Frontiers in Environmental Chemistry

TYPE Review
PUBLISHED 12 January 2026
DOI 10.3389/fenvc.2025.1675784

OPEN ACCESS

EDITED BY
Yawei Shi,
Dalian Maritime University, China

REVIEWED BY
Ponnusami Venkatachalam,
SASTRA University, India
Prerna Mehta,
GD Rungta Educational Society, India

*CORRESPONDENCE
Amina Mumtaz,
✉ amina.mumtaz@unifi.it

RECEIVED 29 July 2025
REVISED 10 October 2025
ACCEPTED 20 October 2025
PUBLISHED 12 January 2026

CITATION
Mumtaz A, Santini S, Albino M, Muzzi B, Marinelli C, Cincinelli A, Sangregorio C and Martellini T (2026) Emerging micropollutants: risks, regulatory trends, and adsorption based-magnetic nanotechnology solutions.
Front. Environ. Chem. 6:1675784.
doi: 10.3389/fenvc.2025.1675784

Emerging micropollutants: risks, regulatory trends, and adsorption based-magnetic nanotechnology solutions

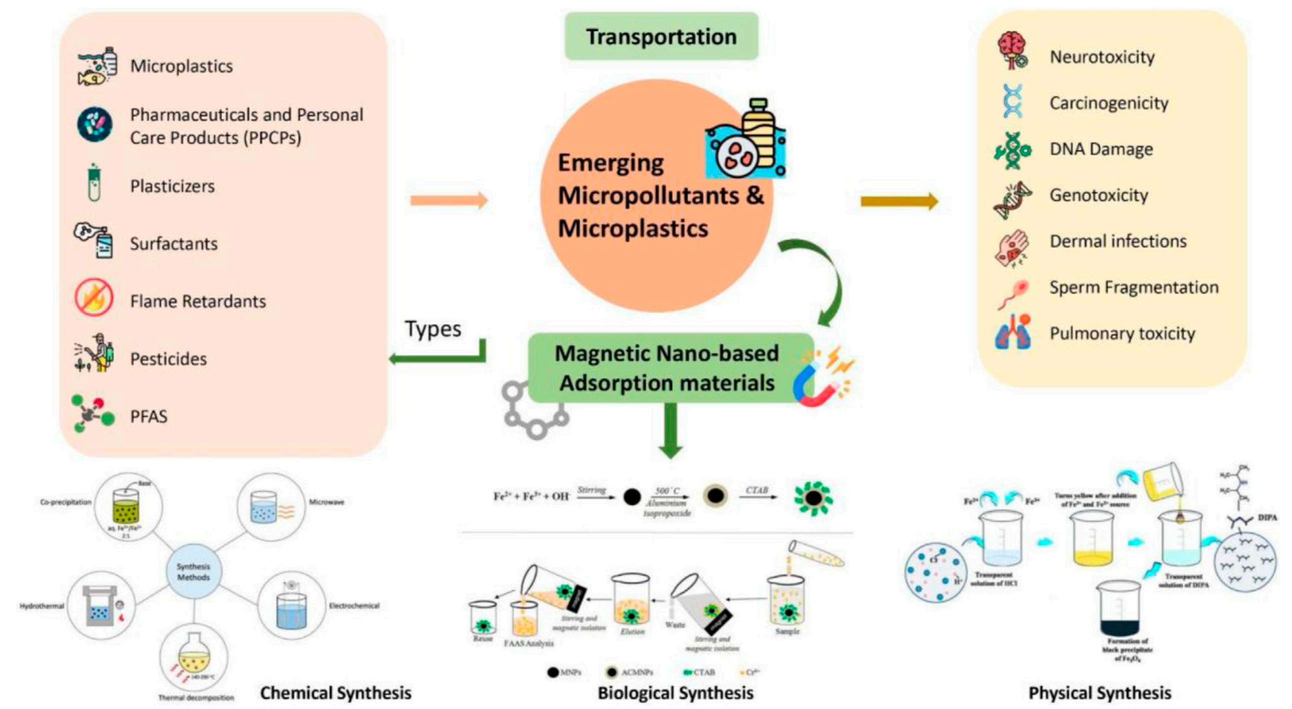
Amina Mumtaz[1]*, Saul Santini[1,2], Martin Albino[2,3], Beatrice Muzzi[2,3], Cristian Marinelli[4], Alessandra Cincinelli[1,2], Claudio Sangregorio[3] and Tania Martellini[1,2]

[1]Department of Chemistry "Ugo Schiff" - University of Florence, Florence, Italy, [2]INSTM, University of Florence, Florence, Italy, [3]ICCOM, National Research Council (CNR), Florence, Italy, [4]ANALYTICAL Food, Florence, Italy

Emerging micropollutants (EMPs) like pharmaceuticals, personal care products, pesticides, microplastics, flame retardants and per- and polyfluoroalkyl substances (PFAS), are a growing concern in aquatic environments due to their persistence, bioaccumulation, and potential toxicity. While traditional wastewater treatment technologies like advanced oxidation processes and microbial degradation may be efficient, they tend to be expensive, sophisticated, and inadequate in fully eliminating EMPs. Adsorption *via* metallic and metal oxide nanomaterials offers an attractive, low-cost and effective option over traditional technologies. This review focuses on various EMPs, pesticides among them, and their adverse impacts. It presents the physical and chemical adsorption processes employed by metal and metal oxide nanomaterials for the removal of these contaminants. Various synthesis techniques of such nanoparticles from chemical, physical, and biological techniques are discussed, highlighting their respective merits and drawbacks. The role of nanomaterials in wastewater treatment, particularly in the removal of heavy metals, antibiotics, and pesticides, is highlighted due to their high adsorption efficiency. The review also discusses the importance of nanoparticle recovery and regeneration to promote green and sustainable water treatment systems. In conclusion, it demonstrates that although nanotechnology offers significant promise for addressing water pollution, more research is needed into eco-friendly synthesis methods to improve its effectiveness in environmental remediation.

KEYWORDS

adsorption, nanomaterials, wastewater treatments, metallic nano-particles, emerging micro pollutants (EMPs), green synthesis



GRAPHICAL ABSTRACT

Highlights

- Emerging micropollutants (EMPs) are posing a significant risk to human and environmental health and are detectable in analytical technique advancements.
- Magnetic and metal oxide nanomaterials provide a major and affordable alternative for the clean-up of EMPs along with their higher adsorption capabilities.

1 Introduction

The recent development of new technologies and the improvement of instrumental sensitivity has led to the identification of new classes of substances, named as emerging micropollutants (EMPs) (Zheng et al., 2025; Ratchnashree et al., 2023). The term 'emerging' is referred to a group of chemical substances that are detected in the environment, particularly in soil, surface water, groundwater, and the atmosphere, and they are not currently (or have only recently been) regulated (Sharma et al., 2025; Ruan et al., 2023). EMPs (Emerging micropollutants) constitute a wider group of synthetic and naturally occurring chemicals present in the environment, generally at trace concentration levels, ranging from picograms per liter (pg/L) to nanograms per liter (ng/L), which are causing growing concern due to their adverse effects on ecosystems and human health (Vasantha Raman et al., 2023; Dubey et al., 2023). Common groups of EMPs may include pharmaceutical and personal care products (PPCPs), per- and poly-fluoroalkyl substances (PFAS), surfactants, industrial chemicals, plasticizers, new pesticides, nanomaterials, and biological toxins (Kumar S. et al., 2025). These contaminants exhibit long-term persistence, capacity for further transformation and ability to undergo long-range transport, leading to their appearance even in regions far from their original sources, including remote areas (Scopetani et al., 2023). EMPs can enter the aquatic environment through various pathways including agricultural practices and run-off, landfill leachate, industrial activities, and direct discharge of treated or raw wastewater from and industrial wastewater treatment plants (WWTPs) (Haider Naqvi et al., 2023; Ayub et al., 2023; Jadaa and Mohammed, 2023; Jampílek and Kráľová, 2025).

Though they have proven effective, traditional water treatment techniques including microbial degradation and enhanced oxidation processes are sometimes hampered by their high costs, intricate operations, and energy-intensive procedures (Kikanme et al., 2024). To clean-up EMPs from contaminated waters, there is a rising demand for alternative, more sustainable treatment techniques than conventional systems (Khajvand et al., 2022; Babaniyi et al., 2023; Ogundele et al., 2023).

The increasing complexity and diversity of pollutants in water systems necessitate the adoption of advanced technologies capable of selectively targeting and removing these compounds. In this context, nanomaterials represent a new Frontier in environmental remediation, offering unprecedented control at the molecular level (Kumar A. et al., 2025; Singh and Saxena, 2022; Karnwal et al., 2024). Their potential to be tailor-made means that particular treatment processes can be designed to deal with specific contaminants, including PFAS, pharmaceuticals, endocrine-disrupting chemicals, and heavy metals (Ben Dassi and Chamam, 2025; Dey et al., 2025). For the technologies to be sustainable and eco-friendly, there is a need to design processes for selective contaminant removal from the nanoparticles and to use efficient nanomaterial recovery and regeneration systems (Ayyadurai and Ragavendran, 2025; Aziz et al., 2025). In addition, application of metallic nanomaterials to adsorption processes is a highly promising route (Babaniyi et al., 2023; Ogundele et al., 2023; Sable et al., 2024). Adsorption as a process employs both physical and chemical forces in capturing and removing pollutants with strong efficiency potential for scaling up and integration into existing water treatment plants (Kumar S. et al., 2025; Singh et al., 2025).

Lastly, the confluence of water treatment and nanotechnology signals a paradigm shift towards next-generation clean-up methods wherein precision, efficiency, and sustainability are in delicate balance to address the global challenge of water pollution. The integration of such cutting-edge materials and methods is not only a technological advancement but also a necessary evolution to safeguard water resources for future generations. An in-depth review of the significant methods of synthesizing metal nanoparticles (MNPs), i.e., chemical, physical, and biological routes, is essential in order to understand their application in wastewater treatment (Chauhan et al., 2022; Li Q. et al., 2024). The review targets the application of MNPs due to their superior performance over other approaches in the removal of pollutants such as heavy metals, antibiotics, and pesticides. Compared to conventional treatment methods such as microbial degradation or oxidative advanced processes the use of MNPs offers a simpler yet efficient option. Their high surface area and catalytic properties make them uniquely capable of capturing and accumulating contaminants through physicochemical processes of adsorption (Ahmed et al., 2022; Kumar and Singh, 2025). Adsorption by metallic nanoparticles is one such trusted alternative to expensive and complex conventional treatment processes involving multiple processes such as microbial degradation, oxidation *etc.* The potential of MNPs for environmentally friendly and efficient water purification makes research in this field an imperative. While green nanotechnology offers valuable prospects for environmental remediation, further studies are essential to address the safety, regeneration, and long-term environmental impacts of MNPs. Therefore, this review aims to explore the synthesis methods, functional properties, and specific advantages of MNPs in wastewater treatment, with a particular attention to their feasibility, effectiveness, and ecological compatibility.

2 Review methodology

This review includes published research from the year 2014–2025, extracted from databases such as Web of Science, Google Scholar, ResearchGate, Scopus, and PubMed. Selection of papers included within relevance to the subject:

The application of nanotechnology in addressing EMPs presents both promising opportunities and notable concerns. One of the most explored treatment strategies involves adsorption-based techniques, which have shown significant potential for removing various pollutants. Comparative studies have been conducted to evaluate the efficiency of different nanomaterials in eliminating these contaminants, highlighting variations in their performance. Despite encouraging laboratory results, the real-world applicability of these technologies remains a challenge due to factors such as scalability, cost, and environmental safety. Additionally, limitations in nanotechnology solutions, including potential toxicity and long-term stability, must be carefully considered. From an environmental and sustainability standpoint, it is essential to balance the benefits of nanotechnology with its potential ecological risks to ensure responsible and effective implementation.

Numerous peer-reviewed studies were systematically screened for relevance to nanotechnology-based micropollutant removal, primarily adopting an adsorption technology and real-world applicability search strategy. Along with the keyword queries such as “Nanomaterials,” “Adsorption,” “Emerging Micropollutants,” and “Wastewater Treatment,” relevant studies were identified through a screening of the full manuscripts. The comparative analysis highlighted the pollutants associated with different wastes, including pharmaceuticals, pesticides, microplastics, plasticizers, surfactants, and flame retardants. In addition, nanotechnology-based solutions had been evaluated against actual implementation, taking into consideration cost, scalability, environmental risk, and regulatory constraints.

3 Advancing nanotechnology in wastewater treatment

The application of nanoparticles in water purification, especially for the removal of emerging micropollutants, offers a significant advantage over conventional methods due to their enhanced surface reactivity, tunable porosity, and superior adsorption efficiency. The fast emergence of micropollutants in wastewater, such as pharmaceuticals and pesticides, and industrial chemicals, has led to the need for efficient treatment technologies. Nanotechnology has been regarded as a revolutionary approach as it provides the highest surface area, with tunable chemical properties and multifunctional properties that enable various interactions with contaminants. A mechanistic classification of nanomaterials provides a clearer picture of their performance, shortcomings, and potential for real-world applications than simply mentioning generic “high efficiency.”

Carbon-based nanomaterials, such as carbon nanotubes (CNTs), graphene oxide (GO), and activated carbon composites, have been extensively investigated due to their strong adsorption capabilities. These materials interact with pollutants through л-л stacking, hydrogen bonding, and electrostatic interactions, mechanisms particularly effective for aromatic compounds present in many pharmaceuticals and pesticides., graphene-oxide-based materials have exhibited greater than 90% removal of diclofenac at neutral pH, while carboxyl-functionalized CNTs have realized 85%–95% removal of atrazine in batch studies (Liu et al., 2022; Singh et al., 2023). With their high adsorption potential and modifiability of surface groups, nanocarbon materials face regeneration difficulties and possible issues of nanofragment release into treated water, thus being considered a key impediment toward upscaling. Metal and metal-oxide NPs-TiO_2, ZnO, Fe_3O_4, and CO_2-provide adsorption functionalities coupled with catalytic or photocatalytic degradation. These nanoparticles can remove pollutants through surface adsorption, redox reactions, and photocatalysis under UV or visible light.

Under UV light, TiO_2 nanoparticles offered a mineralization rate of diclofenac up to 90% in 60 min, whereas adsorption capacities of 150 mg/g were noted by Fe_3O_4 nanoparticles for some antibiotics (Ahmed et al., 2021; Khan et al., 2024). The combination of the adsorption properties with photocatalysis presents certain advantages; however, nanoparticle aggregation, toxic by-product formation, and an expensive synthesis process present a barrier to larger-scale use. It is thus suggested that future studies concentrate on eco-friendly green synthesis methods, along with the reduction of toxic intermediates. Hybrid nanocomposites like magnetic biochar, metal-organic frameworks (MOFs), and silica-graphene composites have been developed for synergistic removal of pollutants. Those materials operate *via* adsorption coupled with catalytic degradation, often surpassing the synthetic ability of single-component systems. For example, magnetic biochar was able to remove more than 96% of bisphenol A, while MOFs show an extraordinary adsorption capacity of up to 473 mg $g{-}^{1}$ for tetracycline (Quan et al., 2019; Liu et al., 2019). If the concern is efficiency, these hybrids, indeed, guarantee that. However, their potential for reuse and for magnetic separation facilitate easy recoveries from the medium. The environmental stability of these materials and the enormous costs of their manufacturing pose great threats to their use, so the emphasis has shifted towards designs that are stable and also economically friendly for large-scale wastewater treatment. Nanoparticle-biology hybrids represent a very recent area of study in wastewater treatment that involve the coupling of nanoparticles with microbial systems to facilitate the degradation of contaminants. Nano-enzymes or magnetic nanoparticles are used for supporting microbial consortia to enhance electron transfer and increase pollutant bioavailability, thereby speeding up degradation. Studies show that these Fe_3O_3-microbe-facilitated degradation systems improve degradation of phenol by 50% compared to microbial treatment alone (Jiang et al., 2024). Apart from being eco-friendly, they also offer an excellent selective removal of contaminants. Maintaining stability at the nano-bio interface and mitigating potential nanotoxic effects on microorganisms remain, however, key research gaps. Future studies should focus on optimization of interface chemistry and long-term stability of these hybrid systems for ensuring reliable performance.

Collectively, these advances illustrate the versatility of nanomaterials in wastewater treatment. Carbon-based nanomaterials excel in adsorption, metal oxides provide catalytic activity, hybrid composites integrate multiple mechanisms, and nano-bio systems introduce environmentally compatible, targeted degradation. Despite promising laboratory results, several challenges including scalability, environmental stability, material recovery, and potential toxicity must be addressed to translate these technologies into practical applications. Addressing these gaps represents a critical direction for future research, aiming to develop sustainable, high-performance nanomaterial-based wastewater treatment strategies. Below a Table showing nanomaterials with micropollutants and their removal efficiency in advance wastewater treatment is reported.

4 Comparative analysis: limitations and real-world challenges of nano-technology based remediation

Nanomaterials represent powerful alternatives to conventional treatment methods being endowed with adsorption power and surface reactivity.

4.1 Comparison of nanomaterials-based technology and conventional methods

They still are a constraint in actual implementation because of high initial cost, uncertain ecotoxicity, and a lack of regulatory policies. Table 1 provides a comparative analysis between conventional methods and their nanotechnology-based alternatives aiming to highlight the major advantages and limitations of each. The incorporation of nanomaterials enhances the conventional processes in terms of adsorption capacity, photocatalytic efficiency and reusability.

However, in addition to the lack of large-scale synthesis methods, nanomaterials encountered hindered large-scale deployment representing a novelty in public acceptance. Yet, the scientific literature is devoid of long-term field studies, and fragmented regulations stand as further roadblocks to development in wastewater infrastructure, especially in developing countries.

4.2 Environmental and economic impact assessment

Nanoparticle-based solutions, while effective, present several economic and environmental challenges. From a cost perspective, nanoparticles are significantly more expensive-up to 5 to 10 times-compared to traditional adsorbents like activated carbon, which limits their feasibility for large-scale applications (Gadel Hak et al., 2023). Additionally, many nanoparticle synthesis methods demand high-temperature processes exceeding 500 °C, leading to increased energy consumption, higher operational costs, and larger carbon footprint (Wang et al., 2024). Another critical concern is waste generation; nanoparticles often become contaminated with metals during use, making their safe disposal difficult due to their persistent and resistant nature (Sable et al., 2024; Kumar M. K. et al., 2025; De Luca et al., 2023). These factors collectively highlight the need for more cost-effective, energy-efficient, and environmentally responsible approaches in nanomaterial development.

