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Innovative strategies for wastewater treatment: harnessing green technologies for sustainable resource recovery. a review

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A major global issue that negatively affects both ecosystems and human populations alike is the inability to supply enough fresh water to fulfill demand. A gap among the supply and demand of water is its defining feature, and it can show itself as either a monetary or physical water shortage. Wastewater treatment plays a vital role in protecting the environment by eliminating contaminants that damage aquatic ecosystems, such as insufficient nutrients that lead to algal blooms, and for safeguarding human health by stopping the spread of pathogens that cause disease. The treatment of wastewater includes conventional physical, chemical, and biological techniques like activated sludge and sedimentation; nanotechnology that uses high-surface-area nanomaterials for adsorption and decomposition; and biotechnological techniques that use microorganisms in systems like oxidation ponds and trickling filters. Biotechnology offers sustainable biological routes to break degrade organic matter, nanotechnology offers sophisticated techniques for eliminating a variety of contaminants, and conventional approaches give a basis. This review highlights the conventional, biotechnological, and nanotechnology-based approaches used in wastewater treatment and discusses the key challenges and future directions in this critical field.

KEYWORDS

wastewater, chemical and physical methods, nanotechnology, biological techniques, physical methods

1 Introduction

The world's water crisis is a serious worldwide scarcity of clean, drinkable fresh water that affects billions of people because of things like pollution, worldwide warming, population expansion, and wasteful water consumption. The causes encompass unsustainable rates of use, polluting water supplies that exacerbate scarcity, and elevated temperatures which trigger droughts. The effects are extensive, leading to shortages of food, health issues, financial stress, and possible social unrest over diminishing resources. Safely regulated drinking water facilities are unavailable to more than 2 billion people globally. For at least a portion of the year, about half of the world's population suffers from acute water scarcity. Diseases linked to poor sanitation, hygiene, and access to clean water claim the lives of millions of children each year (Shemer et al., 2023).

The crisis has several causes, including: (1) Climate Change: the supply of freshwater is declining due to altered weather patterns, greater evaporation, greater severity and frequency of droughts, and melting glaciers. (2) Population Growth: As the world's population rises, increases the need for water across all domains, including home, industrial, and agricultural uses. (3) Pollution: Water sources become unfit for human consumption due to contamination from untreated waste water, waste from factories, and agricultural runoff. (4) Inappropriate Use: Industrial activities also use a lot of water, and agriculture, which consumes the most freshwater worldwide, frequently uses it inefficiently. (5) Insufficient Infrastructure: A lack of infrastructure in many developing countries makes it difficult to efficiently gather, purify, and distribute water, which leads to shortages and uneven distribution (Amparo-Salcedo et al., 2025).

The crisis has had numerous effects, on the following pillars: (1) Human Health: Waterborne illnesses, which are especially harmful to children, are more likely to occur when people have limited access to fresh water and sanitary facilities. (2) Food Security: Insufficient water has an impact on irrigation, which lowers agricultural productivity and raises the risk of malnutrition. (3) Economic Repercussions: National economies may be strained, water prices may increase, and economic growth may be slowed. (4) Environmental Deterioration: Pollution and overexploitation cause rivers, lakes, and aquifers to dry up, which damages ecosystems and causes the extinction of species. (5) Social and Cultural Tensions: Conflicts between nations and groups can escalate due to competition for limited water resources (Aborode et al., 2025).

Wastewater comprises a wide variety of physical, chemical, and biological contaminants, such as suspended particles, heavy metals, and industrial compounds, all of which need to be eliminated before water can be considered safe. The most common contaminates could be seen in (Table 1). Besides, in order to avoid illness, preserve public health, and protect the environment, wastewater must be treated before it can be released or used again. Through the removal of organic matter, nutrients, and diseases that can contaminate beaches, deplete oxygen, and promote eutrophication, it safeguards aquatic habitats and human recreation. By allowing treated wastewater to be reused in industry or agriculture, treatment also helps the circular economy and conserve limited water resources by lowering dependency on natural water sources. Drinking water supplies can get contaminated by bacteria, viruses, and other pathogens found in untreated wastewater, which can lead to deadly illnesses like cholera, typhoid, and hepatitis. Water bodies such as rivers, lakes, and oceans become contaminated when untreated effluent is let into them (Koul et al., 2022). Wastewater treatment reduces the demand on limited freshwater supplies by providing an environmentally friendly supply of water for industrial and agricultural uses. Wastewater treatment promotes economic stability by allowing water reuse and maintaining natural resources, particularly in areas where water is scarce. Additionally, waste is viewed as a supplementary raw element in a circular economy. Healthy ecosystems and leisure pursuits like swimming and fishing depend on clean water. These natural resources are deteriorated by untreated wastewater (Silva, 2023).

Sustainable and resource-focused treatment of wastewater is critical for saving water, regaining valuable assets such as energy and nutrients, decreasing pollution, and lowering greenhouse gas emissions, particularly in light of rising water shortages and worldwide environmental issues. This strategy moves away from just cleaning water and toward a comprehensive system that utilizes water for farming and manufacturing, provides electricity, and produces fertilizers, so supporting economic advantages, encouraging the values of the circular economy, and relieving strain on ecosystems (Ulusoy et al., 2024). Conventional approaches are insufficient for a variety of reasons, including: (1) High Energy Use: Traditional treating techniques are energy-intensive, leading to considerable worldwide energy usage and emissions. (2) Resource Loss: Conventional techniques focus solely on purification, leading to the loss of recyclable assets such as water, energy and nutrients. (3) Sludge Production: These technologies can produce significant volumes of sludge, making disposal challenging. (4) Traditional methods may not be successful in removing newer pollutants and developing toxins (Twi-Yeboah et al., 2024).

2 Conventional wastewater treatment processes including physical, chemical, and biological methods with strengths and limitations

Conventional wastewater processing employs, physical methods (such as screens, grit tanks, and sedimentation) for initial and primary processing, biological techniques (such as activated sludge and anaerobic breakdown) for subsequent treatment that grind down organic matter, and chemical processes (such as decontamination and sophisticated oxidation and ozonation) for supplementary treatment to eliminate nutrients, pathogens, and recalcitrant substances. The process is divided into four phases: initial, primary, secondary, and tertiary/advanced, with each step designed to remove certain types of pollutants, such as big debris, suspended particles, organic matter, and pathogens, in order to achieve water quality criteria for release or reuse (Fernandes et al., 2024) (Figure 1).

2.1 Physical procedures

These methods are designed to remove solid items from wastewater using mechanical and physical methods.

1. Preliminary Treatment: Large debris, particles, and floating objects are removed by barriers, grit vessels, and crushing to prevent equipment damage.
2. Primary Treatment: Sedimentation tanks (clarifiers) settle suspended materials into wastewater, while fats, oils, and oil float to the above as foam. Another approach employed here refers to dissolved air flotation (DAF).
3. Other Physical Techniques: Later steps use sand filtration, adsorption (with activated carbon), and membrane filtration to remove finer suspended particles and certain dissolved pollutants, respectively (Kato and Kansha, 2024).

2.2 Chemical procedures

Chemical procedures react with contaminants and eliminate them, usually in the tertiary or later phases.

TABLE 1 Waste water contaminants and their different impacts.

