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Nanotechnology in Wastewater Treatment: Evolution and Environmental Impact

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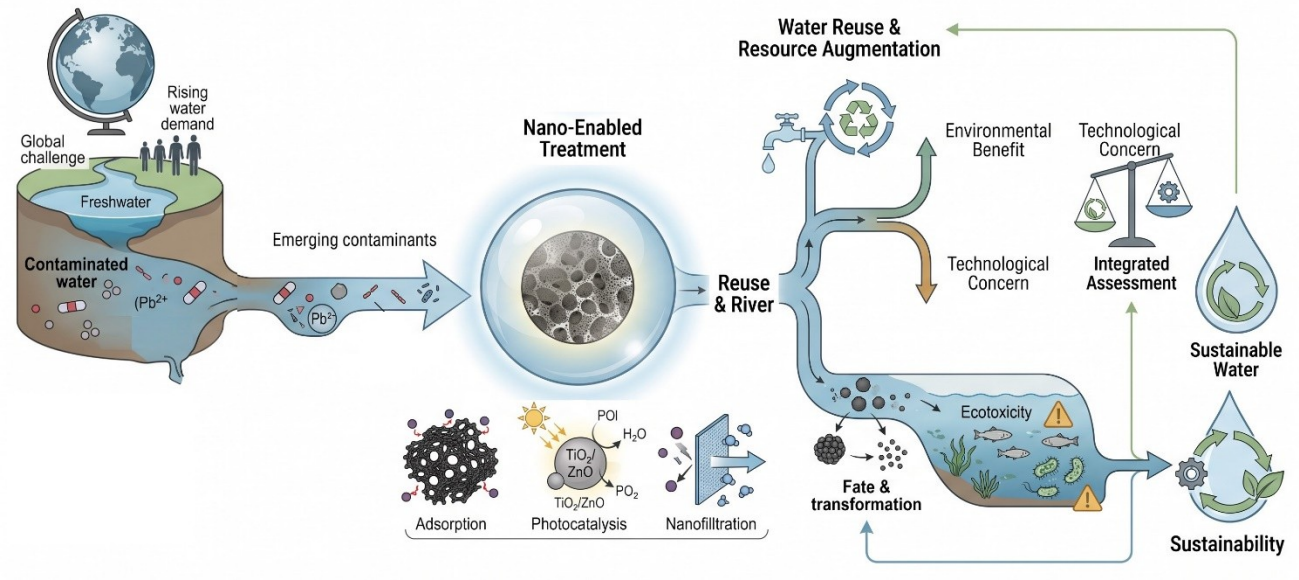
Abstract

Access to affordable, clean water is one of the biggest challenges of the 21st century. Globally, water supply cannot meet rapidly increasing demand. This is made worse by industrialization, population growth, and emerging contaminants. The setbacks in the removal efficiency of conventional water treatment techniques demanding the requirement for technological innovation to address integrated water management systems. Through the safe utilization of advanced research, nanotechnology has emerged as a promising solution for improving water and wastewater treatment efficiency and augmenting water supply. However, unresolved issues remain regarding the fate, transformation, and ecotoxicity of nanomaterials, where their acute impacts on aquatic systems and the broader ecosystem may outweigh technological improvements. Here, we review the contemporary advancements in both nanotechnology and conventional treatment methods. The toxicity of the nanomaterials is discussed, followed by their properties and mechanisms that allow for applications, as well as their benefits and drawbacks in comparison to current methods. This review describes the integrated connectivity between the advancements and obstacles to further develop these unique characteristics for sustainable water treatment by tracing the connectivity between the available treatment methods, technological advancements, and the ecotoxicity of nanomaterials.

Keywords: Nanotechnology; Wastewater treatment; Nanomaterials; Ecotoxicity.

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Graphical Abstract



1. Introduction

One of the most fundamental humanitarian objectives and which all life on earth depends on access to clean water and sanitation. But it continues to be a significant worldwide concern for the twenty-first century. There are many issues with our present water supply, both historic and contemporary. According to WHO (2024) [1] 2.1 billion people worldwide still do not have access to clean drinking water sources**.** Since water and wastewater facilities are frequently nonexistent in the impacted areas (mostly in developing nations), it is imperative to provide basic water treatment. By damaging natural water supplies, human activity is increasingly contributing to the problem of water scarcity in both developed and developing nations.

In the current situation, extensively used water treatment and distribution systems in developed nations are under increased scrutiny because of the stricter water quality regulations and new contaminants. The demand for water is rising due to population growth and rising living standards, and the existing uneven availability of freshwater is being disrupted by climate change. Consequently, areas under water stress are increasingly using brackish water, seawater, and wastewater as alternative sources [2]. Additionally, the infrastructure and technology used for water and wastewater treatment are at their limit in terms of producing water that is suitable for human and environmental demands. Meanwhile, untreated wastewater remains a major global environmental and public health concern, with around 80% discharged without treatment or reuse. Consequently, about 1.8 billion people rely on contaminated water sources [3]. Further increasing the risk of waterborne diseases such as cholera, dysentery, typhoid, and polio. Additionally, sewage treatment plants contribute significantly to the problem by releasing billions of gallons of untreated waste annually [4].

