Current Science
CS 5 (4), 3626-3642 (2025)
Received **12 April** 2025 | **Revised 13 May** 2025 | **Accepted 11 June**. 2025 | **Online Available 18 July** 2025
https://doi.org/ 10.52845/CS/2025-5-4-25

Current Science
Current Science

OPEN ACCESS
ISSN (O) 2795-8639

Original Article

Review on the Application of Novel Materials for Microplastics and Nanoplastics Removal in Drinking Water Treatment Systems

Yueya Chang[1], Jun Yang[2]

[1]School of Municipal and Environmental Engineering, Shanghai Urban Construction Vocational College, Shanghai, 200438, People's Republic of China

[2]School of Mathematics, Physics and Statistics, Shanghai Polytechnic University, Shanghai, 201209, People's Republic of China

[*]Corresponding Author: Yueya Chang

Abstract:
The contamination of drinking water by microplastics (MPs) and nanoplastics (NPs) presents a formidable public health challenge that conventional treatment processes fail to adequately address. This review provides a systematic and critical evaluation of emerging materials engineered for MP and NP remediation, with a specific focus on drinking water treatment. Four principal classes of materials are assessed: (1) sustainable biomass-derived adsorbents, (2) advanced membrane separation technologies, (3) solar-driven photothermal systems, and (4) innovative electrochemical technologies. Fundamental removal mechanisms, material properties, and performance metrics for each class are analyzed to reveal inherent trade-offs between removal efficiency, energy consumption, cost, and technological readiness. Moreover, the analysis highlights overarching challenges to practical implementation, including scalability, long-term stability in complex water matrices, and the risk of secondary pollution. It is concluded that future progress will critically depend on the development of multifunctional hybrid systems and the strategic integration of these novel technologies into existing treatment frameworks. Ultimately, translating laboratory innovations into viable, large-scale solutions requires a concerted, multidisciplinary approach focused on material durability, cost-effectiveness, and comprehensive life cycle assessment to ensure the safety and security of global drinking water.

Keywords: microplastics; nanoplastics; drinking water treatment; novel materials;

1. Introduction

The proliferation of global plastic pollution has established microplastics (MPs, particles <5 mm) and nanoplastics (NPs, <1 μm) as pervasive environmental contaminants that pose significant threats to ecological safety and human health (Bourzac, 2019; Gerdes et al., 2019; Ivleva et al., 2017; Jamieson et al., 2019; Napper et al., 2020; Naqash et al., 2020; Park and Park, 2021; Rakowski and Grzelak, 2020; Rillig and Lehmann, 2020). MPs originate from both primary sources, such as microbeads in industrial products, and the environmental degradation of larger plastic debris (Samsonowska and Kaszuba, 2022). Their ubiquitous presence, confirmed in remote ecosystems from the Mariana Trench to the snowpack of Mount Everest, underscores their alarming dispersal capacity and designates them a global environmental concern (Jamieson et al., 2019; Ju et al., 2023; Lei et al., 2024; Ma et al., 2024; Napper et al., 2020).

This contamination extends critically to drinking water supplies (Kirstein et al., 2021; Pivokonsky et al., 2018; Zhou et al., 2023). Studies consistently reveal high MP prevalence in municipal drinking water globally, with contamination rates reported between 78.1% and

81.1% (Chai et al., 2021; Kosuth et al., 2018). These MPs often originate from pipe abrasion, source water pollution, and breakthrough from upstream treatment plants. A national study in China further quantified this issue, reporting a mean MP concentration of 440 ± 275 particles/L in tap water derived from surface sources (Tong et al., 2020). Critically, these analyses concur that particles of smaller dimensions (<50 µm) constitute the predominant fraction (≥85%), and environmental assessments indicate that NPs are even more abundant than their larger counterparts (Alonso-Vázquez et al., 2023; Pivokonsky et al., 2018).

The potential health hazards of these plastics are a focus of intense scientific scrutiny (Lei et al., 2024; Park and Park, 2021). NPs, in particular, are of high concern due to their ability to penetrate biological barriers, such as cell membranes, and translocate into the bloodstream, lymphatic system, and vital organs (Holloczki and Gehrke, 2019; Ng et al., 2018; Zhu et al., 2018). Ingestion of MPs and NPs may lead to adverse health outcomes, including impaired nutrient absorption, gastrointestinal disturbances, and chronic inflammation (Holloczki and Gehrke, 2019; Roy et al., 2023; Stapleton, 2021). For instance, polystyrene (PS) MPs have been demonstrated to induce intestinal inflammation and disrupt red blood cells (Jin et al., 2019; Peng et al., 2019; Roy et al., 2023; Xu et al., 2024). Furthermore, MPs and NPs can act as vectors for other environmental toxins, such as heavy metals and persistent organic pollutants, by adsorbing them onto their surfaces and amplifying their toxicity upon ingestion (An et al., 2024; Kumar et al., 2022; Naqash et al., 2020).

Conventional drinking water treatment trains—typically comprising coagulation, sedimentation, filtration, and disinfection—were not designed to address MP and NP contamination and thus exhibit significant limitations (Acarer, 2023; Barbier et al., 2022; Z. F. Wang et al., 2020; Xu, 2020). While effective at removing larger MPs (>20 µm), their efficiency declines sharply for smaller particles and is particularly low for NPs (Na et al., 2021). This inefficiency is rooted in the physicochemical properties of smaller plastics, whose high surface area-to-volume ratio enhances their colloidal stability and resistance to removal (Ivleva et al., 2017; Park and Park, 2021). Consequently, the entire conventional process faces overarching challenges, including suboptimal removal efficiency for NPs, the risk of secondary contamination from treatment chemicals, prohibitive operational costs for advanced methods, and a lack of selectivity for diverse plastic types (Lei et al., 2024; Park and Park, 2021).

Therefore, developing materials and strategies specifically engineered for MP and NP removal from drinking water is a pressing priority. Although numerous reviews have covered MP/NP removal in the context of wastewater treatment, a dedicated and systematic review focusing on drinking water systems is conspicuously absent. Existing literature provides limited insight and fails to adequately categorize and evaluate the growing arsenal of novel materials for this specific application. To bridge this critical gap, this review examines the application of emerging materials for MP and NP removal in drinking water treatment. We concentrate on novel material categories, including biomass-derived adsorbents, advanced membranes, photothermal materials, electroactive materials, and multifunctional composites. This review aims to: (1) elucidate the design principles and underlying removal mechanisms of these materials; (2) compare their structural features and functional properties to foster a deeper understanding of their performance; and (3) provide a critical assessment of the advantages and limitations of each material class. Finally, we identify key challenges and propose future research directions in this vital field.

2 Novel Materials for the Removal of MPs and NPs

2.1 **Biomass-derived Adsorbents**

Biomass-derived adsorbents have emerged as a highly promising class of materials for aqueous MP and NP remediation, prized for their sustainability, low cost, and impressive adsorption capabilities (Liu et al., 2024; Qiana et al., 2024; Wu et al., 2024; Wu et al., 2024). Natural polymers such as chitin, cellulose, and their derivatives are particularly advantageous, featuring abundant surface functional groups and inherently hierarchical porous structures that facilitate efficient pollutant capture.

2.1.1 Material Design and Performance

The design of these adsorbents often leverages the unique properties of pristine or modified biopolymers. Chitin, the second most abundant polysaccharide in nature, is a prime example. Recent innovations have focused on engineering its structure to maximize MP/NP interaction. For instance, Wu et al. (2024) developed a novel chitin nanofibrous foam (β/α-CT) from seafood waste. Through a simple process of hydrogen bond rearrangement, they created a material with a hierarchical porous architecture capable of removing MPs across a wide size range (80 nm–5 µm) with exceptional efficiency (e.g., 98.7% for 80 nm particles).