Contaminants	Examples	Impact	References
1a: Chemical and inorganic contaminants			
Nutrients and biproducts	Ammonium, nitrates and phosphorus	Eutrophication in water bodies	Mažeikienė and Šarko (2022)
Heavy metals	Cadmium, chromium, and lead	Accumulate in the environment and food chain, posing serious health risks	Thabede et al. (2024)
Surfactants	Detergents	Membrane fouling, eutrophication of water bodies, and foaming	Mousavi and Khodadoost (2019)
Salts	Sodium chloride, magnesium sulfate, potassium chloride, sodium sulfate, iron salts	Toxic to microorganisms	Guo et al. (2023)
1b: Chemical and organic contaminants			
Pharmaceuticals	Drugs, hormones	Disrupting natural processes	Frascaroli et al. (2021)
Pesticides	Imidacloprid and fipronil	Exceeding ecological benchmarks and increasing in-stream toxicity	Ignatowicz et al. (2023)
(2) Sediments and suspended solids	Sand, clay, plant debris	Affecting aquatic environment	Richter and Ayers (2018)
(3) Microbes	Bacteria and viruses	Water borne infections	Umar et al. (2019)
(4) Radioactive contaminants	Isotopes	Disrupting natural cycles	Liang et al. (2024)

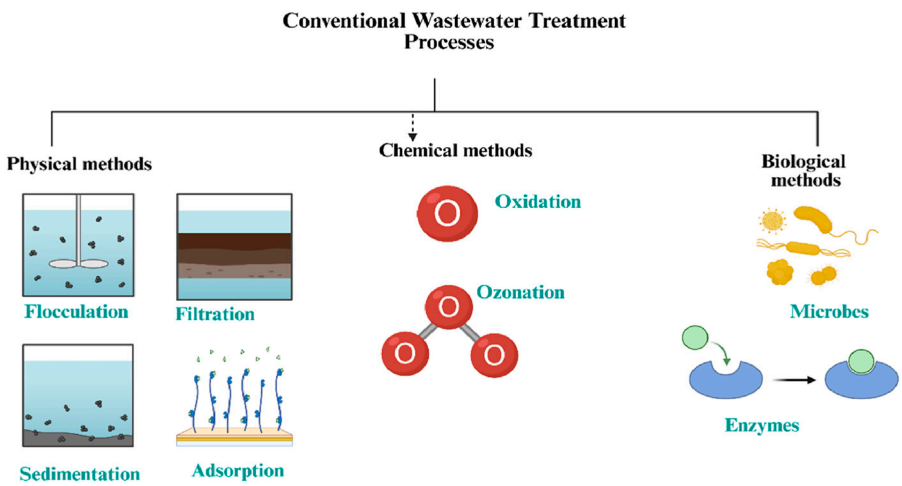

FIGURE 1
Illustration for various traditional protocols for waste water treatments (Physical, chemical, and biological methods).

1. Coagulation/Flocculation involves adding chemicals, such as aluminum salts or polyamide compounds, to clump tiny floating particles into bigger flocs. These flocs can subsequently be removed using sedimentation or filtering.
2. Disinfection involves using chemicals like chlorine, ozone, or chloramine to eliminate harmful bacteria prior to discharge.
3. Advanced Oxidation systems (AOPs) employ strong oxidants for breaking down irreversible organic pollutants that biological systems cannot (Tahraoui et al., 2024).

2.3 Biological procedures

These technologies rely on biological agents, such as bacteria, algae, and other microbes, to degrade organic materials and nutrients.

1. Secondary procedures include activated sludge, which uses microorganisms to absorb soluble and colloid organic waste. The fragments are then deposited in a second clarifier.

TABLE 2 Various classical methods for water treatment and their strength and limitations.

Treatment method	Strengths	Limitations	References
Physical methods	• Simple design and operation • Low chemical requirements • Effective for removing large solids, grit, and suspended particles • Low operational cost	• Ineffective for dissolved pollutants or nutrients • Requires frequent maintenance and sludge disposal • Limited removal of pathogens and organic matter	Wang et al. (2024)
Chemical methods	• Effective for removing dissolved and colloidal impurities • Can target specific contaminants (e.g., phosphates, heavy metals) • Rapid treatment process • Enhances clarity and disinfection efficiency	• High chemical and sludge-handling costs • Risk of secondary pollution from residual chemicals • Requires skilled operation and pH control • Limited biological oxygen demand (BOD) removal	Al-Ajmi et al. (2024)
Biological methods	• Efficient removal of biodegradable organic matter and nutrients • Environmentally friendly and sustainable • Lower chemical use • Can produce useful by-products as biogas	• Sensitive to toxic substances and operational changes • Requires longer retention time and larger area • Produces excess sludge needing further treatment • Less effective for non-biodegradable or toxic compounds	Sravan et al. (2024)

2. Anaerobic digestion involves microorganisms breaking down organic waste in vast tanks without oxygen, resulting in biogas that may be utilized for energy.
3. Nitrification is an enzyme reaction that converts ammonia to nitrate and nitrogen gas, which is then discharged into the atmosphere. Phosphorus may additionally be eliminated biologically by adding it to microbial biomass (Nasir et al., 2024).

Traditional wastewater treatment methods are dependable, broadly applicable, and economical for eliminating traditional pollutants such as suspended objects and organic matter, they are not as effective at eliminating emerging pollutants (such as pharmaceuticals, plastic bags, and genes resistant to antibiotics), they use a lot of energy and land, and they may result in sludge that needs additional handling (Fernandes et al., 2024). The details in (Table 2) summarize the various advantages and disadvantages of physical, chemical and biological methods using in water treatment.

Traditional physical, chemical, and biological wastewater removal technologies, while successful for classical pollutants, are becoming more unsuitable for newly developed pollutants such as pharmaceuticals, cosmetics, microplastics, and endocrine disrupting chemicals. These contaminants frequently survive normal treatment procedures because they are chemically stable and exist in trace amounts. Physical approaches fail to absorb dissolved organics, whereas chemical treatments might generate harmful byproducts and raise operating expenses. Slow decomposition rates and microbial sensitivity to hazardous chemicals constrain biological systems, notwithstanding their long-term sustainability (Rana et al., 2025). Furthermore, conventional systems' high energy consumption and sludge generation make them environmentally unsustainable. In today's sustainable economy and recovery of resources era, treatment plants are expected to retrieve energy, nutrients, and precious materials in addition to purifying water. This necessitates a paradigm change toward sophisticated oxidation procedure membrane processes, and comprehensive resource recovery systems. As a result, relying simply on old approaches is no longer sufficient to satisfy contemporary ecological and long-term goals (Zhang, 2025).