4.3 Problems of implementation in the real world

Despite their promising capabilities, nanoparticle-based techniques for removing EMPs face significant practical and societal challenges. One major limitation is the lack of pilot-scale testing, as most research remains confined to laboratory conditions without real-world validation (Hussain et al., 2023). Furthermore, actual wastewater systems are complex and contain a multitude of competing contaminants, which can hinder the effectiveness of nanoparticle adsorption (Altaf et al., 2022). Public and regulatory acceptance also poses a barrier, largely due to uncertainties regarding the long-term impacts of engineered nanomaterials on both human health and the environment (Dhumal et al., 2025; Dou et al., 2012; Wang et al., 2012). A particular concern is the persistence of nanoparticles in aquatic systems, as their stability makes post-treatment removal difficult and raises environmental safety issues (Edo et al., 2025; Fernandes, 20212; Fernandes et al., 2019; Shatkin, 2017). These limitations underscore the need for

TABLE 1 Comparative overview between conventional water treatment methods and their nanotechnology-based alternatives.

Treatment process	Conventional materials/ methods	Nanomaterial alternatives	Advantages of nanomaterials	Limitations/ challenges	Source
Adsorption	Activated Carbon	TiO_2, Fe_3O_4, CNTs, graphene-based sorbents	High adsorption efficiency *via* π–π stacking, electrostatic attraction, and hydrophobic interactions; large surface area; tunable surface chemistry; regeneration potential.	High cost of synthesis; potential toxicity; scalability issues.	(Alayan et al., 2021; Ahmaruzzaman et al., 2025; Aravind and Kamaraj, 2024; Zheng et al., 2025)
Membrane Filtration	Polymeric/ceramic membranes	Nanocomposite membranes (graphene oxide, TiO_2, AgNP-modified)	Enhanced permeability, antifouling properties, improved rejection of micropollutants and emerging contaminants.	Fabrication cost; nanoparticle leaching; high energy demand for pressure-driven processes.	(Abu-Dalo et al., 2023; Nain et al., 2022; Yin et al., 2020)
Oxidation/ Advanced oxidation	Ozone, UV/H_2O_2	Nano-catalysts (e.g., TiO_2, ZnO, Fe-doped catalysts)	Mineralization of persistent organic micropollutants into CO_2, H_2O, and inorganic ions; efficient photocatalytic degradation under UV/visible light.	Formation of toxic intermediates such as formaldehyde, short-chain aldehydes, or chlorinated by-products; high energy input required.	(Kurian, 2021; Fernandes, 2022; Priyadarshini et al., 2024)
Bioremediation	Native microbial consortia	Nano-bio hybrids (e.g., magnetic nanoparticles with microbes, nano-enzymes)	Enhanced pollutant bioavailability; improved electron transfer between microbes and pollutants; environmentally friendly.	Nanotoxicity risks to microbial communities; stability of nano-bio systems; dependence on environmental conditions.	(Milano et al., 2024; Singh et al., 2025; Singh and Saxena, 2022; Ahmad I. et al., 2024; Kamal et al., 2024)

more comprehensive research, transparent risk assessments, and the development of safer, scalable technologies.

5 Conventional technologies for EMPs removal WWTPs

The current methods for remediating EMPs operate through various mechanisms and offer specific advantages, yet each also presents significant limitations that hinder widespread adoption (Altaf et al., 2022). For example, electro-kinetic remediation is both cost-effective and efficient, particularly in fine-grained or heterogeneous soils (Han et al., 2021). However, it suffers from drawbacks like high energy usage, poor mass transfer, and incomplete removal of organic pollutants bonded to clay particles or microorganisms. Similarly, microbial bioremediation is low-cost, environmentally friendly, and capable of rapid adaptation through genetic mutation, but its effectiveness is often constrained by a dependence on specific environmental conditions (Hofman-Caris and Hofman, 2019).

The advanced oxidation processes (AOPs) are highly effective at breaking down persistent organic pollutants into simpler, more stable substances with minimal sludge production (Paliwal et al., 2012). Nonetheless, concerns over the human health risks posed by hydrogen peroxide (Lama et al., 2022), along with the high costs, substantial energy and chemical demands, and the formation of intermediate by-products, limit their practical use. Membrane filtration offers another approach, known for its compact footprint, reduced sludge generation, and strong performance in removing microcontaminants in an eco-friendly manner. However, its application at large scale is challenged by the high energy requirements, the production of concentrated waste, and the frequent need for membrane replacement (Saravanan et al., 2021).

A variety of technologies-such as advanced oxidation, microbial degradation, and enzymatic catalysis-have been explored to mitigate EMP contamination. While each has proven effective in specific contexts, their broader implementation is limited by prohibitive costs. In contrast, adsorption and biosorption techniques stand out as cost-effective alternatives, especially when employing waste materials for pollutant removal (Krishnan et al., 2023; Sen, 2023).

The current remediation technologies for emerging micropollutants are shown in Table 2. EMPs, including pharmaceuticals, pesticides, and endocrine-disrupting compounds, represent a growing concern in wastewater treatment due to their persistence and harmful effects on ecosystems and human health. Several conventional remediation technologies have been developed to address EMPs, each with distinct mechanisms, benefits, and limitations. Table 2 summarizes the key remediation strategies currently used, including electro-kinetic remediation, microbial bioremediation, advanced oxidation processes, and membrane filtration systems.

While each of these technologies offers unique advantages, their limitations necessitate the exploration of more integrated and effective solutions. One promising direction is the development of hybrid systems, particularly membrano-nano composites, where metallic nanoparticles (MNPs) are embedded into or combined with membrane matrices. These systems have shown improved contaminant adsorption, enhanced reactivity, and reduced fouling, thereby overcoming some of the key shortcomings of standalone membrane and adsorption systems.

For example, incorporating silver, titanium dioxide, or zero-valent iron nanoparticles into polymeric membranes can significantly enhance antimicrobial activity, permeability, and selectivity. Moreover, such hybrid approaches align with environmentally sustainable goals while improving efficiency in removing a broader range of micropollutants.

TABLE 2 Conventional remediation technologies used for EMPs.

Remediation technology	Mechanism	Advantages	Disadvantages	Source
Electro-kinetic Remediation	This is the process of applying a low-voltage direct current to electrodes to affect the migration of charged contaminants in the imposed electric field *via* primary transport mechanisms such as electromigration, electroosmosis, and electrophoresis.	➔ Implementation on-site ➔ Limited soil disturbance ➔ Particularly suitable for fine-grained and heterogenous media. ➔ Minimization of post-treatment waste volume ➔ Economical	➔ Increased energy consumption due to soil acidification and alkalization ➔ Inefficient mass transfer ➔ Remedial organic compound limitation due to limited solubility. ➔ Inability to completely remove organic contaminants bound to clay particles and soil organisms.	(Hassaan and El Nemr, 2020; Chen et al., 2021)
Microbial Bioremediation	It is a method that uses the ability of biological agents (microorganisms) to biodegrade pollutants.	➔ Simple to cultivate ➔ Abundant microbial population ➔ Rapid mutation ➔ Economical ➔ Environmentally friendly ➔ Absence of harmful by-products	➔ Bioremediation efficacy limited by environmental factors (i.e., temperature, pH, oxygen availability, nutrient level)	Bhat et al. (2020)
Advanced Oxidation	It is the process that uses highly reactive oxidizing agents to degrade recalcitrant chemical compounds to less toxic or non-toxic substances by the reduction-oxidation system. Common to Water treatment plants	➔ Treatment of recalcitrant pollutants ➔ Capacity to convert organic chemicals into more stable, simpler inorganic forms ➔ Little sludge generation	➔ High energy consumption ➔ High chemical need ➔ Incomplete mineralization and to formation of high toxic intermediates ➔ High cost ➔ H_2O_2 is hazardous to people	(Bello and Raman, 2018; Kumar and Shah, 2021; Kurul et al., 2025)
Membrane Filtration	The process utilizes membranes as barriers permitting the passage of water while separating contaminants based on their size. Common to Water treatment plants.	➔ Eco-friendly ➔ Easy to use ➔ Effective at removing ➔ microcontaminants. ➔ Less room required. ➔ Less sludge production rate	➔ Not energy saving Intense and complex operational pressures. ➔ Replacing membrane	González et al. (2015)

TABLE 3 Nanomaterials with micropollutants and their removal efficiency.

Nanomaterial class	Typical pollutants	Mechanism	Reported efficiency	Source
Carbon-based (CNTs, GO)	Antibiotics, pesticides, PPCPs	π–π stacking, H-bonding, electrostatic interactions	85%–95% atrazine removal	Liu et al., 2022; Singh et al., 2023
Metal oxides (TiO_2, ZnO, Fe_3O_4)	Pharmaceuticals, hormones, pesticides	Adsorption + photocatalysis	90% diclofenac mineralization under UV	Ahmed et al., 2021; Khan et al., 2024
Hybrid nanocomposites (biochar, MOFs, silica-GO)	BPA, tetracycline, PFAS	Synergistic adsorption and catalysis	96% BPA removal; 473 mg/g tetracycline adsorption	Quan et al., 2019; Liu et al., 2019
Nano-bio hybrids	Phenols, dyes, PPCPs	Enhanced microbial electron transfer	50% faster phenol degradation	Jiang et al. (2024)

Therefore, while the conventional approaches summarized in Table 3 provide foundational insights into current practices, the focus of this review will shift toward emerging nanotechnology-enhanced solutions, particularly the use of metallic nanoparticles, to evaluate their potential in overcoming existing limitations in EMP remediation.

6 Overview of emerging micropollutants

EMPs encompass a broad spectrum of organic and inorganic contaminants that enter aquatic environments through domestic, agricultural, and industrial sources (Gebru and Werkneh, 2024). Among these, Pharmaceuticals and Personal Care Products (PPCPs) represent a particularly concerning subgroup due to their chemical complexity, biological activity, and persistence in the environment (Shah, 2024). Common PPCPs include antibiotics, analgesics, hormones, antiepileptics, fragrances, and sunscreen agents. These compounds are typically present in trace concentrations (ng/L to μg/L), yet they can induce endocrine disruption, antibiotic resistance, and bioaccumulation even at such low levels (Chakraborty et al., 2023; Rehman et al., 2024). The challenge in removing PPCPs from water lies in their low biodegradability and structural diversity, which limit the efficiency of conventional wastewater treatment technologies (Ethiraj and Samuel, 2024; Demaria et al., 2025; Suleiman et al., 2025). As a result, many of these substances pass through treatment plants intact or only partially degraded, eventually entering surface and groundwater systems and posing a long-term risk to ecosystems and public health (Chauhan et al., 2025; Singh et al., 2025; Jayasekara et al., 2025).

Given these limitations, advanced nanomaterials, such as functionalized nanoparticles, nanocomposites, and carbon-based nanomaterials, have emerged as a promising solution for PPCP removal. Their high surface surface-to-volume ratio, tailorable surface properties, and nanoscale reactivity enable the selective adsorption and degradation of complex pollutants that conventional methods cannot address (Rasheed et al., 2020; Ogbeh et al., 2025). In particular, nanomaterials can be engineered with specific surface functionalities to target PPCPs through hydrogen bonding, π-π interactions. or electrostatic attraction. making the process efficient and adaptable (Ojha et al., 2021; Rani et al., 2025; Ali et al., 2019; Padhiary et al., 2025).

Moreover, these technologies offer the added advantage of regeneration and reuse, enhancing their sustainability for long-term water treatment applications. Their integration into hybrid systems (e.g., membrane-nano composites or photocatalytic reactors) is opening new frontiers in environmental remediation-enabling real-time, decentralized, and high-efficiency solutions for emerging pollutants. The urgent need to mitigate the ecological and health risks posed by PPCPs underscores the importance of transitioning toward next-generation water treatment strategies, where nanotechnology plays a pivotal role in achieving safer and cleaner water systems. As illustrated in Figure 1, the adsorption of EMPs depends on both environmental parameters and the physicochemical properties of materials whose surface chemistry and hydrophobicity influence their interaction with various contaminants. In particular, the properties of microplastic, such as particle size, surface area, surface chemistry, and hydrophobicity, are highlighted because they strongly affect adsorption efficiency and interactions with other pollutants.

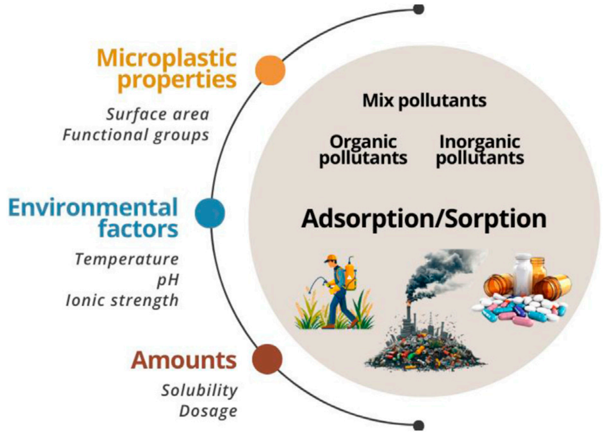


FIGURE 1
Main factors influencing EMPs adsorption/sorption phenomenon. Microplastic properties such as particle size, surface area, and hydrophobicity are included because they significantly affect pollutant adsorption and interactions in aquatic systems.

6.1 Microplastics

MPs have become a pressing concern due to their widespread presence in aquatic environments, which has required stringent regulations and innovative treatment methods (Yang et al., 2022). In fact, WWTPs have long been recognized as a potentially significant source of MPs pollution in aquatic environments due to their polydisperse and degradation-resistant properties of MPs along with their capacity to pass through treatment processes. Several studies (Bilal et al., 2020) have reported the adverse effects of MPs on biota which include disturbances in feeding, mobility and reproduction that can lead to lethal or sub-lethal effects. Moreover, MPs can also contain toxic pollutants, such as heavy metals or endocrine-disrupting chemicals, increasing their bioavailability and toxicity, and affecting development and reproduction in humans and other species.

6.2 Pharmaceuticals and personal care products (PPCPs)

Pharmaceuticals and personal care products have become a major class of emerging micropollutants as they are continuously found in water bodies potentially adversely impacting ecosystems and human health. To tackle this problem, a wide variety of different treatment technologies have been developed and extensively studied, including physical processes such as membrane filtration and adsorption, biological processes using microbial degradation and enzymatic activity, and chemical methods that include AOPs and coagulation-flocculation techniques. While the effectiveness of these methods has been conventionally demonstrated, their various inefficiencies, including incomplete removals, energy-consuming operations, and the generation of secondary pollutants, call for new ideas.

The pharmaceutical and personal care products (PPCPs), including hormones, antibiotics, lipid regulators, beta blockers, non-steroidal anti-inflammatory drugs, antidepressant, anticonvulsants, antineoplastics among pharmaceuticals and fragrances, preservatives, disinfectants and sunscreen agents among personal care products, are EPs which might pose potential hazards to environment and health. These pollutants are becoming ubiquitous in the environments because they cannot be fully removed by the conventional WWTPs due to their toxic and recalcitrant properties. Thus, their presence has received increasing attention in recent years, resulting in great concern on their occurrence, transformation, fate and risk in the environment, and regulatories (Dey et al., 2019; Ziylan-Yavas et al., 2022; Han et al., 2024; Jiang et al., 2025; Kim et al., 2024; Rückbeil et al., 2025; Satyam and Patra, 2024).

6.3 Plasticizers

Plasticizers, such as bisphenol A (BPA) and phthalates, are generally added to materials to increase their softness and flexibility (Fasano and Cirillo, 2018). However, because these compounds are not completely removed by conventional wastewater treatment processes, they increasingly are being recognized as persistent environmental pollutants. Most often, plasticizers persist in treated effluents and sometimes in sewage sludge, thus posing a dual threat of environmental contamination and potential problems with sludge reuse in agriculture or landfills.

They propensity to leach from plastic products and enter aquatic systems increases their impact, contributing to serious health issues such as endocrine disruption, reproductive abnormalities, and an increased risk of cancers (Godswill and Godspel, 2019). Given these challenges, considerable efforts have been to develop nanoparticle-based techniques to increase the removal efficiency of plasticizer from wastewater. Among these, adsorption techniques using engineered nanoparticles have shown impressive performance due to the high surface area of the nanoparticles, easily tunable surface functionalities, and strong affinity for both hydrophobic and hydrophilic pollutants (Raeisi et al., 2017). Examples include nanoparticle carbon-based materials (such as carbon nanotubes and graphene oxide), metal oxides (like titanium dioxide and iron oxide), and functionalized polymers that have been widely investigated for selective adsorption of plasticizers from complex aqueous matrices (Yin and Hakkarainen, 2011; Yin et al., 2014).

6.4 Surfactants

Among the most common organic contaminants found in wastewater, surfactants are the main constituents of cleaning agents and detergents and various industrial products. They are amphiphilic chemicals and thus exhibit hydrophilic and hydrophobic properties, which give them the characteristic tendency to reduce surface tension and thereby increase cleaning effectiveness. However, their structural diversity, from anionic to cationic, including nonionic and zwitterionic forms, significantly challenges conventional treatment methods, since each class displays unique chemical behaviors and persistence in aquatic environments. Although their structures are tailored for rapid biodegradation, intermediate surfactants degradation products often maintain or exceed the toxicity of the parent compounds, hence the environmental and health risks associated with this class of compounds (Knepper and Berna, 2003). The exploration of eco-friendly substitutes and their harmful effects on aquatic organisms is the focus of ongoing research. Regulations have begun to focus more on safety and biodegradability of surfactants in consumer goods.

Numerous articles have been published on the adverse effect of surfactants on the environment, wildlife and humans (Human & Environmental Risk Assessment (HERA) Project, 2002; Human & Environmental Risk Assessment (HERA) Project, 2013).

6.5 Flame retardants

Flame retardants are a group of various chemicals added to plastics, textiles, and electronic materials to reduce their flammability and slow the spread of fire. Although they play a crucial role in improving fire safety, their widespread use has raised concerns about their persistence, bioaccumulation, and adverse impacts on environmental and health issues. Flame retardants, of which BFRs represent a prominent group, including polybrominated diphenyl ethers (PBDEs) and hexabromocyclododecane (HBCD), have been pointed out as an emerging micro pollution given their widespread occurrence in water, soil, and air (Ward et al., 2008; Fromme et al., 2016; GadelHak et al., 2023; Gai et al., 2014). Conventional wastewater treatment processes, such as coagulation, sedimentation, and biological processes, are generally ineffective at removing flame retardants due to their low water solubility and high chemical stability. Advanced treatment processes, such as, AOPs, and membrane filtration, have shown promise but are often inhibited by high operational costs and incomplete removal. Regulatory approaches to mitigate the environmental and health challenges resulting from the use of flame retardants and other EMPs are matched with the development of potentially greener alternatives and innovative treatment technologies, such as nanoparticle-based systems. Such recent developments point to a way forward in efforts to reduce risks from flame retardants while enabling the safe reuse and management of water resources.

