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The rise of polymeric hydrogels, sponges, and electrospun fibers as adsorbents for microplastic removal: prospects for a sustainable future

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Microplastics (MPs) are ubiquitous and recognized as a significant environmental contaminant, owing to their persistent accumulation in terrestrial and aquatic environments. Microplastic pollution is primarily driven by rapid industrialization, improper disposal, and poor plastic waste management practices, and is extremely harmful to the environment and living species. To overcome this issue, sustainable approaches and mitigation strategies are necessary for removing MPs from the environment. In this regard, various approaches have been developed including adsorption, which is considered to be highly efficient. So far, various types of adsorbents, including metal–organic frameworks (MOFs), inorganic nanoparticle-based composites, 2D nanomaterials, and polymeric materials, have been explored for the removal of MPs. Among adsorption-based materials, polymeric hydrogels, sponges, and electrospun fibers have recently attracted significant attention due to their high porosity, tunable surface properties, and excellent adsorption capacity. Additionally, biodegradable polymer-based materials offer the possibility of removing MPs without having any adverse impact on the environment as they do not generate any toxic byproducts upon degradation after their purpose is served. However, several factors including material reusability, long-term stability, and capability to degrade MPs must be resolved for better performances. Hence, in this review, we have comprehensively and critically highlighted recent advancements in polymer-based hydrogels, sponges, and electrospun fibers for MP removal. We also summarize the facts associated with contamination caused by MPs and explore recent MP removal techniques, including physical methods, chemical methods, and biological methods. In addition, we describe the management strategies that can help mitigate issues of MP-based environmental pollution. Finally, we discuss the current challenges associated with these materials for facilitating MP remediation in a more efficient, scalable, and environment-friendly way for a sustainable future.

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1. Introduction

Plastic-based products are more convenient and used worldwide on a mass scale for diverse applications including in healthcare, agriculture, electronics, construction, transportation, and most significantly packaging.[1] The journey of plastics began with the fabrication of the first semisynthetic plastic Xylonite, which was produced by Alexander Parkes in 1861.[2] Following this, several plastics such as polyvinyl chloride (PVC), polyethylene terephthalate (PET), cellophane, polyamide (PA), and polyethylene (PE) were developed. They are extensively utilized because of their low cost, durability, versatility, ease of production, and ability to be moulded into various products that are integral to daily life.[3]

With an exponentially growing population and rapid urbanization, global plastic production was reported to reach 359 million tons in 2018.[4] This demonstrates a substantial leap of 1.2-fold from 299 million tons in a short time frame of 5 years.[5] Despite several benefits, this rapid expansion of plastic utilization combined with inadequate handling and improper disposal of plastic waste has led to significant environmental accumulation, causing detrimental effects.[6] It is anticipated that ~31.9 million metric tons of plastic waste is released into the environment every year due to poor waste management.[7] Furthermore, this plastic waste undergoes fragmentation *via* physical abrasion, chemical corrosion, and photooxidation, resulting in the formation of microplastics

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(MPs) ranging from 1 μm to 5 mm in size.[8] MPs have been identified as one of the emerging pollutants in the aquatic environment. It has been found that ~89% of the Northeast Atlantic ocean, ~70% of Jade Bay South–North sea, and ~95% of Arctic polar water contains MPs, which is a matter of serious concern.[9]

Based on their fabrication, MPs can be of two distinct types *i.e.*, primary and secondary. Primary MPs are generally added to personal care products as microbeads.[10] This also includes marine coatings, wear and tear of tyres, and microfibers coming from household laundry, and factories.[11] In contrast, secondary MPs are generated by the fragmentation of larger plastics *via* various processes, including physical degradation, biodegradation, photodegradation, oxidation, and hydrolysis.[12,13] They may also arise from plastic waste from fishing, products abandoned during tourism, plastic products used in the agriculture sector, and plastic garbage thrown away by residents during their daily lives.[14] MPs are more susceptible to being carried from the soil to the aquatic environment *via* runoff where they accumulate in sediments, and are further ingested by aquatic organisms, posing a significant threat to human health through the consumption of seafoods.[15,16] It should be noted that MPs are cytotoxic, and capable of inducing oxidative stress and inflammation, which may disrupt vascular endothelial cells, and hamper immune and neurological functions in humans.[17] They can enter the brain through the blood–brain barrier and can affect the discharge of essential neuroinflammatory transporters such as chemokine and cytokine.[18] MPs ≤20 μm in size can access the brain through blood vessels and lymphatics. The entry of MPs into the brain may destroy neurons and result in neural dysfunction. Adverse effects of MPs in the brain may be related to the pathogenesis of neurodegenerative disorders, including Parkinson's disease and Alzheimer's disease.[19] Moreover, MPs can undergo an aging process, which alters their size,[20] surface area,[21] hydrophilicity,[22] color,[23] and thermal stability and crystallinity.[24] These transformations further enhance concerns regarding the deeper infiltration of MPs into the ecosystem.[25] Aged MPs have a higher affinity to adsorb heavy metals,[26,27] hydrophobic organic pollutants (*e.g.*, pesticides, pharmaceuticals, polycyclic aromatic hydrocarbons) and polychlorinated biphenyls,[28] from water, which further increases their toxicity.

To combat the issue of MP pollution, several methods have been explored so far including biological processes, membrane filtration, electrocoagulation, and chemical methods such as coagulation, flotation, and adsorption.[29,30] Biological processes exhibit limited removal efficiency for MPs. Although membrane filtration offers a viable solution for capturing large sized MPs, its performance is limited for smaller MPs. These smaller MPs can easily clog the membrane pores and hinder the filtration process.[29] Chemical methods such as coagulation, flotation, and adsorption are more commonly employed owing to their simple operation, cost-effectiveness, and low energy consumption. However, the use of chemical reagents in water treatment makes coagulation and flotation less environment-friendly. In contrast, adsorption is considered to be the most advantageous method for MP removal owing to its low cost, straightforward operation, and the possible recyclability of adsorbents.[30] Previously, several adsorbent materials including layered double oxides, biochar, coffee grounds, and magnetic particles have been explored.[31–33] However, these materials tend to be ineffective against smaller MPs or nanoplastics (NPs), and often face limitations like poor efficacy, prolonged adsorption duration, and low reusability, which hinder their large-scale implementation.[27,30] Compared to the abovementioned traditional adsorbents, polymer-based materials possess interconnected porous architectures, tunable surface functionalities and pore sizes, improved hydrophilic/hydrophobic balance, enhanced mechanical flexibility, and large specific surface areas that altogether enhance their capturing

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efficiency and reduce fouling behaviour.[34,35] The controlled pore size and tailored chemical functionalities also improve the interaction of such materials with MPs, and hence provide a multifunctional platform for designing next-generation separation techniques.

In the given scenario, polymeric hydrogels, sponges, and electrospun fiber-based adsorbents have emerged as a promising platform to remove MPs from the ecosystem. In recent years, a few review articles have been published covering various types of adsorbents, including metal–organic frameworks (MOFs), metal nanoparticle-based composites, and 2D nanomaterials for the removal of MPs.[30,36,37] However, very limited attention has been paid specifically to polymer-based adsorbents, including hydrogels, sponges, and electrospun fibers. Moreover, biodegradable polymer-based materials offer the possibility of removing MPs without having any adverse impact on the environment. Unlike engineered nanomaterials, covalent organic frameworks, and metal organic frameworks, these biocompatible and biodegradable polymer-based materials do not produce toxic by-products upon degradation. Usually, such polymeric materials offer the absorption of MPs through physical interactions such as electrostatic interactions, dipole–dipole interactions, hydrogen bonding, and π–π stacking interactions. Consequently, they are being widely explored as environmentally benign alternatives for microplastic remediation. Hence, a comprehensive review dedicated to these polymeric materials and their use in the removal of MPs can provide critical insights into their design, adsorption mechanisms, and practical applications, thereby guiding future research and development in this field.

Herein, we describe the impact of MP contamination and provide a comprehensive overview of current advances in polymeric hydrogels, sponges, and electrospun fiber-based membranes for eliminating MPs from water. Furthermore, we discuss various management strategies that could help mitigate the detrimental effect of MPs. Lastly, we highlight the key challenges associated with these materials and emphasize the need for continued research to improve their performance for MP remediation on a large scale.

2. Background and motivation to control MP pollution

The use of plastic-based products has significantly risen over the last 50 years. The annual production of plastic was 322 million tons in the year 2015 and is expected to reach 670 million tons in 2040.[38] It should be noted that despite high production and rising demands for plastic-derived products, only 9–10% of plastic waste is recycled, and most of the waste that can be deposited in landfills is discharged into natural water resources.[39] The exact size of MPs is still not defined by the scientific community, and MPs can have a maximum length of 5 mm in the form of fibres, spheres, films, fragments and foams.[40,41] The shape of MPs depends upon their origin. For example, most of the fiber-shaped MPs are produced by the apparel industry, while film-shaped MPs are produced by the packaging industry. Similarly, sphere-shaped MPs are generated by crushing waste generated by abrasives and resin pellet leakage from the transportation industry.[41]

It may be noted that studies have shown that an individual absorbs 39 000–52 000 MPs every year.[42] The microparticles can penetrate the gastrointestinal tract and can cause an inflammatory effect.[43] Chronic exposure to MPs can destroy the immune system and increase the risk of cancer. Moreover, smaller-sized MPs possess the potential for bioaccumulation and can exacerbate health issues (Fig. 1).[44,45] Therefore, MP removal from different sources is crucial to safeguard our environment. Nowadays, different techniques, including physical, chemical, and biological methods, are being used to remove MPs. This review mainly focuses on advances in polymeric hydrogels, sponges, and electrospun fibers for the removal of MPs.

3. Adverse impact of contamination by MPs

The origin of MPs from different sources and their increasing amount in water has emerged as a critical problem, owing to

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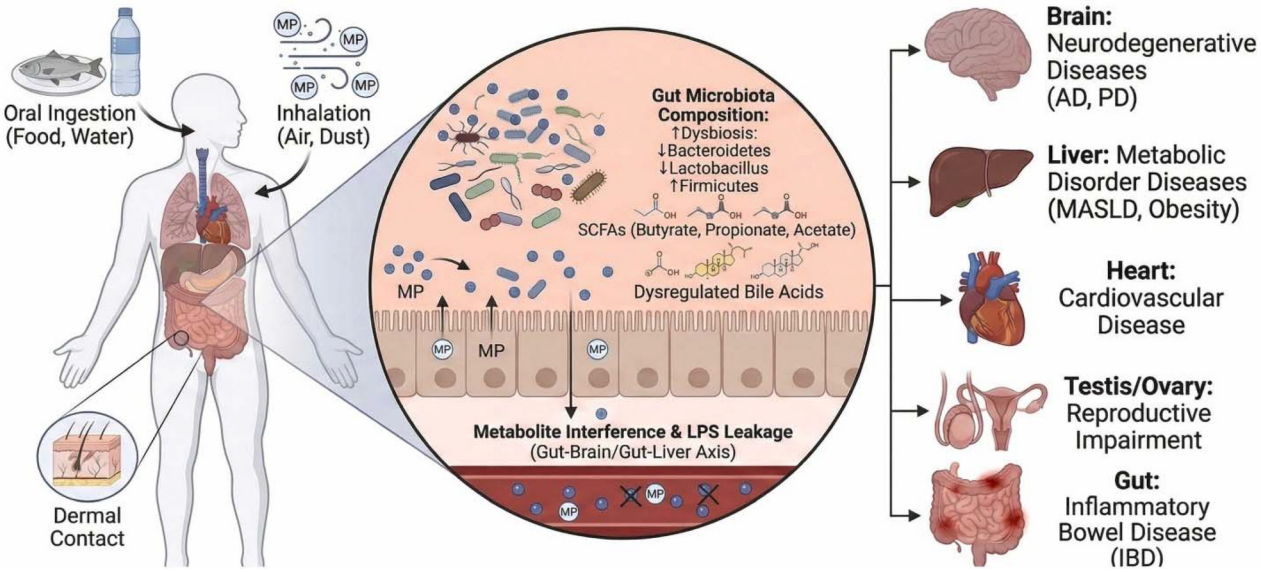

Fig. 1 Different pathways for human exposure to MPs and accumulation in distinct organs. Adapted with permission.[45] Copyright 2026, Publisher Elsevier.

their harmful effects on aquatic life and human health (Fig. 2). It has been reported that over 250 aquatic species are affected by the ingestion of and exposure to MPs.[46] It is evidenced by the presence of MPs in their digestive tracts, which leads to abnormal growth, structural and physical damage, disruption to normal feeding habits, and the suppression of innate immunity.[47] Eventually, the consumption of such seafood by humans results in the accumulation of MPs in their bodies. This was recently indicated by findings suggesting the occurrence of MPs in human stool, tissues, and body fluids.[48–52] Long-term exposure to MPs can also cause skin irritation, cytotoxicity, neurotoxicity, reproductive complications, Alzheimer's disease, and chronic inflammation, which increases the risk of cancer.[47,48] MPs can also affect cell metabolism in humans by altering the activity of the gut microbiota, which reduces the absorption of nutrients in the gut.[53] Furthermore, MPs can also act as a vector for bacteria by providing a substantial surface area for colony formation and proliferation.[54] This can result in tissue damage and increase the risk of infections.[54] Therefore, immediate intervention and the development of novel technological alternatives is of prime importance for mitigating the issues related to MPs.

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4. Techniques for the removal of microplastics

In wastewater treatment plants, the most widely used methods are physical, chemical, and biological methods. All these methods possess specific advantages as well as limitations in the recovery of microplastics from wastewater. A comparative analysis of these methods is summarized in Table 1.