3 Nanotechnology and advanced materials

The use of nanotechnology and cutting-edge materials improves wastewater treatment by employing nanoscale organic, nonorganic, and polymer-based nano-substances (Figure 2) as well as materials such as carbon nanotubes, nanoparticles, and nanohybrid membranes that eliminate pollutants like organic molecules, heavy metals, and pathogens with outstanding effectiveness. These nanomaterials take advantage of special properties, like a substantial surface area and better reactivity, for procedures like adsorption, filtration, and photocatalysis to develop simpler, more robust, and less chemically based treatment systems. Examples of these include nanofiltration membranes that incorporate nanoparticles, nanoadsorbents that capture toxins, and nano-zero-valent iron (nZVI) for disinfection (Ojha, 2020). Nanomaterial-enhanced membrane procedures, along with nanoadsorbents and nanocatalysts, provide sophisticated wastewater treatment alternatives by utilizing the special qualities of nanomaterials, such as their high surface area and reactive characteristics, to effectively remove contaminants like organic substances, heavy metals, and microorganisms. Nanoadsorbents physically absorb pollutants, whereas nanocatalysts help break down pollutants through chemical reactions. Additionally, nanomaterials are used in membrane technologies like nanofiltration to enhance efficiency and make it possible to treat even the tiniest pollutants (Tripathy et al., 2024). Besides, magnetic nanoparticles, with their large surface area, high adsorption capacity, and ease of magnetic separation, provide an effective and practical alternative for wastewater treatment. They can effectively remove heavy metals, dyes, and organic contaminants by adsorption or catalytic degradation. After treatment, the particles may be swiftly retrieved using a magnetic field, allowing for reuse and minimum

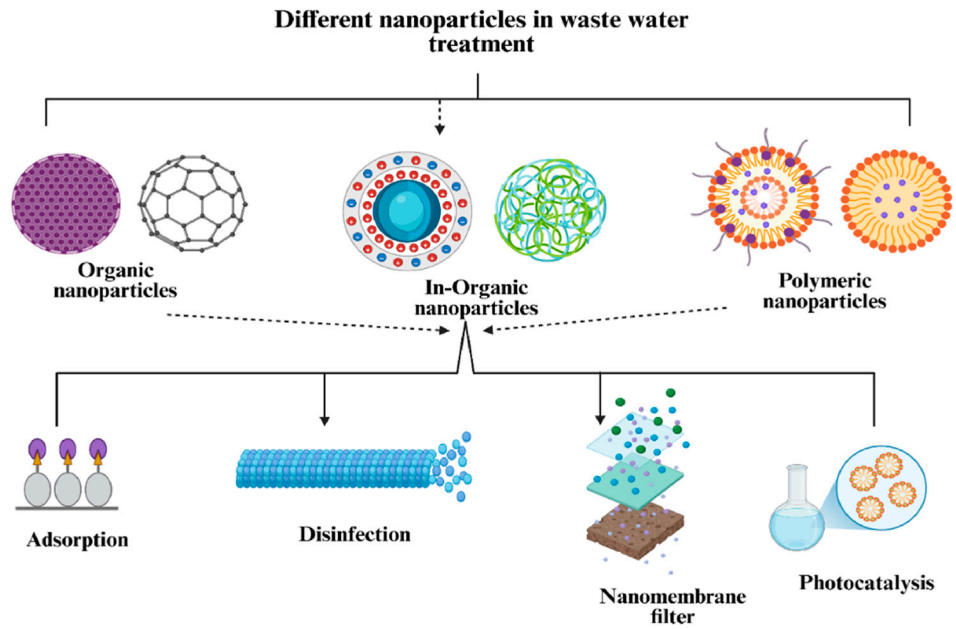

FIGURE 2
Various types of nanoparticles and their functions in wastewater treatment.

secondary waste, making them a cost-effective and sustainable solution for advanced water filtration (Lu et al., 2025).

3.1 Nanoadsorbents and nanocatalysts

Nanotechnology-based methods for water treatment such as nanoadsorbents and nanocatalysts are essential because they use the special qualities of nanomaterials, such as their high surface area and regulated shapes, to eliminate impurities. Physical adsorption is used by nanoadsorbents to absorb pollutants such organic molecules, heavy metals, and infectious agents, while nanocatalysts assist in breaking down organic pollutants that persist by facilitating sophisticated chemical oxidation mechanisms. Even for newly discovered micropollutants, these techniques provide inexpensive, energy-efficient, and extremely effective ways to clean wastewater and sanitize water (Rezania et al., 2024). The quantum-size impact, which increases the energy spectrum and decreases the particle size, is the main benefit of nanotechnology (Epelle et al., 2022). Additionally, as a procedure, photodegradation offers a number of benefits, including low cost, reusability, and generally full deterioration. Despite all of the advancements, there are still certain problems with nanophotocatalysis, such as toxicity and catalyst recovery from mixtures. These kinds of problems restrict the higher-level uses and range of nanophotocatalysts (Friedmann, 2022). Higher photon consumption and restrictions on mass transfer are the main obstacles in the intensification phase (Younis and Kim, 2020). As a result, scientists and researchers are currently concentrating on additional nanocomposite materials that can lower toxicity when used in the course of waste water treatment (Yaqoob et al., 2020). Combining nanocomposites with nanophotocatalytic reactor structures prolongs the solution to the electron pair recombination problem, which is best solved by the notion of nanocomposites. Microfluidic reactors are the new, contemporary reactors that provide a new avenue for in-depth analysis of reaction and synthesis phase features. Reactors that operate on a micro level with reactants are known as microfluidic reactors (Hooshmand et al., 2020; Pervaiz et al., 2025).

On the other hand, other techniques like adsorption were applied whereas nanoadsorbents and nanomaterials efficiently remove contaminants from wastewater by physically attaching to them. They had the following properties: remarkable surface area, improved adsorption sites, and adaptable pore architectures all help and explain their remarkable efficiency as carbon nanotubes and iron oxide nanoparticles. Nanocatalysts break down or change pollutants into less dangerous forms chemical reactions. Advanced oxidation processes, frequently use them. Photocatalysts, such as TiO_2, are materials that, when exposed to light, break degrade persistent organic pollutants. The silver nanoparticles and nanocomposites can be utilized in disinfection have broad-spectrum antibacterial properties (Choi and Lee, 2022). According to the published research, surface changes, chemical stabilizers, and nanoadsorbent shape all affect the harmful effect (Abu-Dief et al., 2025). Therefore, in order to overcome the toxicity difficulties and health dangers, effort must be paid to synthesizing more stable morphology (size and form). Additionally, the bioadsorbents' excellent biodegradability, superior biocompatibility, and nontoxicity make them potentially interchangeable with chemically produced nanosorbents. Since graphene oxide is a relatively new nanomaterial that can be used as a nanosorbent to remove pollutants and because of its outstanding qualities, it is recommended by the scientific community (Georgin et al., 2025). The commonly used nanosorbents, including carbon-based materials, metal oxides, and magnetic nanoparticles, are tailored to remove specific contaminants could be seen in (Table 3). In practice,

TABLE 3 The commonly used nanosorbents in waste water contaminants and their various functions.