To further enhance performance and versatility, researchers have explored the creation of biopolymer composites. Sun et al. (2020) developed a robust chitin/graphene oxide (GO) sponge that demonstrated excellent reusability. In a subsequent breakthrough, Wu et al. (2024) fabricated a self-assembled chitin-cellulose (Ct-Cel) foam from squid-derived β-chitin and cotton cellulose. This composite material showcased remarkable removal efficiency (98.0–99.9%) for various MPs (PS, polymethyl methacrylate (PMMA), polyethylene terephthalare (PET), polypropylene (PP)) in real water samples and maintained over 95% efficiency after five regeneration cycles. As summarized in Table 1, these materials achieve high adsorption capacities, particularly for smaller particles, underscoring their potential for treating nano-scale contamination.

Table 1. Performance of representative biomass-derived adsorbents for MP/NP removal

Adsorbent material	Key features	Target pollutants (Size, Type)	Adsorption capacity (mg g^{-1})	Removal efficiency (%)	Reference
Chitin/GO Sponge	Robust, porous, reusable	PS variants (size not specified)	Not reported	89.8% (after 3 cycles)	Sun et al. (2020)
β/α-CT Foam	Hierarchical pores, functional groups (–OH, –NHCO–)	PS (80 nm–5 µm)	411 (for <1 µm PS)	98.7% (for 80 nm PS)	Wu et al. (2024)
Ct-Cel Foam	Positively charged, porous (97%), cross-linker-free	PS, PMMA, PET, PP (100 nm–3 µm)	349.7 (100 nm PS)-633.2 (3 µm PS)	98.0–99.9% (in real water)	Wu et al. (2024)

Note: GO: graphene oxide; Ct-Cel: chitin-cellulose; CT: chitin; PS: polystyrene; PMMA: polymethyl methacrylate; PET: polyethylene terephthalare; PP: polypropylene;

2.1.2 Multi-level Removal Mechanisms

The efficacy of these biomass adsorbents stems from a synergistic combination of physical and chemical interactions, as illustrated in Figure 1.

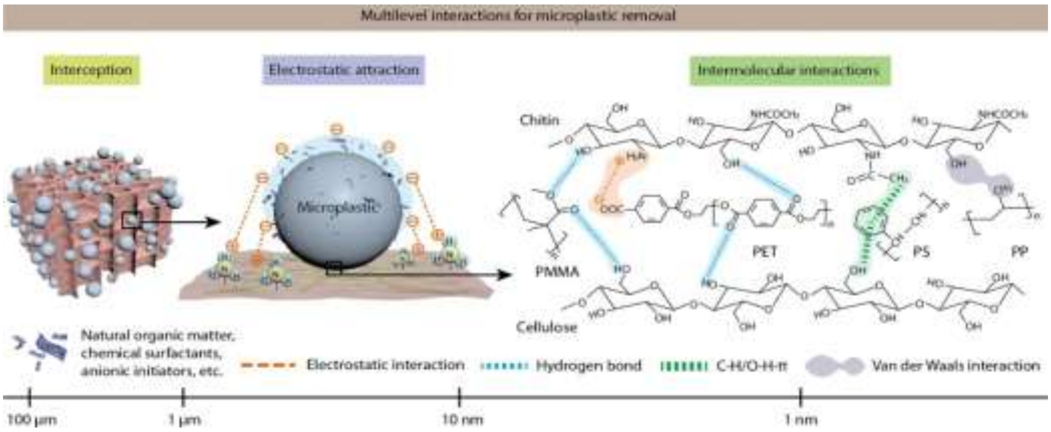

Figure 1 Microplastic removal by the biomass fibrous foam

MP removal by the biomass fibrous foam via multilevel interactions (physical interception, electrostatic attraction, and multiple intermolecular interactions) due to the abundance of reactive functional groups

The primary mechanisms include:

1. Physical interception and sieving: the multi-scale porous structure physically traps larger MPs, with removal efficiency often increasing with particle size.
2. Electrostatic attraction: materials like the Ct-Cel foam are engineered to have a positive surface charge (e.g., from protonated amine groups, $–NH_3^+$), which strongly attracts common, negatively charged MPs (like PS).
3. Hydrogen bonding: abundant hydroxyl (–OH) and amide (–NHCO–) groups on the biopolymer chains act as hydrogen bond donors and acceptors, forming strong connections with polar MPs containing ester or carboxyl groups (e.g., PET, PMMA).
4. Van der Waals (vdW) and π-Interactions: these forces are crucial for adsorbing nonpolar plastics (e.g., PP) and those with aromatic rings (e.g., PS), where C–H···π or O–H···π interactions can occur.

Computational studies have validated these synergistic effects, confirming that a combination of strong vdW forces and hydrogen bonding governs the adsorption process, making these materials effective against a broad spectrum of plastic types.

2.1.3 Challenges and Future Outlook

Despite these promising advancements, practical application of biomass-derived adsorbents faces several hurdles. Key challenges include ensuring long-term structural stability in dynamic flow systems, improving selective adsorption in complex water matrices containing natural organic matter, and developing scalable and cost-effective manufacturing processes to move from the laboratory to industrial production (Lee et al., 2018; Su et al., 2024; Verma et al., 2024; Wang, 2023). Future research should therefore focus on optimizing material durability, enhancing selectivity through targeted surface functionalization, and designing efficient regeneration techniques to support a circular economy approach.

2.2 **Membrane separation for MPs and NPs Removal in Drinking Water Treatment**

Membrane separation technology serves as a formidable physical barrier in water treatment, offering precise size-exclusion capabilities that are highly effective for removing MPs and NPs (Acarer, 2023; Bodzek and Pohl, 2023; Li et al., 2023; Luogo et al., 2022). Unlike conventional methods, pressure-driven membrane processes, including microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO), can provide a more absolute barrier to these contaminants, with performance being intrinsically linked to the membrane's material and structural properties (Table 2).

Table 2 Membrane separation for MPs and NPs removal in tap water treatment

Membrane yype	Treatment plant type/Location	material	Pore size range	Operating pressure	Removal efficiency		Main advantages	Main limitations	Reference
					MP	NP			
MF	Laboratory	PVDF,PC,CA, PTFE,SiC	0.1-10 μm	1-5 bar	81.5-99.8 %	20-44 %	Low energy, high flux	Limited removal of small particles	Pramanik et al., 2021 Pizzichetti et al., 2021
UF	Laboratory	PES,SiC and ZrO_2,PVDF	1-100 nm	1-10 bar	96-100 %	74 %	Balanced removal & flux	Severe membrane fouling	Luogo et al., 2022 Ma et al., 2019

NF	DWTP/France	polypiperazine-amide and PSf	1-10 nm	5-20 bar	99-100 %	92-98.6%	Removal of multivalent ions	High energy, high cost	Barbier et al., 2022
RO	DWTP/Spain	-	~1 nm	10-100 bar	54±27%	95-100 %	Comprehensive removal	Highest energy, susceptibility to	Abdel-Fatah, 2018 Dalmau-So et al., 2021
MBR	-	-	Depends on membrane	0.5-3 bar	Highly efficient		Biological & physical synergy	High investment & operatin	Li et al., 2023 Pizzichetti et al., 2021

Note: MF: microfiltration; UF: ultrafiltration; NF:nanofiltration; RO: reverse osmosis; MBR: membrane bioreactor; DWTP: drinking water treatment plant; ZrO_2: zirconia; SiC: silicon carbide; PVDF: polyvinylidene fluoride; PES: polyethersulfone; PA: polyamide.

2.2.1 Membrane Materials: from Conventional Polymers to Advanced Composites

The choice of material is fundamental to membrane performance. Polymeric membranes, fabricated from compounds like polyvinylidene fluoride (PVDF), polyethersulfone (PES), and polyamide (PA), dominate the market due to their relatively low production cost and processability (Alvi et al., 2019; Gebru and Das, 2017; Yin et al., 2022). However, they are often susceptible to chemical degradation and fouling.