4.1 Physical methods

The physical methods employed for the removal of MPs usually retain the chemical and biological properties of MPs. Commonly employed physical methods may include magnetic separation, froth flotation, filtration, adsorption, the oil film method, *etc*.

Magnetic separation is an effective method for the removal of MPs that uses a variety of materials, including carbon nanotubes, iron nanoparticles and magnetic seeds. The major controlling factors for magnetic separation may include hydrogen

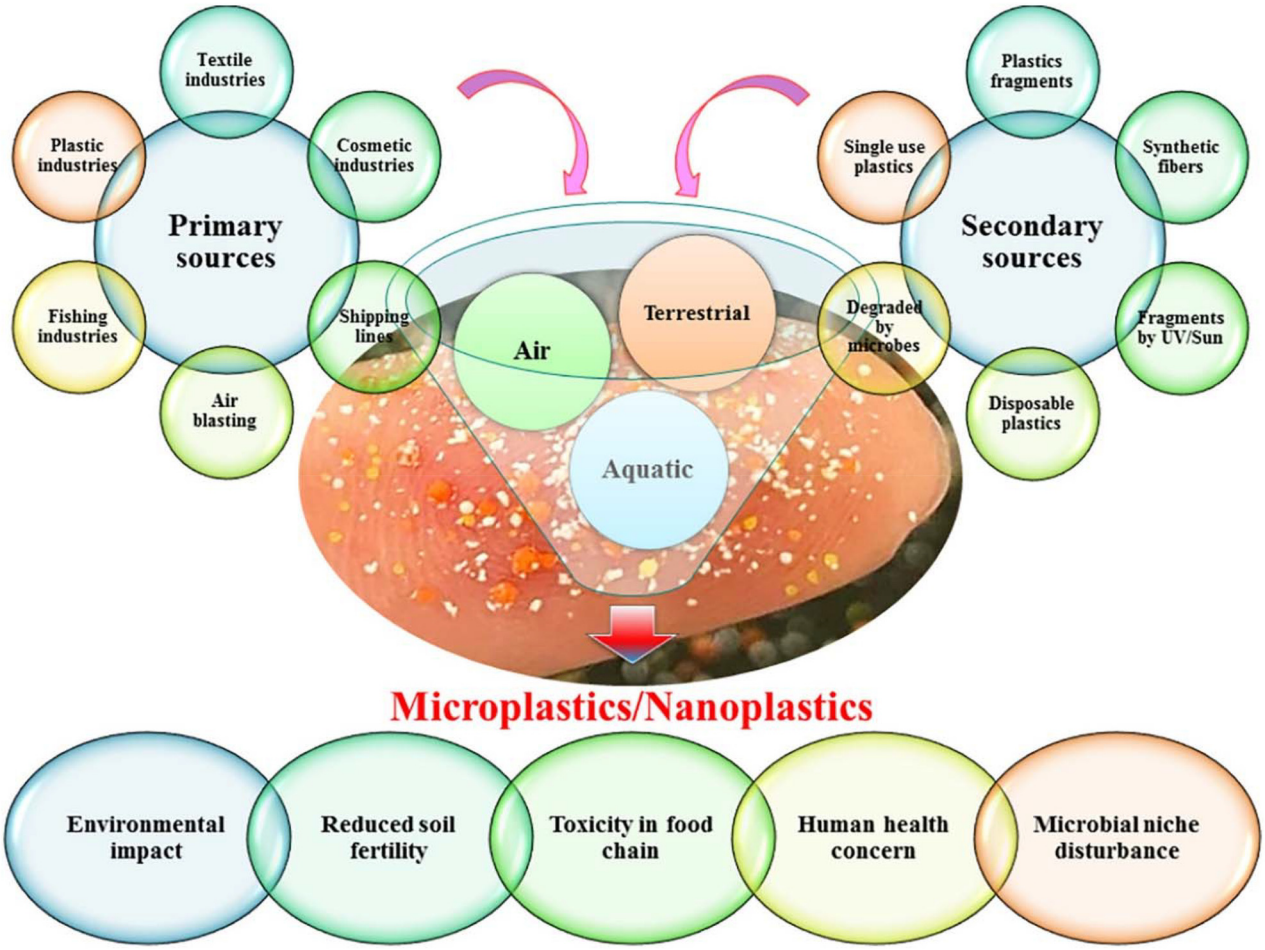

Fig. 2 Sources of MPs/NPs and their harmful impacts. Adapted with permission.[47] Copyright 2022, Publisher Elsevier.

bonding, electric friction and complexation. The separation of MPs is possible due to a variety of removal mechanisms, including electrostatic interactions, hydrophobic interactions, π–π interactions, hydrogen bonding and complexation. Once magnetized, MPs can be effectively separated from water using an external magnetic field. Shi *et al.* reported the synthesis of modified maifanite through high temperature and acid treatment for the effective removal of MPs using the magnetic separation method. Modified maifanite demonstrated 98.46% removal efficiency of polystyrene under the influence of a rerating magnetic field and was recyclable for up to 25 operational cycles.[55]

Similarly, the froth flotation technique with ultrafine bubbles is an effective physical method for removing small MPs, including polylactic acid, polystyrene, polybutylene succinate, and polyethylene terephthalate from wastewater.[56] In this technique, there is the selective adherence of bubbles to the required minerals, and the primary parameters required for froth flotation include surface wettability, a hydrophilic interior, and a hydrophobic outer surface that tends to float in the form of froth aggregations.[57] A study carried out by Jiang *et al.* demonstrated that the efficacy of the froth flotation process for the removal of MPs could be enhanced by using cationic and anionic surfactants.[58]

Filtration of MPs can be carried out by using a sand filter, disc filter or biochar filters. Suspended materials such as MPs can be removed with the help of rapid sand filters because they can cling to the surface of sand grains. In wastewater treatment plants, a rapid sand filter may consist of a series of sand filters having distinct materials of different grain sizes. For example, Chabi *et al.* fabricated a rapid sand filter that could effectively remove MPs of <10 μm in size with 98% removal efficiency and 97% desorption rate. The mechanism involved in this removal method was the synergic combination of physicochemical sorption.[59] Similarly, the disc filtration method is a frequently used method for the physical separation of MPs. In this method, MP removal is mainly dependent on the creation of cakes of sludge inside the filter panels as well as the retention of particles in filters.[60] The disc filtration technique can achieve 98% efficiency for the removal of MPs as indicated by the reported study.[61] However, the removal efficiency can vary depending upon the water quality, filter design, pore size and effectiveness of the disc filters. Biochar-based filters further enhance the removal efficiency of the fil-

Table 1 Comparative analysis of different techniques for the removal of MPs

Method	Key features of the method	Specific example	Type of target MP	Size range of targeted MPs	Surface charges on the adsorbent	Pore/mesh size of the adsorbent	Degradation time	% MP removal efficiency	Removal mechanism	Ref.
Photocatalytic degradation	Durable and eco-friendly	Nb-doped SnO_2 QDs	Polyethylene	350 μm	−35 mV	—	7 h	28.9%	Interactive mechanism of dual defects and photocatalytic mechanism	82
Electrochemical oxidation	Highly efficient; does not require the use of toxic chemical agents	CeO_2–PbO_2-0.005 anode	Polyvinyl chloride	—	—	—	6 h	38.67%	Ce(III)/Ce(IV) valence-modulated mechanism	83
Coagulation	Minimum energy uses for the removal of tiny MPs	Polyaluminum ferric chloride with *Opuntia milpa alta* particles	Polystyrene	2–10 μm	4.52 mV at pH 6 and −0.56 mV at pH 9	380 μm	60 min	94.8%	Charge neutralization and adsorption bridging	84
Electrocoagulation	Economical and energy-efficient; does not require chemical coagulants; efficient at removing small MPs	Al/Fe–graphene–electrocoagulation (EC) system	Polyethylene terephthalate, polypropylene, and polystyrene	45–250 μm	—	—	120 min	96%	Adsorption and electrostatic interactions	85
Sand filtration	Cost-effective and simple to operate	Natural quartz sand in a rapid sand filtration (RSF) system	Polypropylene and polystyrene	<10 μm	−30.1 mV and −32.8 mV	NA	20 min	84–98%	Synergistic combination of physicochemical sorption	59
Disc filtration	Minimum energy consumption for the accelerative removal of MPs	Disc filter	Polyethylene, polystyrene, polyester, polyvinyl chloride	>300 μm	—	15 μm	—	89.7%	MP removal by high-pressure back-flushing	86
Ozonation	Cost-effective and efficient	α-MnO_2 and α-FeOOH	Polystyrene	<1 μm	—	—	8 h	16.5%	Free radical mechanism	71
Froth flotation	Low cost and adaptable for quick operation	Flotation process combining 10 g per ton of sodium oleate	Polyvinyl chloride, acrylonitrile–butadiene styrene	0.074 μm to 5 μm	−33.1 to −14.5 mV	—	24 h	100%	Hydrophilization and electrostatic mechanism	87
Oil film separation	Affordable and simple to use	Castor oil	Polypropylene, polystyrene, polymethyl methacrylate, and glycol modified polyethylene terephthalate	0.3–1.0 mm	—	25 μm	4 h	99%	Lipophilicity-based protocol	88
Biochar filters	Effective at achieving excellent adsorption capacities	Surface-engineered palm kernel shell biochar	Polyethylene, polyamide	159 nm–48 μm	+9.5 to +14.1 mV	0.6–1.18 mm	2 h	96.12%	Electrostatic interaction, hydrophobic interaction, π–π interaction and hydrogen bonding	89

Table 1 *(Contd.)*

Method	Key features of the method	Specific example	Type of target MP	Size range of targeted MPs	Surface charges on the adsorbent	Pore/mesh size of the adsorbent	Degradation time	% MP removal efficiency	Removal mechanism	Ref.
Adsorption removal	Cost-effective, easy to use and reusable in many cycles	Polydopamine-modified sodium alginate hydrogel	Polyethylene, polystyrene	200 nm to 10 μm	−17.9 ± 2.21 mV	—	2 h	99.6%	Chemical adsorption, electrostatic interactions, hydrogen bonding and π–π interactions	90
Membrane bioreactor technology	Precise removal of contaminants at variable MP concentrations, ensuring effective removal	Living membrane bioreactor containing a biological layer as a membrane filter	Polyethylene	≤20 μm	—	0.04 μm	21 days	95%	Electrocoagulation and adsorption	78

tration process. They consist of different media, including anthracite sand and granular activated carbon. Duan *et al.* designed an iron-modified magnetic biochar based on sawdust that depicted 205 mg g^{-1} adsorption capacity for the removal of polystyrene following Elovich kinetics and the Sips isotherm model. The fabricated filter maintained 72% removal efficiency even after six cycles of pyrolysis.[62] The oil film method is a hydrophobicity-based removal technique that is very effective at removing MPs. Wang *et al.* developed a superhydrophobic and multifunctional polyurethane sponge using polydimethylsiloxane (PDMS) and stearic acid-modified TiO_2 nanoparticles. The adsorption capacity of the material reaches 0.45 g g^{-1} within 10 s. In another study, magnetic cobalt ferrite particles were able to remove 100% of microplastics through the oil film method. The material also demonstrated 2.56 g g^{-1} capture capacity and 98% removal efficiency after 10 adsorption–desorption cycles.[63]

Adsorption is the most favorable technique for removing MPs. A variety of adsorbent materials, such as iron oxide, graphene oxide, carbon nanotubes, *etc.*, are employed for the efficient removal of microplastics. For example, a study carried out by Heo *et al.* employed magnetic iron oxide nanoparticles, demonstrating 98.2% adsorption efficiency for the removal of polystyrene MPs.[64] Similarly, reduced graphene oxide nanosheets were capable of removing 99.9% of MPs through an adsorption process.[65] In short, physical methods provide a reliable and non-destructive approach for the removal of MPs. The removal efficiencies can be enhanced by creating superhydrophobic–magnetic sponges, magnetic–biochar composites, and surface-engineered nanoparticles.[66] Of these physical methods, adsorption is considered to be the most versatile, cost-effective and highly efficient technique.

4.2 Chemical methods

Chemical treatment methods are generally employed where the removal of MPs from wastewater is not possible with physical or biological treatment methods. Wastewater treatment using the chemical method may include a series of chemical reactions that help to selectively remove MPs. Electrochemical oxidation, coagulation, flocculation, sol–gel techniques, photocatalytic degradation, and ozonization are frequently used chemical treatment methods for the removal of MPs.

Electrochemical oxidation is an affordable and sustainable method for the treatment of MPs present in wastewater. Instead of MP degradation, this method is suitable for the degradation of toxic dyes, organic pollutants, and medications. This method uses indirect cathode/anode oxidation and produces non-toxic degradation end products such as CO_2 and H_2O. Falco *et al.* demonstrated the fabrication of boron-doped diamond electrodes that could effectively remove 98.5% polystyrene MPs from wastewater at an initial MP concentration of 25 mg L^{-1}, a treatment time of 90 min, and a current density of 8.07 mA cm^{-2} at pH 4.[67] While the fabricated electrode showed a high removal efficiency, sludge generation during the removal process added operational costs related to the disposal of waste. In another study, boron-doped diamond elec-

trodes were also employed for the degradation of polyethylene terephthalate microplastics.[68] The removal efficiency was 81% in synthetic water and 95% in marine water with added salt due to the crucial role of chlorine species present in saline water. Moreover, the removal time was reduced from 12 h to 2 h in saline water.