Over the past 20 years, nanotechnology has advanced dramatically, moving from early discoveries like carbon nanotubes in the 1990s to widespread commercial applications in the early 2000s [5], [6]. Currently, it is a well-established and quickly growing field with wide-ranging applications in organic chemistry, molecular biology, and many other scientific and technological fields [7], [8]. In that way, recent advancements in nanotechnology provide rapid growth opportunities to construct next-generation water supply systems. Our existing methods for treating water mainly rely on centralized systems and transportation, which are unsustainable.

Nanomaterials (NMs) are widely used in daily life, which has unavoidably led to their release and deposition into the environment, including the land, water, and air [9]. Since NMs can interact with organisms once they are in various environmental matrices, the ecotoxicology of NMs in species from various trophic levels has emerged as a global concern. Although they can enter organisms directly or indirectly by ingestion, adsorption, inhalation, or the food chain, they have a significant potential concern in regards of One Health framework [10].

The literature review adopts a thematic, structured narrative approach. Targeted searches in Scopus and Google Scholar (2020-2026) were used to find literature using search strings with combined keywords aligned with each thematic section. It is also supplemented by earlier seminal works when necessary. “Conventional treatment, advanced/hybrid processes, nanotechnology in wastewater treatment, comparative advantages over conventional methods, ecotoxicity, nanotoxicity and ecological impacts of nanomaterials” are the strings utilized for the review. Peer-reviewed journal articles in English focusing on performance, mechanisms, or environmental effects were included, while studies irrelevant to wastewater treatment, lacking experimental or application-oriented data were excluded. Papers were screened by title, abstract, and relevance to the thematic progression. The scope of this review emphasizes the conceptual connectivity and technological evolution across these topics, which highlights how advances in efficiency and functionality drive emerging environmental concerns and inform future research directions.

This review explores how water treatment techniques change throughout time in response to research and technological advancements. It seeks to chart the evolution from conventional water treatment to nanotechnology-based wastewater processes and their ecological implications. In addition, what are the main obstacles that existing therapeutic approaches must overcome, and why and how nanotechnology uses its vast capacity and molecular innovation to address such problems. To what degree do those approaches have advantages over the ones that are now available? The shortcomings of traditional water treatment techniques will be integrated into the role of using nanotechnology to overcome them in the parts that follow. Lastly, it talks about the disadvantages and repercussions associated with offering ongoing strategies for overcoming them.

2. Evolution of conventional water treatment methods

The earliest engineered wastewater systems relied on simple physical operations such as settling ponds, land application, and basic sand filtration, whose main purpose was to remove suspended solids and reduce odour before discharge [11]. As cities expanded and sewage loads increased, these

rudimentary systems proved insufficient to protect public health, leading to the development of multi-stage treatment plants with defined primary, secondary and tertiary steps. Primary treatment introduced sedimentation tanks and, in some cases, dissolved air flotation to separate settleable and floatable solids, producing primary sludge and a clarified effluent for biological treatment [12]. Secondary treatment was dominated by biological processes such as the activated sludge process and trickling filters, where microbial communities oxidized dissolved and colloidal organic matter, thereby significantly reducing biochemical oxygen demand and suspended solids [11], [13]. Tertiary treatment, initially limited to sand filtration and chlorination, was later expanded to include nutrient removal and more refined disinfection technologies to meet tightening discharge standards.