Nanosorbents type	Roles	References
Carbon nanotubes	Elimination of heavy metals and organic pollutants	Li et al. (2022)
Metal oxides	Removal of organic pollutants and exhibit antimicrobial properties	Alhalili (2023)
Magnetic nanosorbents	They have specific affinities for organic contaminants and enabling separation via magnetic fields	Phouthavong et al. (2022)
Nanocomposites	They used in treating wastewater containing organic species, particularly dyes	Khan et al. (2025)
Graphite oxide	Dye removal	Yang et al. (2024)
Polymer fibers	To eliminate the harmful metals, including arsenic	Wang et al. (2025)
Nano-aerogels	In order to obtain uranium from water	Zhao et al. (2023)
Nano-iron oxides	To remove hormones and harmful drugs from water	Abdelghany et al. (2025)

nanoadsorbents and nanocatalysts provide efficient, rapid, and compact wastewater treatment solutions by eliminating a wide spectrum of contaminants at low concentrations. They can be readily incorporated into current treatment systems, enhancing performance without requiring significant infrastructure improvements. Furthermore, their reusable nature, minimal chemical consumption, and excellent treatment effectiveness make them economical and ecologically favorable solutions for real-world wastewater management (Tripathy et al., 2024). Furthermore, when compared to traditional water treatment techniques, nanomaterials can offer more cost-effective alternatives. They can be modified to meet the needs of individual customers and incorporated into current treatment methods. Advanced techniques based on nanomaterials provide wastewater treatment and water purification solutions that are more sustainable and energy-efficient (Sanni et al., 2024). Nanoadsorbents and nanocatalysts exhibit potential effectiveness in pollution removal and degradation process enhancement, but their technological preparedness is generally limited to the laboratory and pilot scale. Scalability is constrained by the costly nature of nanoparticle manufacturing and the difficulties in uniform distribution throughout treatment procedures. From an environmental standpoint, their potential leaking and permanence pose issues regarding secondary contamination. Future research should focus on improving synthesis with green precursors and establishing safe recovering or reuse procedures (Sanni et al., 2024).

3.2 Membrane technologies with nanomaterials

Nanomaterials such as metal oxides (TiO_2, ZnO), carbon nanotubes (CNTs), and metal-organic frameworks (MOFs) are integrated into membranes to increase permeation of water, hardness, and effectiveness in separation while decreasing membrane fouling. This improves wastewater treatment through membrane technologies. Water purification and repurposing can be accomplished more sustainably and effectively with the help of these nanomaterial-modified membranes, which can successfully remove contaminants such as metal ions, organic molecules, colors, and bacteria (Al-Maliki et al., 2022). The membrane's pores can be made larger and more numerous by nanomaterials, which will enable more water to flow through more quickly. The addition of robust nanoparticles increases the membrane's overall strength and durability. By changing the membrane's surface characteristics, nanomaterials can prolong the membrane's life by reducing its susceptibility to fouling by contaminants. Certain nanomaterials, like MOFs for molecular sieving of pollutants, have special qualities for the selective removal of pollutants (Ahmed et al., 2024).

The frequently Adopted Nanomaterials include:

(1) Carbon nanotubes (CNTs) enhance flux, permeability, and fouling resistance in a variety of membrane configurations, such as those employed for the removal of oil and COD. (2) Metal oxides (such as ZnO and TiO_2): Used for their capacity to enhance water flow and selectivity as well as their photocatalytic activity to break down organic contaminants. (3) Metal-Organic Frameworks (MOFs): Provide molecular sieving capabilities and great selectivity for the elimination of contaminants. (4) Silver nanoparticles, or AgNPs, decrease biofouling and increase water flux, especially when treating organic dyes (Manawi et al., 2025).

Membranes enhanced with nanomaterials have great promise for eliminating organic contaminants and recovering metal ions. Nanomaterial-functionalized membranes are efficient at removing bacteria and dyes from wastewater. Membranes are used to improve water recovery and remove certain pollutants from a variety of industrial wastewaters, including those from the metal processing and textile manufacturing sectors (Aydin et al., 2023). Membranes based on nanomaterials provide a technique to create energy-efficient and environmentally friendly treatment of wastewater and water systems. In order to produce optimal membranes with enhanced qualities for water treatment, current research involves developing new synthesis techniques for innovative nanostructures including carbon nanotubes and nanocomposites (Khraisheh et al., 2021). The most common nanomembrane's could be seen in (Table 4). In practice, nanomaterial-enhanced membrane technologies provide excellent filtration efficiency, increased permeability, and good fouling resistance, which makes them ideal for the treatment of wastewater. Incorporating nanomaterials like graphene, TiO_2, or silver nanoparticles enhances antibacterial and self-cleaning capabilities, leading to longer membrane lifespan. These hybrid membranes allow compact, environmentally friendly and ecological treatment of wastewater from industrial and municipal applications (Al-Maliki et al., 2022).

TABLE 4 Different types of nanomembranes and their uses.

Nanomembrane types	Benefits	Drawbacks	Uses	References
Nanofiber membrane	Superior porosity, custom-made, antibacterial, and effective permeation	Blocking pores and potentially releasing nanofibers	Water handling, filter cartridges, prefiltration, ultrafiltration, and independent filtration devices	Tang et al. (2022)
Nanocomposite membrane	Superior water permeability, high scaling resistance, high hydrophilicity, and strong mechanical and thermal stability	When oxidizing nanomaterial, which is utilized to release nanoparticles, a significant amount of resistant material is needed	Water purification and desalination	Sahu et al. (2023)
Nanofiltration membrane	Better selectivity, comparatively lower pressure, and charge-based repulsion	Blocking of membranes	Color, hardness lowering, and odor elimination	Covaliu-Mierlă et al. (2023)
Self-assembling membrane	Uniform nanopores to membranes	Lab level only	Ultrafiltration	Al-Arjan (2023)
Aquaporin-based membrane	Enhanced permeability and ionic affinity	Inadequate mechanical integrity	Water purification and desalination	Yılmaz and Özkan (2022)

In pilot-scale applications, membranes augmented with nanomaterials show moderate to high technological readiness with enhanced selectivity, permeability, and fouling resistance. However, maintenance complexity, endurance in actual wastewater conditions, and membrane manufacture costs limit scalability. Environmental trade-offs include difficulties with end-of-life disposal and the discharge of nanoparticles during operation. For wider industrial adoption, scalable production techniques and the development of sustainable membrane materials will be crucial (Aydin et al., 2023).

3.3 Nano- and micromotors

Nano- and micromotors are emerging as innovative tools in wastewater treatment due to their ability to self-propel and actively interact with pollutants at the micro- and nanoscale. These tiny, autonomous machines can move through water using chemical, magnetic, or light-driven propulsion, allowing them to enhance mass transfer and pollutant contact efficiency. Functionalized nano- and micromotors can adsorb, degrade, or catalytically remove contaminants, including heavy metals, dyes, and pharmaceuticals. Their mobility provides a significant advantage over passive nanomaterials, improving treatment speed and effectiveness. Moreover, some micromotors can be magnetically guided or collected, facilitating reusability and minimizing secondary pollution. Although still in the research phase, these technologies show great potential for next-generation, energy-efficient, and targeted wastewater purification systems (He et al., 2024). Motors can be propelled by internal sources of energy like hydrogen peroxide or external fields like magnetic fields, which cause a chemical reaction. Unlike passive technologies, which rely on sluggish diffusion, their active motion propels fluid mixing, putting the motors closer to the pollutants. The motors' operational surfaces have the ability to chemically attach to and "pick up" contaminants. Certain motors function as catalytic platforms, converting pollutants into less dangerous forms through a chemical reaction. Certain designs' magnetic qualities make it simple to collect and dispose of the motors after usage, allowing for several treating cycles (Ju et al., 2025). Among the benefits are: (1) Increased Efficiency: Because of their dynamic character, pollutants interact more quickly and uniformly, greatly accelerating and enhancing the efficacy of treatment. (2) Lower Costs and Energy: They can reduce overall costs by increasing efficiency and possibly lowering the requirement for conventional energy-intensive treatment steps. (3) Targeted Remediation: By programming sophisticated nanorobots to perform particular tasks, pollutants can be precisely removed. (4) Environmentally Friendly: They can help treat water in a more sustainable way by breaking down contaminants into non-hazardous compounds and providing opportunities for reuse (Dutta et al., 2024). A group of examples nano/micromotor could be seen in (Table 5). Micromotors and nanomotors are a relatively new technology that is mostly limited to proof-of-concept and small-scale lab research. Due to complicated construction, restricted motion control in real matrices, and high energy needs, scalability is still a significant hurdle. Because motors that are powered by chemicals or metals have the potential to produce reactive residues or cause toxicity, their effects on the environment are substantial. The development of micromotors that are recyclable, fuel-free, and biocompatible may increase their potential for environmentally friendly wastewater treatment (Soto et al., 2020).