The coagulation/flocculation method for the removal of MPs involves the neutralization of the charge present on existing colloidal particles, which may form floccules and can be separated through sedimentation or filtration. For example, Zheng *et al.* employed polymeric ferric sulfate and *Opuntia milpa alta* particles for the removal of polystyrene MPs and achieved 93.6% removal efficiency at an *Opuntia milpa alta* concentration of 20 mg L^{-1}, a polymeric ferric sulfate concentration of 120 mg L^{-1} and pH 9.2.[69] In comparison with chemical coagulation, the electrocoagulation method offers the use of metal electrodes, which is preferable over conventional coagulation techniques. For example, Sezer *et al.* suggested optimization of the electrocoagulation method by the Box Behnken design and achieved 99% removal efficiency of MPs obtained from the food packaging industry wastewaters under optimum conditions (*i.e.*, current density: 3.16 mA cm^{-2}, pH: 6.74, and time: 13.58 min).[70]

Ozonization is a tertiary treatment process used for the treatment of MPs present in the leftover residue of the coagulation process. The oxygen functionalities of the MPs can be degraded through ozonization. To improve the efficiency of ozonization, Hu *et al.* introduced 20 mM α-FeOOH into the ozonation system, and the mineralization efficiency in the case of polyethylene MPs was found to be enhanced 3.27-fold due to the accelerated production of OH* free radicals.[71] In another study, the efficiency of ozonization was accelerated by implementing Co(II)-catalyzed ozonation. 1 mM Co^{2+} reduced the turbidity of the wastewater by 20% and achieved 64% mineralization of MPs within a reaction time of 15 min.[72] The major drawback of the ozonization process is its high operation cost. In addition, the incomplete ozonization process can produce intermediate components that can be toxic to the environment and can lead to the generation of reactive oxygen species.

The sol–gel technique is a chemical process that involves the agglomeration of organosilanes into an inorganic–organic macromolecule before its removal from wastewater.[73] Using the sol–gel method, Pacaphol *et al.* demonstrated the removal of small MPs such as polyethylene, polyethylene terephthalate, polystyrene, polyvinyl chloride, polytetrafluoroethylene, polypropylene, and aged tyre rubber. An excellent MP recovery rate (95–100%) was observed using tetraethyl orthosilicate as a floating medium. However, the recovery rates were slightly reduced (82–98%) for finer particles of sizes <40 μm.[74]

Photocatalysis is the most reliable and cost-effective chemical method for degrading toxic organic pollutants, including MPs. In this technique, the oxidation of MPs is carried out with the help of free radicals and reactive oxygen species produced by the semiconductor material while interacting with ultraviolet or visible light. Yang *et al.* prepared a core–shell $BiO_{2-x}/CuBi_2O_4$ heterojunction for the effective degradation of polystyrene MPs. The results indicated that the complete surface of polystyrene was degraded in 30 days using the synthesized photocatalyst.[75] In another study, the photocatalytic degradation of polyethylene microbags was studied using a ZnO-based photocatalysis–persulfate activation system. Hydroxyl and sulfate radicals were the major reactive species in the photocatalysis process, leading to a 50.91% mass loss ratio within 105 h. The photocatalyst was recyclable in many cycles, and the difference in the mass loss ratio of the first and fifth cycles was only 1%.[76]

4.3 Biological methods

Biological methods for MP degradation include the treatment of wastewater with different bacterial isolates. The extent of MP degradation depends upon the type of microplastic and bacterial strain. In comparison with physical and chemical degradation methods, the biological methods of MP degradation are rarely used. However, some studies have suggested the use of bioreactors and dynamic membrane techniques to remove low-density microplastic sources.[77] For example, studies carried out by Corpuz *et al.* showed a 95% reduction in polyethylene MPs using an electrochemically enhanced living membrane bioreactor. Moreover, the live membrane bioreactor migrated the inhibition effect of MPs to PO_4 (P) and NH_4 (N) removal.[78] Lv *et al.* showed the degradation of polystyrene MPs with *Alcanivorax xenomutans* and *Halomonas titanicae* marine bacteria. It was observed that only 4.5% and 1.9% of the plastic films were actually biomineralized with *A. xenomutans* and *H. titanicae* after 30 days of incubation.[79] In another study, *P. aeruginosa* and *S. haemolyticus* were isolated from landfill leachate that had shown the degradation of polypropylene MPs. The maximum degradation efficiency achieved was 25.46% and 7.01% for *S. haemolyticus* and *P. aeruginosa*, respectively.[80] The degradation of polystyrene MPs using edible fungi was also studied by Yu *et al.* and the highest degradation rate (16.17 ± 8.87%) was found with *Pleurotus ostreatus* after 50 days of fungal degradation.[81]

It should be noted that several studies have reported different biological methods for the removal of MPs, but physical and chemical methods for the removal of MPs are more reliable, efficient and economical.

5. Hydrogels and their application in removal of MPs

In recent years, hydrogels have piqued the interest of scientists for addressing the critical issue of MP pollution. Hydrogels leverage their high water-holding capacity and porous architecture to elevate the capture and removal of MPs. They can effectively eliminate MPs from water by simple adsorption, surpassing the limitations of conventional removal techniques and unlocking new possibilities for improving water quality.

5.1 Salient features of hydrogels

Hydrogels are 3D crosslinked networks of polymeric chains that can absorb and retain a significant amount of water

without dissolving.[91,92] These materials exhibit exceptional properties including high porosity, structural flexibility, elasticity, and tunable functionality. Additionally, the possibility of incorporating the features of biocompatibility and biodegradability, through the suitable choice of components and synthetic strategy, makes them an ideal candidate for green adsorbents.[93,94] Fig. 3 summarizes a few examples of different building blocks (*e.g.*, polymers, monomers, comonomers, and crosslinkers) that have been widely utilized for the fabrication of hydrogels.[95–102]

Hydrogels can be synthesized using various natural and synthetic polymers. The use of synthetic polymers offers reproducibility and control over the molecular weight of polymer chains, while natural polymers are employed to utilize their inherent biocompatibility and biodegradability.[103,104] Additionally, a combination of natural and synthetic polymers is also frequently investigated to develop hybrid hydrogels that benefit from the advantages of both types of polymer.[103,104] Moreover, the incorporation of different functional groups (*e.g.*, $-NH_2$, –COOH, –OH, $-CONH_2$) inside the hydrogels during synthesis can enhance their interaction with the guest moieties including NPs and MPs, thus facilitating their effective removal.[105–109]

Furthermore, hydrogel networks are typically formed *via* physical or chemical crosslinking of polymeric chains.[110,111] Physical crosslinking involves hydrogen bonding, electrostatic interactions, hydrophobic/hydrophilic interactions, metal coordination, crystallization/stereocomplex formation, and π–π stacking interactions.[111] In the case of chemical crosslinking, the formation of covalent or dynamic covalent bonds takes place, providing control over the mechanical strength and degradability of hydrogels.[110] Various dynamic covalent bonds including imine,[112] disulfide,[113] boronic ester,[114] and acylhydrazone[115] have been utilized in the literature for the fabrication of degradable hydrogels. These dynamic bonds are

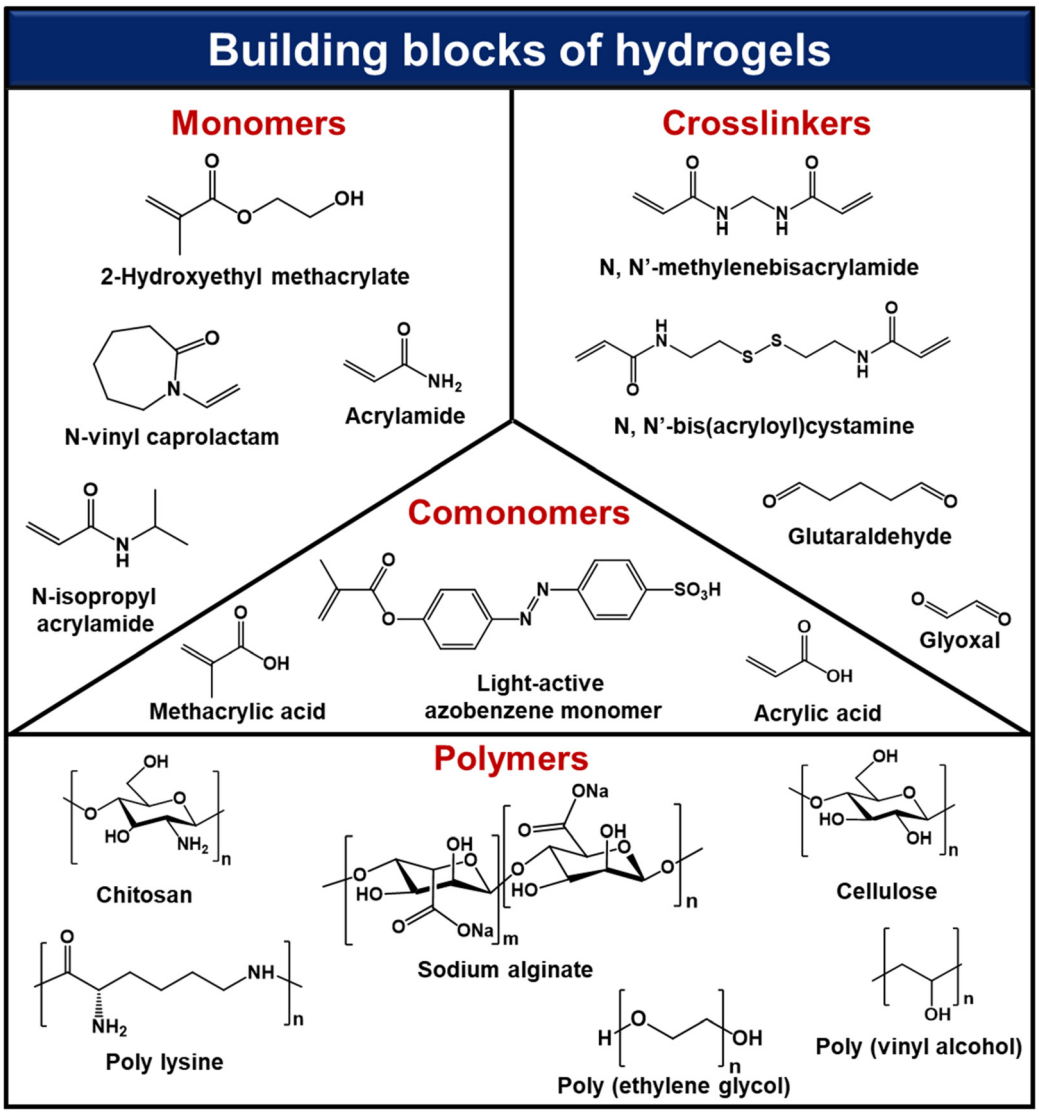

Fig. 3 Examples of key components utilized for the fabrication of hydrogels: monomers, comonomers, crosslinkers and commonly used polymers.

degraded under specific environmental conditions, reducing the risk of secondary pollution that is often associated with persistent synthetic materials.[83–85,116–118]

5.2 Hydrogels for removal of MPs

In recent years, scientists have explored various natural, synthetic, and natural/synthetic hybrid polymer-based hydrogels to mitigate MP pollution. However, the removal efficiency of hydrogels is strongly affected by the pore size of the hydrogel, swelling behaviour, network density and overall accessible surface area.[119] In addition, the size, shape, and surface charge of the target MPs also affect the removal efficiency.[120]

Taking advantage of the attractive features of hydrogels mentioned earlier, Patel *et al.* reported aluminium and iron-incorporated ionotropic chitosan (CS) hydrogels for the removal of PET MPs.[121] Here, the integration of metal cations into CS hydrogels boosted their ionic charge, thus providing a straightforward and efficient method for enhancing the adsorption capacity, while offering a low cost and minimal environmental impact. Interestingly, a pH-based alteration of the adsorption capability of both Al–CS and Fe–CS hydrogels was observed here. At lower pH, the protonation of amino groups in CS combined with the formation of cationic metallic species (*e.g.*, Al^{3+}, $Al(OH)_2^+$, $Al(OH)_2^+$, FeO^+) enhanced the overall positive charge of hydrogels, which in turn helped to achieve greater electrostatic interactions with anionic MPs, leading to 70% adsorptive removal of PET MPs. At higher pH, deprotonation of amino groups in combination with the generation of anionic hydrates (like $Al(OH)_4^-$, $Al(OH)_3$, FeO_2^-, FeO_2H) led to repulsion, thus reducing the adsorption efficiency. Moreover, upon increasing the doping concentration, the adsorption efficiency was comparatively reduced, which could be attributed to the cations occupying the pore regions of hydrogels. Finally, the successful removal of MPs from CS-based hydrogels using NaOH demonstrated the reversibility of adsorption–desorption, confirming that the process was governed by physical adsorption.[121]

Utilizing copper substituted polyoxometalate (Cu-POM) nanoclusters, Dutta *et al.* synthesized a Cu-POM infused triple interpenetrating network hydrogel (pGel@IPN), which was composed of polyaniline (PANI), PVA, and chitosan (CS).[122] This hydrogel matrix exhibited excellent mechanical strength, which could be assigned to strong electrostatic interactions between positively charged PANI and negatively charged Cu-POM. The hydrogel was further strengthened by crosslinking between hydroxyl groups of PVA and aldehyde groups of glutaraldehyde (GA) (Fig. 4). pGel@IPN demonstrated high removal efficiency for both PVC and PP-based MPs, which were labelled with Nile red for their easy detection and analysis *via* fluorescence microscopy. pGel@IPN showed ~95% and ~93% removal efficiency for PVC and PP MPs, respectively, at pH 6.5. Statistical analysis further revealed that the adsorption of MPs followed the Langmuir model ($R^2 > 0.99$), suggesting monolayer sorption of MPs on the hydrogel surface. Notably, the adsorption capacity of the hydrogel was high, reaching 321.87 mg g^{-1} for PVC and 144.29 mg g^{-1} for PP MPs. These hydrogels demonstrated good reusability to capture MPs in up to five cycles. Furthermore, UV-induced degradation of MPs was facilitated by taking advantage of the catalytic properties of Cu-POM, thus combining the concept of efficient capturing and degradation of MPs. Finally, after the hydrogel served its purpose, it was upcycled into carbon nanoparticles, which in turn were utilized as an adsorbent to remove Cr(VI) from contaminated water to move towards a circular economy.[122]

