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Organic Water Pollutants: Sources, Impacts, and Nano-Enabled Remediation—A Comprehensive Review

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A B S T R A C T

Purpose:

Water pollution from organic pollutants has emerged as a critical environmental challenge due to its harmful effects on ecosystems and human health. The purpose of this review is to investigate the sources, impacts, and treatment approaches for organic pollutants in water, with a particular focus on nanotechnology-based remediation strategies.

Method:

This study provides a comprehensive review of existing literature on organic pollutants and remediation technologies. It examines the contribution of different human activities—industrial discharges, agricultural runoff, and domestic waste—to the presence of organic pollutants in water systems. Furthermore, the review evaluates conventional treatment techniques, such as biological, chemical, and physical methods, alongside recent advancements in nanotechnology-driven solutions, including metal and metal oxide nanoparticles, carbon-based nanomaterials, and polymeric nanocomposites.

Results:

The findings highlight that organic pollutants—including pesticides, pharmaceuticals, industrial solvents, and personal care products—pose significant risks due to their toxicity, persistence, bioaccumulation potential, and endocrine-disrupting properties. Conventional treatment methods often fail to fully eliminate these contaminants because of their complex nature. In contrast, nanotechnology-based remediation has demonstrated superior performance in adsorption, catalytic degradation, and selective removal of organic pollutants. Recent studies confirm the effectiveness of nano-enabled techniques, although challenges such as scalability, cost, and environmental safety remain.

Practical Implications:

The integration of nanotechnology into water treatment systems offers a pathway to more efficient, sustainable, and reliable solutions for managing organic pollutants. Adoption of these advanced technologies can improve water quality, protect aquatic ecosystems, and reduce public health risks associated with contaminated water. Policymakers, engineers, and researchers can leverage these insights to develop and implement next-generation treatment infrastructures.

Originality/Novelty:

This review consolidates and critically evaluates the latest progress in nano-enabled remediation of organic water pollutants, offering a forward-looking perspective on their mechanisms, advantages, limitations, and future opportunities. By highlighting the potential of nanotechnology as a transformative tool, the study contributes original insights that can guide the development of innovative and long-term water treatment strategies.

Keywords: *Environmental Remediation, nanoadsorbents, nanotechnology, organic water pollutants, water treatment*

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1. Introduction

Water is an essential resource for all life on Earth and has played a critical role in the evolution and survival of human civilizations. Despite covering approximately 70% of the Earth's surface, only a small amount of water is freshwater, and according to a United Nations (2019) assessment, over 2.2 billion people worldwide do not have access to clean drinking water. Economic limits, political hurdles, technological limitations, and the negative consequences of climate change all serve as barriers to universal access to clean water (Mekonnen and Hoekstra, 2016; IPCC, 2021). Addressing these difficulties requires collaborative efforts, including investments in sustainable infrastructure, innovative technology, water conservation, and international cooperation. Access to clean water, sanitation, and hygiene is not only a basic human right, but also necessary for health, poverty reduction, food security, and environmental sustainability (WHO/UNICEF, 2021). The United Nations Sustainable Development Goals (SDGs) highlight the need for universal access to clean water and sanitation by 2030, with an emphasis on increasing water quality, efficiency, and integrated water resource management (United Nations, 2015).

Organic water pollutants, such as pesticides, medicines, industrial chemicals, petrochemicals, and personal care items, pose a substantial challenge to obtaining clean water. These pollutants reach aquatic bodies via agricultural runoff, industrial discharge, and poor waste management, thereby posing serious threats to human health, ecosystems, and biodiversity. Organic pollutants are particularly problematic because of their toxicity, persistence, and bioaccumulative qualities, which can cause waterborne illnesses, endocrine disruption, and long-term environmental deterioration (Schwarzenbach et al., 2010; Richardson 2009).

Traditional water treatment technologies such as chemical, physical, and biological processes frequently fail to adequately remove organic pollutants. Chemical treatments such as coagulation, flocculation, and disinfection may not completely remove organic pollutants and can produce toxic disinfection byproducts (Shannon et al., 2008). Physical treatments, such as filtration and sedimentation, are ineffective against smaller organic molecules, whereas biological systems fail to break down persistent organic pollutants, such as medicines and pesticides (Crini and Lichtfouse, 2019). These restrictions underscore the critical need for new environmentally friendly methods to address the rising issue of organic water pollution.