6.6 Pesticides

Among the most commonly used agricultural pesticides in agriculture are herbicides, insecticides, and fungicides, all intended to protect crops and improve productivity. Although essential to modern agricultural methods, the excessive and non-selective use of these pesticides has made them one of the most significant emerging micropollutants in water systems. Due to their chemical stability, pesticides often persist in the environment and can reach aquatic ecosystems through agricultural runoff, leaching, and improper disposal. Their occurrence in water poses serious risks for human health, biodiversity, and ecological balances (Mehta, 2023). Many pesticides are designed to resist degradation and remain effective for long periods. This persistence allows them to be transported through soil and water, contaminating groundwater, rivers, and lakes. For example, organochlorine pesticides such as DDT can persist in the environment for decades (Kadiru et al., 2022). The synthesis of magnetite-impregnated functionalized MWCNTs MWCNT–OH–Mag and MWCNT–COOH–Mag for 2,4-D and atrazine adsorptions under optimal pH conditions-enhanced improved adsorption performance, stability, and quick adsorption. The high adsorption capacity combined with rapid adsorption kinetics makes the materials reusable for the adsorption of contaminants from wastewater (Pereira et al., 2023) Currently, there is a strong emphasis on the development of environmentally friendly pesticides and integrated pest management strategies. This shift is driven by a growing awareness of EMPs and their potential risks. Research and regulatory frameworks have intensified in response, with governments around the world focusing on stricter regulations, advanced treatment technologies, and safer alternatives to reduce the impact of these substances. Effectively addressing the challenges posed by EMPs requires a holistic approach that integrates technological innovation, legislative action, and public education. Table 4 provides an overview of the main EMP categories, representative examples, and their reported human health effects according to recent studies.

Traditional wastewater treatment methods, such as coagulation-flocculation, sedimentation, filtration, and activated sludge systems, are not as effective at removing organic pollutants. For instance, the removal efficiency of pharmaceuticals and personal care products (PPCPs) ranges between 20% and 90%, depending on the compound and the process. Hormones such as estradiol and 17α-ethinylestradiol exhibit rather moderate removal efficiencies

TABLE 4 Shows a comprehensive discussion EMPs and their impacts on human health.

Group	Description	Examples	Impacts on human health	Source
MPs	Primary MPs	Nylon, Synthetic fiber, beads, Polyethylene, Polystyrene, Polypropylene, Bisphenol A, PVC	Endocrine disruptors, various cancers, reproductive system disorders, hormones misbalancing, Growth inhibition, Thyroid gland issues, Brain tissue damage, oxidative stress, morphological changes	(Alimba et al., 2021; Johannessen and Shetranjiwalla, 2021)
		Plastic pellets, nurdles, films, foams		
	Secondary MPs	From the breakdown of primary MPs e.g., water bottles		
Pharmaceuticals	Analgesics	Ketoprofen, acetaminophen, Naproxen	(Rat) phthalate syndrome, Depression of testicular function, the elevation of the stimulatory pituitary hormones, the spread of antibiotic-resistant bacteria, disruption of homeostasis, an increase in plasma vitellogenin of chub, reduction on plasma testosterone on goldfish	(Liu and Wong, 2013; Ebele et al., 2017; Al-Baldawi et al., 2021; Krishnan et al., 2021; Lu et al., 2007)
	Antibiotics	Amoxicillin, Doxycycline, Cefalexin, Erythromycin Sulfamethoxazole, Trimethoprim		
	Anticancer drugs	Cytarabine, Ifosfamide, 5-Fluorouracil		
	Anti-inflammatory	Ibuprofen, Diclofenac, Aspirin, Piroxicam		
	Hormones and Steroids	Estrone, Estriol, Testosterone, Estradiol, 17α-ethinylestradiol, Prednisolone, Diethylstilbestrol		
	Beta-blockers	Bisoprolol, Sotalol, Atenolol, Propanolol		
	Lipid regulators	Pravastatin, Clofibric acid, Atorvastatin, Gemfibrozil, Bezafibrate, Fenofibric acid, and Etofibrate		
Personal Care Products (PPCPs)	Sunscreen UV filers	Benzophenone and methylbenzylidene camphor, Octyl-triazone, Oxybenzone, Octinoxate, Octocrylene	main causes of MPs, organ dysfunction, and central respiratory and neurological systems, as well as the development of cancer cells	(Ebele et al., 2017; Al-Baldawi et al., 2021; Krishnan et al., 2021)
	Insect replants	N,N-diethyl-m-toluamide, N,Ndiethyl benzamide		
	Fragrances	Eugenol, musk ketone, limonene, methyl salicylate, musk xylene, nitro musks, polycyclic, macrocyclic musks, methyl dihydrojasmonate, phthalates, galaxolide, tonalide		
	Soaps and Shampoos	Sodium Lauryl Sulfate, Ammonium Lauryl Sulfate, Salicylic acid		
	Preservatives	Sucralose, benzyl acetate, propyl paraben, methyl, ethyl and butyl paraben, 2-phenoxyethanol, ethyl 4-hydroxybenzoate, Butylated Hydroxyanisole		
	Disinfectants	Chloroprene, Methyltriclosan, Triclocarban		
Plasticizers	Organic compounds	Bisphenol A (BPA), Bisphenol A diglcidyl ether (BADGE)	Toxic and carcinogenic effects, endocrine disruptors on both human and animals	Cortina-Puig et al. (2018)
Surfactants	Anionic	Alkyl benzene sulphonic acid (LAS)	Landfills, sludge, toxic degradation products in the environment and their estrogenic properties	(Suresh and Abraham, 2019; Rasheed et al., 2020)
	Cationic	Quaternary ammonium Compounds (QAS)		
	Nonionic	Alkylphenol polyethoxylated (APEOs)		
	Amphoteric	Amine oxides (AOs)		

(Continued on following page)

TABLE 4 (*Continued*) Shows a comprehensive discussion EMPs and their impacts on human health.

Group	Description	Examples	Impacts on human health	Source
Flame Retardants	NBFRs	DBDPE, BTBPE, 2-ethylhexyl-2,3,4,5-tetrabromobenzoate (TBB), bis(2-ethylhexyl)-3,4,5,6-tetrabromo-phthalate (TBPH), 2,4,6-tribromophenol (TBP) TCIPP, TDCIPP, TCEP, TNBP, TPHP, TBOEP	diminished fecundability, IQ deficiencies, thyroid hormone regulation disturbance, change hormone levels, decrease sperm quality, decrease neural plasticity in rats, and cause follicular hypertrophy	(Lazarov, 2022; Kristanti et al., 2023; Haider Naqvi et al., 2023)
	OPFRs			
Pesticides	Organochlorine	1,1-dichloro-2,2-bis(pchlorophenyl)ethane (DDD), Chlordane, DDT, Chlordane, Mirex	Inhibition or failure of reproduction, Endocrine (hormonal) disturbance framework, inhibition of the immune system, malignancies, tumors, and lesions on fish and animals teratogenic consequences effects over generations, DNA, harm to cells, Unhealthy fish, fragility of an eggshell, immunological system impairments, birth defects	(Hansen et al., 2016; Sundari et al., 2019; Zhang et al., 2019)
	Organophosphate	Malathion, Fenthion, Ethion, Trichlorfon		
	Pyrethroids	Pyrethrin, Deltamethrin, Cyfluthrin, Bifenthrin, Lamdacyhalothrin, permethrin		
	Carbamates	Sevin, Carbaryl, Propoxur, Bendiocarb		
	Biological	Dispel, Foray, Thuricide		

(from ~50 to 80%) with conventional systems, and some antibiotics, e.g., amoxicillin and sulfamethoxazole, are removed very poorly (30%–60%).

Similarly, surfactants such as alkyl benzene sulphonic acid (LAS) exhibit efficiencies of 50%–80%, resulting in significant residues in treated water. Flame retardants and pesticides also exhibit removal efficiencies generally below 50%, depending on the property of the chemical being tested. These inefficiencies demonstrate the ability of pollutants to persist and make it mandatory to develop modern remediation technologies. The combined treatment of sewage and industrial effluent tends to improve the efficiency of organic pollutants' removal processes due to the high organic concentrations in industrial effluents. The immediate occurrence of wastewater leads to surface runoff from industrial effluents, resulting in varying wastewater outputs at different times of operation. In this context, the construction of a specialized remediation treatment facility is essential and indispensable.

7 Adsorption: a promising nanotechnology-based strategy for EMP remediation

Adsorption has gained considerable attention as an effective and versatile method for removing EMPs from wastewater. Its appeal lies in its simplicity, efficiency, and adaptability to a wide range of contaminants. When combined with nanotechnology, the adsorption process becomes even more effective due to the unique properties of nanomaterials such as high surface area, tunable porosity, and modifiable surface chemistry—that significantly improve adsorption performance (Alprol, 2024). This method holds great promise for the removal of persistent organic and inorganic compounds, often finding application in industries for product separation and wastewater treatment (Behera et al., 2021).

There are two main types of adsorption: physical and chemical, which differ in both mechanism and strength of interaction. In practical terms, physical adsorption relies on weaker interactions like Van der Waals forces and is often reversible. This makes it suitable for applications requiring regeneration and reusability of the adsorbent-such as magnetic nanoparticles. Chemical adsorption, or chemisorption, forms stronger, often irreversible bonds. This is especially useful when targeting stubborn or reactive pollutants that require more permanent capture (Nayak et al., 2024).

Nanomaterials can be engineered to exhibit one or both of these adsorption behaviors, depending on surface modifications and functionalization. For example, functionalized carbon nanotubes or metal oxide nanoparticles can selectively bind to heavy metals or pharmaceutical residues through surface-active groups, combining the advantages of high affinity and selective (Ibrahim et al., 2024). Moreover, hybrid nanostructures such as metal-organic frameworks (MOFs) or magnetic nanocomposites can be tailored to provide mutli-modal adsorption sites, further enhancing the efficiency of chemical adsorption or chemisorption at higher temperatures. It involves strong intermolecular forces with high activation energies and cannot be reversed. Figure 2 schematically illustrates the adsorption mechanism of nanomaterials used for EMPs followed by the desorption and reuse of MNPs. Chemisorption typically has a high heat of adsorption as it is accompanied by a chemical reaction (Kainth et al., 2024).

8 Synthesis of metal and metal oxide nanoparticles for adsorption systems

The synthesis of metal and metal oxide nanoparticles (MNPs) is fundamental for their effectiveness in environmental remediation, particularly in adsorption-based removal of EMPs. Various chemical, physical, and biological approaches have been developed, each offering different levels of control over

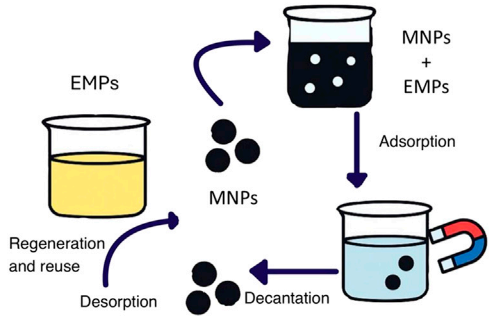


FIGURE 2
Schematic illustration of a typical method for the removal of EMPs from water systems. This general approach includes the following steps: Adsorption of EMPs on MNPs, separation, decantation and regeneration of MNPs and, finally, their reuse.

nanoparticle properties such as size, morphology, crystallinity, and surface reactivity-key parameters in adsorption performance.

8.1 Chemical methods

Chemical synthesis remains one of the most widely used strategies for the production of inorganic nanoparticles (MNPs), which involves the reduction of metal precursors through organic or inorganic reducing agents (Ahmad I. et al., 2024). One such method is the sol-gel approach, which, for example, was used to synthesize titanium oxide nanoparticles by dissolving titanium chloride in an ice bath with urea. The resultanting TiO_2 nanoparticles, with size ranging from 200 to 1,000 nm, exhibited distinct diffraction peaks (101, 004, 200, 105, and 204) in XRD analysis, confirming their crystalline nature. The vibrational bands observed at 3,406 and 3,107 cm^{-1} in the FTIR spectrum further confirmedtheir identity.

Silver nanoparticles have also been synthesized *via* chemical reduction using agents such as sodium borohydride. TEM revealed an average particle size of 24.3 nm, and XRD confirmed crystallinity with peaks at planes (111), (200), (220), (311), and (222) (Ahmad A. et al., 2024). Similarly, (Ali et al., 2024), reported the reduction of silver nitrate using sodium citrate and tannic acid, producing AgNPs with an average diameter of 30 nm.

The co-precipitation is another commonly used chemical method, valued for its simplicity, low cost, scalability (up to kilogram scale), and environmental compatibility (Petrecca et al., 2021). This approach typically involves the addition of a base or reducing agent to aqueous solutions of metal salts-such as chlorides, nitrates, or sulfates—at room or elevated temperatures in an inert atmosphere (Rahimi and Doostmohammadi, 2020; Ranoszek-Soliwoda et al., 2017). Variables including reagent concentration, type of base, pH, ionic strength, and surfactants can be tailored to influence nanoparticle size, shape, and composition (Sharma et al., 2024). However, nanoparticles synthesized *via* co-precipitation often exhibit high polydispersity and poor crystallinity, necessitating post-synthesis annealing to improve magnetic and structural properties (Gholami et al., 2024).

Hydrothermal synthesis is another effective technique in which aqueous metal salts are heated under high pressure in autoclaves, promoting the transformation of metal hydroxides into metal oxide nanoparticles (Iqbal et al., 2024). This method can also use alternative solvents such as ethylene glycol or diethylene glycol in solvothermal synthesis (Jiang et al., 2024). Parameters such as reagent concentration, temperature, and reaction time significantly influence the morphology and crystallinity of the particles (Albino, 2020). Despite its advantage in improving crystallinity, hydrothermal synthesis is limited by slow reaction kinetics and relatively long processing times, which often result in products with broader size distributions.

Among advanced methods, thermal decomposition of organometallic precursors offers precise control over nanoparticle size, shape, and composition (Lartigue et al., 2011; Muzzi et al., 2022). Herein, precursors (e.g., metal carbonyls, metal-acetylacetonates) are decomposed in high-boiling-point solvents (e.g., benzyl ether, 1-octadecene) assisted by surfactants like oleic acid or oleylamine (Hyeon, 2003; Park et al., 2005; Patra et al., 2025). Metal oxide nanoparticles can be produced directly from precursors containing cationic metals, while metal nanoparticles require subsequent oxidation steps for oxide formation (Lefebure et al., 2011). Growth models such as those proposed by LaMer and Dinegar (2002) and further refined by Kwon and Hyeon (2008), help explain nucleation and formation of monodisperse particles.

However, the chemical reduction method presents significant environmental concerns. The use of reducing agents such as sodium borohydride, sodium citrate, liquid paraffin, and oleylamine often leads to the generation of toxic byproducts, sometimes more hazardous than the pollutants involved (Talapin et al., 2001; Calero-DdelC et al., 2010; Tran et al., 2025; Vasantha Raman et al., 2023). These risks, combined with the additional disposal costs, reduce the overall sustainability of these approaches.

8.2 Physical methods

Several physical methods-including pyrolysis, ball milling, ultrasonication, laser ablation, lithography, and sputtering-have been employed for the synthesis of MNPs. Among these, laser ablation is considered an efficient, high-yield alternative to chemical synthesis due to its short processing time and the production of stable nanoparticles (Li et al., 2021). In this method, a high-energy laser pulse targets a solid surface, generating a low-flux plume that subsequently condenses into nanoparticles. For instance, (Li et al., 2014; Mohammed et al., 2021), successfully synthesized copper nanoparticles averaging 51 nm with semi-spherical morphology.

Spray laser pyrolysis has also been used to produce ZnO nanoparticles (10–25 nm) with a hexagonal wurtzite structure, confirmed by TEM analysis. Similarly, evaporation-condensation methods.

The utilization of laser ablation yielded spherical copper oxide nanoparticles between 3 and 40 nm in size (Singh et al., 2008). Laser ablation has also been employed for synthesizing colloidal silver and copper oxide nanoparticles (Kudhur et al., 2024).

Another effective physical approach is sputtering, or physical vapor deposition (PVD), in which high-energy ions collide with a metal target, ejecting atoms that deposit onto a substrate and condense into nanoparticles. This method allows for precise

TABLE 5 Comparison of physical, chemical and biological pathways involved in nanoparticles synthesis.

Method	Advantages	Limitations	Suitability for water treatment adsorbents
Chemical Methods (e.g., sol-gel, co-precipitation, thermal decomposition)	- High control over *size, shape, and crystallinity* - Well-established and scalable - *Functionalizable surfaces* for pollutant-specific targeting -Efficient production of *high-purity* nanoparticles	- Use of toxic reagents (e.g., NaBH4, oleylamine) creates *hazardous by-products* - Potential for *environmental contamination* - Often requires *post-treatment steps* (e.g., annealing) to improve crystallinity	Highly effective and customizable; needs environmental safeguards for greener production
Physical Methods (e.g., laser ablation, sputtering, ball milling)	- No *chemical reagents* involved: low risk of secondary pollution - Produces stable, *high- purity* nanoparticles - Offers precise size and *morphology control* (e.g., through laser/sputtering parameters)	*High energy input* (costly) - Specialized equipment and operation *complexity* - Often *limited yield* and scale	Environmentally clean, but less practical at large scale due to cost and complexity
Biological Methods (e.g., microbial or plant-mediated synthesis)	- *Eco-friendly*, uses natural reducing agents (e.g., plant extracts, bacteria) Avoids toxic chemicals and high- energy inputs - Cost- effective and *sustainable*	- *Limited control* over nanoparticle size, *shape, and crystallinity* - May require strict sterile conditions (especially for microbes) - Challenges in scaling up reproducibly	Promising for green nanotechnology, though precision and scale need improvement

control over particle morphology and distribution (Manninen, 2015). Using this technique, (Pentimalli et al., 2015), synthesized platinum nanoparticles in a glycerol matrix, where particle sizes varied from 1.8 to 3.2 nm depending on argon pressure (1.0–9.0 Pa).

Ball milling is a top-down mechanical process in which metal powders are ground to nanoscale through the transfer of energy from rotating balls. Parameters such as milling time, force, speed, and temperature significantly influence the nanoparticle characteristics (Konnerth et al., 2016). Although effective in producing uniformly sized nanoparticles, physical methods are often limited by high energy consumption and associated costs (Bramsiepe et al., 2012; Meierhofer and Fritsching, 2021).

8.3 Biological methods

Biological nanoparticle synthesis is gaining momentum as an eco-friendly and cost-effective alternative that reduces the toxic byproducts associated with chemical methods (Meierhofer and Fritsching, 2021). This approach uses microbial systems (bacteria and fungi) and plant-derived extracts as reducing and stabilizing agents.

Bacteria such as *Pseudomonas* sp. strain THG-LS1.4 has been used for biosynthesizing silver nanoparticles, with FE-TEM confirming sizes ranging from 10 to 40 nm and irregular shapes (Carrapico et al., 2023). Similarly, *P. aeruginosa* BS-161R produced spherical AgNPs with an average size of 13 nm (Abeer Mohammed, Abd Elhamid et al., 2022). Gold nanoparticles (15–30 nm) were also biosynthesized using *Pseudomonas aeruginosa* strain ATCC 90271 (Menon et al., 2017), while Geobacter sulfurreducens yielded AuNPs with an average diameter of 20 nm (Jimenez-Sandoval et al., 2023).