Developing biomass derived natural polymer-based hydrogels offers a sustainable approach for capturing MPs for water treatment. In this regard, Li *et al.* utilized bamboo-derived lignin in combination with PVA to synthesize a hydrogel for the removal of PS MPs.[123] Here, lignin was subjected to phenolization and ammonization processes that markedly increased the phenolic hydroxyl and long-chain amino group contents in lignin, respectively. The incorporation of amino groups introduced dual functionality in lignin including pollutant adsorption over a broad pH range and improved encapsulation. Aminated lignin/epichlorohydrin/polyvinyl alcohol (LG-GH-PVA) hydrogel was synthesized *via* chemical crosslinking of aminated lignin with epichlorohydrin, as well as ionic crosslinking of PVA with Ca^{2+}. The adsorption process followed a pseudo-second-order kinetic model, while the equilibrium data exhibited the best fit with a Langmuir isotherm, confirming monolayer adsorption with a maximum adsorption capacity of 288.6 mg g^{-1}. Notably, the hydrogel maintained 87.6% of its adsorption capacity even after five regeneration cycles, which was attributed to π–π interactions between the hydrogel and PS MPs in addition to hydrogen bonding between hydroxyl, carboxyl, and amino groups present on both surfaces. The reported hydrogel demonstrated high adsorption of PS MPs in real-world systems, achieving efficiencies of 90.6–92.7% in lake water, 92.2–94.7% in pipeline water, 94.6–97.1% in river water, and 95.5–97.9% in sludge supernatant. In addition to PS MPs, the hydrogel effectively adsorbed four other MPs, namely, PEI MPs, PP MPs, PVC MPs, and PA MPs, even at a low concentration of 10 mg L^{-1}, and thus presents itself as a promising platform for MP removal.[123]

Exploring other natural polymers, Leppänen *et al.* developed cellulose-based hydrogels by using two different grades of cellulose nanofibrils, namely, native cellulose nanofibrils (CNF) and TEMPO-oxidized CNF.[124] These hydrogels were utilized to capture both cationic and anionic PS particles (1 μm and 100 nm) using a microfluidic setup coupled with fluorescence microscopy (Fig. 5a and b). It was reported that the adsorption and removal of PS particles were influenced by the hygroscopic cellulose network and large surface area of hydrogels.[124] The removal mechanism was based on attractive surface interactions when capillary forces were not assisting the capturing process. The larger surface area and enhanced surface interactions were the driving forces for the cohesion between the material's surface and NPs. Next, Yi *et al.* developed dual crosslinked chitin (Ch) nanofibril-based hydrogels by using formaldehyde for chemical crosslinking and ammonia fumigation for physical crosslinking using the freeze–thaw method (Fig. 5c).[125] The dual crosslinked hydrogels exhibited a higher mechanical strength and filtration

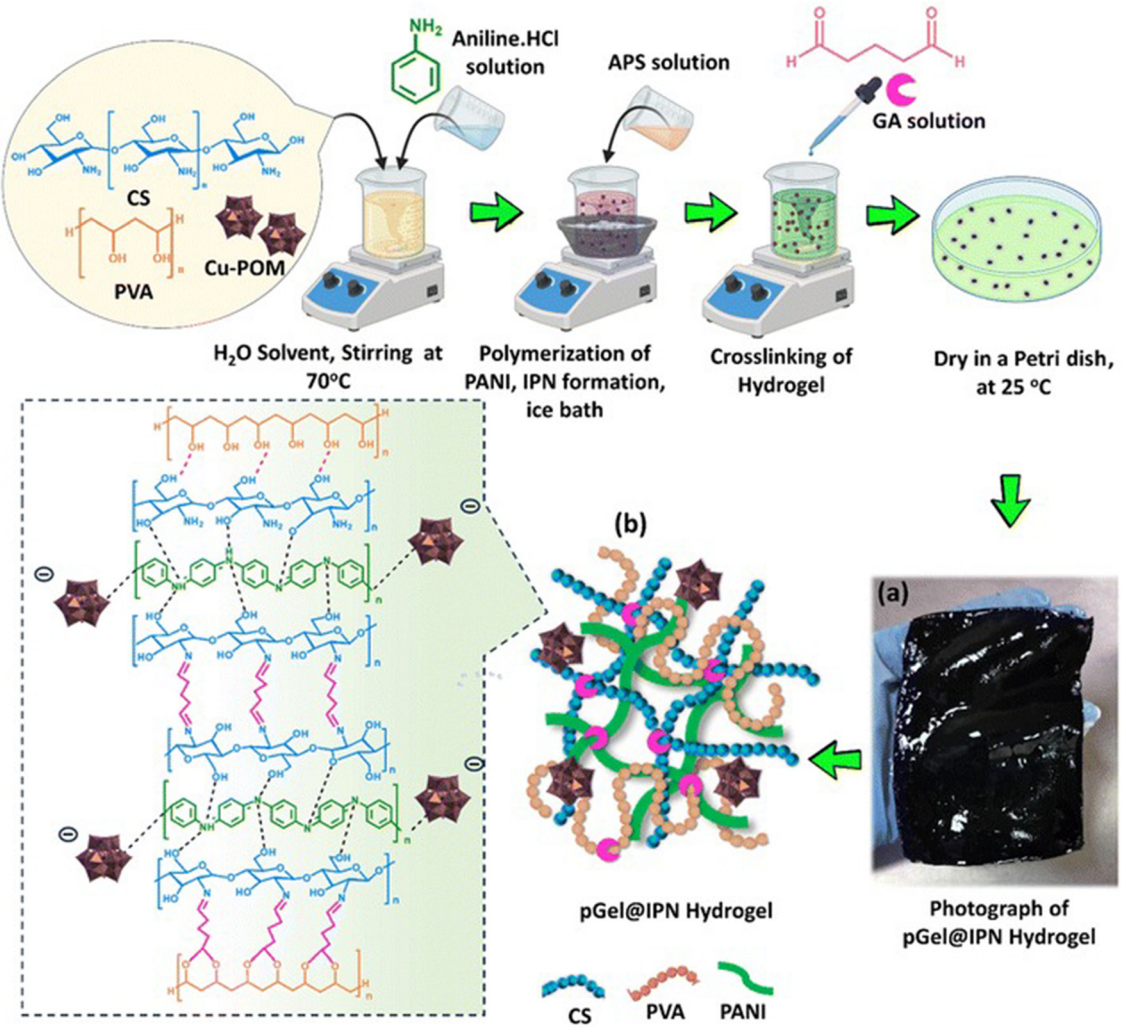

Fig. 4 Scheme showing the step wise synthesis of copper substituted polyoxometalate (Cu-POM) nanoclusters infused triple interpenetrating network hydrogel (pGel@IPN). Reproduced with permission.[122] Copyright 2024, Publisher Royal Society of Chemistry.

efficiency compared to individual physically or chemically crosslinked hydrogels. Moreover, a syringe-based filtration device using the dual crosslinked nanoCh hydrogels was prepared, which could achieve almost complete removal of MPs (size ~ 3 μm) with the highest flux of 8.22 mL cm^{-2} h^{-1} owing to the larger pore size and robust channel structure, offering scalability for large-scale water purification. Finally, after filtration, SEM images of the nanoCh hydrogel (top side and bottom side) were captured and clearly depicted the presence of adsorbed MPs on the top surface, indicating their effective removal (Fig. 5c).[125] The porosity of the dual-crosslinked nanochitin hydrogels was 257.5 m^2 g^{-1} and carried rich pores in the microscale range, which explained effective particle interception both on the surface and within the hydrogel structure with a flux of 8.22 mL cm^{-2} h^{-1}.[125] Overall, the use of these systems for the elimination of MPs could pave a new pathway for next-generation portable wastewater treatment methods.

Considering nature-inspired catechol-based chemistry, Han *et al.* fabricated a polydopamine (PDA)-modified sodium alginate hydrogel (PMSAH) for eliminating MPs from drinking water.[90] Here, PDA-modified sodium alginate was crosslinked using calcium ions and tested for the elimination of different MPs including PE and PS of varying sizes and surface charges (Fig. 6). For real life application, PMSAH was also utilized for the removal of MPs generated by boiling commercially available tea bags. It was reported that PMSAH exhibited the highest removal efficiency of ~99.6%, which could be attributed to various intermolecular interactions, including hydrogen bonding, electrostatic interactions, hydrophobic interactions, and π–π stacking interactions offered by PDA (Fig. 6).[90]

Taking a step further in the direction of combined adsorption, detection, and actuation performance while still considering catechol-based chemistry, Guo *et al.* imparted hydrogels with stimuli responsiveness and multifunctionality to improve their performance for heavy metal adsorbed MP remediation.[126] In this case, a smart light-driven multifunctional hydrogel actuator was engineered for the selective removal of iron adsorbed polystyrene microplastics (Fe^{3+}@PS) from

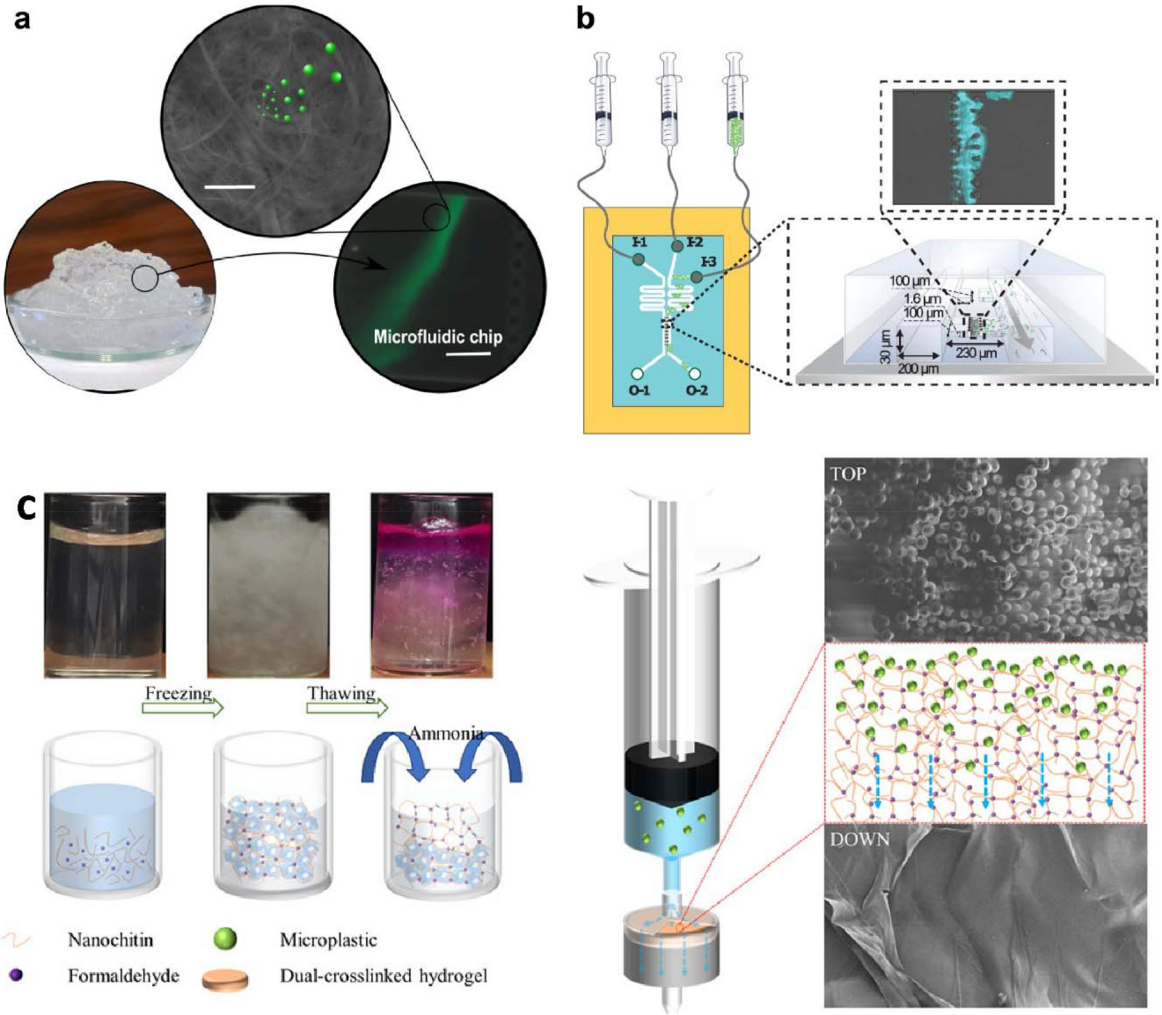

Fig. 5 (a) Schematic representation of a proof of concept for capturing fluorescently labelled MPs by a CNF hydrogel using a microfluidic set-up coupled with fluorescent imaging (scale bar in the SEM image is 1 μm and 25 μm in the microfluidic chip image). (b) Microfluidic setup for a CNF hydrogel containing trap showing the injection of fluorescent MPs and water. Reproduced under the CCBY-license.[124] Copyright 2022, Publisher Nature Portfolio. (c) Images, illustration of the synthetic protocol of nanoCh hydrogels, and the syringe-based filtration device using a dual cross-linked nanoCh hydrogel (inset: SEM image of the top side and bottom (down) side of the nanoCh hydrogel after filtration). Reproduced with permission.[125] Copyright 2025, Publisher Elsevier.