Nanotechnology has emerged as a viable method for removing organic water pollutants. The unique features of nanomaterials, such as their large surface area, reactivity, and customizable surface chemistry, allow for the effective adsorption, degradation, and removal of a wide spectrum of organic pollutants (Qu et al., 2013). Nanomaterials, including nanoadsorbents, nanocatalysts, and nanofiltration membranes, provide considerable benefits in terms of selectivity, scalability, and energy efficiency. These nanotechnology-based methods improve organic pollutant removal efficiency while reducing secondary pollution and environmental effects (Theron et al., 2008).

Recent advances in nanotechnology have proven their ability to handle the complicated issues of organic water pollution. Nano-enabled systems offer long-term, cost-effective alternatives to water treatment, opening new possibilities for improving water quality and accessibility. This study investigated the causes, effects, and types of organic water pollutants, emphasizing the role of nanotechnology in their removal. This study sought to bridge the present knowledge gaps and offer future research paths for more efficient and scalable solutions by reviewing the most recent nanomaterial-based water treatment research and technologies.

2. Literature review

Organic water pollutants are of substantial concern for environmental sustainability and public health worldwide. These pollutants originate from various sources, including industrial effluents, agricultural runoff, domestic garbage, and pharmaceutical residues, all of which contribute to water pollution (Schwarzenbach et al., 2006). Industrial operations release a variety of organic compounds, including solvents, oils, and petrochemical byproducts, which impair the water quality and affect aquatic ecosystems (Ali et al., 2012). Agricultural runoff brings pesticides, herbicides, and fertilizers into rivers and lakes, causing eutrophication and the build-up of hazardous chemicals in aquatic habitats (Carvalho, 2017). Household garbage, notably cleaning agents and personal care items, contains a variety of organic chemicals that enter wastewater treatment systems and eventually pollute natural water sources (Richardson & Ternes, 2018). Furthermore, pharmaceutical residues such as antibiotics, hormones, and other medicines are regularly found in water bodies because of poor disposal and ineffective wastewater treatment operations (Kümmerer, 2009).

Organic pollutants have a substantial influence on water quality, including toxicity in aquatic organisms, the bioaccumulation of dangerous compounds in the food chain, and possible health concerns (Jones & de Voogt, 1999). Persistent organic pollutants (POPs), such as polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs), are particularly problematic because of their potential to accumulate in living organisms over time, resulting in long-term ecological harm (Ritter et al., 1998). Studies have shown that organic pollutants can interfere with the growth and reproduction of aquatic species and disrupt aquatic ecosystems (Borgå et al., 2004). Bioaccumulation exacerbates this problem because hazardous compounds accumulate in predators, such as fish, birds, and humans (Arnot & Gobas, 2006). This poses serious health hazards, including cancer, endocrine diseases, and developmental issues (Diamanti-Kandarakis et al., 2009).

To address these serious challenges, nanotechnology has emerged as a viable method for removing organic water pollutants. Nanomaterials, including nanophotocatalysts, nanosorbents, nanomembranes, and nanoreductive agents, have shown great promise in the degradation, adsorption, and elimination of organic pollutants from water (Qu et al., 2013). Nanophotocatalysts such as titanium dioxide (TiO_2) and zinc oxide (ZnO) use light energy to produce reactive oxygen species (ROS), which degrade organic pollutants into less hazardous byproducts (Fujishima et al., 2008). Carbon-based nanosorbents such as graphene oxide (GO) and carbon nanotubes (CNTs) have large surface areas and functional groups, which improve their adsorption ability for a variety of organic pollutants, including pesticides and medicines (Liu et al., 2014). Nanomembranes containing nanoparticles provide extremely selective filtering, allowing the removal of organic molecules, depending on their size, charge, and chemical characteristics (Shannon et al., 2008). Furthermore, nanoreductive materials such as zero-valent iron (ZVI) nanoparticles can significantly lower the toxicity of organic pollutants through chemical changes, making them less dangerous (Zhang, 2003).