In contrast, inorganic (ceramic) membranes, typically made from materials such as alumina (Al_2O_3), zirconia (ZrO_2), or silicon carbide (SiC), offer superior thermal, chemical, and mechanical stability (He et al., 2019; Hofs et al., 2011). Their high hydrophilicity can lead to higher water flux, and their narrow pore size distribution enhances separation efficiency. Despite a longer operational lifespan (>10 years), the inherent brittleness and high manufacturing cost of ceramic membranes have limited their widespread adoption in municipal drinking water treatment plants (DWTPs).

To bridge this gap, a major research thrust is the development of polymer-based nanocomposite membranes. This strategy involves embedding small quantities of inorganic nanomaterials into a polymer matrix, aiming to synergistically combine the cost-effectiveness of polymers with the enhanced stability and performance of ceramics (Nikita et al., 2019; Polisetti and Ray, 2021; Poon et al., 2023). This approach represents a critical frontier in developing next-generation membranes with high flux, selectivity, and fouling resistance.

2.2.2 Performance of Pressure-Driven Membrane Processes

As summarized in Table 2, the removal efficiency of membrane processes is primarily dictated by pore size, creating a clear trade-off between contaminant removal and energy consumption.

- Microfiltration (MF), with the largest pores (0.1–10 µm), effectively removes the bulk of larger MPs (>81.5%) but demonstrates limited efficacy for NPs (<44%) (Pramanik et al., 2021). Its primary vulnerability is the potential for sharp-edged or flexible MPs to penetrate the membrane pores under pressure (B. D. P. Luogo et al., 2022; Pizzichetti et al., 2021).
- Ultrafiltration (UF) offers a significant improvement, with pore sizes (1–100 nm) small enough to retain nearly all MPs (>96%) and a moderate fraction of NPs (B. Ma et al., 2019). However, this enhanced retention comes at the cost of increased susceptibility to fouling, where MPs can block pores and drastically increase transmembrane pressure, often necessitating pre-treatment like coagulation to aggregate particles for easier removal (Li et al., 2021; Luogo et al., 2022).
- Nanofiltration (NF) and Reverse Osmosis (RO) represent the tightest membrane barriers. With pore sizes in the low nanometer range, they can theoretically achieve near-complete removal of both MPs and NPs (Barbier et al., 2022). However, their application is constrained by substantial energy

requirements, increasing treatment costs by 60–150% (Abdel-Fatah, 2018). Furthermore, full-scale plant studies have shown counterintuitive results; one DWTP using RO reported only 54±27% MP removal, potentially due to the longitudinal penetration of fibrous MPs through membrane seals or defects, a challenge not observed in lab-scale tests (Dalmau-Soler et al., 2021).

2.2.3 Hybrid Systems: Membrane Bioreactors (MBR)

MBR systems integrate biological treatment with membrane filtration (typically MF or UF), offering a synergistic approach to removal. The biofilm developed in the reactor can enhance retention by capturing MPs that might otherwise pass through the membrane, leading to very high removal efficiencies (>96.8%) (Li et al., 2023; Pizzichetti et al., 2021). The primary drawbacks are the high operational costs and the issue of secondary pollution, as the retained MPs become concentrated in the sewage sludge, which requires careful disposal (Aslam et al., 2022).

2.2.4 The Overarching Challenge: Membrane Fouling

Across all membrane types, fouling remains the most significant operational barrier. The accumulation of MPs and other substances on the membrane surface or within its pores reduces water flux, increases energy consumption, and necessitates frequent chemical cleaning. This cleaning regimen (e.g., using NaOH, NaClO) not only adds to operational costs but also degrades the membrane material over time, shortening its effective lifespan by 30–50% and compromising long-term performance (Gan et al., 2021). Developing novel anti-fouling materials and strategies is therefore paramount for the sustainable application of membrane technology in water treatment.

2.3 Solar-Driven Photothermal Removal

Leveraging sunlight as its sole energy source, solar-driven photothermal evaporation has emerged as a sustainable and energy-efficient technology for water purification, particularly for removing non-volatile contaminants like MPs and NPs (Cui et al., 2023). Its operational simplicity and independence from external power grids make it highly suitable for decentralized drinking water treatment in remote or resource-limited settings (Zhang et al., 2025).

2.3.1 Principle of Solar-Driven Separation

The core of this technology is phase-change separation. Water is selectively evaporated at a photothermally-active interface, leaving MPs, NPs, salts, and other contaminants behind. As illustrated in Figure 2, several synergistic mechanisms ensure the retention of plastic particles:

1. Size Exclusion: At the most fundamental level, MPs and NPs are physically blocked from entering the vapor phase due to their immense size relative to water molecules.
2. Surface Phenomena: The hydrophobic nature of most plastics creates an energy barrier (driven by surface tension) that opposes their transition across the liquid-air interface.
3. Thermophoresis: The intense, localized heating of the photothermal material creates a steep temperature gradient, driving particles to migrate away from the hot evaporation zone toward the cooler bulk water below (Rekha et al., 2022).
4. Crystalline Encapsulation: In hard water, the precipitation of minerals like $CaCO_3$ can physically entrap MPs and NPs within the crystal lattice, effectively immobilizing them and preventing their escape (Ding et al., 2023).

Collectively, these mechanisms enable solar evaporators to achieve high removal efficiencies (>90%) for a broad range of MP and NP sizes.

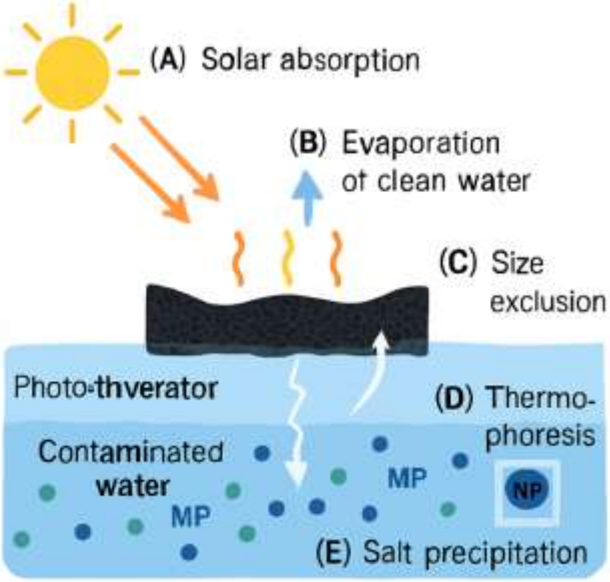

Figure 2. Schematic of solar-driven photothermal evaporation for MP/NP Removal
A solar-driven evaporator, composed of a porous photothermal material, floats on contaminated water. (A) Incoming sunlight is absorbed, generating localized heat. (B) Clean water evaporates from the surface, leaving contaminants behind. The removal is facilitated by multiple mechanisms: (C) Physical size exclusion at the liquid-vapor interface, (D) thermophoretic forces pushing particles toward the cooler bulk liquid, and (E) encapsulation of particles within precipitating salt crystals.

2.3.2 Advanced Photothermal Materials and Structures

The efficiency of solar evaporation is critically dependent on the light-absorbing materials and their architecture. Research is focused on several key categories:

Materials:

- Carbon-based materials: Graphene, carbon nanotubes (CNTs), and biochar are favored for their broad-spectrum light absorption, excellent thermal conductivity, and low cost (Li et al., 2021).
- Plasmonic metals: Nanoparticles of gold (Au) or silver (Ag) exhibit surface plasmon resonance, leading to intense and highly efficient localized heating (Chang et al., 2023).
- Semiconductors: Materials like MoS_2 or TiC offer tunable band gaps for optimized light absorption. Some, like TiO_2, can also provide photocatalytic functions (Chang et al., 2023).
- Conductive polymers: Polypyrrole (PPy) and polyaniline (PANI) are promising due to their cost-effectiveness, flexibility, and ease of processing (Chang et al., 2023).

Structural Designs:

- Porous architectures: Increase the surface area for evaporation and facilitate water transport.
- Graded structures: Help to minimize heat loss to the underlying bulk water, concentrating thermal energy at the evaporation surface.
- Janus surfaces: These are asymmetric surfaces (e.g., hydrophilic on the bottom for water wicking, hydrophobic on top to prevent fouling) that enhance evaporation while resisting the accumulation of salt and MPs.