water.[126] Here, covalently bonded acrylated polyethyleneimine and polydopamine copolymer (M-PEI@PDA), graphene oxide (GO) nanosheets, and poly(*N*-isopropyl acrylamide) (PNIPAM) formed a hierarchical interpenetrating network of hydrogel (M-PEI@PDA/GO/PNIPAM) (Fig. 7a). M-PEI@PDA copolymer was prepared through Michael addition providing fluorescence responsiveness to the hydrogel. Subsequently, a multifunctional crosslinked hydrogel was fabricated *via in situ* radical polymerization between a thermo-responsive NIPAM monomer, an M-PEI@PDA copolymer and an *N*,*N*′-methylene bisacrylamide (MBA) crosslinker (Fig. 7a). Notably, the hydrogel showed strong interfacial interactions between catechol and the amino groups of the polymer and Fe^{3+}@PS, offering an excellent reversible adsorption property (Fig. 7b). Furthermore, by leveraging the temperature responsiveness of PNIPAM, the hydrogel actuator demonstrated an excellent actuation performance (bending speed: 2–4° s^{-1}, and swimming speed: 0.5 mm s^{-1}), thus facilitating the locomotive adsorption of MPs present in water (Fig. 7b). The reported hydrogel displayed the ultralow detection of ferric ions (0.98 μM) and selective adsorption of Fe^{3+}@PS (~97%) with high adsorption (~95%) and desorption efficiency (~99%) for MPs, making it a suitable candidate for removing MPs from water.[126]

6. Sponges for removal of MPs

In addition to hydrogels, hydrogel derived sponges have recently attracted attention as a promising alternative for MP removal owing to their highly porous structures, light weights, and good adsorption capacities. The sponges are typically fab-

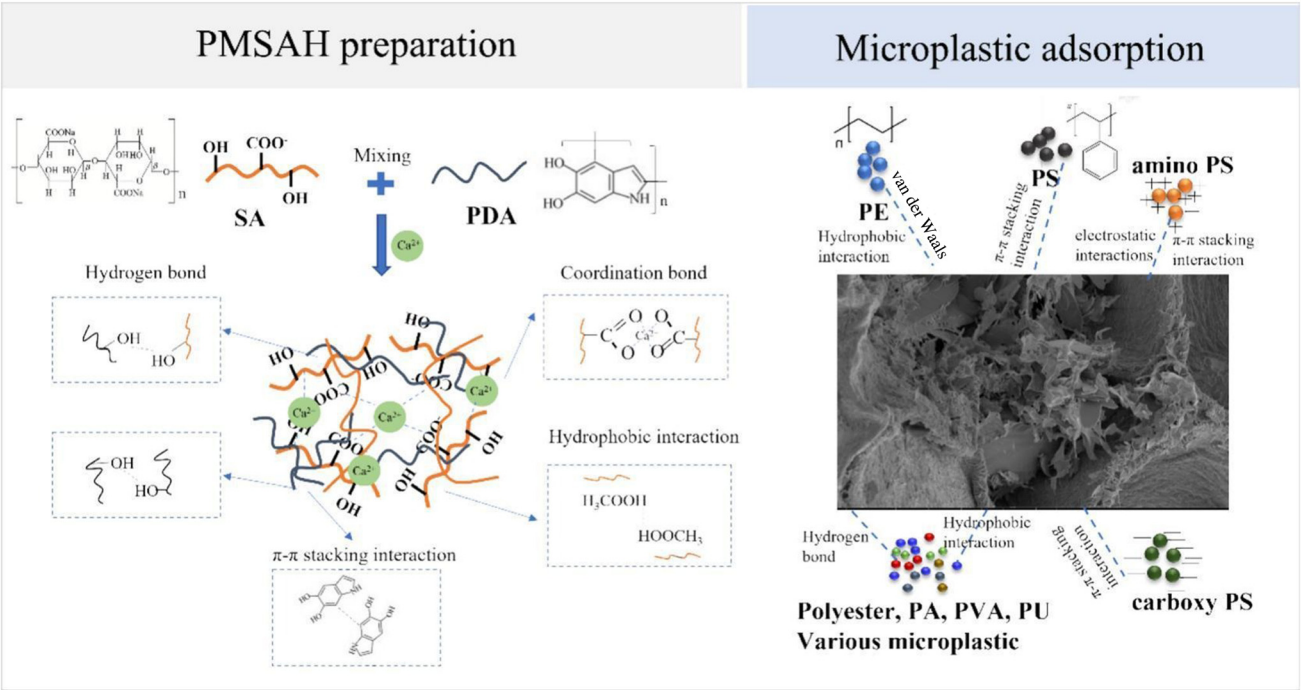

Fig. 6 Schematic representation of the fabrication of the PMSAH hydrogel and interactions involved in MP adsorption. Adapted with permission.[90] Copyright 2025, Publisher Elsevier.

ricated by drying hydrogels using the freeze drying method. For example, Sun *et al.* synthesized graphene oxide-incorporated chitin-based (ChGO) sponges by freeze-drying of the corresponding hydrogel with epichlorohydrin-based crosslinking.[127] ChGO sponges could be reused and showed a high adsorption efficacy of 89.8%, 72.4%, and 88.9% for PS, carboxylated polystyrene (PS-COOH), and aminated polystyrene (PS-NH_2) MPs, respectively, after three adsorption–desorption cycles. The pore size of the sponge was between 50 and 76 μm and it was capable of accommodating polystyrene MPs (1 μm in size) in up to 3 cycles without any degradation. Here, the adsorption of MPs was facilitated by hydrogen bonding, electrostatic interactions, and π–π interactions between MPs and ChGO sponges. Additionally, biodegradation results also confirmed the degradability of ChGO sponges by microorganisms present in soil.[127] Taking this a step further, Sun *et al.* developed various chitin-based sponges including pure chitin (Ch), chitin/O–C_3N_4 (ChCN), chitin/GO (ChGO), chitin/GO/carboxymethyl cellulose (ChGO-CL), and chitin/GO/chitosan (ChGO-CS).[128] It was reported that the incorporation of additional material in chitin sponges further improved their mechanical strength and adsorption capacity. The pore size of the prepared sponges varied between 86 and 181 μm, and the sponges were efficient at removing different functionalized PS MPs (~1 μm) with removal efficiencies ranging from ~71% to ~92%. Moreover, these sponges could be reused in up to three cycles for MP removal.[128]

Next, Zhu *et al.* introduced polyaniline (PANI) into the chitin matrix crosslinked with epichlorohydrin to develop a chitin/polyaniline sponge (ChPANIs) having a macroporous structure with a uniform network.[129] It was reported that upon increasing the hydrophilicity of PANI in ChPANIs, the removal efficacy of polystyrene MPs (size = 1 μm) was enhanced from 84% to 91%, which could be attributed to better dispersibility of PANI in the chitin-based sponge matrix with a porous structure ranging from 190 μm to 470 μm. More hydrophilic PANI in ChPANIs provided more contact area and adsorption sites, which enhanced the electrostatic interactions with MPs, providing an excellent adsorption performance. Furthermore, SEM images demonstrated that ChPANIs efficiently removed MPs without causing significant alterations in its sponge-like morphology, whereas higher magnification clearly confirmed numerous MPs adhered to the surface. The adsorption of MPs followed the Freundlich isotherm, suggesting multi-layer adsorption of MPs on ChPANIs. Moreover, ChPANIs demonstrated good mechanical strength, reusability in up to five cycles, and ~89% degradation over 15 days in soil once their purpose had been served.[129]

Nowadays, fibrous sponges have attracted significant interest for the removal of MPs. In this direction, Wu *et al.* demonstrated that a fibrous framework sponge derived from exfoliated β-chitin nanofibers and suspended cellulose fibers could be derived simply through hydrogen bonding without the use of any crosslinking agents (Fig. 8A). The fibrous sponge was prepared by interrupting the original hydrogen bonds in the presence of an acid, stripping cotton into finer cellulose fibers, exfoliating chitin into a nanofibrous plane, and then interlacing these fibers to induce intermolecular

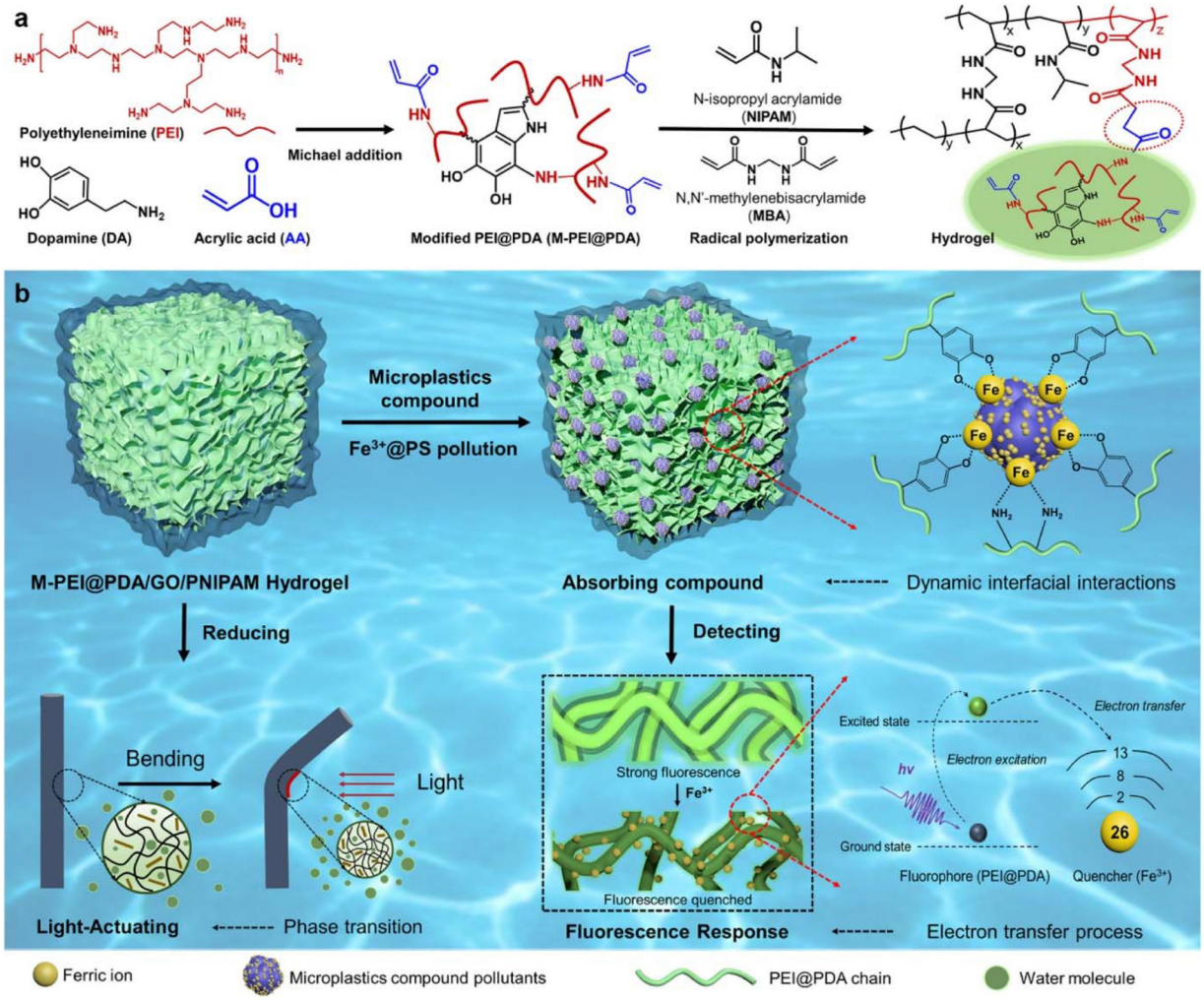

Fig. 7 (a) Schematic illustration of the fabrication of the M-PEI@PDA/GO/PNIPAM-based multifunctional hydrogel. (b) Multifunctional hydrogel with combined adsorption, detection, and actuation performance for efficient removal of Fe^{3+}@PS. Reproduced with permission.[126] Copyright 2022, Publisher American Chemical Society.

hydrogen bonds. The fabricated sponge demonstrated a porous interconnected structure in addition to numerous activated functional groups such as OH^-, NH_3^+, and $NHCO^-$. The presence of these functional groups assured the removal of MPs through multilevel interactions, including electrostatic interactions, hydrogen bonding and van der Waals interactions (Fig. 8B). The fabricated sponge demonstrated 98.0–99.9% MP removal efficiency and was reusable in up to five adsorption–desorption cycles without any effective loss in the degradation efficiency.[130]

Furthermore, Ko *et al.* utilized a freeze-drying method coupled with genipin (GP)-based crosslinking to fabricate cost effective and light-weight graphene oxide/chitosan/genipin sponges (GO_5/CS/GP).[131] These sponges were macroporous (porosity = 95%, pore size = 58.3 ± 47.8 μm, density = 32.6 mg cm^{-3}) and exhibited an excellent capturing rate (~73%) for PS NPs with a diameter of 0.026 μm compared to PS MPs with a diameter of 1.1 μm (~41%). The adsorption of PS MPs on GO_5/CS/GP was attributed to hydrogen bonding, pore filling interactions, hydrophobic interactions, and π–π interactions. This work highlighted the need for developing systems that could be used for the efficient removal of NPs.[131]