3. Material and Methods

The methodology for this comprehensive analysis included a systematic literature search using databases such as PubMed, Scopus, Web of Science, and Google Scholar, which included peer-reviewed articles, book chapters, and technical reports, to guarantee a comprehensive historical and present viewpoint. Keywords such as "organic water pollutants," "nanotechnology for water remediation," and "environmental impacts" were used to identify relevant papers. The obtained data were classified according to pollutant categories (e.g., pesticides and medicines), sources (point and non-point), and environmental and health consequences, with a focus on nanotechnology-based remediation solutions. The inclusion criterion was scientifically sound research, whereas non-peer-reviewed or unrelated articles were excluded. This method ensured a comprehensive study of the evolution of knowledge, identification of research gaps, and critical evaluation of both known and new nano-enabled water pollution remediation methods.

4. Results

ORGANIC POLLUTANTS

Organic water pollutants are a group of chemical compounds that originate from a variety of anthropogenic and natural sources, primarily industrial activity, agricultural runoff, domestic garbage, and pharmaceutical residues. Pesticides, medications, personal care products, industrial solvents, and other synthetic compounds are examples of pollutants. They enter aquatic systems via a variety of pathways and are known for their persistence in aquatic environments and resistance to conventional water treatment methods, making them a major environmental concern, contributing significantly to water quality degradation, and posing serious risks to ecosystems and human health (Ahamed et al., 2021). Understanding the origin of these pollutants is crucial for devising successful mitigation plans.

SOURCS OF ORGANIC WATER POLLUTANTS

Agriculture is a major source of water pollution. The widespread use of pesticides, herbicides, and fertilizers in farming methods causes these chemicals to seep into ground and surface water systems. For example, organochlorine pesticides, such as DDT and atrazine, are regularly found in water bodies around agricultural regions, where they persist because of their chemical stability (Jun et al., 2018).

Industrial operation is another significant source of organic water pollution. The textile, pharmaceutical, petrochemical, and industrial sectors emit a diverse range of organic compounds including dyes, solvents, and heavy metals. For example, untreated or improperly treated wastewater from textile companies delivers hazardous synthetic dyes and aromatic amines to aquatic habitats, making them resistant to typical breakdown processes (Rafeeq et al., 2022). Furthermore, inefficient industrial waste management and unintentional spills have contributed to the poisoning of water resources.

Municipal wastewater contains a substantial amount of organic pollutants, mainly pharmaceuticals and personal care products (PPCP). These pollutants enter water systems via the disposal of unneeded prescriptions, excretion of metabolized drugs, and washing of personal care goods, such as cosmetics and detergents. Antibiotics, analgesics, and hormones are among the most frequently discovered drugs that can alter aquatic life and contribute to the development of antibiotic-resistant bacteria. Furthermore, inadequate removal of these chemicals during traditional wastewater treatment methods results in their persistence in treated effluents and receiving aquatic bodies. Natural sources contribute to organic water pollution, but to a lesser extent than anthropogenic activities. For example, the decomposition of plant and animal waste releases natural organic matter (NOM) into water systems, which can react with disinfectants during water treatment to produce toxic disinfection by-products (DBPs) such as trihalomethanes (Puri et al., 2021). Although NOM is not intrinsically harmful, its interaction with other pollutants and treatment agents might worsen water quality concerns.

IMPACTS OF ORGANIC WATER POLLUTANTS

Organic water pollutants, which originate from various anthropogenic and natural sources, pose serious threats to human health and the environment. These pollutants frequently remain in aquatic environments owing to their resilience to degradation. Their presence in water bodies has been associated with various negative consequences for both human populations and natural systems.

IMPACTS ON HUMAN HEALTH

Organic water pollutants can be ingested through polluted drinking water, polluted aquatic creatures, or skin contact while participating in leisure activities. Such exposure has been linked to both acute and chronic health problems including cancer, endocrine disruption, reproductive abnormalities, and neurotoxicity (Richardson & Ternes, 2018). For example, endocrine-disrupting chemicals (EDCs), including bisphenol A (BPA) and phthalates, can disrupt hormonal systems, resulting in developmental defects and an increased cancer risk (Encarnação et al., 2019). Additionally, medicines, such as antibiotics and analgesics, in water sources contribute to the development of antimicrobial resistance, which is a major public health problem (Rizzo et al., 2019).