3.4 Challenges of toxicity and regeneration

High manufacturing expenses, lack of longevity and robustness, difficulty recovering and regenerating after processing, scaling to large-scale uses, and possible toxicity to ecosystems and human health are the main obstacles facing nano-adsorbents and nano-catalysts in the treatment of waste water. New, non-toxic nanocomposites, more reliable and magnetic recovery techniques, economical synthesis procedures, and additional study into the long-term environmental effects of nanomaterials are all necessary to address these issues and encourage their widespread and sustainable application in wastewater treatment (Akhtar et al., 2024). Nanomaterials can leak and build up in aquatic environments, even those intended for water treatment, which could pose serious threats to human health and the environment. Understanding how nanoparticles behave after application,

TABLE 5 Nano/micromotor and their applications in waste water treatments.

Nano/micromotor	Mechanism of working	Applications	References
A: Catalytic micromotors			
Platinum (Pt)-coated micromotor	It carried by the enzymatic breakdown of H_2O_2 into oxygen bubbles, which generates recoil force	Degrade organic pollutants via a Fenton-like reaction	Naeem et al. (2021)
Iridium-gold (Ir-Au) janus microsphere motor	It propelled by hydrazine vapor in the surrounding atmosphere	Enhance contaminant degradation	Cheng et al. (2025)
Fe/Pt microtubular motor	It uses the Fenton reaction among iron (Fe) and H_2O_2 to produce fuel for propulsion as well as to increase catalytic processes	Water remediation	Zha et al. (2018)
B: Magnetic nanomaterials			
Silica-Coated Fe_3O_4	Use their magnetic properties for separation and the silica shell for adsorption of contaminants	Removing various contaminants from wastewater	Habila et al. (2023)
Chitosan-Magnetic Nanoparticles	Chitosan, a natural biopolymer, is combined with magnetite to create a magnetic bio-sorbent to move move pollutants like heavy metals, dyes, and organic compounds	More robust and easier to separate for pollutant removal	Benettayeb et al. (2023)
Magnetic Activated Carbon	A combination of Fe_3O_4 nanoparticles and activated carbon	Used for removing organic pollutants	Hashemi and Soleimani (2025)
C: Multifunctional micromotors			
Fe/Pt-based tubular micromotors	These micromotors employ hydrogen peroxide (H_2O_2) as power and a reagent for the Fenton reaction, creating reactive hydroxyl radicals (•OH), which destroy organic contaminants	An environmentally friendly and efficient way for treatment contaminated water, which overcomes the limitations of existing technologies	Cui et al. (2023)
Biotemplated micromotors	Micromotors are made by altering natural fibers like kapok fibers with nanoparticles (e.g., MnO_2 NPs and $MnFe_2O_4$ NPs)	Adsorption is used to remove heavy metals, while advanced oxidation is used to destroy organic pollutant by these micromotors	Chen et al. (2024), Shi et al. (2024)

particularly their bioaccumulation mechanisms and long-term impacts on the environment and species, is lacking. Researchers exert many efforts to eliminate these dangers by creating and applying novel nanocomposites with lower toxicity (Xuan et al., 2023).

Besides, it is difficult to accurately separate and retrieve nanoadsorbents and nanocatalysts from treated wastewater mixtures after they have been used. One option to overcoming this is to utilize magnetic nanoparticles that can be recovered using external magnetic fields, however this is not a general solution. To make these nanomaterials more sustainable, effective and affordable technologies for regenerative and repeated recycling are required. High expenses for manufacturing and a present emphasis on laboratory-scale investigations impede the translation of nano-based technologies from investigation to massive usage in industry. Nanomaterials can lose stability and efficiency over time, necessitating regular substitution, which raises operating expenses. One major obstacle is still integrating innovative nanomaterial-based solutions into the current water treatment infrastructure. To guarantee the dependability and efficacy of nanomaterials, more research on how they perform over time in practical settings is necessary (Jackson et al., 2025).

There are currently few established procedures for the safe reuse and disposal of nanomaterials, and technology readiness for controlling their toxicity and regeneration is constantly evolving. Establishing economical regeneration cycles that preserve performance without generating hazardous byproducts is essential for scalability. Because inadequate regeneration might result in the accumulation of nanoparticles and ecological hazards, the environmental trade-offs are crucial. To guarantee environmental safety and the circular use of nanomaterials, it will be crucial to advance green regeneration techniques and lifetime assessments (Sarker and Kaparaju, 2025).

4 Biotechnological approaches

Biological processes comprising bacteria, enzymes, and plants are used in biotechnological wastewater treatment methods to eliminate contaminants, stabilize waste, and provide beneficial byproducts like biogas. For a greener approach to water utilization and resource recovery, key techniques include membrane bioreactors (MBRs), biofilters, activated sludge processes, microbial fuel cells (MFCs), designed wetlands, and omics applications. These techniques provide economical and environmentally friendly substitutes for traditional chemical treatments. In this section we will focus on three of these applications as the following:

4.1 Enzyme-assisted wastewater treatment

Biocatalysts, or enzymes, are used in enzyme-assisted wastewater treatment to break down complex organic contaminants, including proteins, lipids, and medications, into less hazardous forms in mild circumstances. This environmentally friendly technique increases anaerobic digestion, biodegradability, and dewaterability, which boosts the effectiveness of traditional treatments and sludge management. Immobilizing enzymes to increase their longevity and reusability, improving enzyme selectivity for different pollutants, and creating economical methods to get over obstacles like expensive setting up and stability of enzymes are important components (Zhang et al., 2018).

Certain chemical reactions are catalyzed by enzymes, which reduce complicated contaminants to less harmful forms. Proteins, lipids, and phenols can be specifically broken down by enzymes thanks to their active sites, which attach to particular pollutant substrates. When compared to traditional chemical treatments, enzymatic reactions can result in less energy usage and fewer harmful byproducts because they usually take place at mild pH and temperature settings. Because they have a less negative ecological effect and produce fewer harmful byproducts, enzymes are healthier alternatives to harsh chemical procedures. Enzymes improve the general condition of the final effluent and increase the effectiveness of wastewater treatment procedures. Because immobilized enzymes may be recovered and utilized repeatedly, the biocatalyst's lifespan is increased and expenses are decreased (Alaidaroos, 2023). Maintaining enzyme reliability, reusability, and activity under challenging wastewater conditions requires optimizing enzyme immobilization strategies. To maximize enzyme performance, comprehend degradation mechanisms, and create technically and financially efficient enzymatic platforms for large-scale applications, more research is required (Tadesse and Liu, 2025).