2.3.3 System Performance and Integration

Optimized solar-driven systems have demonstrated exceptional performance, achieving >95% removal efficiency for both MPs and NPs while simultaneously removing co-pollutants like heavy metals and organic dyes. Practical water production rates of 1.5–2.5 $L/(m^2 \cdot h)$ under standard 1-sun illumination (1 kW/m^2) have been reported, sufficient for meeting household drinking water needs (Cui et al., 2023).

Recent studies showcase advanced system designs. For example, Ouyang et al. (2025) developed a 3D solar evaporator from biomass (starch, cuttlefish ink, carbonized bamboo) that achieved a high evaporation rate of 3.31 kg m^{-2}h^{-1} while preventing salt accumulation. In a hybrid approach, Meng et al. (2021) created a reactor using a reduced graphene oxide/titanium dioxide (rGO/TiO$_2$) composite that not only removed 97.9% of PE MPs but also photocatalytically converted them into valuable chemicals like formic acid. Such integrated systems, which combine evaporation with adsorption or photocatalysis, can offer enhanced purification and even resource recovery.

2.3.4 Challenges and Future Directions

Despite significant progress, scaling this technology for widespread use presents challenges. Ensuring long-term operational stability, especially against fouling from biological matter or high salt concentrations, remains a primary concern. The potential environmental impact and lifecycle of some advanced nanomaterials must also be rigorously assessed (Zhao et al., 2020).

Future research should prioritize the development of durable, low-cost, and eco-friendly photothermal materials derived from sustainable sources. Optimizing system design to minimize heat loss and integrating these systems with self-cleaning or anti-fouling mechanisms are crucial next steps. With continued innovation, solar-driven purification holds immense promise as a resilient and sustainable solution to the global challenge of MP and NP contamination in drinking water.

2.4 Innovative Applications of Electrochemical Technology in MP/NP removal

Electrochemical technologies are emerging as a powerful and highly controllable approach for MP and NP remediation in drinking water. Their primary advantage lies in using electron-driven reactions to degrade or aggregate contaminants, minimizing the need for chemical additives and reducing the risk of secondary pollution (Chen et al., 2022; Say, 2022).

2.4.1 Core Electrochemical Mechanisms

The removal of MPs and NPs in electrochemical systems is governed by several distinct mechanisms, as illustrated in Figure 3:

1. Direct Oxidation: In this process, the MP or NP particle directly contacts the anode and undergoes electron transfer, leading to the scission of its polymer chains. This requires a high anode potential but offers a direct degradation pathway.
2. Indirect Oxidation: This is often the dominant mechanism, where the system uses water or other ions in the solution to generate highly reactive species. At the anode, water is oxidized to form powerful hydroxyl radicals (·OH), or other radicals (e.g., SO$_4^{-}$·, Cl·) are generated, which then attack and degrade the plastic particles in the bulk solution (Cai et al., 2024).
3. Electro-sorption: This non-destructive mechanism leverages electrostatic forces. By applying a specific voltage, an electrode (typically a high-surface-area material like activated carbon) can be given a surface charge that attracts and adsorbs oppositely charged MPs or NPs. Xiong et al. (2020) demonstrated this by using activated carbon electrodes to achieve a high adsorption capacity of 0.707 g g^{-1} for negatively charged polystyrene NPs.

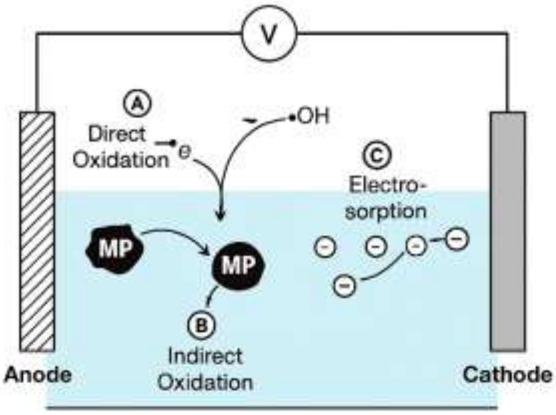

Figure 3. Schematic of key electrochemical mechanisms for MP/NP removal

An electrochemical cell showing different removal pathways. (A) Direct Oxidation: An MP particle directly transfers an electron to the anode surface. (B) Indirect Oxidation: Water is oxidized at the anode to produce a hydroxyl radical (·OH), which then attacks an MP particle in the solution. (C) Electro-sorption: A positively charged electrode electrostatically attracts and adsorbs negatively charged NPs.

2.4.2 Key Electrode Materials

The success of these mechanisms is fundamentally dictated by the choice of electrode material (Table 3).

- Boron-doped diamond (BDD) electrodes are considered the "gold standard" due to their exceptional chemical stability, wide potential window, and high efficiency in generating ·OH radicals. Lu et al. (2022) showed that BDD anodes could degrade over 40% of PS MPs via indirect oxidation. However, their high cost is a major barrier.
- Metal oxide electrodes, such as antimony-doped tin oxide (SnO_2-Sb) and lead dioxide (PbO_2), provide more cost-effective alternatives with robust catalytic activity.
- Innovative composite electrodes are being designed to enhance specific reactions. For example, Miao et al. (2020) developed a TiO_2/graphite composite cathode that facilitated an electro-Fenton process, achieving 75% dechlorination of PVC by generating H_2O_2 in situ.

2.4.3 Advanced system designs and hybrid approaches

Moving beyond simple plate electrodes, advanced reactor designs and hybrid systems are being developed to boost efficiency:

- 3D electrochemical systems, which use particle electrodes or packed beds, significantly increase the active surface area and improve mass transfer between the contaminants and the electrodes. A system using tourmaline particle electrodes enhanced PVC degradation by creating more reaction interfaces (Zheng, 2022).
- Hybrid systems integrate electrochemistry with other technologies for synergistic effects. Electro-Fenton systems, which combine H_2O_2 generation at the cathode with Fe^{2+} catalysis, are particularly effective, with one study reporting 86.8% PS degradation in just 40 minutes (Kiendrebeogo et al., 2021). Other promising hybrids include photoelectrocatalysis (using light to boost radical generation) and ultrasonic-assisted electrolysis (using sound waves to improve particle dispersion). These advanced systems have achieved >95% MP removal in lab settings with practical energy consumption rates (0.5–1.5 kWh/m^3).

Table 3. Performance of representative electrochemical systems for MP/NP removal

Electrochemical system	Electrode material(s)	Target MP/NP	Key performance metric	Reference
Anodic Oxidation	BDD	PS	>40% degradation in 72 h	Lu et al., 2022
Electro-Fenton	TiO_2/graphite cathode	PVC	75% dechlorination in 6 h	Miao et al., 2020
Electro-sorption	AC	PS	0.707 $g\ g^{-1}$ adsorption capacity	Xiong et al., 2020
3D Electrochemical System	Ti/RuO_2-IrO_2 cathode, tourmaline particles	PVC	51.9% degradation in 12 h	Zheng, 2022
Hybrid Electro-Fenton	Not specified	PS	86.8% degradation in 40 min	Kiendrebeogo et al., 2021

Note: BDD: boron-doped diamond; AC: activated carbon; PS: polystyrene; PVC: polyvinyl chloride;

2.4.4 Challenges and future outlook

Despite their high efficiency, significant hurdles remain for the large-scale application of electrochemical technologies in drinking water treatment. Key challenges include the high cost and long-term stability of electrode materials like BDD, the potential formation of harmful disinfection byproducts (e.g., chlorinated organics) in certain water matrices, and reduced efficiency due to interference from natural dissolved organic matter.

Future research must focus on developing low-cost, durable, and eco-friendly electrode materials (e.g., modified biochar or non-noble metal catalysts). Optimizing reactor designs for continuous-flow operation and integrating electrochemical stages with conventional filtration or adsorption processes will be crucial for creating robust, multi-barrier treatment trains. Addressing these challenges will be essential to transition electrochemical technologies from promising lab-scale demonstrations to practical and reliable solutions for safeguarding drinking water.