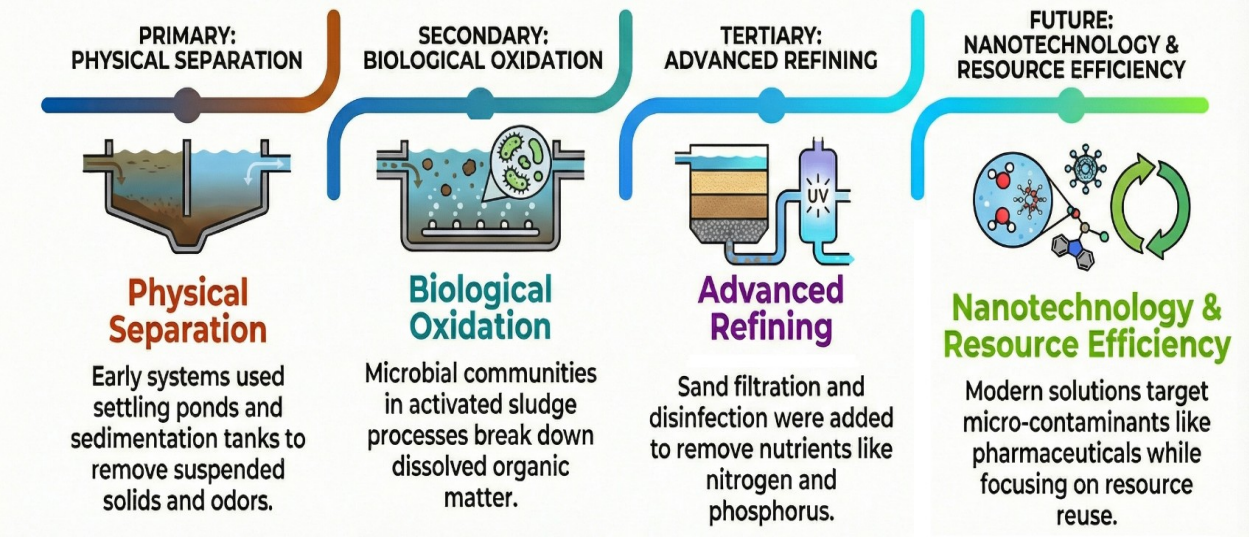


Fig. 1. Detailing of conventional water treatment method and nanotechnology targeted remediation.

2.1 Advanced and hybrid wastewater processes

Advanced wastewater treatment technologies were introduced to bridge the gap between what conventional methods can achieve and, the more stringent requirements associated with reuse and, emerging pollutants [12], [13]. Membrane processes are a central element of this evolution, ranging from microfiltration, ultrafiltration, nanofiltration and reverse osmosis. Each targeting different size fractions and dissolved species [6], [14]. Membrane bioreactors (MBRs) integrate biological degradation with membrane separation, enabling compact plants with high biomass concentrations and effluents of very low turbidity and pathogen content. These systems are now widely applied in municipal and industrial sectors, although fouling control, energy demand and concentrate management remain key design and operational considerations [12], [15].

Alongside membranes, advanced oxidation processes (AOPs) such as ozonation, UV/H_2O_2 and Fenton-type reactions generate highly reactive radicals capable of degrading recalcitrant organic molecules into smaller, often more biodegradable products [13], [16]. These processes are especially relevant for treating pharmaceutical wastewaters and other streams that contain persistent

micro-pollutants [2], [17]. Granular activated carbon adsorption, ion exchange and electrochemical methods provide additional polishing steps for dissolved organic compounds (DOC), metals and colors.

In many modern designs, treatment lines combine multiple processes biological, membrane, adsorption and oxidation into hybrid systems tailored to the specific composition of the wastewater and the desired reuse purpose. The overarching trend is towards modular, intensified configurations that offer higher removal efficiencies and better control over the treated water quality than traditional standalone units [17], [18]. Therefore, even the most advanced modern methods of treating wastewater quickly expire due to the increased demand for water in both domestic and industrial settings, as well as the introduction of new products and chemicals to address the growing problems. This calls for a different approach to wastewater treatment. For this, the main goal should be to identify the new challenges and growing concerns [19], [20].

3. Emerging issues in wastewater treatment

Despite their success in reducing conventional pollutants, modern wastewater now carries a complex mixture of contaminants that were not the primary design targets of older plants, including pharmaceuticals, personal-care products, hormones, flame retardants, microplastics and pesticides, often termed contaminants of emerging concern (CECs) [2], [21], [20]. These compounds occur at very low concentrations but are biologically active and may act synergistically, so long-term exposure can affect ecosystems and human health even when individual concentrations are low. Sources include hospital and household effluents, industrial discharges, and agricultural runoff, meaning CECs continuously enter sewer systems and treatment plants, many of which only partially remove them.

The logistical and environmental weight of the "huge amount of sludge" produced by chemical precipitation is also enormous. The expenses of stabilizing, dewatering, and disposing of hazardous sludge frequently exceed the advantages of the initial treatment. Moreover, the technical intricacy and "high resin cost" of renewing spent resin in ion exchange processes restrict their use in high-volume industrial applications [22]. These outdated techniques are strategically inferior to membrane-based technologies that provide a clean separation of contaminants without the bulk production of secondary waste since they are fundamentally "sludge-heavy" and resource-intensive. Adoption of pressure-driven separation systems results directly from this shift away from byproduct-heavy processes, with nanofiltration becoming the predominant architecture [12].

Many treatment plants also struggled with nutrient removal, especially nitrogen and phosphorus, which drive eutrophication in receiving waters. Operational challenges, including sludge production, energy consumption for aeration and the formation of disinfection by-products, further motivated the search for improved methods [12], [13]. Over time, the focus of wastewater treatment broadened from simple

pollution abatement towards resource efficiency, reuse and removal of emerging contaminants, which paved the way for advanced and hybrid technologies.