Bacteria generate enzymes such as lipases, proteases, and laccases, which are essential for breaking down contaminants in wastewater treatment. These enzymes, which can also be manufactured by engineered microbes, aid in the biodegradation of complicated organic molecules, hence improving the quality of water. Strategies are being investigated to encapsulate these enzymes on scaffolds or to use customized bacterial consortia to improve their durability, usefulness, and effectiveness in treating a variety of wastewater, including waste from factories and cities (Al-Maqdi et al., 2021). In wastewater treatment, indigenous organisms are bacteria that naturally reside in water or soil, whereas non-indigenous or introduced organisms are those that are not native to the environment and are added externally. The distinction is significant because indigenous bacteria are frequently better adapted to local conditions and can be used for long-term activities such as bioremediation, but introduced species can be invasive and require careful control (Shah et al., 2025).

The selective breakdown of complex organic contaminants is a promising application for enzyme-assisted systems, whose technological readiness now ranges from lab to early pilot stage. Enzyme instability, high manufacturing costs, and sensitivity to changing effluent conditions hinder scalability. Although recovering and reusing enzymes is still difficult, enzyme-based operations are generally safe for the environment. Creating economical enzyme carriers and immobilization techniques could improve practical deployment and sustainability (Iroegbu et al., 2025).

4.2 Genetic engineering of microbes for pollutant degradation

GEMs, or genetically engineered microorganisms, improve the natural ability of bacteria, fungus, and algae to degrade heavy metals and hazardous chemicals, providing a practical and economical approach to eliminating pollutants in wastewater treatment. Although there are still issues with scaling up activities and guaranteeing ecological safety, GEMs can demonstrate more degrading efficiency and a wider spectrum of targets than native strains via the introduction of new genes or altering existing ones. Through genetic engineering, genes encoding for highly degradable enzymes, such oxygenases and dehalogenases, are added to or improved within microorganisms (Zhou et al., 2023).

These genetic alterations resulted to: (1) Improved efficacy: Compared to their wild equivalents, engineered microorganisms break down contaminants more quickly and thoroughly. (2) Broader Decomposition: A single microorganism can be genetically modified to degrade a variety of contaminants, such as xenobiotics and heavy metals. (3) Enhanced Adaptability: GEMs may more easily adjust to novel or complicated pollutants, which increases bioremediation's efficacy (Alaidaroos, 2023).

GEMs are designed to target and break down a variety of compounds, including: Toluene, and other chlorinated hydrocarbons as well as: heavy Metals like copper, and mercury can be bound to, volatilized, or removed in different ways by microbes. Besides, to increase the ability of current systems, such as activated sludge processes, to remove pollutants, engineered microbes can be incorporated (Goutam Mukherjee et al., 2022).

Although genetically modified microorganisms are very effective and selective at decomposing resistant pollutants, their technological preparedness is still limited to restricted bioreactor settings and study. Particularly in open systems, scalability faces stability, containment, and regulatory issues. Unintentional evolution of engineered strains, ecological imbalance, and gene transfer concerns are among the environmental trade-offs. For this strategy to be advanced into field applications, strong biosafety frameworks and biocontainment tools are essential (Jarrar et al., 2024).

4.3 Application of omics in wastewater treatment

A thorough grasp of the microbial populations and processes involved in wastewater treatment can be gained by using omics techniques, which investigate entire sets of microbial molecules (genes, RNA, proteins, and metabolites). The advancement of more effective, sustainable, and economical methods for eliminating contaminants and recovery of resources is being made possible by omics strategies which offer new perspectives on biochemical capacity, population structure, as well as reactions to pollutants. These techniques are transforming wastewater treatment (Jayasinghe et al., 2022). The microbial communities and intricate metabolic pathways associated with wastewater treatment can be better understood by researchers using omics methods (metagenomics, transcriptomics, proteomics, and metabolomics) (Figure 3). This knowledge helps them identify important genes

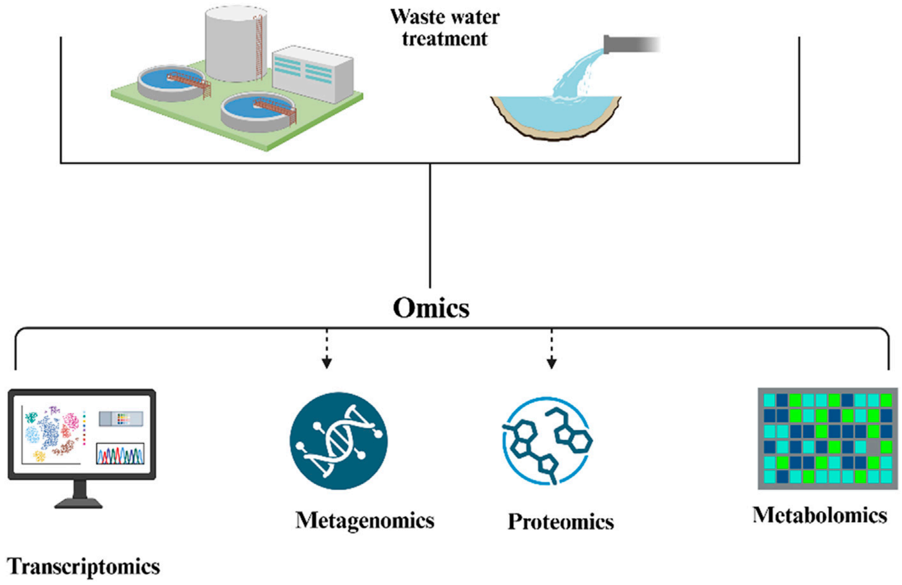

FIGURE 3
Applications of various omics procedures in waste water treatment.

and enzymes, optimize procedures, create new bioremediation techniques, and increase the effectiveness of nutrient removal and the breakdown of pollutants. Omics offers mechanical understanding into how microbes degrade contaminants and how to design these systems for more efficient and sustainable wastewater treatment, including recovering resources and carbon capture, by examining DNA, RNA, proteins, and compounds on a global scale (Renganathan et al., 2025).

The findings of Omics in Wastewater Treatment resulted to: better knowledge of microbial metabolism results in improved nutrient removal from wastewater, helps create procedures for recovering important resources, such as biofuels and bioenergy. New comparable performance measurements for green wastewater treatment facilities focus on thorough ecological effects, moving away from conventional indicators that incorporate Life Cycle Assessment (LCA) for resource loss and global warming, Environmental measures for a holistic ecologic score, overall productivity of factors for technological advancement, real-time ecological tracking using AI, and metrics like energy and ecological burden rate to assess sustainability and efficacy. These modern metrics examine trade-offs among various environmental advantages (Jerves-Cobo et al., 2025). Lower operating costs can result from more effective treatment procedures as green technologies. Aids in creating procedures that lessen the emission of greenhouse gases and pollutants, such as nitrous oxide (N_2O) upon using green technologies (Li et al., 2023).