IMPACTS ON THE ENVIRONMENT

Organic water pollutants also negatively impact aquatic ecosystems and biodiversity. These toxins have the potential to alter the aquatic ecosystem balance by changing the growth, reproduction, and survival rates of aquatic creatures. For example, pesticides, such as organophosphates and chlorinated hydrocarbons, have been found to induce death in fish and invertebrates, resulting in population decrease and biodiversity loss (Schwarzenbach et al., 2006). Furthermore, bioaccumulation and biomagnification of persistent organic pollutants (POPs) in the food chain endanger apex predators, including humans (Jones & De Voogt, 1999). Organic pollutants degrade water quality, which influences ecosystem services such as water purification and nutrient cycling, both of which are critical for maintaining ecological balance (Carpenter et al., 1998).

NANOMATERIALS FOR WATER TREATMENT

Nanomaterials are materials with at least one dimension less than 100 nanometers (nm). These materials can be organic (carbon-based), inorganic (non-carbon-based), or hybrid, and they have unique nanoscale features, such as a high surface-area-to-volume ratio, increased reactivity, and distinct optical, electrical, and mechanical capabilities (Qu et al., 2013). These properties make nanoparticles far more successful in a variety of applications, including water treatment, than their bulk equivalents (Savage and Diallo, 2005). Organic water pollutants such as medications, pesticides, and industrial chemicals are common and play a substantial role in water pollution. Nanomaterials have significant benefits in eliminating these pollutants because of their high pollutant removal efficiency, improved adsorption capacity, and capacity to degrade a wide spectrum of pollutants (Theron et al., 2008). Their large surface area enables more contact with pollutants, increasing their removal effectiveness, while their customizable surface features allow for focused interactions with specific pollutants (Liu et al., 2014).

Nanoadsorbents, nanomembranes, and photocatalysts are the most promising nanomaterials for water treatment. These materials are particularly interesting because of their effectiveness in adsorbing, filtering, and degrading pollutants (Shannon et al., 2008). Nanoadsorbents such as carbon nanotubes (CNTs), graphene oxide (GO), and metal oxide nanoparticles are particularly effective in removing organic pollutants, heavy metals, and colors from water (Ali et al., 2012). Their vast surface area provides abundant adsorption sites, making them excellent for treating water polluted with organic pollutants, such as pesticides and medicines (Gupta et al., 2011). Graphene oxide functional groups and π-π interactions enable the high-efficiency adsorption of drugs such as tetracycline and ibuprofen (Wang et al., 2013). Nanomembranes, typically composed of n Metal oxide nanoparticles, such as Fe_3O_4 and ZnO, have shown high adsorption capacity for heavy metals and organic dyes (Zhang, 2003).

Nanoparticles, such as carbon nanotubes, silica, and metal oxides, have shown considerable promise in filtering processes. Their small pore sizes allow for the selective removal of impurities, such as bacteria, viruses, and dissolved organic and inorganic pollutants, while maintaining high water flow and decreasing membrane fouling (Qu et al., 2013). For example, nanomembranes containing carbon nanotubes have been used to effectively remove organic pollutants and pathogens from wastewater (Das et al., 2014). Nanomembranes containing metal oxide nanoparticles, including TiO_2, can destroy organic pollutants via photocatalytic activity and improve their performance (Fujishima et al., 2008).

Photocatalysts, including TiO_2 and ZnO nanoparticles, can break down organic pollutants using UV or visible light (Fujishima et al., 2008). This process produces reactive oxygen species (ROS) such as hydroxyl radicals (•OH), which break down complex organic compounds into innocuous byproducts such as water and carbon dioxide (Qu et al., 2013). TiO_2 nanoparticles are commonly employed to degrade medicines, insecticides, and dyes in water because of their strong photocatalytic activity and stability (Hoffmann et al., 1995). Recent research has investigated the use of doped or composite photocatalysts, such as nitrogen-doped TiO_2 or TiO_2-graphene composites, to improve light absorption and photocatalytic efficiency under visible light (Asahi et al., 2001).

MECHANISMS OF ACTION OF NANOMATERIALS FOR ORGANIC WATER POLLUTANTS

Nanomaterials have emerged as viable solutions for the remediation of organic water pollutants owing to their unique physicochemical features, including a large surface area, variable surface chemistry, and increased reactivity. These features allow nanomaterials to interact with organic pollutants via a variety of mechanisms including adsorption, photocatalytic degradation, redox reactions, and advanced oxidation processes (AOPs). The key methods of action are described below.