Despite promising results, bacterial synthesis has limitations, including the need for sterile conditions and the potential pathogenicity of some strains. As a result, the focus has increasingly shifted toward the use of plant extracts, rich in phytochemicals and capable of simultaneously reducing and stabilizing metal ions during nanoparticle formation (Chelike et al., 2024; Ali et al., 2021; Mehta et al., 2024). Figure 3 below shows nanoparticle synthesis methods that may involve chemical, physical, and biological pathways. The illustration was prepared using information from the review source (Arbab et al., 2021).

A strategic shift toward eco-design and life-cycle assessment (LCA)-based synthesis optimization will be essential to bridge the gap between lab innovation and real-world application. Additionally, the development of modular pilot-scale production systems that integrate green synthesis with post-processing for magnetic recovery or reuse will further enable nanotechnology to be viably integrated into advanced water treatment infrastructure.

The methods for synthesizing nanoparticles may involve chemical, physical, and biological pathways a summary of these methods is shown in Table 5. However, while many chemical methods prevail due to their scalability and precision, their environmental disadvantages serve to emphasize the need for greener alternatives.

9 Sustainable environmental applications of magnetic nanotechnology

In line with the focus of this review on MNPs-technology-Based solutions, this section summarizes the practical applications of magnetic and metal oxide NPs for the remediation of EMPs. Rather than restating pollutants-specific cases discussed in previous sections, it highlighted how nanomaterials such as magnetic composites, nano-zero-valent, iron, and graphene-magnetic hybrids, serves as multi-functional platforms for the adsorption, catalysis, and separation. Their high surface area, magnetic recoverability, and reusability make them ideal for eco-friendly wastewater treatment systems. The effective removal of steroids, pesticides, antibiotics, and steroids from wastewater has been proven in the literature using metal and metal oxide nanoparticles (Kanan et al., 2022). Due to its sustainability and the wide variety of adsorbents that can be used, adsorption is therefore the method of choice.

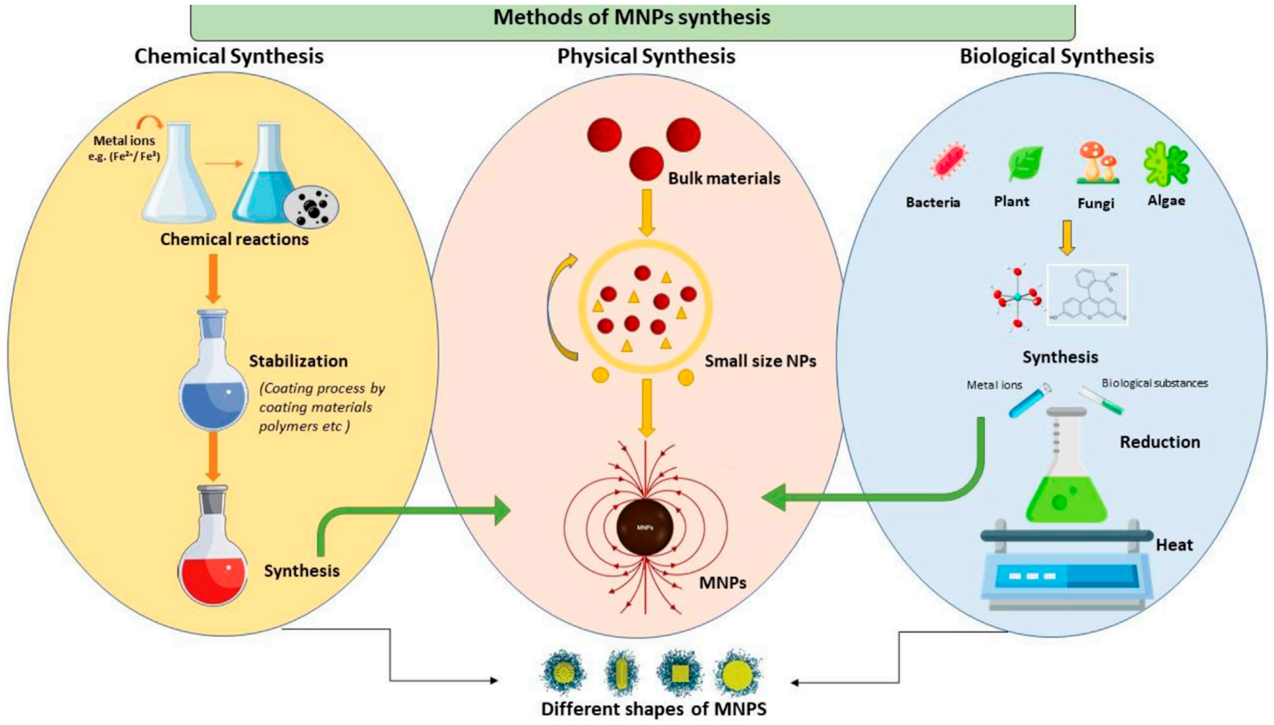


FIGURE 3
Schematic Illustration of different synthetic techniques of metal and metal oxide MNPs adapted from the source (Arbab et al., 2021).

9.1 Removal of pharmaceuticals

The distinctive properties of nanoparticles-such as their large surface area, high reactivity, and customizable functionalities make them highly effective for removing pharmaceutical contaminants from wastewater. Among these, Fe/N-CNT/beta-cyclodextrin nanoparticles demonstrated excellent performance in photocatalytic adsorption, with aspirin removal reaching 71.9%. This effectiveness was validated through various characterization techniques including UV-Vis spectroscopy, scanning electron microscopy (SEM), and Fourier Transform Infrared Spectroscopy (FTIR). Similarly, Ca(II)-doped chitosan/beta-cyclodextrin composites, characterized using UV-Vis, FTIR, Thermogravimetric-Differential Analysis (TGDA), SEM, and Energy-Dispersive X-ray (EDX), showed an outstanding removal efficiency of 99.09% for acetaminophen.

Further characterization using SEM, Transmission Electron Microscopy (TEM), X-ray Diffraction (XRD), UV-Vis spectroscopy, and X-ray Photoelectron Spectroscopy (XPS) indicated that the magnetic graphene oxide sponges (MGOS) had a maximum adsorption capacity of 473.0 mg/g for tetracycline. Furthermore, diclofenac treated with Cu-NPs exhibited a removal rate of 91.4%, as indicated by UV-Vis and XRD analysis. Photocatalytic degradation of cefixime using TiO2 nanoparticles achieved a removal efficiency of 90.0%, as supported by zeta potential analysis, FTIR, and UV-Vis spectroscopy (Islas-Flores et al., 2013; Praskova et al., 2014; Mphahlele et al., 2015; Liu et al., 2019; Rahman and Nasir, 2020).

These findings highlight the significant potential of metal and metal oxide nanoparticles to enhance chemical treatment methods for pharmaceutical pollutants in water. Their large specific surface area, high reactivity, and amenability to target specific contaminants make them ideal for multi-component pharmaceutical mixtures that are commonly found in wastewater. Advanced characterization methods enable a greater insight into removal mechanisms and nanoparticle interactions, supporting the optimization and real-world application of these technologies. Thus, nanoparticle-based solutions hold a future solution to pharmaceutical pollution in aquatic ecosystems, in the interest of public health and environmental sustainability.

9.2 Removal of MPs

The use of nanoparticle-based materials for the removal of microplastics (MPs) and related contaminants such as bisphenol A (BPA) from aquatic systems has emerged as a promising and efficient strategy. Due to their high adsorption capabilities, various metal and metal oxide nanoparticles have been employed for this purpose. For instance, chitosan-nanoscale zero-valent iron (nZVI) composites have demonstrated a BPA removal efficiency of 95.0%, as confirmed through characterization techniques like Fourier-Transform Infrared Spectroscopy (FTIR), X-ray Diffraction (XRD), Scanning Electron Microscopy (SEM), and Transmission Electron Microscopy (TEM). Similarly, magnetic biochar nanoparticles achieved a 96.3% BPA removal rate, as verified through X-ray Photoelectron Spectroscopy (XPS), XRD, TEM, FTIR, and Raman spectroscopy. Moreover, graphene aerogel embedded with magnetic iron oxide nanoparticles (IO-NPs) showed a remarkable BPA adsorption capacity of 353.8 mg/g, determined using SEM, XRD, FTIR, and Raman spectroscopy

(Nizamuddin et al., 2019; Quan et al., 2019; Dehghani et al., 2020; Karri et al., 2020; He et al., 2020).

These studies underscore the effectiveness of nanoparticle-based materials in adsorbing and eliminating MPs and associated organic pollutants like BPA. The high surface area and tunable surface properties of nanoparticles enhance their ability to trap such contaminants efficiently (Quan et al., 2019). The activation potential of nanoparticles also contributes to improved selectivity and stronger binding with a variety of pollutants. Additionally, the application of advanced characterization techniques helps to thoroughly understand the interactions between nanoparticles and pollutants. This knowledge enables the optimization of these materials for broader environmental applications, supporting efforts to protect freshwater sources and mitigate the harmful impacts of plastic pollution on ecosystems and human health.

9.3 Removal of PPCPs

Nanoparticles are able to perform optimally in environmental remediation because they have a large surface area, are tunable, and thus reusable for the effective adsorption of PPCPs contaminants. For example, TiO_2 and ZnO nanoparticles have been shown to have photocatalytic activity leading to the adsorption and degradation of organic UV filters benzophenone and octinoxate by Ahmad A. et al. (2024). Carbon nanomaterials such as graphene oxide and activated carbon are able to adsorb the insect repellents like N,N-Diethyl-m-toluamide (DEET) effectively by π-π interaction and high surface area (Li J. et al., 2024). Similarly, silica nanoparticles and magnetite (Fe_3O_4) can capture aromatic fragrances and phthalates due to their functionalized surface and magnetic recoverability (Albino, 2020). Clay nanoparticles and nano-zero valent iron (nZVI) are highly efficient at adsorbing surfactants and sulfates contained in soaps and shampoos (Rahimi and Doostmohammadi, 2020). Al_2O_3 and CeO_2 metal oxides are used for the removal of paraben and phenolic preservatives, while silver nanoparticles (AgNPs) and zeolites remove triclosan and triclocarban disinfectants (Carrapico et al., 2023; Singh et al., 2008). However, despite these advantages in terms of selective adsorption and regenerability, some challenges remain: nanoparticles can be incredibly expensive and have a huge environmental impact. On this front, advances in environment-friendly synthesis and large-scale application can mitigate these problems and increase efficiency against various PPCP pollutants.

9.4 Removal of plasticizers

Nanoparticles are highly efficient adsorbents for toxic and carcinogenic plasticizers such as Bisphenol A (BPA) and Bisphenol A diglycidyl ether (BADGE), which are endocrine disruptors consequently having human and environmental implications. BPA removal through carbon-based nanomaterials of graphene oxide and MWCNTs occurred through adsorption at high capacities because of π-π stacking and hydrogen bonding interactions and thus removal mechanisms in water sources (Li Q. et al., 2024). Nano-zero valent iron (nZVI), and magnetic nanoparticles (such as Fe_3O_4) can adsorb contaminants while providing facile recovery due to their magnetic characteristics and surface activity (Rahimi and Doostmohammadi, 2020). Metal-organic frameworks (MOFs) and mesoporous silica nanoparticles exhibited target adsorption affinity to plasticizers by means of their tunable porosity and functionalized surfaces for contaminants (Bellusci et al., 2024). Although highly effective, their synthesis optimization for least environmental imprint and optimized capability becomes utmost to be a worthy answer to the challenges in plasticizers contamination.

9.5 Removal of surfactants

Nanoparticles could bring about an extremely effective surfactant remediation system, which are some of the major persistent contaminants found in landfills, sludge, and wastewater. Surfactants such as alkyl benzene sulfonic acid (anionic surfactants), quaternary ammonium compounds (cationic surfactants), alkylphenol polyethoxylates (nonionic surfactants), and amine oxides (amphoteric surfactants) usually degrade into byproducts that are toxic and can display estrogenic activities. Nanomaterials such as TiO_2, nZVI, graphene oxide, silica nanoparticles, and CNTs are useful, particularly in surfactant removal. These nanomaterials act through different adsorption processes: electrostatic interactions, ion exchange, and π-π stacking to capture and eliminate surfactants from water and soil samples. They utilize nanoproperties such as adsorption, high surface area, and reactivity for degradation and sequestration of such pollutants. Thus, the environment becomes cleaner and safer (Rahimi and Doostmohammadi, 2020; Sharma, et al., 2024).

9.6 Removal of flame retardants

Flame retardants such as the more recent brominated flame retardants DBDPE, TBB, and TBPH, along with organophosphorus flame retardants TDCIPP and TCEP, are considered hazardous to humans and the environment due to their persistence and toxicity. These chemicals can interfere with hormone regulation, affect sperm quality, developmental, and neurological functions. Therefore, there is a growing demand for new nanomaterials such as graphene oxide, Fe_3O_4 nanoparticles, biochar, and zeolites, among these emerging contaminants. Remediation mechanisms may include adsorption by means of hydrogen bonding, π-π stacking, and photocatalysis. These nanomaterials provide a sustainable and efficient mechanism to reduce the environmental load of flame retardants, consequently reducing their harmful impact on ecosystems and human health (Carrapico et al., 2023).

9.7 Removal of pesticides

Several nanomaterials have been investigated for use in removing pesticide residues from drinking water, agricultural runoff, and wastewater. Carbon-based nanomaterials such as graphene, with a high adsorption capacity of200–600 mg/g, are well known for their usefulness in water purification (Rosales et al., 2021). Their high-performance results from properties such as high surface area, reactivity, and variability. Nanoparticles are considered highly effective for pesticide removal. For example, aldrin removal was procured at about 95.0% using palladium/iron bimetallic nanoparticles, as witnessed by TEM and GC-MS analyses, with ZnO-chitosan nanoparticles achieving a 99.0% removal for permethrin. Raman spectroscopy, XRD, and SEM analysis revealed 99.9% removal of malathion and 93.7% of lindane using SDS-1-modified $Al(OH)_2$ nanoparticles. Beta-CD/MRGO composites removed 93.2% of dieldrin, confirmed through VSM, FTIR, SEM, GC-ECD, MSPE, and XRD. Silica-modified graphene also improved adsorption of organophosphorus pesticides (Moradi Dehaghi et al., 2014; Dehghani et al., 2017; Mahpishanian and Sereshti, 2017; Rosales et al., 2021; Narwal et al., 2023; Katyal et al., 2023).

Metal oxide nanomaterials like magnesium, cerium, and titanium oxides have also proven effective due to their strong adsorption ability (Zhang et al., 2024). Nanocrystalline cerium (IV) oxide, under suitable conditions, degraded parathion methyl into less harmful compounds (Moradi Dehaghi et al., 2014). The high surface area and reactivity of nanoparticles enhance pesticide adsorption, reducing contaminant levels in water (Narwal et al., 2023; Katyal et al., 2023). Functionalization further improves their selectivity and binding affinity. Advanced characterization techniques provide insights into these interactions, enabling material optimization. Thus, nanoparticle-based strategies offer a promising solution for minimizing pesticide pollution and protecting water quality and public health (Mahpishanian and Sereshti, 2017). Some recent Nanomaterials which are used in EMPs removal are reported in Table 6.

10 Recovery and regeneration of nanoparticles

To prevent potential downstream environmental impacts, nano-adsorbents must be removed from the water after adsorbing micropollutants. In addition, these recovered nano-adsorbents should be regenerated and reused in other processes to support sustainable development goals (Nzilu et al., 2023). Efficient, easy-to-use, fast, economical, and energy-saving methods are essential for nano-adsorbents recovery (Gul et al., 2024). Magnetic nanoparticles can be extracted using an external magnetic field, while filtration and centrifugation facilitate their recovery (Dhiman et al., 2021). Several dehydrating agents, including ultrapure water, HCl, H_3SO_4, H_3PO_4, NaOH, and NaCl, have been evaluated for their effectiveness. Among these, hydrochloric acid demonstrated the highest performance, with removal efficiencies ranging from 60% to 86% for various adsorbents, such as plant-based biochar (Ahammad et al., 2021). Conversely, adsorbed pollutants could not be effectively removed using water or sodium chloride. The study also revealed that although increasing the HCl concentration initially increased the desorption efficiency, excessively high concentrations could damage the adsorbent. Moreover, the desorption efficiency improved with increased contact time until equilibrium was reached (Chen et al., 2007; Conti et al., 2021; Wang et al., 2024).

For the adsorption process to be both technologically and commercially viable, regeneration is essential. The choice of regeneration technique depends largely on the nature and cost of the adsorbent. For instance, banana peel has been used as a bio-adsorbent for copper removal, with desorption rates up to 94% using 0.1 N sulfuric acid. Repeating this process up to seven times yielded consistent and efficient results. Other tested solvents -such as NaOH, CH_3COOH, distilled water, and tap water-achieved desorption rates less than 30% (De Gisi et al., 2016; Dehghani et al., 2023). In another study, chromium was removed from waste using stability-enhanced magnetic nanoparticles. Desorption was found to be effective under alkaline conditions using NaOH, and even after six regeneration cycles, the adsorption capacity decreased by only 9% (Kulkarni and Kaware, 2014).

Solvent washing has also proven effective for the recovery of various solutes. Notably, the use of non-thermal plasma instead of conventional electric heating has shown encouraging results in terms of energy-savings. MEA-impregnated silica has proven as a promising alternative for the efficient adsorption and desorption of carbon dioxide (Kulkarni and Kaware, 2014; Bao et al., 2024). A variety of techniques-or combinations thereof-have been used to develop nano-adsorbents with high adsorption capacity and selectivity for emerging micropollutants (Moreira et al., 2022). Factors such as the type of adsorbent and adsorbate, as well as stability and toxicity concerns, play a significant role in selecting an appropriate regeneration method.

To maintain the long-term performance of nano-adsorbents, thermal, chemical, and electrochemical methods are commonly used for media regeneration (Gómez-Pastora et al., 2014; Moreira et al., 2022). Regeneration is vital not only for environmental conservation but also for economic efficiency. A key issue in adsorption technologies is managing the disposal of spent adsorbents, and regeneration helps mitigate this problem by reducing the need for constant replacement and minimizing waste (Younas et al., 2021). Multiple regeneration strategies-such as solvent washing, thermal treatments, chemical regeneration, and electrochemical methods have been employed with varying success levels (Natarajan et al., 2022; Ahmadi et al., 2023). Figure 4 shows the scheme prepared based on the source (Hassan et al., 2020) about a procedure of regeneration and reuse of MPs, that includes treatment with acid or base followed by washing and reuse with a lower efficiency than the first cycle, respectively.