This historical development created the platform on which modern nanotechnology-enhanced solutions come in. We can no longer sustain our current methods of water treatment, distribution, or discharge, which mostly rely on centralized infrastructure and transportation. It is anticipated that the highly effective, modular, and multipurpose processes will be made possible by nanotechnology. Which expected to offer high-performing, reasonably priced water and wastewater treatment solutions that depend less on sizable infrastructures [16].

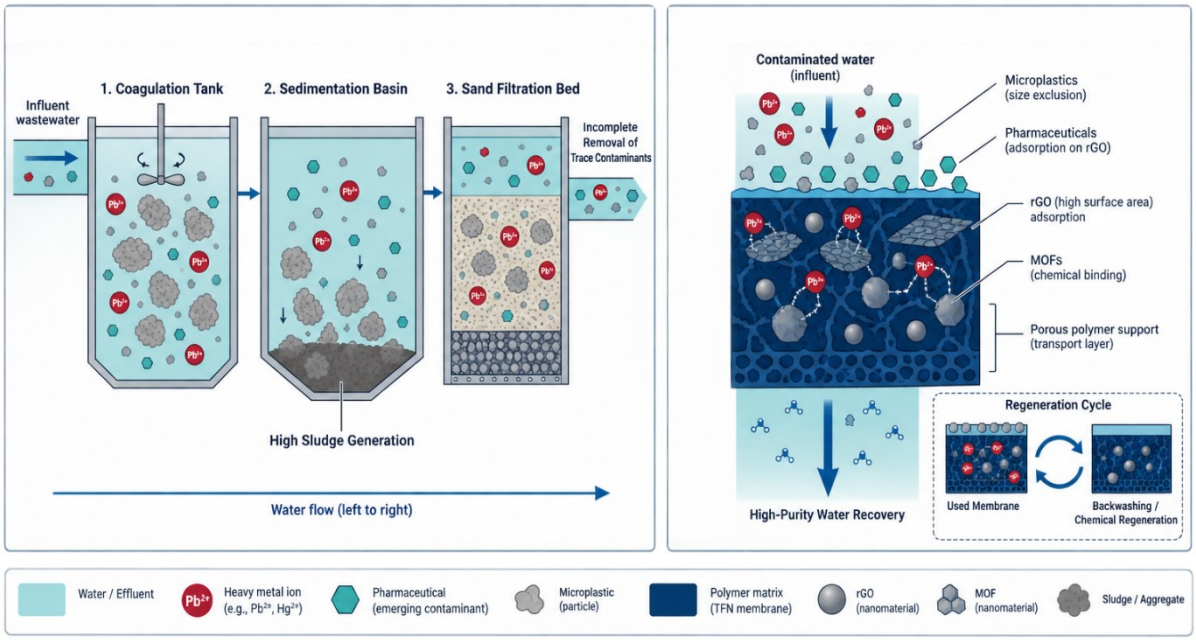


Fig. 2. Comparison of conventional and nanotechnology-based wastewater treatment systems. Conventional treatment shows high sludge generation and incomplete removal of trace contaminants. Nano-enabled filters achieving high-purity water recovery through adsorption, size exclusion, and chemical binding.

4. Nanotechnology in Wastewater Treatment

The performance of nanomaterials has been investigated in the past few years in a variety of aquatic habitats, such as lakes, rivers, wetlands, and the ocean. Environmental research groups have found that finding environmentally friendly remediating chemicals to restore contaminated soil and water bodies is a shared issue in the pursuit of an environmentally growing economy [23], [24]. The removal of charged components from solutions, such as the production of fresh water from brackish water, is the subject of several recent investigations on electro membrane (separation) technologies [25], [26].

Currently, nanomaterials are mostly used for sewage treatment, and nano-photocatalytic technology is widely used to oxidize a variety of organic compounds found in water by producing hydroxide and superoxide ions with high oxidation and superior activity. Many nanostructured materials are currently employed in capacitive deionization (CDI), a new water treatment technology. In aquatic environments, the nanoparticles exhibit varying characteristics. Some of these nanomaterials have

shown greater promise for cleaning up contaminated water. In addition, pressure-driven membranes are used in nanofiltration (NF) membrane technology, which separates the materials found in sewage [27].

Furthermore, strong adsorption of metal ions and organic contaminants is demonstrated by some nanomaterials because of surface hydroxyl groups that bind targeted cations. Particularly, carbon-based nanoparticles provide superior wastewater remediation over traditional treatment techniques due to their excellent stability over a broad pH range, large specific surface area, abundance of active sites, and porous architectures. [28]. Materials having adjustable surface chemistry and special catalytic or magnetic qualities are made possible by nanotechnology for the treatment of wastewater. High adsorption capacities are demonstrated by nanomaterials such as metal-oxide nanoparticles, magnetic nanoparticles, carbon nanotubes, and graphene-based composites, which achieve removal efficiencies of 50–98% for organic pollutants and 80–99% for inorganic contaminants. [27]. These materials can be used as dispersed adsorbents, as coatings on larger supports, or embedded in membranes and filters to enhance selectivity and flux.

