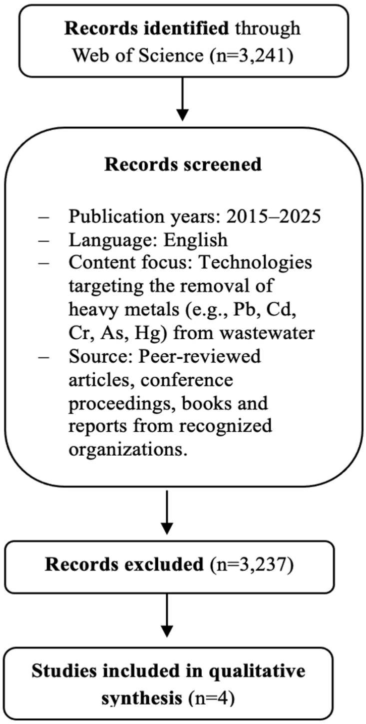

Fig. 1. PRISMA diagram

3 Comprehensive Literature Review Findings

3.1 Recent Advancements in Sustainable Technologies for Heavy Metal Removal

An extensive review of scholarly literature was conducted using Google Scholar to explore recent advancements in sustainable water technologies for heavy metal removal from wastewater. The search employed key terms including "sustainable/green water technologies," "wastewater treatment," and "water sustainability" to capture a comprehensive range of relevant studies. Screening criteria focused on green technologies such as nanomaterials, adsorption, ion exchange, precipitation, phytoremediation, and hybrid systems, emphasizing studies that provided metal removal efficiency and adsorption capacity, and included experimental validation at laboratory, pilot, or scale-up levels. Economic feasibility and environmental impacts were critical inclusion factors. The technologies reviewed encompass a diverse set of physical, chemical, and biological processes. Advanced methods like adsorption, ion exchange, bioremediation, electrochemical techniques, and green chemical precipitation demonstrate promising removal efficiencies often exceeding 90%. The following findings synthesize insights, highlighting both the potential and limitations of current sustainable water treatment technologies for heavy metal remediation.

3.2 Attributes of Sustainable Water Technologies

As freshwater resources become scarcer, developing cost-effective, efficient, and scalable water treatment technologies is critical. Sustainable water technologies refer to a diverse set of innovations and systems designed to ensure the long-term availability, quality, and equitable distribution of water resources. These technologies aim to maximize water efficiency, minimize environmental impacts, and promote the circular use of water in urban, agricultural, and industrial contexts [20]. Sustainable water technologies are characterized by efficiency, adaptability, low environmental impact, resilience and circularity [9]. See Table 1.

Table 1. Attributes of sustainable water technologies.

Attribute	Brief description
Efficiency	Maximize output, while minimizing water, energy, and chemical inputs
Adaptability	Scalable and context-specific (urban, rural, industrial, etc.)
Low Environmental Impact	Reduces pollution, emissions, and waste generation throughout operation.
Resilience	Withstands climate variability, droughts, and flood conditions
Circularity	Promotes reuse, recycling, and recovery within water cycles

3.3 Water treatment, recycling, and purification technologies

Water treatment, recycling, and purification technologies play a pivotal role in achieving water sustainability by reducing freshwater demand through reuse and recycling; preventing environmental contamination from toxic effluents, safeguarding public health by ensuring potable water meets safety standards and supporting circular economy goals in industry, agriculture, and urban planning [19]. Recycling and advanced treatment technologies enable the transformation of wastewater into a valuable resource, reducing the stress on freshwater ecosystems [8]. Water treatment, recycling, and purification technologies encompass a range of physical, chemical, and biological processes. Traditional techniques such as sedimentation and chemical coagulation are often insufficient for heavy metal removal due to the solubility and stability of metal ions. Therefore, the focus has shifted towards advanced treatment methods with higher selectivity and efficiency (Table 2). These include:

- Adsorption
- Membrane Filtration

- Ion Exchange
- Bioremediation
- Electrochemical Techniques
- Chemical Precipitation
- Hybrid and Integrated Water Treatment Systems

Adsorption. Adsorption techniques using activated carbon, nanomaterials, and biochar demonstrate high efficiency (>90%) for various metal ions, though issues related to saturation and regeneration limit their long-term applicability. However, these materials often suffer from saturation, low selectivity, and high regeneration costs [9, 11].

Membrane Filtration. Membrane filtration offers high removal rates but is constrained by energy demands. Advancements in nanocomposite membranes have enhanced selectivity and resistance to fouling, though energy consumption remains high [8, 12, 36].