Similarly, Risch *et al.* freeze dried a chitosan electrospun nanofiber-based suspension followed by crosslinking with GA to develop chitosan nanofiber sponges (CSNFs) with good water stability.[132] CSNFs exhibited a bulk density of 5.77 mg cm^{-3}, a pore diameter 163 ± 41 μm and a porosity of 99.59%. The hierarchical pore structure of CSNFs was utilized to remove PET MPs and Arizona test dust (ISO 12103-1) suspensions. These sponges exhibited high selectivity for the adsorption of PET MPs from water with ~99% removal efficiency, suggesting their application in tackling MP-based pollution.[132]

In another direction, taking inspiration from anisotropic vessels in hardwood, Xu *et al.* developed biomimetic, double crosslinked CS-based sponges (BGCSs) by combining directional freezing with freeze drying and GA-based cross-

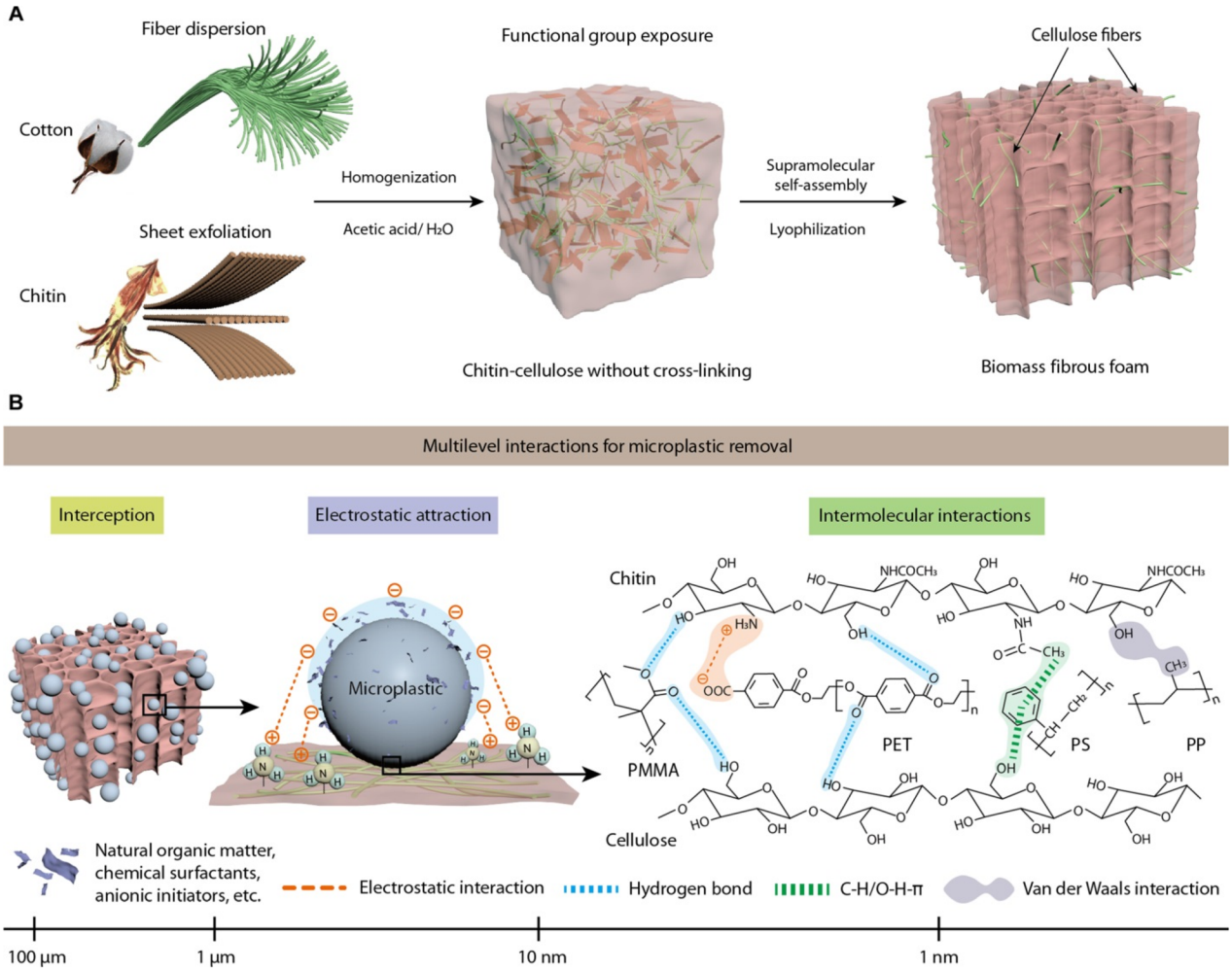

Fig. 8 (A) Schematic illustration of the self-assembly of chitin/cotton fibrous foam, and (B) mechanistic pathway showing multilevel interactions for the removal of MPs. Reproduced with permission.[130] Copyright 2024, Publisher Science.

linking.[133] Here, sponges were reinforced with flexible bacterial cellulose fibrils, which served as physical crosslinkers by forming supramolecular assemblies with chitosan (soft phase). Additionally, treatment with GA vapor further resulted in a covalently crosslinked network (hard phase) in sponges (Fig. 9a). Moreover, BGCS displayed an excellent wet compressive resilience with a retention rate of ~95% even after 100 compression cycles. It was reported that the anisotropic structure of the sponges served as a rapid water treatment channel and removed ~78% of PS MPs (~1 μm in size) within 420 min at room temperature. Owing to its higher wet compressibility, the developed sponge demonstrated a good removal efficiency for PS MPs (~47%) even after 20 cycles (Fig. 9b). Here, electrostatic interactions, conjugation, and intraparticle diffusion were identified as primary forces for the adsorption of PS MPs on sponges.[133]

Building on the concept of enhancing mechanical strength and improving water stability *via* crosslinking, Ma *et al.* synthesized Ca^{2+} crosslinked sodium alginate-based sponges *via* a secondary freeze-drying method.[134] These sponges exhibited excellent water absorption (~1193–5232%), high porosity (~89%), good mechanical properties, and remarkable PS MP (≤5 μm) removal efficiency (~92%). The adsorption of MPs on sponges was attributed to intra-particle diffusion, hydrogen bonding, and π–π interactions. Overall, the above-mentioned examples clearly signify the potential of polymeric sponges for addressing the issue of MP pollution to move towards sustainable development.

7. Electrospun fiber-based membranes for removal of MPs

In recent years, electrospun polymeric nanofiber-based membranes have emerged as a potential candidate for water purification. These membranes display a high surface area to volume ratio, a highly interconnected pore structure, and adjustable physicochemical properties (*e.g.*, wettability) that help to increase the fluid flow rate while reducing fouling.[135–138] In the literature, nanofibrous membranes have

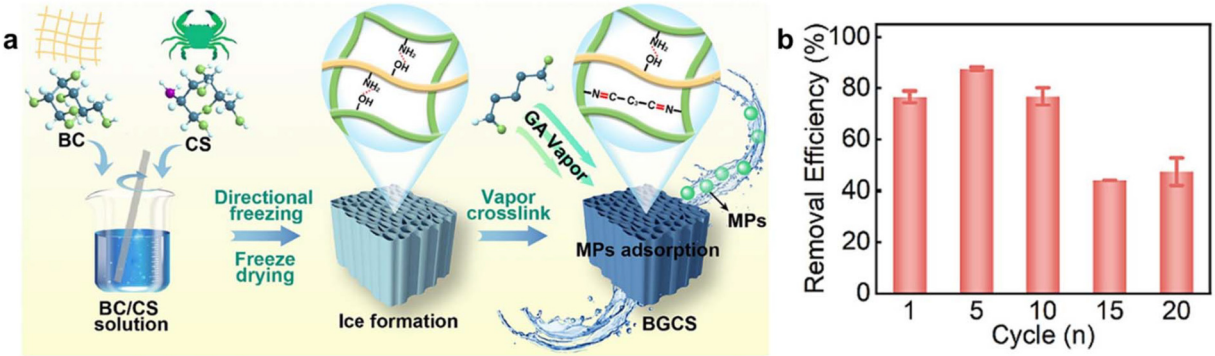

Fig. 9 (a) Synthetic route for the fabrication of biomimetic, double crosslinked chitosan-based sponges (BGCS). (b) Histogram showing the efficiency of BGCS in removing PS MPs for up to 20 cycles. Reproduced with permission.[133] Copyright 2023, Publisher Elsevier.

been developed through electrospinning of both natural and synthetic polymer-based solutions.[139,140] The morphology and architecture of these electrospun fibers can be tuned by adjusting several parameters, including polymer solution related parameters (concentration, viscosity, and conductivity), electrospinning process parameters (flow rate, voltage, and distance between the spinneret and collector), and environmental parameters (temperature or humidity).[139,141] The resulting fibrous mat can also be processed to form a dispersion of nanofibers, which in turn can be used for the preparation of sponges or wet-laid membranes.[142,143] So far, electrospun fiber-based membranes have been widely explored for removing organic and inorganic pollutants including heavy metal ions, dyes, and oil from the aqueous environment due to their large surface area and adjustable wettability.[144,145] The main driving force behind the removal of pollutants from the aqueous environment is adsorption. Recently, scientists started to explore electrospun nanofiber-based membranes for the removal of MPs.

In this direction, Wang *et al.* fabricated polyacrylonitrile (PAN)-based nanofiber membranes by electrospinning followed by a hot-pressing method.[146] The fiber diameter, membrane thickness, and membrane porosity were optimized by adjusting various processing parameters. These membranes were utilized for the removal of PS beads (0.2 μm and 0.1 μm) from water. It was reported that the rate of rejection of membranes for 0.2 μm PS beads approached ~100% upon reducing the porosity of the membrane. Moreover, membranes with relatively small nanofiber diameters were able to completely reject all the 0.1 μm PS beads while maintaining a high flux and low degree of fouling. This study demonstrated that the fiber diameter and membrane porosity played a crucial role in determining the equivalent/apparent pore size, which in turn directly related to the microfiltration performance.[146]

With the aim of developing a self-standing membrane without any supporting substrates, Juraij *et al.* developed a polyurethane/graphene oxide–montmorillonite-based electrospun composite (PGT) membrane (Fig. 10a).[147] Here, different amounts of graphene oxide–montmorillonite (GOMt), ranging from 5 to 20 wt%, were loaded into the PGT membrane. Based on a high tensile strength (6.6 MPa), porosity (~61%), superhydrophilicity, pressure-driven water flux (8163 L m^{-2} h^{-1}), and higher gravity-driven water flux (793 L m^{-2} h^{-1}), the PGT membrane containing 20 wt% GOMt was chosen for MP and NP

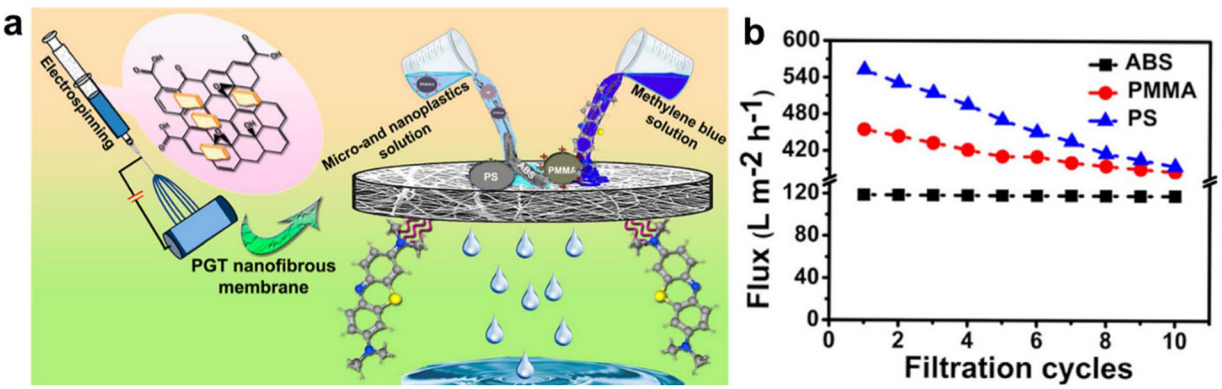

Fig. 10 (a) Schematic representation showing a PGT-based electrospun composite membrane for the removal of MPs, NPs, and MB from water. (b) Graph showing the variation in flux associated with the reusability of the PGT electrospun membrane for up to 10 filtration cycles. Reproduced with permission.[147] Copyright 2023, Publisher American Chemical Society.

separation from water. For separation studies, three individual dispersions of MPs and NPs were prepared, namely, acrylonitrile butadiene styrene MPs (ABS MPs), PS NPs, and poly (methyl methacrylate) NPs (PMMA NPs). Experimental results showed that ABS MPs, PMMA NPs, and PS NPs followed cake formation (R^2 = 0.9997), intermediate blocking (R^2 = 0.9998), and standard blocking (R^2 = 0.9907) fouling mechanisms, respectively. Here, the removal efficiencies of ABS MPs, PMMA NPs, and PS NPs were 98%, 97%, and 95%, respectively. In the case of ABS MPs, constant flux was observed due to easy removal of the cake layer from the membrane. However, flux reduction was reported in the case of PMMA NP (385.87 L m^{-2} h^{-1}) and PS NP (395 L m^{-2} h^{-1}) filtration owing to the adherence of NPs on the membrane (Fig. 10b). Overall, this electrospun fiber-based membrane showed a good performance for the separation of both MPs and NPs for up to 10 cycles, further confirming its reusability. In addition to MP and NP removal, the membrane also exhibited a selective adsorption capacity of methylene blue (MB) (417 mg g^{-1}) from a methylene blue/methyl orange (MB/MO) mixture, thus rendering itself a promising candidate for water purification.[147] ABS MPs followed the cake formation mechanism with R^2 = 0.9997, while the intermediate blocking mechanism was the predominant mechanism in the case of PMMA NPs (R^2 = 0.9998) and PS NPs (R^2 = 0.9907). This may be because the size of ABS MPs (624 nm) is greater than the pores of the electrospun composite, which favours the formation of a cake layer and causes extensive relative flux decay (85%) during the filtration of ABS MPs. Here, cake formation was responsible for the efficient removal efficiencies of ABS MPs. In contrast, in the cases of PS NPs and PMMA NPs, electrostatic interactions between negatively charged electrospun composite fibers (ζ potential = −42 mV) and positively charged NPs (ζ potential = +38 mV for PS NPs and ζ potential = +41.7 mV for PMMA NPs) were responsible for the removal of NPs.[147]