3. Comparative assessment and future perspectives

The preceding sections have systematically reviewed four distinct classes of emerging technologies for the remediation of MPs and NPs. While each approach demonstrates considerable potential, a holistic and critical assessment is required to contextualize their respective advantages and to identify the shared barriers that currently impede their transition from laboratory curiosities to viable, full-scale treatment solutions. This chapter presents a comparative evaluation of these technologies, elucidates the overarching challenges to their practical implementation, and proposes strategic directions for future research.

3.1. Comparative Evaluation of Novel Technologies

A direct comparison of the four technology platforms reveals a series of fundamental trade-offs between removal efficacy, energy consumption, cost, and technological maturity, as summarized in Table 4.

Table 4. A comparative matrix of novel MP/NP removal technologies

Technology category	MP removal	NP removal	Energy consumption	Cost (Capital & Operations)	Scalability / TRL*	Core advantage	Key limitation
Biomass adsorption	High	Medium-High	Very Low	Very Low	Medium	Sustainable; low-cost	Finite capacity; regeneration
Membrane separation	Very high	Medium-very High	Medium-High	High	High	Proven physical barrier	Fouling; energy intensity
Solar-driven systems	High	High	None	Medium-High	Low	Zero operational energy	Intermittency; material stability
Electrochemical technology	High	High	High	High	Low-Medium	High efficiency; destructive	Cost; energy; byproduct formation

Note: *TRL: technology readiness level

Pressure-driven membrane separation, particularly NF and RO, stands out for its high Technology Readiness Level (TRL) and its capacity to serve as a reliable physical barrier to nearly all plastic particulates. This high efficiency, however, is intrinsically linked to significant energy demands and the persistent operational challenge of membrane fouling. Similarly, advanced electrochemical oxidation can achieve high degradation rates but is presently constrained by the high capital cost and limited operational lifespan of high-performance electrode materials.

Conversely, biomass adsorption and solar-driven processes epitomize a paradigm of sustainability and low operational cost. Biomass-derived adsorbents are notable for their low cost and derivation from renewable resources, yet their utility is circumscribed by finite adsorption capacities and challenges associated with material regeneration. Solar-driven systems offer the compelling advantage of zero-energy input but remain at a low TRL, with performance contingent on climatic conditions and unresolved questions regarding the long-term stability of photothermal materials.

3.2. Overarching Challenges to Practical Implementation

Beyond their individual limitations, all these emerging technologies confront a set of common, formidable challenges that must be addressed to enable their practical application in drinking water treatment.

3.2.1. Scalability and Complex Water Matrices

A significant gap persists between performance in controlled laboratory settings and that in real-world operational environments. Firstly, scalability remains a critical barrier; the cost-effective fabrication of advanced materials at the scale required for municipal water treatment is a major engineering hurdle. Secondly, the vast majority of published studies utilize idealized water matrices. The performance in real drinking water—a complex aqueous solution containing natural organic matter (NOM), inorganic ions, and microorganisms—is often substantially lower due to phenomena such as competitive adsorption, surface passivation, and catalyst poisoning.

3.2.2. Long-term operational stability and durability

The operational lifespan of these novel materials is a crucial yet underexplored aspect. Most research is confined to short-term experiments, offering limited insight into the materials' long-term stability. The physicochemical integrity and performance degradation of these materials under continuous operation, including exposure to hydraulic stress and chemical cleaning regimens, must be systematically investigated to determine their true life cycle and economic feasibility.

3.2.3. Ultimate Fate and Potential for Secondary Pollution

A critical consideration is the ultimate environmental fate of the removed MPs and NPs.

- Non-degradative technologies (adsorption, membrane filtration) concentrate the pollutants into a secondary waste stream (e.g., saturated adsorbent, membrane concentrate). The management and disposal of this contaminated stream pose a significant challenge, with a risk of re-releasing pollutants into the environment.
- Degradative technologies (solar-driven, electrochemical) raise concerns about incomplete mineralization. The formation of potentially more hazardous or bioavailable transformation byproducts must be rigorously investigated to ensure that the treatment process does not inadvertently increase the overall toxicity of the water.

3.3. Strategic Directions for Future Research

To bridge the gap between current potential and future application, research efforts should be strategically focused on the following areas:

3.3.1. Advanced Material Development

Future work should prioritize the design of multifunctional materials that integrate complementary processes, such as adsorption and subsequent in-situ catalytic degradation. A strong emphasis should be placed on developing materials from sustainable and low-cost precursors (e.g., waste biomass, earth-abundant metals) and engineering anti-fouling or self-cleaning surfaces to enhance operational durability.

3.3.2. System Integration and Hybrid Processes

Rather than viewing these technologies as standalone solutions, future research should explore their role within hybrid systems. Integrating a novel process as a pre-treatment or polishing step within a conventional treatment train may offer the most pragmatic path to implementation. Concurrently, the establishment of standardized testing protocols is urgently needed to enable meaningful and direct comparison of performance data across different studies.

3.3.3. Environmental Safety and Life Cycle Assessment

A comprehensive evaluation of the most promising technologies requires a Life Cycle Assessment (LCA) to quantify their overall environmental footprint. Furthermore, a dedicated research focus on the toxicological assessment of transformation byproducts generated during degradation processes is essential to guarantee the biological safety of the treated effluent.

4. Conclusion

The escalating contamination of global water resources by micro- and nanoplastics constitutes a significant environmental and public health challenge. The novel materials and technologies surveyed in this review—spanning biomass adsorption, advanced membrane separation, solar-driven systems, and electrochemical processes—represent significant advancements in the scientific effort to address this issue. While their potential is undeniable, their pathway to practical application is contingent upon resolving critical challenges related to scalability, long-term stability, and the management of secondary pollutants.

The ultimate solution will likely not be a single, monolithic technology but rather the strategic integration of multiple processes into robust, multi-barrier treatment frameworks. Advancing this field requires a concerted, multidisciplinary effort focused on developing materials that are not only highly efficient but also sustainable, cost-effective, and demonstrably safe over their entire life cycle. Through such a strategic approach, the innovations of materials science can be effectively translated into tangible technologies that protect the integrity of our global drinking water supply.

Compliance with ethical standards

The author hereby confirms that this research complies with all applicable ethical standards and guidelines.

Conflict of interest

The author declares no potential or actual conflicts of interest concerning the research, authorship, and publication of this study.

Author contributions

Jun Yang performed formal analysis, investigation, and project administration, while also contributing to resources, visualization, and the original draft. Yueya Chang was responsible for conceptualization, data curation, investigation, software implementation, and resources, as well as taking the lead in manuscript preparation, revision, and editing.

Funding

The author declares that no funds, grants, or other support were received during the preparation of this manuscript.