Beyond conventional adsorbents, an expanding set of nano-adsorbent classes is being studied for wastewater, including:

a) Metal-oxide nanoparticles (e.g. TiO_2, ZnO, Fe_3O_4, MnO_2) for heavy metals, dyes and organic pollutants.
b) Carbon-based nanomaterials (CNTs, graphene, graphene oxide, nanodiamonds) with high capacity for heavy metals, dyes and pharmaceuticals.
c) Magnetic nanocomposites (e.g. Fe_3O_4-coated carbon or polymer beads) that can be rapidly separated by magnetic fields, simplifying recovery and regeneration.
d) Metal–organic frameworks (MOFs) and covalent organic frameworks (COFs), which offer highly tunable pore structures and surface functionalities for targeted removal of pharmaceuticals, PFAS and dyes.
e) Polymeric and biopolymer-based nano-adsorbents, including chitosan, cellulose nanofibers and polymer-filled nanomembranes with functional groups such as amine, carboxyl and sulfonic acid for selective metal and dye binding.

Nanomaterials also play a central role in catalytic and photocatalytic treatments. Semiconductor nanoparticles such as TiO_2 and ZnO, including doped variants, act as photocatalysts under UV or visible light, generating reactive radicals that degrade persistent organic pollutants. These catalysts can be integrated into coatings, suspended photocatalytic slurries, or nanocomposite membranes to simultaneously degrade micro-pollutants and filter solids. Other nano-catalysts, including noble metal nanoparticles and nano-Fenton catalysts, enhance AOPs by accelerating radical generation and electron transfer.

5. Advantages of nanotechnology compared to conventional methods.

Industrial wastewater remediation is a key component of the infrastructure for public health and environmental engineering globally. The release of hazardous heavy metal ions from the production of paint, automobile batteries, pigments, and fertilizer has increased to catastrophic levels as industrial operations expand. Since excessive exposure causes long-term harm to the reproductive, cardiovascular, and immune systems as well as to the kidneys, liver, and brain, these effluents are a systemic hazard [7], [17].

Table 1. Application of various nanomaterials in the remediation of water contamination

No	Nanomaterial	Common Manufacturing Techniques	Mechanism	Remediation	Reference
1	Graphene Nanomaterial	Chemical oxidation-reduction, mechanical milling, pyrolysis, photocatalytic reduction, carbon nanotube (CNT) conversion, and plasma synthesis	The pollutants in the water are absorbed by the nanomaterial's porous features.	Heavy metals and Dyes	[29]
2	Titanium dioxide (TiO_2) nanoparticles	Gas and Liquid phase techniques	Stronger photo-oxidation and reduction capabilities might be produced by the stimulation of TiO2 nanoparticles by ultraviolet (UV) light, which would also produce free radicals with significant catalytic activity.	Different organic substances like formaldehyde and certain inorganic substance	[30]
3	Nano-Zerovalent iron (nZVI)	Reduction	Through surface complexation and electrostatic interaction, the thin iron oxide core could facilitate the adsorption of pollutants.	Heavy metals, chlorinated aromatic compounds, nitro-aromatic compounds, azodyes and, organo-chlorine	[31]
4	Nanofiber Material	Centrifugal jet spinning (CJS), solution blowing, electrospinning (ES), electrohydraulic dynamic (EHD) direct writing, molecular methods, etc.	Using membranes with different pore widths, particles of different dimensions are filtered.	Various contaminants in eutrophicated landscape water	[32]
5	Silver Nanoparticles	Laser ablation method, photoreduction, radiation, electroplating, chemical vapor deposition	By interacting with the enzymes that the bacteria use for metabolism, the bacteria will become dried out and eventually perish. Smaller particles have better germicidal efficacy.	Water photocatalyst and antibacterial agent	[33]

Previously, promising outcomes have been demonstrated by traditional methods such as biological treatments, coagulation/flocculation, and flotation. However, the high sludge production, limited removal rates for diluted metals, and pH sensitivity are since held to be drawbacks [34]. The emerging shortcomings of traditional treatment techniques, which are progressively unable to manage the evolving stoichiometry of contemporary industrial waste, highlight the need for this shift. These limitations are often constrained by their expense, side effects, or inefficiency [35]. According to [36] conventional ponding and coagulation-flocculation systems have to deal with enlarged treatment timeframes, substantial land utilization, secondary sludge formation, and uneven pollutant removal.

High surface-to-volume ratios, high adsorption capacity, and simple functionalization are how nanotechnology gets beyond these restrictions [37], [38]. Nanofibrous membranes remove up to 98% of heavy metals, while nanoparticle-infused membranes remove up to 99% [34]. NF has a lower energy requirement than RO and operates at 5–20 bar with strong divalent-ion rejection [37].