Taking this a step further, Rist *et al.* developed self-standing electrospun fiber membranes from bio-based polyamide 6.9 (PA@EFMs).[142] Here, polyamide 6.9 was prepared using hexamethylene diamine and azelaic acid derived from plant oil. PA@EFMs exhibited good mechanical strength and high resistance to solvents. The highly porous architecture of PA@EFMs (pore diameter = 0.55 μm to 1.14 μm) showed a remarkable efficacy of >99.7% for the filtration of PS MPs (~679 nm) from water. Additionally, the high hydrophobicity of PA@EFMs facilitated the efficient adsorption of oil from water, achieving a separation efficacy of 99.9%, while retaining a high permeate flux of 5345 L m^{-2} h^{-1}. Furthermore, the recyclability of PA@EFMs was demonstrated through back flushing, highlighting the sustainable potential of these membranes.[142]

Next, to enhance the structural integrity of electrospun membranes, Gopakumar *et al.* fabricated electrospun fibers of PVA, which were crosslinked with GA to form a stable nanofibrous membrane.[148] The MP removal efficacy of the membrane was evaluated using PE MPs (5 μm ≤ d ≤ 25 μm) (~99% removal efficiency) and PS MPs (d ≤ 1 μm) (~77% removal efficiency). Furthermore, an excellent recovery in performance was observed by backwashing, even after five cycles, thus showcasing the durability and reusability of the PVA membrane. Additionally, the membrane displayed ~69% removal efficiency for lead at pH 6, demonstrating its capability to handle water pollution from different fronts.[148]

In another direction, Wang *et al.* utilized a layer-by-layer assembly (LbL) technique to fabricate three different membranes (M^0, M^-, and M^+), exhibiting neutral, negative, and positive charges at physiological pH 7.4.[149] These membranes were fabricated by assembling three layers of PEI and PAA onto the hydrolysed electrospun PAN membrane. The hydrolysis step was carried out to incorporate negatively charged carboxylic groups, promoting the LbL assembly process. Furthermore, three different sizes of PS NPs (50 nm, 100 nm and 500 nm) were chosen to evaluate the removal efficacy of membranes under very low pressure. Among these modified membranes, M^+ membranes showed an excellent performance in removing PS NPs of different sizes, with rejection efficiencies of ~99.4% for 500 nm, ~99.3% for 100 nm, and ~89.9% for 50 nm, while maintaining a high flux. It was reported that the removal of PS NPs was primarily governed by electrostatic interactions rather than pore-size exclusion. However, M^- and M^0 membranes had a limited rejection efficiency due to their similar or neutral surface charges in connection to PS NPs. Additionally, these membranes successfully retained bacterial contaminants like *E. coli* and *S. aureus* during filtration, which was attributed to the smaller pore size of membranes. Thus, the multifunctional nature of the M^+ membrane presents it as a promising alternative for addressing NP water pollution.[149]

Recently, creating eco-friendly materials with advanced 3D printing technology paved the way for developing tailored water filtration systems, notably beneficial for regions facing clean water scarcity. A persistent challenge in sustainable water treatment is the need for multifunctional, durable, reusable, and high-flux filtration solutions. In this regard, 3D printing has emerged as an efficient technique that has revolutionized design, prototyping, and manufacturing.[150] The flexibility of 3D printing facilitates the design of complex shapes and customized structures, permitting the development of membranes that are tailored to meet the specific requirements of wastewater treatment.[151] Considering the advantages of 3D printing, Fijoł *et al.* constructed fully bio-based and biodegradable polylactic acid (PLA)-based composite water filters *via* fused deposition modelling (FDM) 3D printing.[152] PLA filters reinforced with TEMPO-oxidized cellulose nanofibers (TCNF) and chitin nanofibers (ChNF) resulted in improved water throughput and mechanical strength compared to pristine PLA. The biocomposite filters were 3D printed in cylindrical and hourglass geometries with varying, multiscale pore architectures. In addition to their structural benefits, the filters exhibited a significant adsorption capacity for Cu^{2+} ions (234 and 208 mg g_{NF}^{-1} for TCNF and ChNF-reinforced filters, respectively), and PS MP (50–100 μm) removal from laundry water (54% for TCNF, and 35% for ChNF-reinforced filters). Moreover, metal ion adsorption was mainly governed by electrostatic interactions, while MP removal was due to size

exclusion and physical bonding to the filter surface. Other than that, PLA-based composite water filters demonstrated recyclability multiple times.[152] To the best of our knowledge, only one report is available in the literature on 3D printed filters for MP removal, emphasizing the need for further research and development to unlock their full potential in real-world wastewater treatment applications.

8. Comparative performance metrics

An extensive literature survey demonstrated that several materials, including hydrogels, electrospun fibers and sponges, had already been reported for the removal of MPs. Here, we have compared and summarized recent examples of hydrogels, sponges and electrospun fibers based upon their maximum removal efficiency and maximum adsorption capacity (Table 2). In addition to MP removal, some polymer-based materials have shown good potential to remove NPs based on the size exclusion mechanism and electrostatic interactions between oppositely charged surfaces. These examples are also included in Table 2 as the degradation of MPs in the surrounding medium over time may lead to the formation of NPs, which are also hazardous, like MPs, due to their small size.

It should be noted that although the electrospun fibers have shown significant potential to remove MPs from contaminated wastewater, they are still rarely employed in industrial-scale wastewater treatment plants due to their higher costs in comparison with those of hydrogels and sponges. Moreover, despite growing interest in utilizing polymeric systems in biological and chemical approaches for MP removal, this area remains less explored than conventional physical adsorption and filtration systems. This might be due to the difficulty of integrating catalytic and biological functionalities into polymeric matrices while maintaining sufficient permeability, mechanical stability, and long-term operational performance. The biological treatment process using enzyme-functionalized hydrogels usually exhibits limited environmental stability, slow degradation kinetics, pH sensitivity, temperature variations, and biofouling-related performance decline, and hence, it is rarely explored.

9. Management strategies

The management of MP contamination for a safe environment requires a multidimensional approach including the involvement of the public, industries, governments, and international organizations. In this direction, the first step is to reduce overall plastic consumption. Furthermore, public awareness programs should be conducted to educate people regarding the negative impacts of MPs on our environment and the significance of reducing plastic usage. This can be done by conducting outreach activities in schools, colleges, and community organizations. It has been found that the main source of MP production is single-use plastic (SUP).[162] To eliminate SUP from the environment, people should be encouraged to utilize reusable containers, bottles, and bags.

Furthermore, governments, industries, scientists, and individuals must work together to reduce plastic trash, improve plastic waste management, and create new alternatives. Governments may consider monitoring and limiting the usage of MPs in cosmetics, cleansing agents, and other personal care products. Furthermore, modern filtration technologies may be implemented to upgrade existing wastewater treatment facilities to eliminate MPs prior to their discharge into waterbodies.[163,164] Additionally, enhanced producer responsibility can be implemented.[165] Furthermore, governments should encourage industry to work on sustainable practices such as minimizing plastic-based packaging and increasing their efforts in plastic waste management. This may be done by rewarding organizations that take significant steps in this direction and invest in eco-friendly alternatives.

Waste management follows the five Rs hierarchy: reduce, reuse, recycle, redesign, and recover.[166] The generation of MPs can be reduced by minimizing the production of plastic. Reusing and recycling plastic products further helps to reduce the amount of plastic debris.[167] Furthermore, the sustainable management of plastic waste can also be achieved *via* upcycling, which provides other value added materials.[168] A portion of the energy can be recovered from plastic by incineration and approaches like co-fuelling of kilns, offering a practical route to achieving reasonable energy efficiency.[169] These strategies are advantageous compared to landfill disposal, as they enable energy recovery from plastic to some extent.[166]

Moreover, the molecular redesign of plastics has emerged as a new approach in green chemistry, and should be integrated into the design and life cycle analysis of plastics. In line with this, some alternatives can be used to minimize the excessive use of chemicals in plastic manufacturing, for example, citrates can be used as a substitute for synthetic plasticizers.[166] Similarly, zeolites can be employed to produce sustainable plastics from bio-based feedstock.[165] Zeolites can turn lactic acid into lactide, which is a key ingredient for making biodegradable plastics like PLA.[165] These innovations not only lower the environmental footprint of plastic production but also support the transition towards a circular and more sustainable material economy.

10. Challenges and future perspectives

MPs have been globally recognized as a major pollutant, leading to a surge in scientific efforts to develop strategies for handling MP pollution. In this regard, hydrogels have recently emerged as a potential candidate due to their unique swelling properties, allowing them to adsorb MPs on their surface and within the porous network, thus removing MPs from water. However, for effective application, hydrogels must be optimized to enhance their adsorption efficiency and mechanical

Table 2 Comparative analysis of different materials used for the removal of MPs

Material used	Type of matrix	Synthesis method	Type of microplastic removed	Size range of targeted MPs	Surface charges on the adsorbent	Pore/mesh size of the adsorbent	Maximum removal efficiency (%)	Maximum adsorption capacity (mg g^{-1})	Removal mechanism and remarks	Ref.
Lignin/poly(vinyl alcohol) hydrogel	Hydrogel	Functionalization of lignin through phenolization and ammoniation	Polystyrene Polyamide	5 μm	12 mV to 25 mV	23.77 nm	97.9 99.7	288.6	Adsorption	108
ChNFs/lignin composite hydrogel	Hydrogel	Chemical crosslinking of epichlorohydrin onto chitin nanofibrils and quaternized kraft lignin	Polystyrene	166.5 nm	~+12.1 mV	>100 μm	93.7	1790.8	Electrostatic interactions and π–π interactions	153
Polydopamine-modified sodium alginate hydrogel	Hydrogel	Ionic gelation in combination with *in situ* polydopamine coating/ polymerization	Polystyrene	0.1–1.5 μm	−19.63 mV	200 nm to 10 μm	99.6	154.57	Chemical adsorption, π–π interactions and electrostatic interactions	90
Gelatin–sodium alginate aerogel	Hydrogel	Chemical crosslinking of gelatin and sodium alginate with glutaraldehyde	Polystyrene	50 μm	—	1–10 μm	90	—	Adsorption, hydrogen bonding, ionic interactions and physical interception within the aerogel's 3D-network	154
Taro stem-sourced cellulose/ polypyrrole hybrid aerogel	Hydrogel	Chemical crosslinking and freeze-drying	Polystyrene	200–2000 nm	—	6.45 nm	91.55	818.06	Physical entrapment, hydrogen bonding, electrostatic interactions, and π–π interactions	155
Melamine sponges modified with mussel-inspired polydopamine	Sponge	Surface functionalization of melamine sponge with PDA–PEI coating	Micro- and nanoplastics	10 μm	—	160.85 μm	90	302	Electrostatic attractions, hydrophobic interactions, and π–π stacking with aromatic polymers	156
MOF-based superhydrophobic sponge	Sponge	Auto-polymerization of polydopamine followed by coprecipitation of Ni-MOF and PDA-modified sponge	Polystyrene, acrylonitrile–butadiene–styrene, polyvinyl chloride, polyethylene, and polypropylene	6.5–150 μm	65 mV	—	95.1	67.4	Electrostatic interactions, capillary force of inner pores, hydrogen bonding, hydrophobic interactions, and p–π conjugation	157
Chitin-cellulose nanofiber nanosponges	Electrospun nanofiber sponge	Controlled chemical modifications of starch and pectin followed by freeze–thaw technique to design ChCNF nanosponge	Polystyrene	1 μm	—	—	93.07	116.34	Intraparticle diffusion mechanism	158
Cu/Co-LDH-based superhydrophobic sponge	Sponge	PDA coating, *in situ* growth of CuCo-LDHs, and HDTMS surface modification on a pretreated melamine sponge	Polyethylene and polypropylene	6.5–150 μm	62 mV	—	100	56.2	Electrostatic attraction, and hydrogen bonding through intraparticle diffusion mechanisms	159
Wood derived cellulose sponges	Sponge	Delignification of balsa wood and sulfonation modification of wood derived cellulose sponges	Amine-modified polystyrene microspheres	500 nm	−8.5 mV to −94.4 mV	—	88.8	586.95	Electrostatic attraction, hydrogen bonding and van der Waals forces	160