Ion Exchange. Ion exchange is an effective technique for removing heavy metals from wastewater, applied in both industrial and municipal treatment systems. The process relies on the reversible exchange of ions between a solid phase (usually an ion-exchange resin and contaminated water, enabling the selective removal of toxic metal ions such as lead (Pb^{2+}), cadmium (Cd^{2+}), copper (Cu^{2+}), and chromium (Cr^{3+}/Cr^{6+}). Ion exchange has gained prominence due to its high efficiency, ability to achieve low detection limits, and potential for regenerating the adsorbent material. One of the major strengths of ion exchange lies in its selectivity and precision, particularly in treating wastewater with low to moderate concentrations of heavy metals. It offers rapid processing times and consistently high removal efficiencies, often exceeding 90%, especially when using synthetic resins tailored for specific contaminants. Additionally, ion exchange resins can be regenerated and reused multiple times, reducing operational costs and waste generation [9, 35].

Bioremediation. It presents a green alternative, with scalability and control being central challenges. Techniques such as nanofiltration, reverse osmosis, and ultrafiltration can effectively separate metal ions [12, 35, 36]. Fungi, algae, and bacteria have demonstrated bioaccumulation and biosorption capacities [1, 28]. Genetic engineering and reactor design improvements are addressing scalability concerns.

Electrochemical Methods. Electrochemical methods, particularly electrocoagulation and electrodialysis, provide promising pathways for efficient, low-chemical treatment. Innovations in electrode materials and energy optimization are progressively overcoming technical barriers. Electrocoagulation and electrodialysis allow efficient metal removal with minimal chemical additives [6]. Research is advancing the design of low-energy systems and durable electrode materials [9].

Green Chemical Precipitation. Green chemical precipitation using plant-based coagulants has emerged as an eco-friendly option [26]. The use of plant-based coagulants and biodegradable agents offers a low-cost, environmentally friendly alternative [30].

Despite advancements in green technologies such as nanomaterials, adsorbents, and bioremediation, limitations remain that hinder application in complex wastewater treatment. Persistent challenges such as material regeneration, cost, environmental risks, and scalability highlight the need for integrated and hybrid treatment approaches that leverage the strengths of multiple technologies [4,39].

Hybrid and Integrated Water Treatment Systems. As the complexity of industrial wastewater increases, especially in the presence of persistent contaminants such as heavy metals, single-method treatment approaches often fall short in achieving optimal removal efficiency, cost-effectiveness, and environmental sustainability. Consequently, the integration of multiple treatment technologies into hybrid systems has gained increasing attention as a promising strategy to address the multifaceted challenges of water pollution. Hybrid and integrated water treatment systems are designed to exploit the complementary strengths of different technologies, offering enhanced performance through synergistic effects [34].

Table 2. Comparison of water treatment technologies for heavy metal removal

Technology	Mechanism	Advantages	Limitations
Adsorption	Surface binding of metal ions using activated carbon, biochar, zeolites, or metal-organic frameworks (MOFs)	Low-cost, effective at low concentrations	Regeneration challenges, potential issues with spent adsorbent disposal
Membrane Filtration (e.g., RO, NF, UF)	Size exclusion and charge-based separation using semi-permeable membranes	High removal efficiency; suitable for a wide range of contaminants	High energy consumption; membrane fouling and replacement costs
Ion Exchange	Exchange of metal ions with harmless ions on resin beads	High selectivity; high capacity for target metals	Resin cost, requires chemical regeneration and produces secondary waste
Electrochemical Methods	Electrodeposition, electrocoagulation processes to remove metals from solution	On-site applicability, minimal chemical usage	Energy intensive, limited scalability and challenging maintenance
Phytoremediation	Use of plants to absorb and immobilize metals in soil or water	Eco-friendly low-cost	Slow, limited to specific environment and climate and contaminant types
Green Chemical Precipitation	Conversion of dissolved metals into insoluble salts for removal	Simple, cost-effective, widely used	Sludge generation, chemical use and handling concerns
Hybrid and Integrated Systems	Synergistic combination of technologies (e.g., adsorption–membrane,	Enhanced efficiency, customizable;	System complexity, integration cost,

	biochar–nanoparticle composites)	higher removal efficiency & selectivity	need for careful optimization

4 Systematic Literature Review Findings

Through the application of the PRISMA framework, four recent scholarly articles were systematically selected from an initial pool of 3,241 publications. These articles were retained after a rigorous filtering process based on relevance, content, and thematic alignment. They demonstrate the breadth and depth of emerging solutions in sustainable water treatment technologies. These studies highlight key technological advancements and emerging trends shaping the future of sustainable water treatment. Below is a summary of the main ideas and findings of these four articles, outlining their respective contributions to the discourse on sustainable water treatment.