Table 2: Key performance indicators with essential trade-off interpretation for wastewater treatment systems based on traditional and nanotechnology

Metric	Conventional Systems	Nanotechnology Systems	Key Trade-Off	Reference
Removal Efficiency	56.7% COD (coagulation) (Naguib et al., 2024)	93% COD (Fe/Cu NPs, 30 min), 95% dye (24 h), up to 99% heavy metals	Nano removes 1.6-1.8× more material at a higher expense.	[34], [41], [42]
Contact Time	Hours to days (ponding, digestion) (Raji et al., 2026)	30 min (Fe/Cu NPs), 24 h (bio-NP dye removal)	Faster kinetics; however, contact time varies depending on the type of NP and contaminant	[41], [42]
Stability	Well-characterized. Polymer degradation under high pressure (Jain et al., 2021)	Graphene oxide enhances mechanical stability of adsorbents. Long-term stability unproven	Although field evidence is scarce, nanotechnology increases material stability.	[38], [43]
Regeneration	Limited; sludge-bound contaminants difficult to recover (Malik et al., 2022)	Magnetically separable NPs permit multiple reuse cycles, Reusability remains a major problem	Regeneration is feasible but not yet dependable on a large scale.	[34], [37]
Cost	Lower capital; high disposal and sludge management costs (Ayach et al., 2024)	High-purity nanomaterials costly; ~90% cost reduction with lower-purity substitutes, Long-term reusability offsets cost	Reuse cycles and purity trade-offs determine how cost-effective it is.	[37]

The cost of developing nanomaterials is still a significant obstacle. Although replacing ultrapure C60 with lower-purity materials like fullerene soot can cut costs by about 90% with little loss in efficacy [37]. Lab-scale efficiency has not been verified at the volumes required for municipal deployment, and there are few industrial-scale investigations [39], [40]. Wastewater sludge contains nanoparticles including Mg, Ni, Ag, and Cd. At the plant level, disposing of this polluted material is still a big challenge [38]. Although pH, concentration, and contact duration all affect how harmful nanomaterials are [37].

Table 2 comparatively discusses the major parameter metrics along with their key trade-off markups. It reveals that, although nanotechnology systems provide 1.6 to 1.8 times greater removal efficiency and faster kinetics, these benefits are contingent upon contact time, NP type, and contaminant specificity. In 30 minutes, Fe/Cu nanoparticles remove 93% of COD at pH 7.5, whereas coagulation removes only 56.7% at pH 8.5 [41]. One important cost component is regeneration capacity. Reusability of nanoadsorbents is still a significant issue, although magnetically separable multifunctional nanomaterials allow for several reuse cycles [34], [37]. The balance between nanomaterial purity, regeneration cycles, and disposal of NP-laden sludge is the cost frontier, and it is unavoidable to incorporate these aspects to meet treatment enhancement [37], [38].

Despite these advantages, large-scale deployment of nanotechnology in wastewater treatment faces obstacles, including relatively high production costs, energy- or solvent-intensive synthesis routes and concerns over environmental release, ecotoxicity and bioaccumulation of engineered nanoparticles. Current research therefore emphasizes immobilizing nanoparticles on stable supports, using bio-based or biodegradable nanomaterials and performing full life-cycle and risk assessments to ensure safe, economically viable applications.

6. Ecological impacts of nanomaterials.

Nanomaterials are currently being used widely and progressively in a number of fields apart from water treatment, including materials science, cosmetics, medicines, and more. However, using nanomaterials also has adverse effects on ecology and the greater environment [44], [45]. It is inevitable for a number of nanomaterials to end up in rivers, lakes, and the ocean. In the end, these nanoparticles can also affect potable water. Therefore, the contamination of water habitats caused by these nanoparticles is hazardous to human and aquatic life [46], [47]. It has been observed that different types of nanomaterials, or even similar types of nanoparticles at different sizes, have an incompatible detrimental effect on some organisms. Because of their strong reactivity, it is evident that nanoparticles change from their original, manufactured state regardless of the kind, quantity, or route of environmental nanoparticle release.

Numerous mechanisms, including aggregation/agglomeration, redox reactions, dissolution, surface moiety exchange, and reactivity with biomacromolecules, can lead to transformations [48]. The transport, destiny, and toxicity of nanoparticles in the environment are all impacted by these dynamic

alterations, hence it is essential to comprehend and describe them. Several reviews have provided a thorough explanation of the current analytical instruments used to quantify the properties of nanoparticles [49].