References

1. Abdel-Fatah, M. A. (2018). Nanofiltration Systems and Applications in Wastewater Treatment: Review Article. *Ain Shams Engineer Journal, 9*(4), 3077-3092. doi:10.1016/j.asej.2018.08.001
2. Acarer, S. (2023). A Review of Microplastic Removal from Water and Wastewater by Membrane Technologies. *Water Science and Technology, 88*(1), 199-219. doi:10.2166/wst.2023.186
3. Alonso-Vázquez, P., Luján-Facundo, M.-J., Cuartas-Uribe, B., Bes-Piá, A., Alonso-Molina, J.-L., and Mendoza-Roca, J.-A. (2023). Advances in Analysis of Microplastics in Drinking Water Treatment Plants. Fluorescence Techniques Using Idye Pink. *Environmental Technology and Innovation, Vol.32*, 103430. doi:10.1016/j.eti.2023.103430
4. Alvi, M., Khalid, M. W., Ahmad, N. M., Niazi, M. B. K., Anwar, M. N., Batool, M., Cheema, W., and Rafiq, S. (2019). Polymer Concentration and Solvent Variation Correlation with the Morphology and Water Filtration Analysis of Polyether Sulfone Microfiltration Membrane. *Advances in Polymer Technology, 2019*. doi:10.1155/2019/8074626
5. An, Q., Wen, C., and Yan, C. (2024). Meta-Analysis Reveals the Combined Effects of Microplastics and Heavy Metal on Plants. *Journal of Hazardous Materials, 476*. doi:10.1016/j.jhazmat.2024.135028
6. Aslam, A., Khan, S. J., and Shahzad, H. M. A. (2022). Anaerobic Membrane Bioreactors (Anmbrs) for Municipal Wastewater Treatment- Potential Benefits, Constraints, and Future Perspectives: An Updated Review. *Science of the Total Environment, 802*, 149612. doi:https://doi.org/10.1016/j.scitotenv.2021.149612
7. Barbier, J. S., Dris, R., Lecarpentier, C., Raymond, V., Delabre, K., Thibert, S., Tassin, B., and Gasperi, J. (2022). Microplastic Occurrence after Conventional and Nanofiltration Processes at Drinking Water Treatment Plants: Preliminary Results. *Frontiers in Water, 4*. doi:10.3389/frwa.2022.886703
8. Bodzek, M., and Pohl, A. (2023). Possibilities of Removing Microplastics from the Aquatic Environment Using Membrane Processes. *Des*

alination and Water Treatment, 288, 104-120. doi:10.5004/dwt.2023.29154

9. Bourzac, K. (2019). Estimating Microplastic Consumption. *Chemical & Engineering News, 97*(23), 10-10. DOI: 10.1021/cen-09723-scicon6
10. Cai, C., Gong, Y., Fotouhi, A., and Auger, D. J. (2024). A Novel Hybrid Electrochemical Equivalent Circuit Model for Online Battery Management Systems. *Journal of Energy Storage, 99*. doi:10.1016/j.est.2024.113142
11. Chai, R., Zhang, X., Xu, C., Wang, Y., Pan, L., Wang, B., and Duan, H. (2021). Distribution of Microplastics in Drinking Water in Qingdao. *Journal of Shandong University (Health Sciences), 59*(12), 58-62.
12. Chang, C., Yang, S., Liu, S., Wang, H., Liu, H., Qu, J., Jin, W., Wang, C., and Chen, Y. (2023). Energy-Efficient and Green Extraction of Bismuth Metal in Methanesulfonic Acid-Based Membrane Electrochemical Systems. *Acs Sustainable Chemistry and Engineering, 11*(20), 7851-7862. doi:10.1021/acssuschemeng.3c00899
13. Chen, Z., Wei, W., Liu, X., and Ni, B.-J. (2022). Emerging Electrochemical Techniques for Identifying and Removing Micro/Nanoplastics in Urban Waters. *Water Research, 221*. doi:10.1016/j.watres.2022.118846
14. Cui, L., Wang, P., Che, H., Chen, J., Liu, B., and Ao, Y. (2023). Solar-Driven Interfacial Water Evaporation for Wastewater Purification: Recent Advances and Challenges. *Chemical Engineering Journal, 477*. doi:10.1016/j.cej.2023.147158
15. Dalmau-Soler, J., Ballesteros-Cano, R., Boleda, M. R., Paraira, M., Ferrer, N., and Lacorte, S. (2021). Microplastics from Headwaters to Tap Water: Occurrence and Removal in a Drinking Water Treatment Plant in Barcelona Metropolitan Area (Catalonia, Ne Spain). *Environmental Science and Pollution Research, 28*(42), 59462-59472. doi:10.1007/s11356-021-13220-1
16. Ding, S., Zhang, T., Wu, M., and Wang, X. (2023). Photothermal Dual-Layer Hydrophilic/Hydrophobic Composite Nanofibrous Membrane for Efficient Solar-Driven Membrane Distillation. *Journal of Membrane Science, 680*. doi:10.1016/j.memsci.2023.121740
17. Gan, X., Lin, T., Jiang, F., and Zhang, X. (2021). Impacts on Characteristics and Effluent Safety of Pvdf Ultrafiltration Membranes Aged by Different Chemical Cleaning Types. *Journal of Membrane Science, 640*. doi:10.1016/j.memsci.2021.119770
18. Gebru, K. A., and Das, C. (2017). Effects of Solubility Parameter Differences among Peg, Pvp and Ca on the Preparation of Ultrafiltration Membranes: Impacts of Solvents and Additives on Morphology, Permeability and Fouling Performances. *Chinese Journal of Chemical Engineering, 25*(7), 911-923. doi:10.1016/j.cjche.2016.11.017
19. Gerdes, Z., Ogonowski, M., Nybom, I., Ek, C., Adolfsson-Erici, M., Barth, A., and Gorokhova, E. (2019). Microplastic-Mediated Transport of Pcbs? A Depuration Study with <I>Daphnia Magna</I>. *Plos One, 14*(2). doi:10.1371/journal.pone.0205378
20. He, Z. M., Lyu, Z. Y., Gu, Q. L., Zhang, L., and Wang, J. (2019). Ceramic-Based Membranes for Water and Wastewater Treatment. *Colloids and Surfaces A-physicochemical and Engineering Aspects, 578*. doi:10.1016/j.colsurfa.2019.05.074
21. Hofs, B., Ogier, J., Vries, D., Beerendonk, E. F., and Cornelissen, E. R. (2011). Comparison of Ceramic and Polymeric Membrane Permeability and Fouling Using Surface Water. *Separation and Purification Technology, 79*(3), 365-374. doi:10.1016/j.seppur.2011.03.025
22. Holloczki, O., and Gehrke, S. (2019). Nanoplastics Can Change the Secondary Structure of Proteins. *Scientific Reports 9*. doi:10.1038/s41598-019-52495-w
23. Ivleva, N. P., Wiesheu, A. C., and Niessner, R. (2017). Microplastic in Aquatic Ecosystems. *Angewandte Chemie-International Edition, 56*(7), 1720-1739. doi:10.1002/anie.201606957
24. Jamieson, A. J., Brooks, L. S. R., Reid, W. D. K., Piertney, S. B., Narayanaswamy, B. E., and Linley, T. D. (2019). Microplastics and Synthetic Particles Ingested by Deep-Sea Amphipods in Six of the Deepest Marine Ecosystems on Earth. *Royal Society Open Science, 6*(2).doi:10.1098/rsos.180667
25. Jin, Y., Lu, L., Tu, W., Luo, T., and Fu, Z. (2019). Impacts of Polystyrene Microplastic on the Gut Barrier, Microbiota and Metabolism of Mice. *Science of the Total Environment, 649*, 308-317. doi:10.1016/j.scitotenv.2018.08.353
26. Ju, H., Yang, X., Osman, R., and Geissen, V. (2023). The Role of Microplastic Aging on Chlorpyrifos Adsorption-Desorption and Micropl

astic Bioconcentration. *Environmental Pollution, 331*. doi:10.1016/j.envpol.2023.121910