4.1 Low-grade waste heat recovery for wastewater treatment using clathrate hydrate-based technology (Sun et al., 2024).

This article proposes a novel hybrid thermophysical approach to water treatment that differs fundamentally from conventional methods like adsorption, membrane filtration, ion exchange, bioremediation, electrochemical techniques, and chemical precipitation (Table 3) [29]. This approach leverages gas hydrate-based separation, a relatively new and less commonly applied methodology in wastewater treatment. This system primarily utilizes a gas hydrate-based separation process facilitated by low-grade waste heat. Hydrate formation occurs when a gas (in this case, R134a) forms crystalline compounds with water under specific pressure and temperature conditions. The process includes:

- Hydrate formation: Under controlled low temperatures and pressure, water molecules form cage-like structures (hydrates) that encapsulate gas molecules. This process selectively excludes impurities such as organic dyes and heavy metals from the crystalline structure.
- Hydrate dissociation: Heating (via low-grade waste heat) releases the gas and yields purified water, separating it from the concentrated waste stream.

This standout innovation lies in combining low-grade waste heat recovery with hydrate-based separation processes. Sun et al. introduced a novel thermophysical system using R134a hydrate formation to remove contaminants, including Cr^{3+}, Ni^{2+}, Zn^{2+}, and Cu^{2+}, with remarkable efficiency. Notably, the system achieves an energy efficiency of 23.5%, demonstrating how resource synergies can be harnessed for dual environmental benefits—energy reuse and water purification. This approach marks a transformative step toward operational sustainability by combining energy recovery (from low-grade waste heat) with effective pollutant removal.

Table 3: Innovative aspects of the hybrid thermophysical approach

Technology	**Mechanism**	**Comparison with Hydrate-Based Method**
Adsorption	Surface capture on porous materials	Hydrate-based methods are not surface-dependent and can be regenerated more effectively.
Membrane Filtration	Physical sieving via membranes	Avoids issues like membrane fouling and high energy input for pressure-driven processes.
Ion Exchange	Ion substitution on resins	Does not rely on resin regeneration; handles multi-contaminant streams more efficiently.
Bioremediation	Microbial degradation	Faster and not limited by microbial sensitivity to toxic heavy metals.
Electrochemical Techniques	Redox reactions via electrodes	Requires less electrical energy; uses thermal energy from waste heat instead.
Chemical Precipitation	Formation of insoluble compounds	Less sludge production; selectively separates water via hydrate formation.

Key Innovations:

- Dual-functionality: Simultaneous low-grade heat recovery and water purification.
- Thermodynamic advantage: Utilizes exergy from low-grade waste heat, which is generally underutilized.
- High contaminant removal efficiency: Competitive or superior to many conventional methods, especially for heavy metals and organics.

This hydrate-based water treatment system represents an innovative and integrated approach not widely adopted in industrial or municipal wastewater management. By combining waste heat recovery with effective contaminant removal, it advances beyond conventional technologies in both sustainability and efficiency, in scenarios involving low-grade thermal resources and multi-pollutant wastewater streams(Sun et al., 2024). This method can be fully implemented using existing industrial equipment, eliminating the need for complex new machinery or advanced materials. This significantly enhances its feasibility and scalability. The hydrate-based approach demonstrates significant potential not only for effective wastewater treatment but also as a viable means of recovering low-grade waste heat, thereby contributing to broader sustainability and decarbonization objectives.

4.2 Assessment of sustainability of a hybrid of advanced treatment technologies for recycling industrial wastewater in developing countries: Case study of Iranian industrial parks (Piadeh et al., 2018).

Piadeh et al. (2018) present a robust application of Multi-Criteria Decision Analysis (MCDA) to support the selection of sustainable water treatment technologies for heavy metal removal, emphasizing the importance of contextual adaptability [21]. Their model incorporates weighted criteria—including economic viability, technological robustness, environmental impact, and social acceptance—to facilitate context-specific and data-driven decision-making. This study tailors the approach to the complex realities of transitional economies, where decision-makers often face interlinked financial, technical, environmental, and socio-political constraints. The study demonstrates how MCDA can be operationalized to prioritize technologies that are not only technically sound but also socioeconomically and environmentally appropriate for regions undergoing rapid change.

4.3 Comprehensive Insights into Water Remediation: Chemical, Biotechnological, and Nanotechnological Perspectives (Rathod et al., 2024)

In this article, nanotechnology emerges as a frontier solution for precision remediation. Nanomaterials such as nanoscale zero-valent iron (nZVI), carbon nanotubes, and metal oxide nanoparticles are highlighted for their exceptional properties, including high surface area, reactivity, and selectivity. These characteristics make them highly effective for the removal of toxic heavy metals like Pb^{2+}, Cd^{2+}, Hg^{2+}, and Cr^{6+} from wastewater. The mechanisms by which these nanomaterials operate—adsorption, reduction, ion exchange, and complexation—are particularly well-suited for immobilizing or detoxifying heavy metals, thereby contributing to more efficient and sustainable water treatment solutions (Rathod et al., 2024). The study cautions against overlooking toxicity, long-term environmental effects, and scalability. It calls for interdisciplinary research and regulatory frameworks to responsibly harness nanotech potential.