1***. Adsorption:*** Adsorption is one of the most common ways in which nanomaterials can remove organic pollutants from water. Carbon-based nanomaterials (e.g., graphene oxide and carbon nanotubes) and metal-organic frameworks (MOFs) exhibit significant adsorption capabilities owing to their large surface areas and porous architectures. Adsorption occurs through electrostatic interactions, hydrogen bonding, π–π stacking, and van der Waals forces between nanomaterial surfaces and organic pollutants (Baig et al., 2019). For example, graphene oxide has been demonstrated to successfully adsorb polycyclic aromatic hydrocarbons (PAHs) and dyes because of its oxygen-containing functional groups, which increase its affinity for organic molecules (Zhang et al., 2016).

2***. Photocatalytic Degradation:*** Photocatalytic degradation uses semiconductor nanoparticles like TiO_2, ZnO, and BiOX, to degrade organic pollutants by light irradiation. When exposed to light, these nanomaterials form electron-hole pairs that react with water and oxygen, producing reactive oxygen species (ROS) such hydroxyl radicals (•OH) and superoxide anions ($O_2^{\bullet -}$). ROS are highly reactive and convert organic pollutants into less hazardous byproducts, including CO_2 and H_2O (Qu et al., 2013). TiO_2 nanoparticles can effectively decompose phenolic chemicals and pharmaceutical residues in water (Hoffmann et al., 1995).

3***. Redox Reactions:*** Nanomaterials can also help decompose organic pollutants by facilitating redox reactions. Zero-valent iron nanoparticles (nZVI) and bimetallic nanoparticles (e.g., Fe/Pd) are particularly useful in this respect. These nanomaterials function as reducing agents, transferring electrons to organic pollutants and converting complicated molecules into simpler, less hazardous molecules. For example, nZVI has been used to convert chlorinated hydrocarbons such as trichloroethylene (TCE) into non-toxic hydrocarbons (Zhang, 2003).

4***. Advanced Oxidation Processes (AOPs):*** Nanomaterials can improve the efficiency of AOPs, such as Fenton and Fenton-type reactions, by stimulating ROS production. Iron-based nanoparticles, such as magnetite (Fe_3O_4) and hematite (α-Fe_2O_3), are often utilized in Fenton reactions to decompose organic pollutants. These processes convert hydrogen peroxide (H_2O_2) into hydroxyl radicals, which oxidize organic pollutants (Wang et al., 2016). Furthermore, nanomaterials can be used with other AOPs such as ozonation and sonolysis to improve pollutant degradation (Gogoi et al., 2017).

5***. Enzymatic Degradation:*** Some nanomaterials, such as nanozymes, exhibit the catalytic activity of natural enzymes and can break down organic pollutants via enzymatic processes. Iron oxide nanoparticles (Fe_3O_4) have peroxidase-like activity and may oxidize organic pollutants in the presence of H_2O_2 (Wei and Wang, 2013). This method is very effective for the breakdown of resistant pollutants such as dyes and medicines.

6***. Membrane Filtration:*** Nanomaterials are also used in membranes to remove organic pollutants via size exclusion and adsorption. Nanocomposite membranes, such as those containing carbon nanotubes or silver nanoparticles, may efficiently filter organic pollutants while allowing water to flow through (Esfahani et al., 2019). These membranes are particularly efficient in removing big organic compounds like humic acids and proteins.

FUNCTIONALIZATION OF NANOMATERIALS

Functionalization refers to the addition of certain chemical groups or molecules to the surface of nanomaterials such as carbon nanotubes, graphene oxide, metal-organic frameworks (MOFs), and metal oxide nanoparticles. These alterations increase the selectivity, stability, and reactivity of nanomaterials toward certain pollutants. Adding carboxyl, amino, or thiol groups to the surface of carbon-based nanomaterials improves their affinity for organic pollutants via electrostatic interactions, hydrogen bonding, and π–π stacking (Jun et al., 2018).

Functionalization of nanomaterials has emerged as a critical technique for resolving the issues raised by organic water pollutants. Organic pollutants persist in aquatic ecosystems because of their intricate structure and resistance to natural degradation processes (Ahamed et al., 2021). Functionalized nanomaterials have increased adsorption, catalytic, and photocatalytic characteristics owing to specific surface changes, making them particularly successful in the restoration of polluted water systems.