11 Challenges and perspectives: scalability, sustainability, and regulation

The review highlights the transformative potential of nanotechnology in addressing aquatic environmental contamination. Nanoparticles particularly metal and metal oxide nanomaterials have shown excellent efficacy in removing a wide range of pollutants, including pharmaceuticals, pesticides, plasticizers, surfactants, and flame retardants. Their large surface area, tunable reactivity, and easiness of functionalization make them ideal candidates for adsorption and degradation processes. Among them, green-synthesized nanoparticles stand out as cost-effective and environmentally friendly alternatives, offering sustainable synthesis routes using plant extracts and waste materials.

TABLE 6 Some recent Nanomaterials used in EMPs removal.

EMPs Category	Micropollutants	Nanomaterial used	Process	% Removal efficiency adsorption capacity	Characterization techniques	Source
Pharmaceuticals	Aspirin	Fe/N-CNT/beta-cyclodextrin	Adsorption	71.9%	UV-Vis, SEM, FTIR	Mphahlele et al. (2015)
	Acetaminophen	Ca (II)-doped chitosan/ beta-cyclodextrin	Adsorption	99.09%	UV-Vis, FTIR, TGDA, SEM, EDX	Rahman and Nasir, (2020)
	Tetracycline	Magnetic graphene sponge (MGOS)	Adsorption	473.0 mg/g	SEM, TEM, XRD, UV-Vis, XPS	Liu et al. (2019)
	Diclofenac	Cu-NPs	Sorption	91.4%	UV-Vis, XRD	Praskova et al. (2014)
	Cefixime	TiO_2-NPs	Photocatalysis	90.0%	UV-Vis, FTIR, zeta potential	Islas-Flores et al. (2013)
MPs	Bisphenol A	Chitosan-nZVI	Adsorption	95.0%	FTIR, XRD, SEM, TEM	He et al. (2020)
	Bisphenol A	Magnetic biochar-NPs	Adsorption	96.3%	XPS, XRD, TEM, FTIR, Raman	Quan et al. (2019)
	Bisphenol A	Magnetic (IO-NPs) graphene aerogel	Adsorption	353.8 mg/g	SEM, XRD, FTIR, Raman Spectroscopy	Dehghani et al. (2020)
Plasticizers	BPA, BADGE	MWCNTs/nano-zero valent iron) nZVI)	Adsorption	87.0%	SEM, XRD, TEM, FTIR	(Nizamuddin et al., 2019; Nwankwo et al., 2025)
PPCPS	Benzophenone octinoxate	TiO2, ZnO	Adsorption	1 mg/g	UV-Vis, TEM, EDS, FTIR	(Dehghani et al., 2020; Demaria et al., 2025; Dehghani et al., 2017)
	DEET	Activated Carbon, Graphene oxide	Adsorption	155.6 mg/g	FTIR, SEM, TEM, EDX	Sadeghi et al. (2020)
	Phthalates, Musk xylene	Silica NPs magnetite	Adsorption	83.7%	SEM, XRD, TEM, FTIR	(Guan et al., 2018; De Luca et al., 2005)
	Triclosan	Iron-oxide/NPs, zeolites	Adsorption	90.0%	DLS, SEM	Bhanjana et al. (2017)
Surfactants	**Anionic** (alkyl benzene sulphonic acid)	TiO_2, nano-zero valent iron (nZVI), graphene oxide	Adsorption	89.4%	UV-Vis, TEM, EDS, FTIR	Guan et al. (2018)
	Cationic (Quaternary ammonium compounds)	Silica NPs modified magnetite	Adsorption	91.3%	SEM, XRD, TEM, FTIR	Le et al. (2025)
	Nonionic (Alkylphenol polyethoxylated)	MOFs, Activated Carbon	Adsorption	93.7%	DLS, SEM	Sadeghi et al. (2020)
	Amphoteric (Amine oxides)	Carbon Nanotubes, Clay NPs	Adsorption	86.5%	SEM, XRD, TEM, FTIR	(Bracco et al., 2023)
Flame Retardants	NBFRs (DBDPE, TBB, TBPH)	Graphene oxide. Fe_2O_3 biochar NPs	Adsorption, hydrogen bonding	87%	SEM, TEM, FTIR	Le and Nguyen (2024)
	OPFRS (TCEP, TDCIPP)	Zeolites, TiO_2,	Adsorption and ion exchange	86.4%	SEM, XRD, TEM, FTIR	Yung et al. (2023)
Pesticides	Aldrin	Palladium/Iron Bimetallic NPs	Adsorption	95.0%	TEM, GC-MS	Rosales et al. (2021)
	Permethrin	ZnO-Chitosan NPs	Adsorption	99.0%	GC-MS, TEM	Moradi Dehaghi et al. (2014)
	Malathion	MWCNTs	Adsorption	99.9%	Raman, XRD, SEM	Dehghani et al. (2017)
	Lindane	SMNAH (SDS-modified $Al(OH)_2$ NPs	Adsorption	93.7%	Zeta potential, BET, FTIR, SEM, XRD	Narwal et al. (2023)
	Dieldrin	Beta-CD/MRGO	Adsorption	93.2%	VSM, FTIR SEM, GC-ECD, MSPE, XRD	Mahpishanian and Sereshti, (2017)

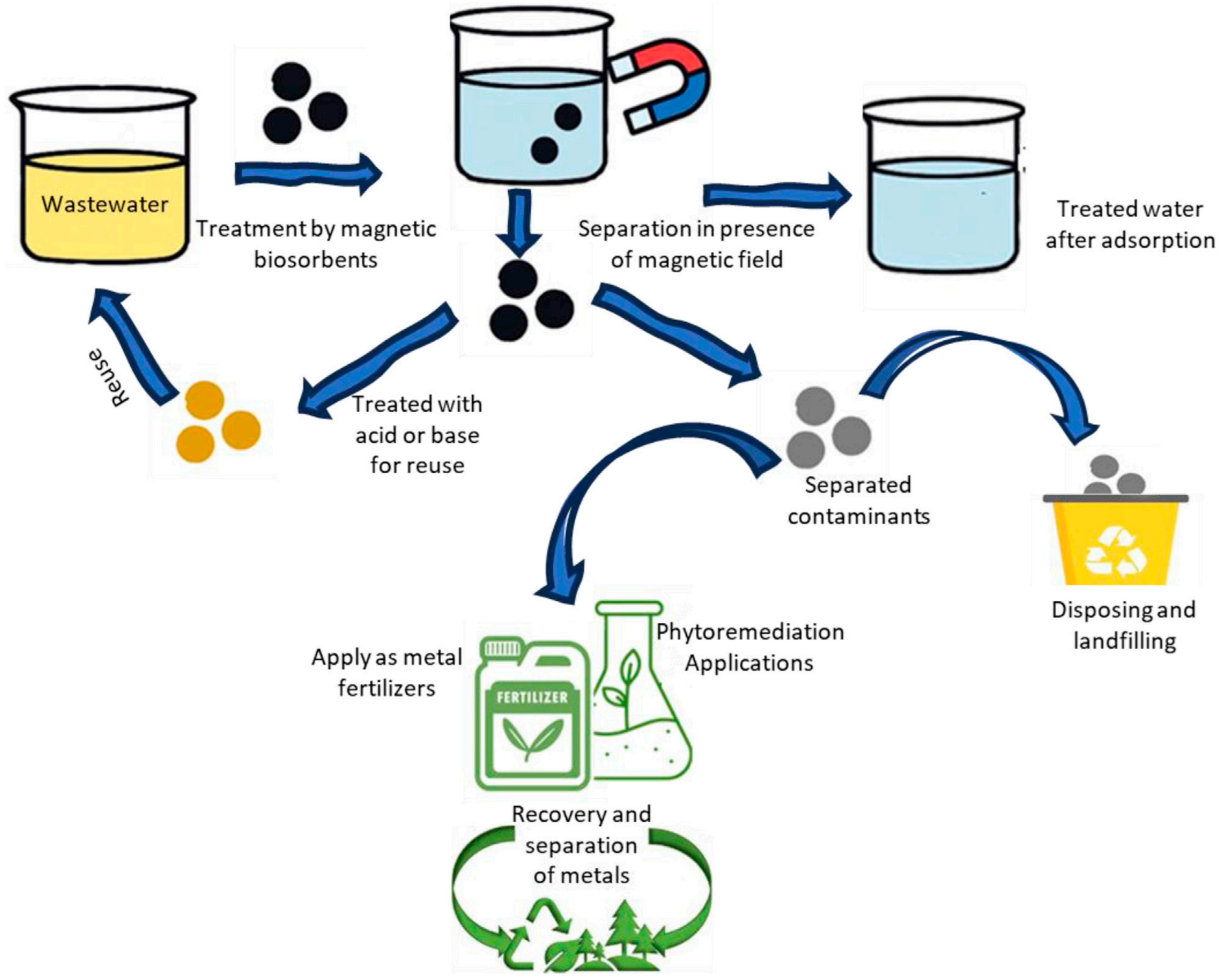


FIGURE 4
A general representation of regeneration and reuse of MNPs.

11.1 Challenges and perspectives

Despite their promise, several challenges must be addressed to translate laboratory success into field-scale implementation. Scaling up nanoparticle synthesis, particularly with eco-friendly and cost-effective methods, remains a bottleneck. Mass production without compromising the particles' uniformity, functionality, and eco-safety is a critical obstacle. Moreover, the long-term environmental toxicity of nanoparticles post-application is not yet fully understood. Concerns include bioaccumulation, ecological disruption, and toxicity to non-target organisms, which require further toxicological and ecotoxicological assessment under real-world conditions. Furthermore, the absence of an explicit rule and a consistent set of verification criteria obviously hinders the safe laboratory studies for commercial applications. The scientific community is at the forefront of public trust; if these communities themselves begin to doubt the safety of nanotechnology, even that scant inch of acceptance will be more difficult to achieve. Eliminating barriers can only be achieved through open collaboration of barriers across disciplines, through accurate assessment of the nanoparticle lifecycle, and transparent dialogue between researchers, policymakers, industry, and the society at large. Regulatory frameworks for the use of nanomaterial in environmental applications are at different stages of maturity across regions:

European Union (EU): The EU has taken a relatively proactive stance with regulations such as REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals), which includes specific provisions for nanomaterials. The European Chemicals Agency (ECHA) has issued published guidelines for nanoparticle characterization, safety data sheets, and environmental risk assessments. However, implementation at the WWTP level remains limited, and standard monitoring methods for nanomaterials in effluents are still lacking.

United States (US): Regulatory progress is more fragmented. Agencies such as the EPA and FDA address nanomaterials under general chemical safety laws (e.g., TSCA), but no nanotechnology-specific mandates exist for wastewater treatment applications. Efforts remain largely voluntary or at the research funding level, such as through the National Nanotechnology Initiative (NNI).

Emerging Economies (e.g., India, Brazil, South Africa): Regulatory frameworks are nascent or absent. Although nanotechnology R&D is accelerating, regulations are often outpaced by innovation. Furthermore, infrastructure for nanoparticle monitoring, safety assessments, and workforce training is limited, making safe implementation difficult.

Additionally, legislation surrounding the use of nanomaterials in WWTPs is still evolving. While some countries have initiated frameworks for nanoparticle use in environmental remediation, a globally harmonized regulatory guideline is lacking, especially concerning nanoparticle disposal, fate, and monitoring in treabted water effluents.

11.2 Key message and future directions

Nanotechnology offers a promising path for next-generation water treatment, especially in tackling complex and trace-level micropollutants. Based on current research, the most promising nanomaterials include Fe_3O_4-based magnetic composites, green-synthesized TiO_2 and ZnO, carbon-based materials (GO, CNTs), and hybrid MOFs, many of which are currently at TRL 4–6, with pilot testing beginning in select regions.

A strategic roadmap to advance this field should include:

1. **Short-term** (1–3 years): Standardization of green synthesis protocols, comprehensive life cycle and risk assessments, and improved nanoparticle recovery methods.
2. **Mid-term** (3–6 years): Integration of nano-based systems into existing WWTPs, development of nano-enabled filtration membranes, and establishment of pilot-scale demonstrations.
3. **Long-term** (6–10 years): Regulatory harmonization across regions, industrial-scale deployment, and creation of circular systems for nanoparticle regeneration and reuse.

In conclusion, advancing nanotechnology for environmental remediation demands interdisciplinary collaboration, responsible innovation, and evidence-based regulation. If these efforts align, nanoparticle-enabled water treatment can play a pivotal role in ensuring safe, sustainable, and resilient water systems globally.

Author contributions

AM: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review and editing. SS: Conceptualization, Data curation, Methodology, Supervision, Validation, Visualization, Writing – review and editing. MA: Data curation, Investigation, Methodology, Validation, Visualization, Writing – review and editing. BM: Investigation, Supervision, Validation, Visualization, Writing – review and editing. CM: Funding acquisition, Resources, Supervision, Writing – review and editing. AC: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing – review and editing. CS: Data curation, Funding acquisition, Investigation, Methodology, Resources, Supervision, Validation, Visualization, Writing – review and editing. TM: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – review and editing.

Funding

The authors declare that financial support was not received for the research and/or publication of this article.

Acknowledgements

Special thanks is extended to the Analytical Group for the valuable assistance throughout the paper and research.

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.

Generative AI statement

The authors declare that no Generative AI was used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

References

Abeer Mohammed, A. B., Abd Elhamid, M. M., Khalil, M. K. M., Ali, A. S., and Abbas, R. N. (2022). The potential activity of biosynthesized silver nanoparticles of *Pseudomonas aeruginosa* as an antibacterial agent against multidrug-resistant isolates from intensive care unit and anticancer agent. *Environ. Sci. Eur.* 34, 109. doi:10.1186/s12302-022-00684-2

Abu-Dalo, M. A., Bozeya, A., Sawalmeh, Z., Albiss, B., Alnairat, N., and Abu-Zurayk, R. (2023). Antifouling polymeric nanocomposite membrane based on interfacial polymerization of polyamide enhanced with green TiO_2 nanoparticles for water desalination. *PeerJ Anal. Chem.* 5, e26. doi:10.7717/peerj-achem.26

Ahammad, N. A., Zulkifli, M. A., Ahmad, M. A., Hameed, B. H., and Mohd Din, A. T. (2021). Desorption of chloramphenicol from ordered mesoporous carbon-alginate beads: effects of operating parameters, and isotherm, kinetics, and regeneration studies. *J. Environ. Chem. Eng.* 9 (1), 105015. doi:10.1016/j.jece.2020.105015

Ahmad, A., Haneef, M., Ahmad, N., Kamal, A., Jaswani, S., and Khan, F. (2024). Biological synthesis of silver nanoparticles and their medical applications. *World Acad. Sci. J.* 6. doi:10.1016/j.ccr.2024.215904

Ahmad, I., Aftab, M. A., Fatima, A., Mekkey, S. D., Melhi, S., and Ikram, S. (2024). A comprehensive review on the advancement of transition metals incorporated on functional magnetic nanocomposites for the catalytic reduction and photocatalytic degradation of organic pollutants. *Coord. Chem. Rev.* 514, 215904. doi:10.1016/j.ccr.2024.215904

Ahmadi, R., Ardjmand, M., Rashidi, A., and Rafizadeh, M. (2023). Enhanced gas adsorption using an effective nanoadsorbent with high surface area based on waste jute as cellulose fiber. *Biomass Convers. Biorefinery* 13 (4), 3071–3086. doi:10.1007/s13399-021-01370-8

Ahmaruzzaman, M., Roy, S., Singha, A., Rtimi, S., and Aminabhavi, T. M. (2025). Emerging nanotechnologies in adsorption of dyes: a comprehensive review of carbon and metal oxide-based nanomaterials. *Adsorption* 31 (2), 34. doi:10.1007/s10450-024-00588-y

Ahmed, M., Mumtaz, R., and Hassan Zaidi, S. M. (2021). Analysis of water quality indices and machine learning techniques for rating water pollution: a case study of Rawal dam, Pakistan. *Water Supply* 21 (6), 3225–3250. doi:10.2166/ws.2021.082

Ahmed, S. F., Mofijur, M., Parisa, T. A., Islam, N., Kusumo, F., Inayat, A., et al. (2022). Progress and challenges of contaminate removal from wastewater using microalgae biomass. *Chemosphere* 286 (Pt 1), 131656. doi:10.1016/j.chemosphere.2021.131656

Al-Baldawi, I. A., Mohammed, A. A., Mutar, Z. H., Abdullah, S. R. S., Jasim, S. S., Almansoory, A. F., et al. (2021). Application of phytotechnology in alleviating pharmaceuticals and personal care products (PPCPs) in wastewater: source, impacts, treatment, mechanisms, fate, and SWOT analysis. *J. Clean. Prod.* 319, 128584. doi:10.1016/j.jclepro.2021.128584

Alayan, H. M., Clumsily, M. M., Alasdair, M. A., Mallis, F. S., and Hashim, M. A. (2021). A review exploring the adsorptive removal of organic micropollutants on tailored hierarchical carbon nanotubes. *Toxicol. Environ. Chem.* 103 (4), 282–325. doi:10.1080/02772248.2021.1932888

Albino, M. (2020). Nanometric spinel ferrites: a versatile platform for biomedical and energy applications. PhD Thesis. Florence: University of Florence.

Ali, M. U., Liu, G., Yousaf, B., Ullah, H., Abbas, Q., and Munir, M. A. M. (2019). A systematic review on global pollution status of particulate matter-associated potential toxic elements and health perspectives in urban environment. *Environ. Geochem. Health* 41 (3), 1131–1162. doi:10.1007/s10653-018-0203-z

Ali, A., Shah, T., Ullah, R., Zhou, P., Guo, M., Ovais, M., et al. (2021). Review on recent progress in magnetic nanoparticles: synthesis, characterization, and diverse applications. *Front. Chem.* 9, 629054. doi:10.3389/fchem.2021.629054

Ali, S., Verma, S., Agarwal, M. B., Islam, R., Mehrotra, M., Deolia, R. K., et al. (2024). Groundwater quality assessment using water quality index and principal component analysis in the Achnera block, Agra district, Uttar Pradesh, Northern India. *Sci. Reports* 14 (1), 5381. doi:10.1038/s41598-024-56056-8

Alimba, C. G., Faggio, C., Sivanesan, S., Ogunkanmi, A. L., and Krishnamurthi, K. (2021). Micro(nano)-plastics in the environment and risk of carcinogenesis: insight into possible mechanisms. *J. Hazard. Mater.* 416, 126143. doi:10.1016/j.jhazmat.2021.126143

Alprol, A. E. (2024). The use of adsorption technology in the removal of dyes and heavy metals from aqueous solution by agricultural wastes. *Blue Econ.* 2 (1). doi:10.57241/2805-2994.1015

Altaf, F., Hashmi, M. Z., Farooq, U., Rehman, Z. U., Hmeed, M. U., Batool, R., et al. (2022). Nanotechnology to treat the environmental micropollutants. *Environ. Micropollutants*, 407–441. doi:10.1016/b978-0-323-90555-8.00017-9

Aravind, J., and Kamaraj, M. (2024). *Carbon-based composites and nanocomposites: adsorbents and membranes for environmental remediation* (Berlin: Walter de Gruyter GmbH and Co KG).