27. Kiendrebeogo, M., Estahbanati, M. R. K., Mostafazadeh, A. K., Drogui, P., and Tyagi, R. D. (2021). Treatment of Microplastics in Water by Anodic Oxidation: A Case Study for Polystyrene. *Environmental Pollution, 269*. doi:10.1016/j.envpol.2020.116168
28. Kirstein, I. V., Gomiero, A., and Vollertsen, J. (2021). Microplastic Pollution in Drinking Water. *Current Opinion in Toxicology, Vol.28*(Suppl C), 70-75. doi:10.1016/j.cotox.2021.09.003
29. Kosuth, M., Mason, S., and Wattenberg, E. (2018). Anthropogenic Contamination of Tap Water, Beer, and Sea Salt. *Plos One, 13*, e0194970. doi:10.1371/journal.pone.0194970
30. Kumar, R., Ivy, N., Bhattacharya, S., Dey, A., and Sharma, P. (2022). Coupled Effects of Microplastics and Heavy Metals on Plants: Uptake, Bioaccumulation, and Environmental Health Perspectives. *Science of the Total Environment, 836*. doi:10.1016/j.scitotenv.2022.155619
31. Lee, M. H., Ok, Y. S., and Hur, J. (2018). Dynamic Variations in Dissolved Organic Matter and the Precursors of Disinfection by-Products Leached from Biochars: Leaching Experiments Simulating Intermittent Rain Events. *Environmental Pollution, 242*, 1912-1920. doi:10.1016/j.envpol.2018.07.073
32. Lei, J., Ma, Q., Ding, X., Pang, Y., Liu, Q., Wu, J., Zhang, H., and Zhang, T. (2024). Microplastic Environmental Behavior and Health Risk Assessment: A Review. *Environmental Chemistry Letters, 22*(6), 2913-2941. doi:10.1007/s10311-024-01771-x
33. Li, C. H., Yang, R., Zhou, L., Zeng, S. Y., Mavrovouniotis, M., Yang, M., Yang, S. X., and Wu, M. (2021). Adaptive Multipopulation Evolutionary Algorithm for Contamination Source Identification in Water Distribution Systems. *Journal of Water Resources Planning and Management, 147*(5). doi:10.1061/(ASCE)WR.1943-5452.0001362
34. Li, H., Li, L., Xiong, L., Wang, B., Wang, G., Ma, S., and Han, X. (2021). Sio2/Mxene/Poly(Tetrafluoroethylene)-Based Janus Membranes as Solar Absorbers for Solar Steam Generation. *Acs Applied Nano Materials, 4*(12), 14274-14284. doi:10.1021/acsanm.1c03873
35. Li, L., Li, S., Xu, Y., Ren, L., Yang, L., Liu, X., Dai, Y., Zhao, J., and Yue, T. (2023). Distinguishing the Nanoplastic-Cell Membrane Interface by Polymer Type and Aging Properties: Translocation, Transformation and Perturbation. *Environmental Science-Nano, 10*(2), 440-453. doi:10.1039/d2en00800a
36. Liu, F., Wu, Y., Long, M., Ma, Y., Zheng, M., Cao, S., Chen, S., Du, Y., Chen, C., and Deng, H. (2024). Activating Adsorption Sites of Waste Crayfish Shells Via Chemical Decalcification for Efficient Capturing of Nanoplastics. *Acs Nano, 18*(24), 15779-15789. doi:10.1021/acsnano.4c02511
37. Lu, J. R., Hou, R., Wang, Y., Zhou, L. H., and Yuan, Y. (2022). Surfactant-Sodium Dodecyl Sulfate Enhanced Degradation of Polystyrene Microplastics with an Energy-Saving Electrochemical Advanced Oxidation Process (Eaop) Strategy. *Water Research, 226*. doi:10.1016/j.watres.2022.119277
38. Luogo, B. D., Salim, T., Zhang, W. J., Hartmann, N. B., Malpei, F., and Candelario, V. M. (2022). Reuse of Water in Laundry Applications with Micro- and Ultrafiltration Ceramic Membrane. *Membranes, 12*(2). doi:10.3390/membranes12020223
39. Luogo, B. D. P., Salim, T., Zhang, W., Hartmann, N. B., Malpei, F., and Candelario, V. M. (2022). Reuse of Water in Laundry Applications with Micro- and Ultrafiltration Ceramic Membrane. *Membranes, 12*(2). doi:10.3390/membranes12020223
40. Ma, B., Xue, W., Hu, C., Liu, H., Qu, J., and Li, L. (2019). Characteristics of Microplastic Removal Via Coagulation and Ultrafiltration During Drinking Water Treatment. *Chemical Engineering Journal, 359*, 159-167. doi:https://doi.org/10.1016/j.cej.2018.11.155
41. Ma, H., Chao, L., Wan, H., and Zhu, Q. (2024). Microplastic Pollution in Water Systems: Characteristics and Control Methods. *Diversity-Basel, 16*(1). doi:10.3390/d16010070
42. Meng, X., Peng, X., Xue, J., Wei, Y., Sun, Y., and Dai, Y. (2021). A Biomass-Derived, All-Day-Round Solar Evaporation Platform for Harvesting Clean Water from Microplastic Pollution. *Journal of Materials Chemistry A, 9*(17), 11013-11024. doi:10.1039/d1ta02004h
43. Miao, F., Liu, Y. F., Gao, M. M., Yu, X., Xiao, P. W., Wang, M., Wang, S. G., and Wang, X. H. (2020). Degradation of Polyvinyl Chloride Microplastics Via an Electro-Fenton-Like System with a Tio2/Graphite Cathode. *Journal of Hazardous Materials, 399*. doi:10.1016/j.jhaz

mat.2020.123023

44. Na, S.-H., Kim, M.-J., Kim, J.-T., Jeong, S., Lee, S., Chung, J., and Kim, E.-J. (2021). Microplastic Removal in Conventional Drinking Water Treatment Processes: Performance, Mechanism, and Potential Risk. *Water Research, 202*, 117417. doi:https://doi.org/10.1016/j.watres.2021.117417
45. Napper, I. E., Davies, B. F. R., Clifford, H., Elvin, S., Koldewey, H. J., Mayewski, P. A., Miner, K. R., Potocki, M., Elmore, A. C., Gajurel, A. P., and Thompson, R. C. (2020). Reaching New Heights in Plastic Pollution-Preliminary Findings of Microplastics on Mount Everest. *One Earth, 3*(5), 621-630. doi:10.1016/j.oneear.2020.10.020
46. Naqash, N., Prakash, S., Kapoor, D., and Singh, R. (2020). Interaction of Freshwater Microplastics with Biota and Heavy Metals: A Review. *Environmental Chemistry Letters, 18*(6), 1813-1824. doi:10.1007/s10311-020-01044-3
47. Ng, E.-L., Lwanga, E. H., Eldridge, S. M., Johnston, P., Hu, H.-W., Geissen, V., and Chen, D. (2018). An Overview of Microplastic and Nanoplastic Pollution in Agroecosystems. *Science of the Total Environment, 627*, 1377-1388. doi:10.1016/j.scitotenv.2018.01.341
48. Nikita, K., Karkare, P., Ray, D., Aswal, V. K., Singh, P. S., and Murthy, C. N. (2019). Understanding the Morphology of Mwcnt/Pes Mixed-Matrix Membranes Using Sans: Interpretation and Rejection Performance. *Applied Water Science, 9*(7). doi:10.1007/s13201-019-1035-4
49. Park, H., and Park, B. (2021). Review of Microplastic Distribution, Toxicity, Analysis Methods, and Removal Technologies. *Water, 13*(19). doi:10.3390/w13192736
50. Peng, B. Y., Su, Y. M., Chen, Z. B., Chen, J. B., Zhou, X. F., Benbow, M. E., Griddle, C. S., Wu, W. M., and Zhang, Y. L. (2019). Biodegradation of Polystyrene by Dark (Tenebrio Obscurus) and Yellow (Tenebrio Molitor) Mealworms (Coleoptera: Tenebrionidae). *Environmental Science and Technology, 53*(9), 5256-5265. doi:10.1021/acs.est.8b06963
51. Pivokonsky, M., Cermakova, L., Novotna, K., Peer, P., Cajthaml, T., and Janda, V. (2018). Occurrence of Microplastics in Raw and Treated Drinking Water. *Science of the Total Environment, 643*, 1644-1651. doi:10.1016/j.scitotenv.2018.08.102
52. Pizzichetti, A. R. P., Pablos, C., Álvarez-Fernández, C., Reynolds, K., Stanley, S., and Marugán, J. (2021). Evaluation of Membranes Performance for Microplastic Removal in a Simple and Low-Cost Filtration System. *Case Studies in Chemical and Environmental Engineering, 3*, 100075. doi:https://doi.org/10.1016/j.cscee.2020.100075
53. Polisetti, V., and Ray, P. (2021). Nano Sio2 and Tio2 Embedded Polyacrylonitrile/Polyvinylidene Fluoride Ultrafiltration Membranes: Improvement in Flux and Antifouling Properties. *Journal of Applied Polymer Science, 138*(1), 49606. doi:https://doi.org/10.1002/app.49606
54. Poon, Y. K., Ab Rahim, S. K. E., Ng, Q. H., Hoo, P. Y., Abdullah, N. Y., Nasib, A., and Abdullah, N. S. (2023). Synthesis and Characterisation of Self-Cleaning Tio2/Pes Mixed Matrix Membranes in the Removal of Humic Acid. *Membranes, 13*(4). doi:10.3390/membranes13040373
55. Pramanik, B. K., Pramanik, S. K., and Monira, S. (2021). Understanding the Fragmentation of Microplastics into Nano-Plastics and Removal of Nano/Microplastics from Wastewater Using Membrane, Air Flotation and Nano-Ferrofluid Processes. *Chemosphere, 282*. doi:10.1016/j.chemosphere.2021.131053
56. Qiana, N., Gaoa, X., Lang, X., Deng, H., Bratu, T. M., Chen, Q., Stapleton, P., Yan, B., and Min, W. (2024). Rapid Single- Particle Chemical Imaging of Nanoplastics by Srs Microscopy. *Proceedings of the National Academy of Sciences of the United States of America, 121*(3). doi:10.1073/pnas.2300582121
57. Rakowski, M., and Grzelak, A. (2020). A New Occupational and Environmental Hazard - Nanoplastic. *Medycyna Pracy, 71*(6), 743-756. doi:10.13075/mp.5893.00990
58. Rekha, M. B., Sarris, I. E., Madhukesh, J. K., Raghunatha, K. R., and Prasannakumara, B. C. (2022). Impact of Thermophoretic Particle Deposition on Heat Transfer and Nanofluid Flow through Different Geometries: An Application to Solar Energy. *Chinese Journal of Physics, 80*, 190-205. doi:10.1016/j.cjph.2022.06.023
59. Rillig, M. C., and Lehmann, A. (2020). Microplastic in Terrestrial Ecosystems. *Science, 368*(6498), 1430-1431. doi:10.1126/science.abb5979
60. Roy, T., Dey, T. K., and Jamal, M. (2023). Microplastic/Nanoplastic Toxicity in Plants: An I