Omics aids in comprehending how microorganisms and microalgae work together to effectively remove nutrients and collect carbon dioxide from wastewater. Furthermore, through the examination of microorganisms' operational genes, proteins, and metabolites, omics approaches can pinpoint and improve the processes in biology that break down and change contaminants. Omics can also be utilized to enhance microalgal strains for improved efficacy in treatment of wastewater purposes. Omics can help create treatment procedures that are more robust by revealing how microbial communities react to contaminants, hazardous metals, and other stresses in wastewater (Roothans et al., 2025; Chen et al., 2022). Lastly, permits the creation of systems that are more flexible and resilient to address new pollutants (Roothans et al., 2025).

Artificial Intelligence (AI) is revolutionizing wastewater treatment by making it possible to monitor, regulate, and optimize treatment processes more effectively. AI can use machine learning and data processing to examine huge sensor information in order to anticipate pollutant levels, optimize chemical dosage, and reduce consumption of energy. It improves real-time decision-making and ensures reliable operation in varied settings. AI models can also aid with defect identification and maintenance scheduling, reducing downtime and operating expenses. Furthermore, AI-powered systems help to migrate to resource recovery and ecological treatment of wastewater by improving effectiveness and lowering waste output. The use of artificial neural networks (ANNs), fuzzy theory (FL), and biological algorithms (GAs) are examples of key AI technologies that are utilized in machine learning for tasks including energy management, pollutant removal, and predictive maintenance (El et al., 2023; Liu and Liang, 2024; Ugural et al., 2024).

In sophisticated research facilities, omics technologies—such as proteomics, metabolomics, and genomics—provide profound insights into microbial communities, enhancing process optimization and monitoring with a moderate level of technological preparedness. High analytical expenses, complicated data, and the requirement for specialized infrastructure all hinder scalability. Although omics techniques themselves have little effect on the environment, they rely on computational resources that are high in energy. Scalable, data-driven wastewater management and

TABLE 6 The techniques comparing and bring in factors with the point of lifting current status of the technologies regarding implementation.

Technology	Environmental impact	Operational complexity	Resource recovery potential	Current implementation status/TRL	Key integration potential	References
Enzyme-Assisted wastewater treatment	Low—biodegradable and non-toxic; minimal secondary pollution	Moderate—requires enzyme stabilization and immobilization techniques	Moderate—possible recovery of valuable by-products (e.g., biosurfactants, intermediates)	Pilot scale (TRL 5–6)	Easily integrated into existing biological reactors or tertiary treatment stages	Mousavi et al. (2021)
Genetic engineering of microbes for pollutant degradation	Low to moderate—depends on containment; risk of gene transfer if released	High—requires controlled environments, regulatory compliance, and monitoring	High—potential for recovery of biogas, nutrients, and value-added compounds	Laboratory to pilot scale (TRL 3–5)	Integrates with bioreactors under controlled or closed-loop systems	Sharma et al. (2023)
Application of omics in wastewater treatment	Very low—analytical and data-driven with minimal environmental footprint	High—demands advanced data analysis, sequencing, and bioinformatics infrastructure	Indirect—enhances optimization of resource recovery through microbial management	Laboratory to applied research stage (TRL 3–4)	Supports process optimization, monitoring, and predictive control in treatment plants	McDaniel et al. (2021)
AI integration in wastewater treatment	Very low — mainly computational; minimal direct environmental footprint	High — requires sensor networks, data infrastructure, and algorithm training	Indirect — optimizes energy use, sludge management, and resource recovery efficiency	Pilot to full-scale implementation (TRL 6–8)	Strong integration potential for process control, predictive maintenance, and decision-making in existing infrastructure	Senthil Rathi et al. (2025)

research innovation may be able to meet through the integration of omics data into real-time control systems (Vitorino, 2024).

Recent developments in biotechnology, such as omics-based methods, genetically modified microorganisms, and enzyme-assisted systems, have created new opportunities for the sustainable treatment of wastewater. Highly selective and ecologically friendly, enzyme-assisted methods provide quick breakdown of certain contaminants with little secondary contamination. Although immobilization techniques are making integration into current bioreactors easier, their primary limitations include enzyme instability and regeneration costs. The application of genetically modified bacteria is limited by biosafety, regulatory barriers, and ecological hazards, but can improve pollution breakdown by modifying metabolic pathways to target resistant chemicals. Despite not directly treating wastewater, omics technologies—which include proteomics, metabolomics, and genomics—offer profound functional insight into microbial communities, facilitating improved operational control and biological process optimization (Renganathan et al., 2025). When combined, these strategies form a multi-layered integration pathway: omics function as monitoring and diagnostic tools that improve process stability and efficiency, while enzymes and modified microorganisms operate as active therapy agents. They complement rather than compete with one another in promoting sustainable wastewater management, as demonstrated by the clear benefits and trade-offs revealed by evaluating their operational complexity, scalability, and environmental impact (Mohr et al., 2024). The techniques comparing and bring in factors like environmental impact, operational complexity, resource recovery potential together with the point of lifting current status of the technologies regarding implementation could be seen in (Table 6).

5 Comparative scalability and applicability of the technologies described (nanotechnologies and bio/omics-based techniques)

Although nanomaterial-enhanced membranes, nanoadsorbents, and nanocatalysts exhibit high pollution removal efficiency, full-scale implementation is constrained by their high synthesis costs and toxicity issues (mostly nanoparticle leaching). Although their efficacy is encouraging, scalability and environmental safety have not yet been confirmed for nano- and micromotors, which are still in the conceptual or experimental stage. On the other hand, genetically modified microorganisms and enzyme-assisted systems exhibit great biodegradation selectivity with low levels of secondary pollution; nonetheless, operational stability and cost continue to be major obstacles. In contrast to direct treatment, omics-based techniques provide useful insights into system optimization, supporting microbial community management and process control instead of primary remediation (Asghar et al., 2024).

Since enzyme-based and omics-driven methods can frequently be adopted with little change to current infrastructure, they provide improved compatibility with current bioreactor and sludge treatment systems from the standpoints of scalability and integration. To control particle retention and reduce any environmental hazards, on the other hand, nanomaterial-based systems usually require extra parts, like specialist filtration or recovery units. One can better comprehend how near these breakthroughs are to practical use by assessing each technology according to its readiness level, efficacy, toxicity, scalability, cost, and integration possibilities. By highlighting the relative maturity and viability of each green technology, this comparative viewpoint shows how they might work together to develop wastewater treatment methods that are more flexible and sustainable (Renganathan et al., 2025).

6 Future directions and challenges

Nanotechnology and novel compounds hold promise for treatment of wastewater in the future due to better removing pollutants, resource recovery, and ecological sustainability, but scalability, cost, security for the environment, and residual pollutant management remain issues. Future directions include: (1) The development of more advanced nanocomposites and polymer materials, such as nanohybrid membranes with increased hydrophilicity and mechanical stability, may considerably improve the elimination of pollutants. (2) Using nanoparticles like titanium dioxide (TiO_2) as photocatalysts can destroy organic pollutants and microbes when triggered by light, providing a sustainable oxidation technique. (3) Nanomaterials may be utilized for recovering valuable assets from wastewater, including heavy metals, helping to create a recycled economy and improve sustainability. (4) The use of machine learning and AI is advancing adsorption methods by optimizing procedures for treatment, lowering costs, and reducing environmental effect. (5) Nanomaterials' capacity to be tuned with particular surface chemistries and green technology which enables the production of extremely selective adsorbents to collect specific pollutants, such as heavy metals or viruses, at low micropollutant concentrations (Annu Mittal et al., 2024).