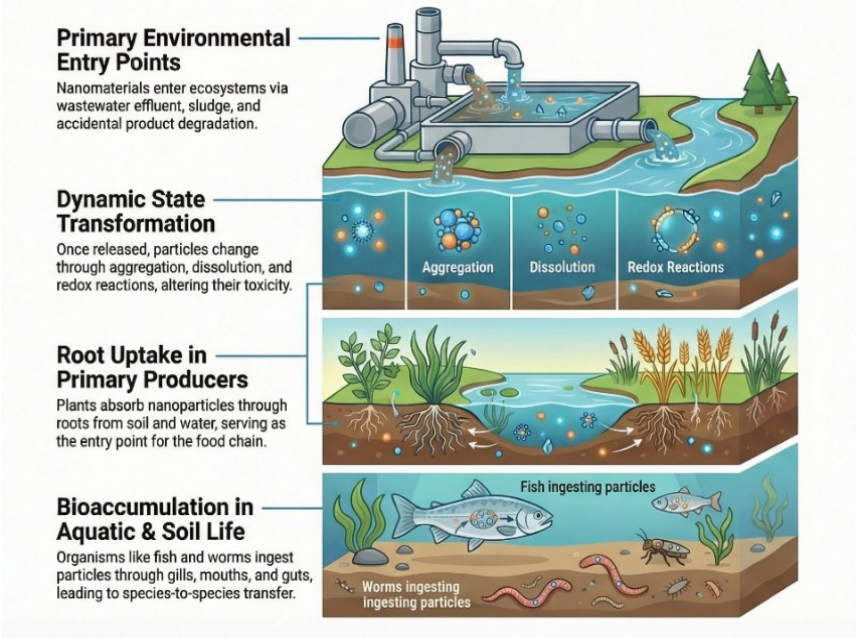


Fig. 3. The path of nanotoxicity: From release to the food chain.

Due to their interactions with soil, water, and air, all of which may contain nanoparticles, plants are especially pertinent when considering eco-nanotoxicity. Additionally, because lower trophic level organisms, animals, and humans eat plants, they offer a substantial possibility to enhance the transfer of nanoparticles among different species in the food chain. Although the ecosystem has a wide range of plant species, the majority of research on nanotoxicity to date has concentrated on plants that are consumed by humans, such as maize, wheat, soybean, tobacco, and numerous fruit or vegetable plants, including pumpkin, cucumber, and radish [50], [51]. Consequently, living organisms are exposed to nanoparticles in different ways depending on where they live. As was recently discovered, entry through roots is a major issue for plants. Nanoparticles that are present in the aqueous or soil phases give fish in water or worms in soil a way to enter the animal (gills, mouth, or gut), which may be significantly changed by the surface characteristics of the nanoparticle.

Early research on the toxicity of nanomaterials in fish concentrated on a small number of larger animals that humans might consume, like fish and salmon, with as few as three fish being employed for crucial measures. The biological impacts of hydrophobic carbon-based materials are caused by organic solvent impurities and degradation products, which amply illustrates the necessity of appropriate controls [52]. The function, as well as toxicity, of commonly used nanomaterials in aqueous surroundings are presented in Table 3.

Table 3. The role and toxicity of certain widely utilized nanomaterials in water environments.

No	Nanomaterial	Concentration/Toxicity	Behavior/Remediation	Reference
1	Graphene oxide	Lethal effects for *Artemia salina* have only been observed at high concentrations of graphene oxide (500 ppm), whereas sublethal toxicity (growth obstruction) has been observed at loading levels as low as 1 ppm. This could be caused by the oxidative stress that graphene oxide induces. At a maximum dose of 10 mg/L, pure graphene did not exhibit any harm in the acute toxicity test in *Artemia salina*. A similar toxicity propensity was demonstrated by different nanomaterials in additional crab species.	Adsorb heavy metal ions as well as organic pollutants.	[53], [54]
2	Nano-zerovalent iron	The EC50 of the bacteria against pristine pyrophoric nano zerovalent iron was found to be 0.30–1.10 g/L after six bacteria were tested for nZVI concentration. All of the examined bacteria showed a similar trend in the formation of malondialdehyde, regardless of the variation in EC50 values.	the iron in the aging nanozerovalent iron was reduced to the Fe2+ ion.	[55], [56]
3	Zinc oxide nanoparticle	When exposed to *Hydra magnipapillata* for 96, 72, and 48 hours, the median lethal concentrations of 20 nm zinc oxide nanoparticles were 7.0, 8.70, and 55.30 g/mL, while the median lethal concentrations of 100 nm zinc oxide nanoparticles were 9.90, 14.90, and 262.0 g, respectively.	absorbing many elements, changing their speciation in the media and, consequently, their bioavailability, such as Cd, Ni, Cu, Pb, Hg, Mo, Al, and As.	[57]
4	Nanofiber Material	ROS and oxidative stress can be produced by the leaching of Ag^{+} and Zn^{2+} in electrospun Ag- and ZnO/Ag_2nanofiber systems. Daphnia and other aquatic invertebrates exhibit sublethal reproductive and metabolic deficits with extremely low AgNPs (≈0.0050.02 mg/L). ZnO dissolution prevents microbial activity in sludge, which interferes with the removal of nutrients. In algae, invertebrates, and fish, long-term leaching, particle detachment, and transformation facilitate bioaccumulation and trophic transmission.	Activated carbon, biochar, or functionalized carbon–metal adsorbents can be used to capture released Ag^{+}/AgNPs and Zn^{2+}. Separation is made simple by magnetic FeO-based sorbents. Discharge is decreased by immobilizing nanofibers in membrane or fixed-bed modules and then polishing (adsorption, coagulation-flocculation, or membrane filtering).	[36]