4.4 Comprehensive Insights into Water Remediation: Chemical, Biotechnological, and Nanotechnological Perspectives (Huang et al., 2023)

Huang et al. redirect the focus to resource recovery—recovering Cu^{2+} and Ni^{2+} from electroplating wastewater through technologies like electrodeposition and membrane filtration. The paper critiques the prevailing lab-scale orientation and advocates for pilot-scale testing and life cycle assessments. By emphasizing the reuse of recovered metal products, it aligns wastewater treatment with circular economy principles and underlines the importance of closing resource loops in industrial processes.

Huang et al. highlight a critical shift in sustainable water treatment - from conventional heavy metal removal and detoxification to integrated strategies focused on resource recovery and circular economy practices [16]. This transition reflects modern sustainability paradigms by emphasizing not only environmental protection but also the economic value of recovering resources from industrial effluents. The review underscores the need to connect technical feasibility with environmental and economic outcomes. It advocates for life cycle thinking, pilot-scale implementation, and systems integration as key steps toward practical application. Taken together, these elements position the work as a potential roadmap for advancing sustainable, circular solutions to heavy metal pollution.

4.5. Synthesis

These studies show that the field is moving toward integrated, adaptive, and resource-efficient systems to clean water, but also recover resources**,** reuse energy**,** and are adapted to local needs and environmental constraints**.** These four articles demonstrate a shift in industrial wastewater management—from pollutant removal to integrated sustainability. The field is advancing in several dimensions:

- Technological Synergy: Integrating thermal, chemical, and physical mechanisms improves energy efficiency and treatment outcomes.
- Contextual Adaptability: Decision-support frameworks ensure that technologies are not only effective but also locally viable and responsive to socio-economic realities.
- Environmental Stewardship: The rise of nanotechnology and resource recovery aligns treatment technologies with broader ecological and sustainability goals.
- Scalability and Systems Thinking: There is a growing recognition of the need for pilot-scale deployment, systemic reuse, and life cycle thinking to transition from innovation to implementation.

5 Future Research Directions and Conclusion

A notable progress in water technologies have significantly enhanced the removal of heavy metal from wastewater. However, the translation of laboratory-scale innovations into field-scale, economically viable applications remains a critical challenge. Persistent barriers include high operational costs, intensive energy requirements, limited institutional capacity, and policy fragmentation in many developing regions [13]. Addressing these challenges requires technical refinement and stronger governance, cross-sectoral collaboration, and investment in research and infrastructure [3, 27, 38].

The review highlights that no single technology can comprehensively address multifaceted issue of heavy metal contamination. Instead, hybrid systems, integrating adsorption, electrochemical, biological, and membrane -based processes, offer the most promising pathway toward sustainable and context-appropriate solutions. Among these, hybrid thermophysical systems and nanomaterial electrochemical approaches stand out for their high removal efficiency, potential for energy recovery and scalability.

Key directions for future research include:

- Hybrid System Optimization: develop integrated models to enhance system performance and energy efficiency.
- Decentralized and Modular Systems Design: support adaptable technologies for rural and remote settings.
- Policy and Governance Innovation: strengthen regulatory framework and institutional coordination

In the context of Mongolia, where water quality is an increasing concern, successful outcomes will require tailored technology transfer, strong environmental policies, and multi-stakeholder collaboration. Continued R&D is vital to developing affordable, efficient, and sustainable solutions. Scaling up these technologies demands more than technical refinement; it also calls for strategic policy development, infrastructure investment, and financial mobilization [13, 25]. Modular systems are advantageous for decentralized and rural settings [34]. Public-private partnerships and government incentives for R&D are crucial to reducing capital and operational costs. Finally, treatment technologies should undergo life-cycle analysis for environmental and economic sustainability, considering energy consumption, material use, emissions, and long-term operating costs [22]. Among the most effective methods for heavy metal removal are membrane filtration and electrochemical techniques for multi-metal contamination. Adsorption technologies using biochar and engineered nanomaterials offer targeted metal removal. Bioremediation and green precipitation methods provide low-cost and ecologically sound options for rural areas.

In conclusion, the convergence of technological innovation, policy support and contextual adaptation will be critical to achieving sustainable wastewater treatment. By bridging the gap between research and implementation, future systems can enhance water security, and support long term environmental resilience.

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