Nanomaterials have a favorable impact on wastewater treatment by increasing the elimination of contaminants via adsorption and catalytic degradation, as well as improving filtration membranes, resulting in cleaner water. However, negative consequences include possible damage to aquatic organisms and soil bacteria, the production of reactive oxygen species (ROS), which causes oxidative stress, and the danger of human health problems from bioaccumulation if not appropriately handled. Additional study and careful monitoring are required to mitigate these concerns and ensure the safe and sustained usage of nanomaterials in ecological applications. More study is necessary to fully comprehend the underlying processes of nanotoxicity, how they interact in real-world settings, and their consequences on ecosystems. Clear standards for the safe manufacturing, use, and management of nanomaterials are required to reduce negative impacts and optimize benefits. Collaboration amongst scientists, businesses, government agencies, and other parties is required to guarantee the safe and long-term development and deployment of nanotechnology (Roy et al., 2021; Chávez-Hernández et al., 2024; Khatoon and Velidandi, 2025).

Nano- and micromotors present numerous obstacles, including the ongoing difficulty of developing complex, multipurpose nanorobots with behavioral adaptations and communication. A future goal is to demonstrate these methods at a big industrial scale or for municipal wastewater treatment. Developing a consistent and trustworthy means to produce the requisite asymmetry for autonomous motion is critical (Urso et al., 2023; Das and Sultana, 2024). The growing interest in using nanotechnology to reduce costs in wastewater management has evolved in an upsurge in research into sustainable nanoparticle production methods to measure industrial and municipal-scale feasibility. Certain researchers have proposed that sustainable and inexpensive raw materials be employed in the manufacturing of cheaper nanoparticles (Gupta et al., 2023; Saxena et al., 2025). This has prompted an increase in research into the creation of nanoparticles from plant sources. Furthermore, biological nanoparticle manufacturing has been identified as a promising, low-cost technique of creating nanoparticles. According to several studies, reusing nanoparticles has the potential to lower the cost of using freshly manufactured nanoparticles. An in-depth market evaluation of nanoparticle applications and the financial potential of nanoparticle usage in Waste water Treatment Plants (Mpongwana and Rathilal, 2022). Although several attempts have been made to minimize the costs associated with the use of nanotechnology in wastewater, contrasting it with other technologies revealed that nanotechnology remains expensive for wastewater treatment, despite recent improvements (Rathod et al., 2024; Jackson et al., 2025). As a result, further advancements are required to reduce costs to the point where this technology may be used in developing nations (Rathod et al., 2024; Abu-Dief et al., 2025).

Improved techniques for microplastic identification and removal, improved integration of AI and machine learning for process improvement, standardized collection and analytical tools for wastewater monitoring, an improved comprehension of the combined effectiveness of new innovations, and an increased awareness of the pattern of antibiotic-resistant gene and bacteria propagation from wastewater to the natural world and human populations are some of the major research gaps in wastewater treatment. To safeguard the environment and public health, these gaps must be filled in order to create creative and long-lasting wastewater treatment systems (Enyoh et al., 2025).

These new technologies have a lot of potential to revolutionize wastewater treatment, but they also have some serious drawbacks. The majority of biotechnological approaches, including genetically modified microbes and enzyme-assisted systems, are still in laboratory or pilot-scale progress in terms of technological readiness. Stability problems, cost of production, and inconsistent efficiency under actual wastewater conditions prevent scalability. Although omics-based technologies are effective for monitoring and optimizing systems, their use in traditional treatment plants is still constrained by their high computational and technical requirements. The efficiency of AI integration continues to rely on data quality, model accessibility, and compatibility with current process control systems, even if it is moving closer to operational deployment (Sharma et al., 2023).

Concerns regarding toxicity, permanence, and possible ecological disturbance if not appropriately confined or recovered are raised by nanomaterials and engineered microorganisms from the standpoint of environmental safety. Although AI-driven and enzyme-driven systems are often safer, if they are not adjusted, they may unintentionally increase energy use or waste production. The expense of producing enzymes, the cost of monitoring tools for omics analysis, and the initial outlay required for AI infrastructure all make it difficult for these technologies to be widely adopted economically (Xuan et al., 2023).

Whereas limitations include the following: (1) Implementing sophisticated nanomaterial-based treatment methods on a large industrial scale remains a substantial problem that need more research and development. (2) The cost of making and using these sophisticated materials might be expensive, which must be resolved before broad usage in wastewater treatment. (3) The enduring health and safety effects of nanomaterials, including possible ecotoxicity from disposal and manufacture, must be carefully considered and investigated. (4) If not adequately controlled, certain nanomaterials may lead to the production of secondary contaminants, demanding stringent safety measures and containment techniques. (5) Industrial effluents frequently include complex pollutant combinations, necessitating the development of innovative treatment technologies (Parvin et al., 2025).

The ramifications for regulations and policy are equally significant. While applications of nanomaterials necessitate more precise standards for environmental risk assessment and disposal, the release or widespread usage of genetically modified microbes necessitates stringent biosafety and containment restrictions. Additional concerns about cybersecurity, data governance, and utility standardization are brought up by the use of AI and digital systems. Policymakers must create integrated legal frameworks and financial incentives that enable safe scale-up, stimulate pilot demonstrations, and push the concepts of the circular economy in order to accelerate practical deployment. Translating these promising advances from experimental concepts to wastewater treatment systems that are both environmentally and commercially sustainable will require a concerted effort from researchers, industry stakeholders, and regulatory agencies (Chávez-Hernández et al., 2024; Puteri et al., 2025).

7 Conclusion

Nanotechnology offers very effective, flexible solutions because of the special qualities of nanoparticles, but it has difficulties with toxicity, scalability, and possible environmental effects. Conventional methods are well-established, but they are expensive and have limitations in eliminating some contaminants. While biotechnological methods are less expensive, environmentally friendly, and produce less sludge, they might not be efficient against all contaminants. The best course of action is to combine these techniques in integrated approaches, which take advantage of each technology's advantages to overcome constraints and create future wastewater treatment systems that are efficient and sustainable. Integrating these strategies is the most promising course of action. For example, nanotechnology can boost biological processes to promote pollutant removal, and membranes customized with nanoparticles can improve the effectiveness of treatment. Future treatment of wastewater should strive for recovery of resources and waste valorization in line with the sustainable economy model, which allows for the reuse of treated water and the extraction of valuable resources from waste. The limits of each approach must be addressed by further studies, with a special emphasis on the synthesis of affordable, environmentally friendly nanomaterials, guaranteeing their ongoing safety, and creating effective, scalable technologies that can satisfy international sustainability objectives.

Author contributions

AMHA-R: Conceptualization, Writing – original draft, Writing – review and editing. TMA: Conceptualization, Writing – original draft, Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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