5	Titanium dioxide nanoparticle	Sperm cell speed decreased and superoxide dismutase activity and total glutathione levels increased when the concentration of titanium dioxide nanoparticles reached 10 parts per million.	Resilient absorbability to As(V), As(III), and Cd.	[58], [59]
6	Silver nanoparticle	The biological behavior of *Corbicula fluminea* was inhibited when the concentration of silver nanoparticles was 0.1 ppm. *Corbicula fluminea*'s physiological metabolism was once more inhibited when the concentration of silver nanoparticles reached 2 ppm. *Labeo rohita*, a freshwater fish, was exposed to a 25 mg/L nanoparticle for 21 days. Fish survival was unaffected. showed reduced toxicity. For five and fifteen days, *Prochilodus lineatus* fish were exposed to 2.5 and 25.0 g of L1 nanoparticles. The concentration of muscle protein decreased, the activity of all antioxidant enzymes increased, the liver's ACAP decreased, and the muscle and liver's glycogen content increased.	Zinc and copper ions are among the heavy metal ions in water that silver nanoparticles can absorb. Silver can be extracted from water by using activated carbon as an adsorbent.	[60]–[62]
7	Nickel nanoparticle	*Labeo rohita*, a freshwater fish, was exposed to a 25 mg/L nanoparticle for 21 days. Fish survival was unaffected. Significant growth and hemoglobin reductions were noted. An increase in total protein was seen.	Magnetic hydroxyapatite nanocomposite can be utilized as an adsorbent to remove	[63], [64]
8	Cobalt nanoparticle	*Labeo rohita*, a freshwater fish, was exposed to a 25 mg/L nanoparticle for 21 days. Fish survival was unaffected. An increase in total protein was seen.	Can be removed using zinc oxide nanopowder	[65]
9	Chromium oxide nanoparticle	*Labeo rohita*, a freshwater fish, was exposed to a 25 mg/L nanoparticle for 21 days. Fish mortality was initially caused by Cr3O4 nanoparticles. remarkable decline in hemoglobin and growth. An increase in total protein was seen.	Can be removed using superparamagnetic iron oxide nanoparticles.	[66]

7. Conclusion and Future Perspectives.

Nanotechnology has emerged as a transformative platform for addressing the limitations of conventional wastewater treatment, offering unprecedented capabilities in adsorption, catalytic degradation, membrane selectivity, and targeted removal of contaminants of emerging concern. The reviewed literature demonstrates that nanomaterials-particularly metal-oxide nanoparticles, carbon-based structures, magnetic composites, and advanced frameworks such as MOFs and COFs provide high surface reactivity, tunable physicochemical properties, and superior removal efficiencies for a wide spectrum of pollutants. Nevertheless, the environmental implications associated with nanoparticle release, transformation, and bioaccumulation underscore the need for a balanced and precautionary approach to their deployment.

Despite significant progress, several scientific and technological gaps remain. The long-term fate of engineered nanomaterials in complex aquatic matrices is not yet fully understood, and current toxicity assessments often fail to capture chronic, low-dose, or synergistic effects. Moreover, the scalability of nanotechnology-enabled systems is constrained by production costs, energy requirements, and the absence of standardized protocols for evaluating environmental safety and life-cycle impacts.

Looking forward, future research should prioritize the development of immobilized, recoverable, and biodegradable nanomaterials that minimize ecological risks while maintaining high treatment performance. Advancements in thin-film nanocomposite membranes, bio-based nanostructures, and photocatalysts responsive to visible light are expected to enhance both efficiency and sustainability. Integrating nanotechnology with digital monitoring tools, such as AI-assisted process control and real-time sensing, may further optimize treatment performance and reduce operational burdens.

Equally important is the establishment of comprehensive regulatory frameworks, harmonized characterization standards, and robust life-cycle assessment methodologies to ensure responsible innovation. Collaborative efforts between material scientists, environmental engineers, toxicologists, and policymakers will be essential to translate laboratory-scale advances into safe, economically viable, and environmentally resilient treatment solutions.

In summary, nanotechnology holds substantial promises for shaping the next generation of wastewater treatment systems. Realizing this potential will require a concerted focus on safety, sustainability, and interdisciplinary integration to ensure that technological progress aligns with environmental stewardship and public health protection.

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