Arbab, S., Ullah, H., Weiwei, W., Wei, X., Ahmad, S. U., Wu, L., et al. (2021). Comparative study of antimicrobial action of aloe vera and antibiotics against different bacterial isolates from skin infection. *Veterinary Medicine Science* 7 (5), 2061–2067. doi:10.1002/vms3.488

Ayub, S., Parnia, S., Poddar, K., Bachu, A. K., Sullivan, A., Khan, A. M., et al. (2023). Xylazine in the opioid epidemic: a systematic review of case reports and clinical implications. *Cureus* 15 (3), e36864. doi:10.7759/cureus.36864

Ayyadurai, P., and Ragavendran, C. (2025). Green nanotechnologies for removing cosmetic pollutants: approach towards preserving and protecting aquatic health. *Nanotechnol. Environ. Eng.* 10 (2), 21. doi:10.1007/s41204-025-00416-w

Aziz, K., Raza, N., Kanwal, N., Khairy, M., Ahmadi, Y., and Kim, K. H. (2025). Recent advances in nanomaterial-based adsorbents for removal of pharmaceutical pollutants from wastewater. *Mater. Horizons.* 12, 6043–6068. doi:10.1039/D5MH00627A

Babaniyi, B. R., Ogundele, O. D., Bisi-Omotosho, A., Babaniyi, E. E., and Aransiola, S. A. (2023). Remediation approaches in environmental sustainability. *Microbiol. Clean. Prod. Environ. Sustain.*, 321–346. doi:10.1201/9781003394600-17

Bao, J., Sun, X., Ning, P., Li, K., Yang, J., Wang, F., et al. (2024). Industrial solid wastes to environmental protection materials for removal of gaseous pollutants: a review. *Green Energy Environ.* 10, 34–83. doi:10.1016/j.gee.2024.01.006

Behera, S. S., Murmu, B. M., Ray, A., Ghosh, D., Bindhani, B. K., and Parhi, P. K. (2021). Surface modified highly activated adsorbent for effective removal of hazardous organic. *Chem. Modification Solid Surfaces by Use Addit.* 60. doi:10.2174/9789815036817121010007

Bello, M. M., and Raman, A. A. A. (2018). Adsorption and oxidation techniques to remove organic pollutants from water. *Green Adsorbents Pollut. Remov.*, 249–300. doi:10.1007/978-3-319-92111-2_8

Bellusci, M., Albino, M., Masi, A., Peddis, D., Innocenti, C., and Varsano, F. (2024). High porosity-magnetic composite materials for magnetic induction swing adsorption (MISA): improvement of performance properties. *Mater. Chem. Phys.* 311, 128525. doi:10.1016/j.matchemphys.2023.128525

Ben Dassi, R., and Chamam, B. (2025). Nanomaterial-enhanced membranes for advanced water and wastewater treatment: a comprehensive review. *Rev. Environ. Sci. Bio/Technol.* 2, 1–35. doi:10.1007/s11157-025-09723-9

Bhanjana, G., Dilbaghi, N., Kim, K.-H., and Kumar, S. (2017). Carbon nanotubes as sorbent material for removal of cadmium. *J. Mol. Liq.* 242, 966–970. doi:10.1016/j.molliq.2017.07.072

Bhat, S. A., Qadri, H., Cui, G., and Li, F. (2020). Remediation of pesticides through microbial and phytoremediation techniques. *Fresh Water Pollut. Dyn. Remediat.* 1, 235–245. doi:10.1007/978-981-13-8277-2_13

Bilal, M., Bashir, M. F., Benghoul, M., Numan, U., Shakoor, A., Komal, B., et al. (2020). Environmental pollution and COVID-19 outbreak: insights from Germany. *Air Qual. Atmos. Health* 13 (11), 1385–1394. doi:10.1007/s11869-020-00893-9

Bramsiepe, C., Sievers, S., Seifert, T., Stefanidis, G. D., Vlachos, D. G., Schnitzer, H., et al. (2012). Low-cost small scale processing technologies for production applications in various environments—mass produced factories. *Chem. Eng. Process. Process Intensif.* 51, 32–52. doi:10.1016/j.cep.2011.08.005

Bracco, E. B., Marco-Brown, J. L., Butler, M., and Candal, R. J. (2023). Degradation of oxytetracycline and characterization of byproducts generated by Fenton or photo-Fenton like processes after adsorption on natural and iron (III)-modified montmorillonite clays. *Environ. Nanotechnol. Monit. Manage.* 19, 100778.

Calero-DdelC, V. L., Gonzalez, A. M., and Rinaldi, C. (2010). A statistical analysis to control the growth of cobalt ferrite nanoparticles synthesized by the thermodecomposition method. *J. Manuf. Sci. Eng.* 132 (3), 030914. doi:10.1115/1.4001717

Carrapico, A., Martins, M. R., Caldeira, A. T., Mirao, J., and Dias, L. (2023). Biosynthesis of metal and metal oxide nanoparticles using microbial cultures: mechanisms, antimicrobial activity and applications to cultural Heritage. *Microorganisms* 11 (2), 378. doi:10.3390/microorganisms11020378

Chakraborty, A., Adhikary, S., Bhattacharya, S., Dutta, S., Chatterjee, S., Banerjee, D., et al. (2023). Pharmaceuticals and personal care products as emerging environmental contaminants: prevalence, toxicity, and remedial approaches. *J ACS Chem. Health Saf.* 30 (6), 362–388. doi:10.1021/acs.chas.3c00071

Chauhan, G., Gonzalez-Gonzalez, R. B., and Iqbal, H. M. N. (2022). Bioremediation and decontamination potentials of metallic nanoparticles loaded nanohybrid matrices - a review. *Environ. Res.* 204 (Pt D), 112407. doi:10.1016/j.envres.2021.112407

Chauhan, S. B., Singh, I., Singh, M., and Sominder, A. (2025). Biotechnological advancements in active pharmaceutical ingredient removal: sustainable solutions for pharmaceutical wastewater treatment. *Curr. Green Chem.* 13 (1), 103–123.

Chelike, D. K., Mehta, P., and Kumar, A. (2024). A recent review of the synthesis of plant-derived iron oxide nanoparticles for metal ion removal. *Inorg. Chem. Commun.* 166, 112611. doi:10.1016/j.inoche.2024.112611

Chen, H., Zhao, Y., and Wang, A. (2007). Removal of Cu(II) from aqueous solution by adsorption onto acid-activated palygorskite. *J. Hazard Mater* 149 (2), 346–354. doi:10.1016/j.jhazmat.2007.03.085

Chen, Y., Zhi, D., Zhou, Y., Huang, A., Wu, S., Yao, B., et al. (2021). Electrokinetic techniques, their enhancement techniques and composite techniques with other processes for persistent organic pollutants remediation in soil: a review. *J. Industrial Eng. Chem.* 97, 163–172. doi:10.1016/j.jiec.2021.03.009

Conti, L., Flore, N., Formica, M., Giorgi, L., Pagliai, M., Mancini, L., et al. (2021). Glyphosate and AMPA binding by two polyamino-phenolic ligands and their dinuclear Zn (II) complexes. *Inorganica Chim. Acta* 519, 120261. doi:10.1016/j.ica.2021.120261

Cortina-Puig, M., Hurtado-Fernandez, E., and Lacorte, S. (2018). Plasticizers in drinking water and beverages. *Curr. Anal. Chem.* 14 (4), 344–357. doi:10.2174/1573411013666170922145949

De Gisi, S., Lofrano, G., Grassi, M., and Notarnicola, M. (2016). Characteristics and adsorption capacities of low-cost sorbents for wastewater treatment: a review. *Sustain. Mater. Technol.* 9, 10–40. doi:10.1016/j.susmat.2016.06.002

De Luca, G., Furesi, A., Micera, G., Panzanelli, A., Piu, P. C., Pilo, M. I., et al. (2005). Nature, distribution and origin of polycyclic aromatic hydrocarbons (PAHs) in the sediments of Olbia harbor (Northern Sardinia, Italy). *Mar. Pollut. Bull.* 50 (11), 1223–1232. doi:10.1016/j.marpolbul.2005.04.021

De Luca, D. A., Papara, C., Vorobyev, A., Staiger, H., Bieber, K., Thaçi, D., et al. (2023). Lichen sclerosus: the 2023 update. *Front. Medicine* 10, 1106318. doi:10.3389/fmed.2023.1106318

Dehghani, M. H., Niasar, Z. S., Mehrnia, M. R., Shayeghi, M., Al-Ghouti, M. A., Heibati, B., et al. (2017). Optimizing the removal of organophosphorus pesticide malathion from water using multi-walled carbon nanotubes. *Chem. Eng. J.* 310, 22–32. doi:10.1016/j.cej.2016.10.057

Dehghani, M. H., Karri, R. R., Alimohammadi, M., Nazmara, S., Zarei, A., and Saeedi, Z. (2020). Insights into endocrine-disrupting Bisphenol-A adsorption from pharmaceutical effluent by chitosan immobilized nanoscale zero-valent iron nanoparticles. *J. Mol. Liq.* 311, 113317. doi:10.1016/j.molliq.2020.113317

Dehghani, M. H., Ahmadi, S., Ghosh, S., Othmani, A., Osagie, C., Meskini, M., et al. (2023). Recent advances on sustainable adsorbents for the remediation of noxious pollutants from water and wastewater: a critical review. *Arabian J. Chem.* 16 (12), 105303. doi:10.1016/j.arabjc.2023.105303

Demaria, F., Suleiman, M., Corvini, P., and Junier, P. (2025). Microbes as resources to remove PPCPs and improve water quality. *J. Microb. Biotechnol.* 18 (1), e70084. doi:10.1111/1751-7915.70084

Dey, S., Bano, F., and Malik, A. (2019). "Pharmaceuticals and personal care product (PPCP) contamination—a global discharge inventory," in *Pharmaceuticals and personal care products: waste management and treatment technology* (Oxford: Butterworth-Heinemann), 1–26.

Dey, N., Vinayagam, S., Kamaraj, C., Gnanasekaran, L., Goyal, K., Ali, H., et al. (2025). Ecotoxicological evaluation of nanosized particles with emerging contaminants and their impact assessment in the aquatic environment: a review. *J. Nanoparticle Res.* 27 (4), 1–21. doi:10.1007/s11051-025-06306-1

Dhiman, M., Kaur, B., and Kaur, B. (2021). Application of magnetic nanoparticles and their composites as adsorbents for wastewater treatment: a brief review. ferrite: nanostructures, Tunable properties. *Diverse Appl.* 112, 246–278. doi:10.21741/9781644901595-7

Dhumal, P., Bhadane, P., Ibrahim, B., and Chakraborty, S. (2025). Evaluating the path to sustainability: SWOT analysis of safe and sustainable by design approaches for metal-organic frameworks. *Green Chem.* 27, 3815–3850. doi:10.1039/d5gc00424a

Dou, B. C., Chen, H., Song, Y., Xie, B., Xu, Y., Tan, C., et al. (2012). Research progress of hot gas filtration, desulphurization and HCl removal in coal-derived fuel gas: a review. *Chem. Eng. Res. Des.* 90 (11), 1901–1917. doi:10.1016/j.cherd.2012.04.009

Dubey, S. K., Biswas, B., Halder, D., Mallick, S., Saha, I., Gupta, K., et al. (2023). Multifunctional Interpenetrated 3D supramolecular structure based on 1D coordination polymers: selective adsorption, magnetism, optical property, theoretical analysis, and electrical conductivity. *Cryst. Growth Des.* 23 (10), 7066–7075. doi:10.1021/acs.cgd.3c00175

Ebele, A. J., Abou-Elwafa Abdallah, M., and Harrad, S. (2017). Pharmaceuticals and personal care products (PPCPs) in the freshwater aquatic environment. *Emerg. Contam.* 3 (1), 1–16. doi:10.1016/j.emcon.2016.12.004

Edo, G. I., Mafe, A. N., Ali, A. B., Akpoghelie, P. O., Yousif, E., Isoje, E. F., et al. (2025). Green biosynthesis of nanoparticles using plant extracts: mechanisms, advances, challenges, and applications. *J. BioNanoScience* 15 (2), 267. doi:10.1007/s12668-025-01883-w

Ethiraj, S., Samuel, M. S., and S.M., I. (2024). A comprehensive review of the challenges and opportunities in microalgae-based wastewater treatment for eliminating organic, inorganic, and emerging pollutants. *Biocatal. Agric. Biotechnol.* 60, 103316. doi:10.1016/j.bcab.2024.103316

Fasano, E., and Cirillo, T. (2018). Plasticizers and bisphenol as food contaminants: sources and human risk. *Curr. Anal. Chem.* 14 (4), 296–305. doi:10.2174/1573411013666170822153906

Fernandes, L. (2022). Advances in environmental chemistry: tackling pollution and waste management. *Austra Lian J. Basic Sci.* 3 (3), 1–8.

Fernandes, A., Gągol, M., Makoś, P., Khan, J. A., and Boczkaj, G. (2019). Integrated photocatalytic advanced oxidation system ($TiO_2/UV/O_3/H_2O_2$) for degradation of volatile organic compounds. *Sep. Purif. Technol.* 224, 1–14. doi:10.1016/j.seppur.2019.05.012

Fromme, H., Becher, G., Hilger, B., and Volkel, W. (2016). Brominated flame retardants - exposure and risk assessment for the general population. *Int. J. Hyg. Environ. Health* 219 (1), 1–23. doi:10.1016/j.ijheh.2015.08.004

GadelHak, Y., El-Azazy, M., Shibl, M. F., and Mahmoud, R. K. (2023). Cost estimation of synthesis and utilization of nano-adsorbents on the laboratory and industrial scales: a detailed review. *Sci. Total Environ.* 875, 162629. doi:10.1016/j.scitotenv.2023.162629

Gai, S., Li, C., Yang, P., and Lin, J. (2014). Recent progress in rare earth micro/nanocrystals: soft chemical synthesis, luminescent properties, and biomedical applications. *Chem. Rev.* 114 (4), 2343–2389. doi:10.1021/cr4001594

Gebru, S. B., and Werkneh, A. A. (2024). Applications of constructed wetlands in removing emerging micropollutants from wastewater: occurrence, public health concerns, and removal performances – a review. *South Afr. J. Chem. Eng.* 48 (1), 395–416. doi:10.1016/j.sajce.2024.03.004

Gholami, F., Roushani, M., Hosseini, H., and Karazan, Z. M. (2024). Synthesis of metal–organic framework ZIF-9-Mel and its application as an electrochemical modifier in Pb2+ detection. *Microchem. J.* 201, 110634. doi:10.1016/j.microc.2024.110634

Godswill, A. C., and Godspel, A. C. (2019). Physiological effects of plastic wastes on the endocrine system (Bisphenol A, Phthalates, Bisphenol S, PBDEs, TBBPA). *Int. J. Chem. Biol. Eng. (IJCBB)* 4, 11–29.

Gómez-Pastora, J., Bringas, E., and Ortiz, I. (2014). Recent progress and future challenges on the use of high performance magnetic nano-adsorbents in environmental applications. *Chem. Eng. J.* 256, 187–204. doi:10.1016/j.cej.2014.06.119

González, O., Bayarri, B., Aceña, J., Pérez, S., and Barceló, D. (2015). "Treatment technologies for wastewater reuse: fate of contaminants of emerging concern," in *Advanced treatment technologies for urban wastewater reuse* (Cham: Springer International), 5–37.

Guan, Y., Hu, T., Wu, J., Zhao, L., Tian, F., Pan, W., et al. (2018). Enhanced photocatalytic activity of TiO_2/graphene by tailoring oxidation degrees of graphene oxide for gaseous mercury removal. *Korean J. Chem. Eng.* 36 (1), 115–125. doi:10.1007/s11814-018-0148-z

Gul, M. Z., Rao, B. S., and Rupula, K. (2024). Nanotechnology-based applications. *Aquat. Contam.*, 291–312. doi:10.1002/9781119989318.ch17

Haider Naqvi, S. L., Ayub, F., Yasar, A., Tabinda, A. B., Nawaz, H., and Tanveer, R. (2023). Pollution status monitoring and indices development for evaluating sustainable environmental management practices (SEMP) in Quaid-e-Azam Industrial Estate, Pakistan. *J. Clean. Prod.* 405, 136944. doi:10.1016/j.jclepro.2023.136944

Han, D., Wu, X., Li, R., Tang, X., Xiao, S., and Scholz, M. (2021). Critical review of electro-kinetic remediation of contaminated soils and sediments: mechanisms, performances and technologies. *Water, Air, Soil Pollut.* 232, 335. doi:10.1007/s11270-021-05182-4

Han, J., Choong, C. E., Jang, M., Lee, J., Hyun, S., Lee, W. S., et al. (2024). Causative mechanisms limiting the removal efficiency of short-chain per-and polyfluoroalkyl substances (PFAS) by activated carbon. *Chemosphere* 365, 143320. doi:10.1016/j.chemosphere.2024.143320

Hansen, H. K., Ottosen, L. M., and Ribeiro, A. B. (2016). *Electrokinetic soil remediation: an overview. Electrokinetics across disciplines and continents.* Cham: Springer International Publishing. 3–18.

Hassaan, M. A., and El Nemr, A. (2020). Pesticides pollution: classifications, human health impact, extraction and treatment techniques. *Egypt. J. Aquatic Res.* 46 (3), 207–220. doi:10.1016/j.ejar.2020.08.007

Hassan, M., Naidu, R., Du, J., Liu, Y., and Qi, F. (2020). Critical review of magnetic biosorbents: their preparation, application, and regeneration for wastewater treatment. *Sci. Total Environ.* 702, 134893. doi:10.1016/j.scitotenv.2019.134893

He, L., Yang, Y., Kim, J., Yao, L., Dong, X., Li, T., et al. (2020). Multi-layered enzyme coating on highly conductive magnetic biochar nanoparticles for bisphenol A sensing in water. *Chem. Eng. J.* 384, 123276. doi:10.1016/j.cej.2019.123276

Hofman-Caris, R., and Hofman, J. (2019). Limitations of conventional drinking water technologies in pollutant removal. *Appl. Adv. Oxid. Process. (AOPs) Drink. Water Treat.*, 21–51. doi:10.1007/698_2017_83

Human & Environmental Risk Assessment (HERA) Project (2002). *Human and Environmental Risk Assessment (HERA) Report: Linear Alkylbenzene Sulphonate (LAS).* AISE & Cefic. (Technical report).

Human & Environmental Risk Assessment (HERA) Project (2013). *Revised HERA Report: Linear Alkylbenzene Sulphonate (LAS).* AISE & Cefic. (Technical report).