Functionalizing titanium dioxide (TiO_2) nanoparticles with noble metals such as gold or silver enhances their photocatalytic activity in visible light, enabling the destruction of refractory organic pollutants (Haghshenas et al., 2023).

The functionalization technique also tackles issues such as nanoparticle agglomeration and poor dispersion in aqueous conditions. For example, covering iron oxide nanoparticles with polymers, such as polyethylene glycol (PEG) or polyvinylpyrrolidone (PVP), increases colloidal stability, inhibits agglomeration, and increases pollutant removal efficiency (Rafeeq et al., 2022). Furthermore, incorporating magnetic characteristics into functionalized nanoparticles facilitates separation and recovery from treated water, thereby lowering secondary pollutants and operating costs (Puri et al., 2021).

Recent advances in nanotechnology have made it possible to create multifunctional nanomaterials that can simultaneously adsorb and degrade organic pollutants at the same time. For example, graphene oxide functionalized with iron oxide and titanium dioxide showed synergistic effects in dye adsorption and subsequent photocatalytic degradation (Feng et al., 2022). Such advancements demonstrate the potential of functionalized nanomaterials for providing sustainable and effective water treatment solutions.

OPPORTUNITIES IN NANO ENABLED REMEDIATIONS

Nanomaterials have several potential applications in the removal of organic water pollutants owing to their unique properties such as large surface area, reactivity, and flexibility to be designed for specific purposes. The following are some important potentials that nanoparticles provide for organic water pollutant removal:

1***. High Surface Area and Reactivity*****:** Nanomaterials with extremely large surface areas and reactivity, such as carbon nanotubes, graphene oxide, and metal-oxide nanoparticles, allow for the effective adsorption and degradation of organic pollutants (Savage et al. 2005).

2. Enhanced Catalytic Properties**:** Nanoparticles such as titanium dioxide (TiO_2) and zinc oxide (ZnO) have high photocatalytic activity under UV or visible light, converting complex organic pollutants into less hazardous byproducts (Qu et al., 2013).

3. Selective Targeting**:** Functionalized nanomaterials may be designed to specifically target certain pollutants, such as dyes, insecticides, or medicines, thereby increasing remediation efficiency (Baig et al., 2019).

4. Reusability and Stability**:** Many nanomaterials, including magnetic nanoparticles, can be easily recovered and reused, thereby lowering operational costs and environmental effects (Gupta & Nayak, 2012).

5. Versatility: Nano-based materials may be incorporated into a variety of remediation methods, including filtration membranes, adsorbents, and advanced oxidation processes (AOPs), providing adaptable solutions for a wide range of water treatment situations (Mishra, 2020).

CHALLENGES AND LIMITATIONS

Although nanoparticles appear to be promising solutions for the removal of organic water pollutants, various hurdles and restrictions must be overcome before they can be completely realized in large-scale and practical applications. These challenges include the following.

***1. High Production Costs*:** Nanomaterials Nanomaterials are frequently synthesized using sophisticated and expensive procedures, which limits their large-scale application in water treatment (Khin et al., 2012).

2. Potential Toxicity: Some nanomaterials, such as silver nanoparticles, may present ecological and human health problems if discharged into the environment, raising questions regarding their safety (Bundschuh et al., 2018).

***3.Aggregation and Stability Issues*:** Nanoparticles agglomerate under aquatic conditions, limiting their efficiency and necessitating further stabilizing methods (Hotze et al., 2010).

***4. Limited Understanding of Long-Term Impacts*:** The long-term environmental destiny and behavior of nanomaterials remain unknown, prompting further studies to identify their ecological dangers (Klaine et al., 2008).

***5. Regulatory and Ethical Concerns*:** The absence of established standards for the use and disposal of nanomaterials in water treatment makes their widespread adoption difficult (Nel et al., 2006).

5. Discussion

The findings of this review coincide with and build on the conclusions of previous research on water pollution and nanotechnology-based treatments. For example, the identification of industrial discharge, agricultural runoff, and domestic wastewater as primary sources of organic water pollutants was consistent with the findings of Schwarzenbach et al. (2010), who highlighted the widespread presence of synthetic chemicals in aquatic systems as a result of human activity. Similarly, the negative ecological and human health effects of organic pollutants, such as endocrine disruption and carcinogenicity, support Khan et al.'s (2020) results, which stress the long-term effects of persistent organic pollutants (POPs) on biodiversity and public health.