mminent Concern. *Environmental Monitoring and Assessment, 195*(1). doi:10.1007/s10661-022-10654-z

61. Samsonowska, K., and Kaszuba, A. (2022). Microplastic. *Polimery, 67*(1), 28-33. doi:10.14314/polimery.2022.1.4
62. Say, M. G. Z. (2022). *Hybrid Materials for Wearable Electronics and Electrochemical Systems*.
63. Stapleton, P. A. (2021). Microplastic and Nanoplastic Transfer, Accumulation, and Toxicity in Humans. *Current Opinion in Toxicology, 28*, 62-69. doi:10.1016/j.cotox.2021.10.001
64. Su, J., Zhu, Y. C., Chen, X., Lu, X. C., Yan, J., Yan, L., and Zou, W. X. (2024). Biochar Influences Polyethylene Microplastic-Contaminated Soil Properties and Enzyme Activities. *Agronomy-Basel, 14*(12). doi:10.3390/agronomy14122919
65. Sun, C., Wang, Z., Chen, L., and Li, F. (2020). Fabrication of Robust and Compressive Chitin and Graphene Oxide Sponges for Removal of Microplastics with Different Functional Groups. *Chemical Engineering Journal, 393*, 124796. doi:https://doi.org/10.1016/j.cej.2020.124796
66. Tong, H., Jiang, Q., Hu, X., and Zhong, X. (2020). Occurrence and Identification of Microplastics in Tap Water from China. *Chemosphere, 252*, 126493. doi:10.1016/j.chemosphere.2020.126493
67. Verma, M., Singh, P., and Dhanorkar, M. (2024). Remediation of Emerging Pollutants Using Biochar Derived from Aquatic Biomass for Sustainable Waste and Pollution Management: A Review. *Journal of Chemical Technology and Biotechnology, 99*(2), 330-342. doi:10.1002/jctb.7548
68. Wang, Z. (2023). *An Investigation of Hydraulic and Adsorption Behaviour of Biochar-Sand Mixtures*.
69. Wang, Z. F., Lin, T., and Chen, W. (2020). Occurrence and Removal of Microplastics in an Advanced Drinking Water Treatment Plant (Adwtp). *Science of the Total Environment, 700*. doi:10.1016/j.scitotenv.2019.134520
70. Wu, Y., Chen, S., Wu, J., Liu, F., Chen, C., Ding, B., Zhou, X., and Deng, H. (2024). Revivable Self-Assembled Supramolecular Biomass Fibrous Framework for Efficient Microplastic Removal. *Science Advances, 10*(48). doi:10.1126/sciadv.adn8662
71. Wu, Y., Ye, C., Liu, F., Gu, X., Yu, L., Shi, X., Du, Y., Ding, M., Chen, C., and Deng, H. (2024). Highly Efficient, Recyclable Microplastic Adsorption Enabled by Chitin Hydrogen Bond Network Rearrangement. *Advanced Functional Materials, 34*(32). doi:10.1002/adfm.202311075
72. Xiong, Y. C., Zhao, J. H., Li, L. Q., Wang, Y. Y., Dai, X. H., Yu, F., and Ma, J. (2020). Interfacial Interaction between Micro/Nanoplastics and Typical Ppcps and Nanoplastics Removal Via Electrosorption from an Aqueous Solution. *Water Reseach, 184*. doi:10.1016/j.watres.2020.116100
73. Xu, L. W. Z. (2020). Occurrence and Removal of Microplastics in a Water Treatment Plant. *Water Purification Technology, 7*(39), 109-113.
74. Xu, M., Niu, H., Wu, L., Xing, M., Mo, Z., Chen, Z., Li, X., and Lou, X. (2024). Impact of Microplastic Exposure on Blood Glucose Levels and Gut Microbiota: Differential Effects under Normal or High-Fat Diet Conditions. *Metabolites, 14*(9). doi:10.3390/metabo14090504
75. Yin, J. Y., Boaretti, C., Lorenzetti, A., Martucci, A., Roso, M., and Modesti, M. (2022). Effects of Solvent and Electrospinning Parameters on the Morphology and Piezoelectric Properties of Pvdf Nanofibrous Membrane. *Nanomaterials, 12*(6). doi:10.3390/nano12060962
76. Zhang, Y., Wang, H., and Zhang, J. (2025). Application of Graphene-Based Solar Driven Interfacial Evaporation-Coupled Photocatalysis in Water Treatment. *Catalysts, 15*(4). doi:10.3390/catal15040336
77. Zhao, M., Chen, T., He, B., Hu, X., Huang, J., Yi, P., Wang, Y., Chen, Y., Li, Z., and Liu, X. (2020). Photothermal Effect-Enhanced Photoelectrochemical Water Splitting of a Bivo4photoanode Modified with Dual-Functional Polyaniline. *Journal of Materials Chemistry A, 8*(31), 15976-15983. doi:10.1039/d0ta03698f
78. Zheng, X. J. (2022). *Study on the Degradation of Polyvinyl Chloride by Threedimensional Electrochemical Reactor.* (p.h.D.), East China Normal University, Shanghai.
79. Zhou, G., Wu, Q., Wei, X.-F., Chen, C., Ma, J., Crittenden, J. C., and Liu, B. (2023). Tracing Microplastics in Rural Drinking Water in Chongqing, China: Their Presence and Pathways from Source to Tap. *Journal of Hazardous Materials, 459*(Suppl C), 132206. doi:10.1016/j.jhazmat.2023.132206

80. Zhu, B. K., Fang, Y. M., Zhu, D., Christie, P., Ke, X., and Zhu, Y. G. (2018). Exposure to Nanoplastics Disturbs the Gut Microbiome in the Soil Oligochaete Enchytraeus Crypticus. *Environmental Pollution, 239*, 408-415. doi:10.1016/j.envpol.2018.04.017