Hussain, K., Khan, N. A., Farooqi, I. H., and Ahmed, S. (2023). Biodegradation technology for the removal of micropollutants: a critical review. *Manag. Wastewater Sludge*, 181–201. doi:10.1201/9781003202431-11

Hyeon, T. (2003). Chemical synthesis of magnetic nanoparticles. *Chem. Commun. (Camb)* 8, 927–934. doi:10.1039/b207789b

Ibrahim, G. M., Alshahrani, S. M., Alosaimi, E. H., Alshahrani, W. A., El-Gammal, B., Fawzy, A., et al. (2024). Adsorption mechanism elucidation of Anionic Congo red onto modified magnetic nanoparticle structures by Quantum chemical and molecular dynamics. *J. Mol. Struct.* 1298, 136992. doi:10.1016/j.molstruc.2023.136992

Iqbal, Y., Hussain Shah, W., Yaqoob Khan, M., Ahmed, P., Tauseef Qureshi, M., Mohamed Khaled, A., et al. (2024). Optimizing the magnetic field strength and concentration of silica coated cobalt ferrite nanoparticles for magnetic hyperthermia. *Inorg. Chem. Commun.* 167, 112796. doi:10.1016/j.inoche.2024.112796

Islas-Flores, H., Gomez-Olivan, L. M., Galar-Martinez, M., Colin-Cruz, A., Neri-Cruz, N., and Garcia-Medina, S. (2013). Diclofenac-induced oxidative stress in brain, liver, gill and blood of common carp (*Cyprinus carpio*). *Ecotoxicol. Environ. Saf.* 92, 32–38. doi:10.1016/j.ecoenv.2013.01.025

Jadaa, W., and Mohammed, H. (2023). Heavy metals–definition, natural and anthropogenic sources of releasing into ecosystems, toxicity, and removal methods–an overview study. *J. Ecol. Eng.* 24, 249–271. doi:10.12911/22998993/162955

Jampílek, J., and Kráľová, K. (2025). "Nanotoxicity effects of metal oxide nanoparticles on aquatic and soil ecosystems," in *Nanoscience and soil-water interaction in agroecosystem*. Boca Raton, FL: CRC Press, 79–129.

Jayasekara, U. G., Hadibarata, T., Hindarti, D., Kurniawan, B., Jusoh, M. N. H., Gani, P., et al. (2025). Environmental bioremediation of pharmaceutical residues: microbial processes and technological innovations: a review. *Bioproc. Biosyst. Eng.* 48, 1–19.

Jiang, H., Deng, D., Kita, Y., Hattori, M., Kamata, K., and Hara, M. (2024). Tuning the selectivity of catalytic nitrile hydrogenation with phase-controlled co nanoparticles prepared by hydrosilane-assisted method. *J. Am. Chem. Soc.* 146 (30), 20919–20929. doi:10.1021/jacs.4c04780

Jiang, L., Chen, X., Carey, G. R., Liu, X., Lowry, G. V., Fan, D., et al. (2025). Effects of physical and chemical aging of colloidal activated carbon on the adsorption of per-and polyfluoroalkyl substances. *Environ. Sci. Technol.* 59 (7), 3691–3702. doi:10.1021/acs.est.4c07958

Jimenez-Sandoval, R., Pedireddy, S., Katuri, K. P., and Saikaly, P. E. (2023). Facile biological-based synthesis of size-controlled palladium nanoclusters anchored on the surface of Geobacter sulfurreducens and their application in electrocatalysis. *ACS Sustain. Chem. Eng.* 11 (3), 1100–1109. doi:10.1021/acssuschemeng.2c06143

Johannessen, C., and Shetranjiwalla, S. (2021). Role of structural morphology of commodity polymers in microplastics and nanoplastics formation: fragmentation, effects and associated toxicity in the aquatic environment. *Rev. Environ. Contam. Toxicol.* 259, 123–169. doi:10.1007/398_2021_80

Kadiru, S., Patil, S., and D'Souza, R. (2022). Effect of pesticide toxicity in aquatic environments: a recent review. *Int. J. Fish. Aquatic Stud.* 10 (3), 113–118. doi:10.22271/fish.2022.v10.i3b.2679

Kainth, S., Sharma, P., and Pandey, O. P. (2024). Green sorbents from agricultural wastes: a review of sustainable adsorption materials. *Appl. Surf. Sci. Adv.* 19, 100562. doi:10.1016/j.apsadv.2023.100562

Kamal, K. H., Hassan, M. A., Kamel, S., and El-Sayed, N. S. (2024). Efficient removal of Cd2+ ions and methylene blue from aqueous solutions by polyanionic sodium alginate-derived hydrogel. *Surfaces Interfaces* 51, 104596. doi:10.1016/j.surfin.2024.104596

Kanan, S., Moyet, M., Obeideen, K., El-Sayed, Y., and Mohamed, A. A. (2022). Occurrence, analysis and removal of pesticides, hormones, pharmaceuticals, and other contaminants in soil and water streams for the past two decades: a review. *Res. Chem. Intermed.* 48 (9), 3633–3683. doi:10.1007/s11164-022-04778-7

Karnwal, A., Martolia, S., Dohroo, A., Al-Tawaha, A. R. M. S., and Malik, T. (2024). Exploring bioremediation strategies for heavy metals and POPs pollution: the role of microbes, plants, and nanotechnology. *Front. Environ. Sci.* 12, 1397850. doi:10.3389/fenvs.2024.1397850

Karri, R. R., Sahu, J. N., and Meikap, B. C. (2020). Improving efficacy of Cr (VI) adsorption process on sustainable adsorbent derived from waste biomass (sugarcane bagasse) with help of ant colony optimization. *Industrial Crops Prod.* 143, 111927. doi:10.1016/j.indcrop.2019.111927

Katyal, S., Lumma, A. L., Goldin, P. R., and Roy, S. (2023). Editorial: the varieties of contemplative experiences and practices. *Front. Psychol.* 14, 1232999. doi:10.3389/fpsyg.2023.1232999

Khajvand, M., Mostafazadeh, A. K., Drogui, P., and Tyagi, R. D. (2022). Management of greywater: environmental impact, treatment, resource recovery, water recycling, and decentralization. *Water Sci. Technol.* 86 (5), 909–937. doi:10.2166/wst.2022.226

Khan, U. A., Löffler, P., Spilsbury, F., Wiberg, K., Lundborg, C. S., and Lai, F. Y. (2024). Towards sustainable water reuse: a critical review and meta-analysis of emerging chemical contaminants with risk-based evaluation, health hazard prediction and prioritization for assessment of effluent water quality. *J. Hazard. Mater.* 480, 136175. doi:10.1016/j.jhazmat.2024.136175

Kikanme, K. N., Dennis, N. M., Orikpete, O. F., and Ewim, D. R. E. (2024). PFAS in Nigeria: identifying data gaps that hinder assessments of ecotoxicological and human health impacts. *Heliyon* 10 (9), e29922. doi:10.1016/j.heliyon.2024.e29922

Kim, G., Mengesha, D. N., and Choi, Y. (2024). Adsorption dynamics of per-and polyfluoroalkyl substances (PFAS) on activated carbon: interplay of surface chemistry and PFAS structural properties. *Sep. Purif. Technol.* 349, 127851. doi:10.1016/j.seppur.2024.127851

Knepper, T. P., and Berna, J. L. (2003). Chapter 1 surfactants: properties, production, and environmental Aspects. *Analysis Fate Surfactants Aquatic Environ.*, 1–49. doi:10.1016/s0166-526x(03)40004-4

Konnerth, C., Flach, F., Breitung-Faes, S., Damm, C., Schmidt, J., Kwade, A., et al. (2016). Impact of stressing conditions and polymer–surfactant interactions on product characteristics of organic nanoparticles produced by media milling. *Powder Technol.* 294, 71–79. doi:10.1016/j.powtec.2016.02.016

Krishnan, R. Y., Manikandan, S., Subbaiya, R., Biruntha, M., Govarthanan, M., and Karmegam, N. (2021). Removal of emerging micropollutants originating from pharmaceuticals and personal care products (PPCPs) in water and wastewater by advanced oxidation processes: a review. *Environ. Technol. Innovation* 23, 101757. doi:10.1016/j.eti.2021.101757

Krishnan, R. Y., Manikandan, S., Subbaiya, R., Karmegam, N., Kim, W., and Govarthanan, M. (2023). Recent approaches and advanced wastewater treatment technologies for mitigating emerging microplastics contamination - a critical review. *Sci. Total Environ.* 858 (Pt 1), 159681. doi:10.1016/j.scitotenv.2022.159681

Kristanti, R. A., Tirtalistyani, R., Tang, Y. Y., Thao, N. T. T., Kasongo, J., and Wijayanti, Y. (2023). Phytoremediation mechanism for emerging pollutants: a review. *Trop. Aquatic Soil Pollut.* 3 (1), 88–108. doi:10.53623/tasp.v3i1.222

Kudhur, A. Y., Salim, E. T., Kara, I., Fakhri, M. A., and Mahdi, R. O. (2024). Structural optical and morphological properties of copper oxide nanoparticles ablated using pulsed laser ablation in liquid. *J. Opt.* 53, 1936–1945. doi:10.1007/s12596-023-01331-6

Kulkarni, S., and Kaware, J. (2014). Regeneration and recovery in adsorption-a review. *Int. J. Innov. Sci. Eng. Technol.* 1, 61–64.

Kumar, A., Seema, K., and Kumar, A. (2025). "Sensors and biosensors for emerging contaminants in industrial wastewater," in *Emerging contaminants in water and wastewater: sources and substances*. Cham: Springer Nature Switzerland, 11–41.

Kumar, V., and Shah, M. P. (2021). Advanced oxidation processes for complex wastewater treatment. *Adv. Oxid. Process. Effl. Treat. Plants*, 1–31. doi:10.1016/b978-0-12-821011-6.00001-3

Kumar, P., and Singh, J. (2025). "Perspective and challenges of synergistic removal of toxic contaminants from effluent using different treatment techniques," in *Microbial niche nexus sustaining environmental biological wastewater and water-energy-environment nexus*. Cham: Springer Nature Switzerland, 419–451.

Kumar, M. K., Kumar, K. M., and Kumar, N. S. (2025). Innovative approaches to water purification harnessing bio-chemical adsorbents for multistage potable water filtration. Innovative materials for environmental and aerospace applications. *IGI Glob. Sci. Publ.* 389–458.

Kumar, S., Singh, H., Singh, H., Soni, H., Bechelany, M., and Singh, J. (2025). Extraction of metallic nanoparticles from electronic waste for biomedical applications: pioneering sustainable technological progress. *Sustainability* 17 (5), 2100. doi:10.3390/su17052100

Kurian, M. (2021). Advanced oxidation processes and nanomaterials-a review. *Clean. Eng. Technol.* 2, 100090. doi:10.1016/j.clet.2021.100090

Kurul, F., Doruk, B., and Topkaya, S. N. (2025). Principles of green chemistry: building a sustainable future. *J. Discov. Chem.* 2 (1), 68. doi:10.1007/s44371-025-00152-9

Kwon, S. G., and Hyeon, T. (2008). Colloidal chemical synthesis and formation kinetics of uniformly sized nanocrystals of metals, oxides, and chalcogenides. *Acc. Chem. Res.* 41 (12), 1696–1709. doi:10.1021/ar8000537

Lama, G., Meijide, J., Sanromán, A., and Pazos, M. (2022). Heterogeneous advanced oxidation processes: current approaches for wastewater treatment. *Catalysts* 12 (3), 344. doi:10.3390/catal12030344

LaMer, V. K., and Dinegar, R. H. (2002). Theory, production and mechanism of formation of monodispersed hydrosols. *J. Am. Chem. Soc.* 72 (11), 4847–4854. doi:10.1021/ja01167a001

Lartigue, L., Innocenti, C., Kalaivani, T., Awwad, A., del Mar Sanchez, M., Guari, Y., et al. (2011). Water-dispersible sugar-coated iron oxide nanoparticles. An evaluation of their relaxometric and magnetic hyperthermia properties. *J. Am. Chem. Soc.* 133, 10459–10472. doi:10.1021/ja111448t

Lazarov, B. (2022). *Characterisation of flame retardant emissions from treated consumer and building products in laboratory conditions and real-life indoor environments*. (doctoral dissertation). University of Antwerp, Antwerp, Belgium.

Le, T. V., and Nguyen, B. T. (2024). Heavy metal pollution in surface water bodies in provincial Khanh Hoa, Vietnam: pollution and human health risk assessment, source quantification, and implications for sustainable management and development. *Environ. Pollut.* 343, 123216. doi:10.1016/j.envpol.2023.123216

Le, N. D., Dinh, T. T. H., Vu, T. H., Le, P. T., Nguyen, T. M. H., Hoang, T. T. H., et al. (2025). Occurrence and ecological risks of antibiotics and antiparasitics in surface water in urban lakes in Hanoi city, Vietnam. *Environ. Sci. Pollut. Res.* 32 (3), 1447–1465. doi:10.1007/s11356-024-35726-0

Lefebure, S., Dubois, E., Cabuil, V., Neveu, S., and Massart, R. (2011). Monodisperse magnetic nanoparticles: preparation and dispersion in water and oils. *J. Mater. Res.* 13 (10), 2975–2981. doi:10.1557/jmr.1998.0407

Li, J., Lu, J., Li, X., Ren, T., Cong, R., and Zhou, L. (2014). Dynamics of potassium release and adsorption on rice straw residue. *PLoS One* 9 (2), e90440. doi:10.1371/journal.pone.0090440

Li, L., Zhang, J., Wang, Y., Zaman, F. U., Zhang, Y., Hou, L., et al. (2021). Laser irradiation construction of nanomaterials toward electrochemical energy storage and conversion: ongoing progresses and challenges. *InfoMat* 3 (12), 1393–1421. doi:10.1002/inf2.12218

Li, J., Li, Z., Sun, Q., Wang, Y., Li, Y., Peng, Y. K., et al. (2024). Recent advances in the large-scale production of photo/electrocatalysts for energy conversion and beyond. *J. Adv. Energy Mater.* 14 (45), 2402441. doi:10.1002/aenm.202402441

Li, Q., Ai, R., Fan, J., Fu, X., Zhu, L., Zhou, Q., et al. (2024). AgNPs-loaded chitosan/sodium alginate hydrogel film by *in-situ* green reduction with tannins for enhancing antibacterial activity. *Mater. Today Commun.* 38, 107927. doi:10.1016/j.mtcomm.2023.107927

Liu, J. L., and Wong, M. H. (2013). Pharmaceuticals and personal care products (PPCPs): a review on environmental contamination in China. *Environ. Int.* 59, 208–224. doi:10.1016/j.envint.2013.06.012

Liu, J., Yu, X., Wang, L., Guo, M., Tian, S., and Zhu, W. (2019). Photocatalytic degradation of oxytetracycline hydrochloride pollutants in marine aquaculture wastewater under visible light. *J. Environ. Sci. Health A Tox Hazard Subst. Environ. Eng.* 54 (14), 1423–1429. doi:10.1080/10934529.2019.1651589

Liu, Y., Tong, D., Cheng, J., Davis, S. J., Yu, S., Yarlagadda, B., et al. (2022). Role of climate goals and clean-air policies on reducing future air pollution deaths in China: a modelling study. *Lancet Planet. Health* 6 (2), e92–e99. doi:10.1016/s2542-5196(21)00326-0

Lu, A. H., Salabas, E. L., and Schuth, F. (2007). Magnetic nanoparticles: synthesis, protection, functionalization, and application. *Angew. Chem. Int. Ed. Engl.* 46 (8), 1222–1244. doi:10.1002/anie.200602866

Mahpishanian, S., and Sereshti, H. (2017). One-step green synthesis of beta-cyclodextrin/iron oxide-reduced graphene oxide nanocomposite with high supramolecular recognition capability: application for vortex-assisted magnetic solid phase extraction of organochlorine pesticides residue from honey samples. *J. Chromatogr. A* 1485, 32–43. doi:10.1016/j.chroma.2017.01.035

Manninen, N. K. A. D. S. (2015). *Silver segregation in Ag/aC nanocomposite coatings for potential application as antibacterial surfaces*. (doctoral dissertation). University of Coimbra, Coimbra, Portugal.

Mehta, P. (2023). Nanoparticles in agriculture and wastewater treatment: evaluating dual impacts across nations. *Inter. Monthly, Peer-Reviewed, Refereed, Indexed J Issue*, 584–1785.

Mehta, P., Chelike, D. K., and Rathore, R. K. (2024). Adsorption-based approaches for exploring nanoparticle effectiveness in wastewater treatment. *ChemistrySelect* 9 (25), e202400959. doi:10.1002/slct.202400959

Meierhofer, F., and Fritsching, U. (2021). Synthesis of metal oxide nanoparticles in flame sprays: review on process technology, modeling, and diagnostics. *Energy Fuels* 35 (7), 5495–5537. doi:10.1021/acs.energyfuels.0c04054

Menon, S., S, R., and V. K. S, (2017). A review on biogenic synthesis of gold nanoparticles, characterization, and its applications. *Resource-Efficient Technol.* 3 (4), 516–527. doi:10.18799/24056529/2017/4/166

Milano, F., Giotta, L., and Lambreva, M. D. (2024). Perspectives on nanomaterial-empowered bioremediation of heavy metals by photosynthetic microorganisms. *Plant Physiology Biochem.* 216, 109090. doi:10.1016/j.plaphy.2024.109090

Mohammed, M., Diwan, A., Saleh, S. M., and Salih, B. A. S. (2021). Fabrication of copper nanoparticles by pulse laser ablation. *Kufa J. Eng.* 10 (1), 1–11. doi:10.30572/2018/kje/100101

Moradi Dehaghi, S., Rahmanifar, B., Moradi, A. M., and Azar, P. A. (2014). Removal of permethrin pesticide from water by chitosan–zinc oxide nanoparticles composite as an adsorbent. *J. Saudi Chem. Soc.* 18 (4), 348–355. doi:10.1016/j.jscs.2014.01.004

Moreira, J. B., Santos, T. D., Zaparoli, M., de Almeida, A. C. A., Costa, J. A. V., and de Morais, M. G. (2022). An overview of nanofiltration and nanoadsorption technologies to emerging pollutants treatment. *Appl. Sci.* 12 (16), 8352. doi:10.3390/app12168352

Mphahlele, K., Onyango, M. S., and Mhlanga, S. D. (2015). Adsorption of aspirin and paracetamol from aqueous solution using Fe/N-CNT/β-cyclodextrin nanocomopsites synthesized *via* a benign microwave assisted method. *J. Environ. Chem. Eng.* 3 (4), 2619–2630. doi:10.1016/j.jece.2015.02.018

Muzzi, B., Albino, M., Gabbani, A., Omelyanchik, A., Kozenkova, E., Petrecca, M., et al. (2022). Star-shaped magnetic-plasmonic Au@Fe3O4 nano-heterostructures for photothermal therapy. *ACS Appl. Mater. Inter.* 14 (25), 29087–29098. doi:10.1021/acsami.2c04865

Nain, A., Sangili, A., Hu, S. R., Chen, C. H., Chen, Y. L., and Chang, H. T. (2022). Recent progress in nanomaterial-functionalized membranes for removal of pollutants. *Iscience* 25 (7), 104616. doi:10.1016/j.isci.2022.104616

Narwal, N., Katyal, D., Kataria, N., Rose, P. K., Warkar, S. G., Pugazhendhi, A., et al. (2023). Emerging micropollutants in aquatic ecosystems and nanotechnology-based removal alternatives: a review. *Chemosphere* 341, 139945. doi:10.1016/j.chemosphere.2023.139945

Natarajan, R., Saikia, K., Ponnusamy, S. K., Rathankumar, A. K., Rajendran, D. S., Venkataraman, S., et al. (2022). Understanding the factors affecting adsorption of pharmaceuticals on different adsorbents - a critical literature update. *Chemosphere* 287 (Pt 1), 131958. doi:10.1016/j.chemosphere.2021.131958

Nayak, A., Bhushan, B., and Kotnala, S. (2024). "Fundamentals and mechanism of adsorption," in *Sustainable technologies for remediation of emerging pollutants from aqueous environment*, (Amsterdam: Elsevier), 29–62.