The emphasis of the review on nano-enabled remediation strategies, including the use of nanomaterials such as carbon nanotubes, graphene oxide, and metal-organic frameworks (MOFs), is consistent with the advances described by Qu et al. (2013). Their findings indicated the excellent adsorption capability and selectivity of graphene-based nanoparticles for the elimination of organic pollutants from water. However, this analysis takes a step further by critically examining these materials' limits, such as possible ecotoxicity and scaling issues, which were also identified by Bundschuh et al. (2018) in their assessment of nanomaterial safety and environmental concerns.

In contrast to Ray and Shipley's (2015) study, which focused on traditional remediation methods, such as activated carbon adsorption and advanced oxidation processes, this assessment emphasizes the greater efficiency and variety of nano-enabled systems. Liu et al. (2014) found that using photocatalytic nanomaterials like TiO_2 and ZnO may degrade organic pollutants when exposed to light. However, this analysis highlights the drawbacks of photocatalysis, such as poor quantum yield and dependency on UV light, which have not been comprehensively examined in previous studies.

Furthermore, the study expands on Luo et al.'s (2014) work by emphasizing the importance of nanotechnology in tackling rising organic pollutants, such as pharmaceuticals and personal care products (PPCPs). Luo et al. (2014) focused on the detection and occurrence of PPCPs in aquatic environments. This study included a detailed examination of nano-enabled techniques for their removal, such as membrane filtration and advanced oxidation processes boosted by nanomaterials.

Despite these advances, this study emphasizes the need for more research into the long-term environmental implications of nanomaterials, a concern shared by Nel et al. (2006). The potential for nanoparticle aggregation, release into ecosystems, and bioaccumulation highlights the significance of designing sustainable and environmentally friendly nanomaterials, as proposed by Savage et al. (2005).

6. CONCLUSION AND FUTURE PROSPECTIVES

Organic water pollutants present a significant threat to both aquatic ecosystems and human health, demanding the development of effective and sustainable cleanup techniques. This research highlights the various sources of these pollutants, including industrial discharge, agricultural runoff, and household waste, all of which contribute to widespread water contamination. These pollutants can be categorized based on their toxicity (e.g., pesticides and pharmaceuticals that pose direct health risks), persistence (e.g., per- and polyfluoroalkyl substances (PFAS) that resist degradation), and environmental impact (e.g., endocrine disruptors that alter aquatic biodiversity). Their negative effects, such as bioaccumulation and disruption of the ecological balance, necessitate urgent action for novel remediation strategies. Given their complexity and persistence, a multi-faceted approach is needed for effective treatment.

Emerging nano-enabled remediation technologies, such as nanoadsorbents, nanocatalysts, and nanomembranes, have demonstrated substantial potential in addressing these challenges. These materials can remove organic pollutants with high efficiency, selectivity, and scalability. However, significant challenges remain in ensuring their safe application. The potential toxicity of nanoparticles and their long-term ecological consequences are critical concerns. Additionally, the ability of nanoparticles to accumulate in the environment and their impact on non-target organisms requires thorough investigation. To mitigate these risks, research must focus on optimizing the manufacturing, stability, reusability, and environmental compatibility of nanomaterials, ensuring that they are safe for widespread use.

While nanotechnology offers promising solutions, it is important to emphasize the complementary role of traditional water treatment methods, such as biological, chemical, and physical processes. These methods, although useful, often fail to completely eliminate more persistent or complex organic pollutants. Thus, a hybrid approach, combining the strengths of both traditional methods and advanced nanotechnology, is essential to address the full spectrum of organic water pollutants. For example, biological treatment processes could be enhanced with nanocatalysts to break down organic compounds, or nanomembranes could be integrated into existing filtration systems to improve their effectiveness.

To ensure the responsible application of these emerging technologies, strong policy actions are needed. Policymakers must establish clear regulations and guidelines that govern the safe use of nanotechnology in water treatment, addressing concerns related to toxicity, ecological impact, and waste disposal. Moreover, it is crucial to foster interdisciplinary collaboration between scientists, policymakers, and industry stakeholders to guide research and facilitate the development of safe, sustainable, and scalable solutions. By doing so, we can ensure that nanotechnology is applied responsibly, minimizing environmental risks while maximizing its potential to address global water pollution challenges.

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