Nizamuddin, S., Siddiqui, M. T. H., Mubarak, N. M., Baloch, H. A., Abdullah, E. C., Mazari, S. A., et al. (2019). Iron oxide nanomaterials for the removal of heavy metals and dyes from wastewater. *Nanoscale Mater. Water Purif.*, 447–472. doi:10.1016/b978-0-12-813926-4.00023-9

Nwankwo, C. E. I., Okeke, E. S., Umeoguaju, F. U., Ejeromedoghene, O., Adedipe, D. T., and Ezeorba, T. P. C.(2025). Addressing emerging contaminants in agriculture affecting plant–soil interaction: a review on bio-based and nano-enhanced strategies for soil health and global food security (GFS). *Dis. Toxicol.* 2(1): 1–30.

Nzilu, D. M., Madivoli, E. S., Makhanu, D. s., Otenda, B. V., Kareru, P. G., Kairigo, P. k., et al. (2023). Environmental remediation using nanomaterial as adsorbents for emerging micropollutants. *Environ. Nanotechnol. Monit. Manag.* 20, 100789. doi:10.1016/j.enmm.2023.100789

Ogbeh, G. O., Ogunlela, A. O., Akinbile, C. O., and Iwar, R. T. (2025). Adsorption of organic micropollutants in water: a review of advances in modelling, mechanisms, adsorbents, and their characteristics. *Environ. Eng. Res.* 30 (2), 230733.

Ogundele, O. D., Anaun, T. E. O., and Afolabi, A. B. (2023). Advanced oxidation processes for sustainable reme-diation and waste water treatment. *J Eng Tech App Sci* 1 (1), 01–10.

Ojha, A., Tiwary, D., Oraon, R., and Singh, P. (2021). Degradations of endocrine-disrupting chemicals and pharmaceutical compounds in wastewater with carbon-based nanomaterials: a critical review. *Environ. Sci. Pollut. Res.* 28 (24), 30573–30594. doi:10.1007/s11356-021-13939-x

Padhiary, M., Roy, D., and Dey, P. (2025). Mapping the landscape of biogenic nanoparticles in bioinformatics and nanobiotechnology: AI-driven insights. Synthesizing and characterizing plant-mediated biocompatible metal nanoparticles. *IGI Glob.*, 337–376.

Paliwal, V., Puranik, S., and Purohit, H. J. (2012). Integrated perspective for effective bioremediation. *Appl. Biochem. Biotechnol.* 166 (4), 903–924. doi:10.1007/s12010-011-9479-5

Park, J., Lee, E., Hwang, N. M., Kang, M., Kim, S. C., Hwang, Y., et al. (2005). One-nanometer-scale size-controlled synthesis of monodisperse magnetic iron oxide nanoparticles. *Angew. Chem.* 117 (19), 2932–2937. doi:10.1002/ange.200461665

Patra, K., Dey, S., Solanki, C., Sengupta, A., and Mittal, V. K. (2025). Harnessing advanced porous materials, covalent organic frameworks, and porous organic polymers as next-generation porous frameworks for targeted removal of emerging water contaminants. *J. ACS Appl. Eng. Mater.* 3, 1130–1165. doi:10.1021/acsaenm.5c00187

Pentimalli, M., Bellusci, M., and Padella, F. (2015). High-Energy ball milling as a general tool for nanomaterials synthesis and processing. *Handb. Mech. Nanostructuring*, 663–679. doi:10.1002/9783527674947.ch28

Pereira, H. A., da Boit Martinello, K., Vieira, Y., Diel, J. C., Netto, M. S., Reske, G. D., et al. (2023). Adsorptive behavior of multi-walled carbon nanotubes immobilized magnetic nanoparticles for removing selected pesticides from aqueous matrices. *Chemosphere* 325, 138384. doi:10.1016/j.chemosphere.2023.138384

Petrecca, M., Muzzi, B., Olivieri, S., Albino, M., Yaacoub, N., Peddis, D., et al. (2021). Optimizing the magnetic properties of hard and soft materials for producing exchange spring permanent magnets. *J. Phys. D. Appl. Phys.* 54, 134003. doi:10.1088/1361-6463/abf51f

Praskova, E., Plhalova, L., Chromcova, L., Stepanova, S., Bedanova, I., Blahova, J., et al. (2014). Effects of subchronic exposure of diclofenac on growth, histopathological changes, and oxidative stress in zebrafish (*Danio rerio*). *ScientificWorldJournal* 2014, 1–5. doi:10.1155/2014/645737

Priyadarshini, M., Das, I., Ghangrekar, M. M., and Blaney, L. (2024). Advanced oxidation processes: performance, advantages, and scale-up of emerging technologies. *J. Environ. Manage.* 316, 115295. doi:10.1016/j.jenvman.2022.115295

Quan, L. D., Dang, N. H., Tu, T. H., Phuong Linh, V. N., Mong Thy, L. T., Nam, H. M., et al. (2019). Preparation of magnetic iron oxide/graphene aerogel nanocomposites for removal of bisphenol A from water. *Synth. Met.* 255, 116106. doi:10.1016/j.synthmet.2019.116106

Raeisi, A., Faghihi, K., and Shabanian, M. (2017). Designed biocompatible nano-inhibitor based on poly(β-cyclodextrin-ester) for reduction of the DEHP migration from plasticized PVC. *Carbohydr. Polym.* 174, 858–868. doi:10.1016/j.carbpol.2017.06.105

Rahimi, H.-R., and Doostmohammadi, M. (2020). "Nanoparticle synthesis, applications, and toxicity," in *Applications of nanobiotechnology*. London, United Kingdom: IntechOpen.

Rahman, N., and Nasir, M. (2020). Effective removal of acetaminophen from aqueous solution using Ca (II)-doped chitosan/β-cyclodextrin composite. *J. Mol. Liq.* 301, 112454. doi:10.1016/j.molliq.2020.112454

Rani, J., Goyal, T., Kaur, A., Ganesan, S., Sharma, A. K., Chauhan, A. S., et al. (2025). Bimetallic nanoparticles as pioneering eco-friendly catalysts for remediation of pharmaceuticals and personal care products (PPCPs). *Nanoscale Adv.* 7, 3160–3188. doi:10.1039/D5NA00151J

Ranoszek-Soliwoda, K., Tomaszewska, E., Socha, E., Krzyczmonik, P., Ignaczak, A., Orlowski, P., et al. (2017). The role of tannic acid and sodium citrate in the synthesis of silver nanoparticles. *J. Nanopart Res.* 19 (8), 273. doi:10.1007/s11051-017-3973-9

Rasheed, T., Shafi, S., Bilal, M., Hussain, T., Sher, F., and Rizwan, K. (2020). Surfactants-based remediation as an effective approach for removal of environmental pollutants—A review. *J. Mol. Liq.* 318, 113960. doi:10.1016/j.molliq.2020.113960

Ratchnashree, S. R., Karmegam, N., Selvam, M., Manikandan, S., Deena, S. R., Subbaiya, R., et al. (2023). Advanced technologies for the determination of quantitative structure-activity relationships and degradation efficiency of micropollutants and their removal in water - a review. *Sci. Total Environ.* 904, 166563. doi:10.1016/j.scitotenv.2023.166563

Rehman, M. U., Nisar, B., Yatoo, A. M., Sehar, N., Tomar, R., Tariq, L., et al. (2024). After effects of Pharmaceuticals and Personal Care Products (PPCPs) on the biosphere and their counteractive ways. *Sep. Purificat. Technol.* 320, 126921.

Rosales, G. G., Ávila-Pérez, P., Reza-García, J. O., Cabral-Prieto, A., Pérez-Gómez, E. O., and Penoni, A. (2021). Nanoparticle beads of chitosan-ethylene glycol diglycidyl Ether/Fe for the removal of aldrin. *J. Chem.* 2021, 1–13. doi:10.1155/2021/8421840

Ruan, T., Li, P., Wang, H., Li, T., and Jiang, G. (2023). Identification and prioritization of environmental organic pollutants: from an analytical and toxicological perspective. *Chem. Rev.* 123 (17), 10584–10640. doi:10.1021/acs.chemrev.3c00056

Rückbeil, F. E., Sperlich, A., Gnirss, R., Dittmann, D., Kämpfe, A., Höra, C., et al. (2025). Comparing activated carbons, ion exchange resins and alternative adsorbents for the removal of perfluoroalkyl and other persistent and mobile substances. *Chem. Eng. J.* 516, 164070. doi:10.1016/j.cej.2025.164070

Sable, H., Kumar, V., Singh, V., Rustagi, S., Chahal, S., and Chaudhary, V. (2024). Strategically engineering advanced nanomaterials for heavy-metal remediation from wastewater. *Coord. Chem. Rev.* 518, 216079. doi:10.1016/j.ccr.2024.216079

Sadeghi, M. H., Tofighy, M. A., and Mohammadi, T. (2020). One-dimensional graphene for efficient aqueous heavy metal adsorption: rapid removal of arsenic and mercury ions by graphene oxide nanoribbons (GONRs). *Chemosphere* 253, 126647. doi:10.1016/j.chemosphere.2020.126647

Saravanan, A., Senthil Kumar, P., Jeevanantham, S., Karishma, S., Tajsabreen, B., Yaashikaa, P. R., et al. (2021). Effective water/wastewater treatment methodologies for toxic pollutants removal: processes and applications towards sustainable development. *Chemosphere* 280, 130595. doi:10.1016/j.chemosphere.2021.130595

Satyam, S., and Patra, S. (2024). Innovations and challenges in adsorption-based wastewater remediation: a comprehensive review. *Heliyon* 10 (9), e29573. doi:10.1016/j.heliyon.2024.e29573

Scopetani, C., Cincinelli, A., Martellini, T., and Rodrigues, A. C. (2023). Editorial: hazardous contaminants associated with plastics: occurrence and environmental effects. *Front. Environ. Sci.* 11, 1341738. doi:10.3389/fenvs.2023.1341738

Sen, T. K. (2023). Agricultural solid wastes based adsorbent materials in the remediation of heavy metal ions from water and wastewater by adsorption: a review. *Molecules* 28 (14), 5575. doi:10.3390/molecules28145575

Shah, M. P. (2024). *Emerging innovative trends in the application of biological processes for industrial wastewater treatment*. Amsterdam: Elsevier.

Sharma, A., Goyal, A., Kumari, S., Garg, M., Kaur, A., Mehta, D., et al. (2024). A comprehensive review on synthesis of silver nano-particles: an update. *Nanosci. Nanotechnology-Asia* 14 (2), e020224226663.

Sharma, I., Khare, N., Singh, K., and Dahiya, V. S. (2025). Environmental applications and emerging pollutants: monitoring and remediation techniques. *Biotechnol. Environ. Sustain.*, 637–660. doi:10.1007/978-981-97-7221-6_21

Shatkin, J. A. (2017). Introduction: assessing nanotechnology health and environmental risks. *Nanotechnology*, 1–29. doi:10.1201/9781315216799-1

Singh, Y., and Saxena, M. K. (2022). Insights into the recent advances in nano-bioremediation of pesticides from the contaminated soil. *Front. Microbiol.* 13, 982611. doi:10.3389/fmicb.2022.982611

Singh, R. C., Singh, O., Singh, M. P., and Chandi, P. S. (2008). Synthesis of zinc oxide nanorods and nanoparticles by chemical route and their comparative study as ethanol sensors. *Sensors Actuators B Chem.* 135 (1), 352–357. doi:10.1016/j.snb.2008.09.004

Singh, S., Balasubramanian, S., and Kavassalis, S. C. (2023). Complex linkages between agriculture and air pollution pose a major threat to food security in India. *Environ. Res. Lett.* 18 (12), 121001. doi:10.1088/1748-9326/ad0682

Singh, S., Kumar, A., Krishna, R., Jaiswal, D. K., Chouhan, G. K., and Verma, J. P. (2025). "Role of microbial enzymes in nano-bioremediation process and its mechanism," in *Nano-bioinoculants* (Cambridge, MA: Academic Press), 265–275.

Suleiman, M. A., Zaini, M. A. A., and Mu'azu, N. D. (2025). Pomegranate peel adsorbents for water pollutants removal: preparation, characterization and applications. *Int. J. Phytoremediation* 27 (8), 1119–1139. doi:10.1080/15226514.2025.2484292

Sundari, S. K., Prakash, A., Yadav, P., and Kumari, A. (2019). Plant growth-promoting microbes as front-runners for On-site remediation of organophosphate pesticide residues in agriculture soils. *Phyto Rhizo Remediat.*, 249–285. doi:10.1007/978-981-32-9664-0_11

Suresh, A., and Abraham, J. (2019). An overview on the microbial degradation of Linear Alkylbenzene Sulfonate (LAS) surfactants. *Phyto Rhizo Remediat.*, 301–313. doi:10.1007/978-981-32-9664-0_13

Talapin, D. V., Rogach, A. L., Haase, M., and Weller, H. (2001). Evolution of an ensemble of nanoparticles in a colloidal solution: theoretical Study. *J. Phys. Chem. B* 105 (49), 12278–12285. doi:10.1021/jp012229m

Tran, V., Nguyen, N., Renkes, S., Nguyen, K. T., Nguyen, T., and Alexandrakis, G. (2025). Current and near-future technologies to quantify nanoparticle therapeutic loading efficiency and surface coating efficiency with targeted moieties. *J. Bioeng.* 12 (4), 362. doi:10.3390/bioengineering12040362

Vasantha Raman, N., Dubey, A., Millar, E., Nava, V., Leoni, B., and Gallego, I. (2023). Monitoring contaminants of emerging concern in aquatic systems through the lens of citizen science. *Sci. Total Environ.* 874, 162527. doi:10.1016/j.scitotenv.2023.162527

Wang, Y. Q., Zhang, Z. B., Liu, Y. H., Cao, X. H., Liu, Y. T., and Li, Q. (2012). Adsorption of U (VI) from aqueous solution by the carboxyl-mesoporous carbon. *Chem. Eng. J.* 198, 246–253. doi:10.1016/j.cej.2012.05.112

Wang, D., Ding, S., Wang, X., Qiu, L., Qin, H., Ni, Y. Q., et al. (2024). Low-cost flash graphene from carbon black to reinforce cementitious composites for carbon footprint reduction. *Chem. Eng. J.* 500, 156926. doi:10.1016/j.cej.2024.156926

Ward, J., Mohapatra, S. P., and Mitchell, A. (2008). An overview of policies for managing polybrominated diphenyl ethers (PBDEs) in the Great Lakes basin. *Environ. Int.* 34 (8), 1148–1156. doi:10.1016/j.envint.2008.05.003

Yang, Y., Zhang, X., Jiang, J., Han, J., Li, W., Li, X., et al. (2022). Which micropollutants in water environments deserve more attention globally? *Environ. Sci. Technol.* 56 (1), 13–29. doi:10.1021/acs.est.1c04250

Yin, B., and Hakkarainen, M. (2011). Core–shell nanoparticle–plasticizers for design of high-performance polymeric materials with improved stiffness and toughness. *J. Mater. Chem.* 21 (24), 8670–8677. doi:10.1039/c1jm10624d

Yin, L., Lin, Y., and Jia, L. (2014). Graphene oxide functionalized magnetic nanoparticles as adsorbents for removal of phthalate esters. *Microchim. Acta* 181, 957–965. doi:10.1007/s00604-014-1187-8

Yin, Z., Cui, C., Chen, H., Yu, X., and Qian, W. (2020). The application of carbon nanotube/graphene-based nanomaterials in wastewater treatment. *Small* 16 (15), 1902301. doi:10.1002/smll.201902301

Younas, F., Mustafa, A., Farooqi, Z. U. R., Wang, X., Younas, S., Mohy-Ud-Din, W., et al. (2021). Current and emerging adsorbent technologies for wastewater treatment: trends, limitations, and environmental implications. *Water* 13 (2), 215. doi:10.3390/w13020215

Yung, Y. L., Lakshmanan, S., Chu, C. M., Tham, H. J., and Kumaresan, S. (2023). Optimization of water washing for mitigation of 3-monochloropropane 1, 2 diol ester in palm oil physical refining process. *Food Addit. Contam. Part A* 40 (12), 1541–1550. doi:10.1080/19440049.2023.2283873

Zhang, S., He, Y., Wu, L., Wan, J., Ye, M., Long, T., et al. (2019). Remediation of organochlorine pesticide-contaminated soils by surfactant-enhanced washing combined with activated carbon selective adsorption. *Pedosphere* 29 (3), 400–408. doi:10.1016/s1002-0160(17)60328-x

Zhang, Y., Zhang, Y., and Wu, A. (2024). Design and construction of magnetic nanomaterials and their remediation mechanisms for heavy metal contaminated soil. *Sci. Total Environ.* 951, 175369. doi:10.1016/j.scitotenv.2024.175369

Zheng, A. L. T., Teo, E. Y. L., Seenivasagam, S., Yiu, P. H., Boonyuen, S., Chung, E. L. T., et al. (2025). Recent review on porous adsorbents for water decontamination: strategies for enhanced removal of tetracycline. *J. Porous Mater.* 32 (1), 1–25.

Zheng, A. L. T., Teo, E. Y. L., Seenivasagam, S., Yiu, P. H., Boonyuen, S., Chung, E. L. T., et al. (2025). Recent review on porous adsorbents for water decontamination: strategies for enhanced removal of tetracycline. *J. Porous Mater.* 32 (1), 1–25. doi:10.1007/s10934-024-01699-1

Ziylan-Yavas, A., Santos, D., Flores, E. M. M., and Ince, N. H. (2022). Pharmaceuticals and personal care products (PPCPs): environmental and public health risks. *Environ. Prog. Sustain. Energy* 41 (4), e13821. doi:10.1002/ep.13821