Table 2 *(Contd.)*

Material used	Type of matrix	Synthesis method	Type of microplastic removed	Size range of targeted MPs	Surface charges on the adsorbent	Pore/mesh size of the adsorbent	Maximum removal efficiency (%)	Maximum adsorption capacity (mg g^{-1})	Removal mechanism and remarks	Ref.
Loofah plant-derived biodegradable superhydrophobic sponge	Sponge	Dip-coating method	Polystyrene microplastics	5 μm	—	—	99.9	569	Monolayer and multilayer adsorption mechanisms	161
Hardwood vessel-inspired chitosan-based sponge	Sponge	Directional freeze-casting of a chitosan solution followed by glutaraldehyde vapor crosslinking, neutralization, and freeze-drying	Polystyrene	1 μm	—	—	94.9	0.26	Adsorption mechanism through electrostatic bonding and p–π interactions	133
Bio-based electrospun polyamide membrane	Electrospun fiber	Melt polycondensation of hexamethylenediamine–azelaic acid, followed by electrospinning and emulsion polymerization	Polystyrene	0.3 μm	–	0.55–1.14 μm	99.8	–	Surface filtration mechanism with 123% high initial permeability, 99.9% separation efficiency for oil–water emulsion with a high flux of 5345 L m^{-2} h^{-1}, significant antifouling property of the membrane up to 10 cycles	142
Electrospun polyurethane nanofiber membrane	Electrospun fiber	Surfactant-free emulsion polymerization followed by electrospinning	Acrylonitrile butadiene styrene, polystyrene and polymethylmethacrylate	90–825 nm	−42 mV	1309 nm	93%	—	Cake formation, intermediate blocking, and standard blocking fouling mechanisms, 8163 L m^{-2} h^{-1} pressure-driven water flow and 793 L m^{-2} h^{-1} gravity-driven water flux, reusability up to 10 filtration cycles	147
Polyvinyl alcohol nanofibrous membrane	Electrospun fiber	Electrospinning 7% and 10 wt% aqueous PVA solutions at 20 kV using a rotary drum collector under optimized flow rate and spinning conditions	Polyethylene and polystyrene	<50 μm	—	169 nm and 113 nm	77.3	—	Size exclusion mechanism 109 ± 1.67 L m^{-2} min^{-1} membrane flux at 5 psi, reduced fouling time with 75% ± 3.5% efficiency after 5 round of filtration cycles	148
Electrospun polyacrylonitrile membrane	Electrospun fiber	Electrospinning fabrication of PAN nanofibrous membrane followed by layer-by-layer (LbL) surface modification using PEI/PAA polyelectrolyte assembly	Polystyrene	50–500 nm	+18 mV to −60 mV	—	89.9	—	Electrostatic attraction-driven adsorption and low pressure driven by low pressure, 1452.4 L m^{-2}·h^{-1} highest flux of the membrane in pure water, promising fouling resistances to bacteria, recyclability of the membrane up to two filtration cycles	149

Table 2 *(Contd.)*

Material used	Type of matrix	Synthesis method	Type of microplastic removed	Size range of targeted MPs	Surface charges on the adsorbent	Pore/mesh size of the adsorbent	Maximum removal efficiency (%)	Maximum adsorption capacity ($mg\ g^{-1}$)	Removal mechanism and remarks	Ref.
Chitosan/ polyethylene oxide nanofiber sponge	Electrospun fiber sponge	Electrospinning, followed by neutralization of chitosan–polyethylene oxide nanofiber and preparation of chitosan NF sponges	Poly(ethylene terephthalate)	48.7 μm	—	130 μm	99.46	335.3	—	132
Electrospun polyacrylonitrile membrane	Electrospun fiber	Electrospinning and subsequent surface modification *via* layer-by-layer assembly	Polystyrene	50–500 nm	—	—	89.9	—	Electrostatic attraction	149

robustness under diverse environmental conditions. It is also crucial to investigate how these hydrogels interact with MPs, specifically under different pH, temperature, and saline conditions. In future, studies should be performed to understand molecular-level interactions focusing on the effects of charge, hydrophobicity, surface chemistry, and other physicochemical properties of hydrogels on the adsorption process.

Furthermore, attention should be paid to tuning the chemical structure of polymeric hydrogels, sponges, and electrospun fibers for selectivity towards specific types of MPs. The incorporation of stimuli responsive features in these adsorbent materials may further aid in the easy capture and removal of MPs.[126] In addition to the adsorption of MPs, the overall composition of these materials should be chosen in such a way that the degradation of MPs can also be achieved. This direction can be explored by embedding photocatalytic nanomaterials inside the polymeric matrix.[122] Moreover, sustainability, biodegradability, reusability, processability, scalability, and reduced secondary pollution are important criteria for analyzing the practical applicability of these materials. Hence, a thorough analysis of existing materials with regard to these aspects is essential.

It should be noted that MPs are easier to detect, monitor, and remove using existing analytical and separation techniques due to their micron-scale dimensions. However, NPs pose a significant challenge even with existing techniques due to their smaller size. Additionally, NPs exhibit greater ecotoxicological impacts and can easily penetrate through cell membranes compared to MPs. Due to their large surface to volume ratio, NPs can exhibit higher uptake of toxic chemicals compared to the same mass of MPs, and may produce a Trojan horse effect.[170] Although advanced characterization methods such as electron microscopy, Raman spectroscopy, dynamic light scattering analysis, Fourier-transform infrared spectroscopy and thermal analysis have been explored for the quantification and detection of NPs, their precise identification and monitoring remain a major challenge that requires further technological advancements to solve.

Effective utilization of the aforementioned adsorbent materials on a large scale is another hurdle. Although lab-scale results are promising, scaling up to larger operations demands cost effectiveness, easy material accessibility, and broad applicability of a single system. Moreover, strategies for incorporating these materials into filters, membranes, or reactors utilized in municipal and industrial water treatment should be investigated to facilitate their large-scale utilization. Furthermore, the exploration of AI in the context of wastewater treatment still remains at a nascent stage. The application of AI models in this context may help in the automation of such water treatment facilities, resulting in easy and low-cost operations.[171,172] This can also help in predicting the removal efficiency of hydrogels, sponges, and electrospun fiber-based materials under complex and continuously varying wastewater conditions.[173]

Finally, researchers should concentrate on fabricating biodegradable hydrogels, sponges, and electrospun fiber-based

materials that can be readily disposed of or repurposed at the end of their life cycles, thereby minimizing secondary environmental pollution. Considering the *waste-to-wealth* approach, different waste resources or biomass can be employed for fabrication of these materials. Additionally, new approaches must be developed to reprocess used materials into other useful value-added materials that can be further utilized for the benefit of society. Moreover, the long-term ecological and biological impact of employing these materials for MP and NP extraction should also be evaluated along with their life cycle analysis.

11. Conclusion

MP pollution has become an alarming environmental concern due to the widespread applicability of plastic products and adverse impact on both terrestrial and aquatic ecosystems. This review highlights the importance of different removal methods and recently explored materials. Distinct studies represented the effectiveness of the adsorption method for MP removal. In this regard, polymeric hydrogels, sponges, and electrospun fibers have attracted significant interest as potential adsorbent materials owing to their highly porous architectures, which provide a greater surface area for the capture of MPs and NPs. Recent laboratory studies have shown >99% MP removal efficiencies using polydopamine-modified sodium alginate hydrogel. Similarly, Loofah plant-derived biodegradable superhydrophobic sponges have shown >99.9% MP removal potential. Furthermore, in some cases, the incorporation of different additives into these materials improves their mechanical strength and helps to shorten the adsorption time, while also offering the capability of MP degradation. However, research on polymeric hydrogels, sponges, and electrospun fibers for MP and NP removal still remains in its nascent stage. Continued research and innovation in these materials are essential for optimizing their usage and ensuring their economic feasibility to take a step further to move towards global sustainable development goals.

Conflicts of interest

The authors declare no conflicts of interest.

Abbreviations

AA	Acrylic acid
ABS	Acrylonitrile butadiene styrene
AM	Acrylamide
AOPs	Advanced oxidation processes
BC	Bacterial cellulose
BGCS	Double crosslinked chitosan-based sponge
Ch	Chitin
ChCN	Chitin/O-C_3N_4
ChGO	Graphene oxide-incorporated chitin
ChGO-CL	Chitin/GO/carboxymethyl cellulose
ChGO-CS	Chitin/GO/chitosan
ChNF	Chitin nanofibers
ChPANIs	Chitin–PANI sponge
CNF	Cellulose nanofiber
CS	Chitosan
CSNF	Chitosan nanofiber sponges
Cu-POM	Copper substituted polyoxometalate
FDM	Fused deposition modelling
Fe^{3+}@PS	Iron doped polystyrene microplastics
GA	Glutaraldehyde
GO	Graphene oxide
GO_5/CS/GP	Graphene oxide/chitin/genipin sponges
GOMt	Graphene oxide–montmorillonite
GP	Genipin
IPNs	Interpenetrating networks
LbL assembly	Layer-by-layer assembly
LG-GH-PVA	Lignin/epichlorohydrin/polyvinyl alcohol
MA	Methacrylic acid
MB	Methylene blue
MBA	*N*,*N*′-Methylene bisacrylamide
MO	Methylene orange
MOFs	Metal–organic frameworks
MPs	Microplastics
NIPAM	*N*-Isopropylacrylamide
NPs	Nanoplastics
NVCL	*N*-Vinyl caprolactam
NVP	*N*-Vinylpyrrolidone
PA	Polyamide
PAA	Polyacrylic acid
PAHs	Polycyclic aromatic hydrocarbons
PAN	Polyacrylonitrile
PANI	Polyaniline
PC	Polycarbonate
PCBs	Polychlorinated biphenyls
PDA	Polydopamine
PE	Polyethylene
PEG	Polyethylene glycol
PEI	Polyethylene imine
PA@EFMs	Polyamide electrospun fiber-based membranes
PEI@PDA	Polyethyleneimine and polydopamine copolymer
PET	Polyethylene terephthalate
pGel@IPN	Cu-POM infused triple interpenetrating network hydrogel
PGT membrane	Polyurethane/graphene oxide–montmorillonite electrospun composite membrane
PLA	Polylactic acid
PMMA	Polymethyl methacrylate nanoplastics
PNIPAM	Poly(*N*-isopropyl acrylamide)
PP	Polypropylene
PS	Polystyrene
PS-COOH	Carboxylate-functionalized polystyrene
PS-NH_2	Amine-functionalized polystyrene
PU	Polyurethane

PVA	Polyvinyl alcohol
PVC	Polyvinyl chloride
PVDF	Polyvinylidene fluoride
ROS	Reactive oxygen species
SEM	Scanning electron microscopy
SUP	Single-use plastic
TCNF	TEMPO-oxidized cellulose nanofibers

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

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References

1 E. Huo, H. Lei, C. Liu, Y. Zhang, L. Xin, Y. Zhao, M. Qian, Q. Zhang, X. Lin and C. Wang, Jet fuel and hydrogen produced from waste plastics catalytic pyrolysis with activated carbon and MgO, *Sci. Total Environ.*, 2020, **727**, 138411.
2 I. Conti, C. Simioni, G. Varano, C. Brenna, E. Costanzi and L. M. Neri, Legislation to limit the environmental plastic and microplastic pollution and their influence on human exposure, *Environ. Pollut.*, 2021, **288**, 117708.
3 Y. Xiang, L. Jiang, Y. Zhou, Z. Luo, D. Zhi, J. Yang and S. S. Lam, Microplastics and environmental pollutants: Key interaction and toxicology in aquatic and soil environments, *J. Hazard. Mater.*, 2022, **422**, 126843.
4 A. Reichelt-Brushett, *Marine pollution–monitoring, management and mitigation*, Springer Nature, 2023.
5 C. H. Ng, M. A. Mistoh, S. H. Teo, A. Galassi, A. Ibrahim, C. S. Sipaut, J. Foo, J. Seay, Y. H. Taufiq-Yap and J. Janaun, Plastic waste and microplastic issues in Southeast Asia, *Front. Environ. Sci.*, 2023, **11**, 1142071.
6 P. Li, X. Wang, M. Su, X. Zou, L. Duan and H. Zhang, Characteristics of plastic pollution in the environment: a review, *Bull. Environ. Contam. Toxicol.*, 2021, **107**(4), 577–584.
7 L. Yao, L. Hui, Z. Yang, X. Chen and A. Xiao, Freshwater microplastics pollution: detecting and visualizing emerging trends based on Citespace II, *Chemosphere*, 2020, **245**, 125627.
8 V. Fakhri, A. Hamzehlouy, A. J. Dehchani, E. Moradi, M. T. Dare, A. Jafari and H. A. Khonakdar, Green solutions for blue waters: Using biomaterials to purify water from microplastics and nanoplastics, *J. Water Process Eng.*, 2024, **65**, 105854.
9 X.-T. Bui, P.-T. Nguyen, V.-T. Nguyen, T.-S. Dao and P.-D. Nguyen, Microplastics pollution in wastewater: Characteristics, occurrence and removal technologies, *Environ. Technol. Innovation*, 2020, **19**, 101013.
10 S. Ghosh, J. K. Sinha, S. Ghosh, K. Vashisth, S. Han and R. Bhaskar, Microplastics as an emerging threat to the global environment and human health, *Sustainability*, 2023, **15**(14), 10821.
11 A. P. Periyasamy and A. Tehrani-Bagha, A review on microplastic emission from textile materials and its reduction techniques, *Polym. Degrad. Stab.*, 2022, **199**, 109901.
12 A. L. Andrady, P. W. Barnes, J. F. Bornman, T. Gouin, S. Madronich, C. White, R. G. Zepp and M. A. Jansen, Oxidation and fragmentation of plastics in a changing environment; from UV-radiation to biological degradation, *Sci. Total Environ.*, 2022, **851**, 158022.
13 P. R. Sutkar, R. D. Gadewar and V. P. Dhulap, Recent trends in degradation of microplastics in the environment: A state-of-the-art review, *J. Hazard. Mater. Adv.*, 2023, **11**, 100343.
14 I. Sa'adu and A. Farsang, Plastic contamination in agricultural soils: a review, *Environ. Sci. Eur.*, 2023, **35**(1), 13.
15 H. Yang, Y. Yumeng, Y. Yu, H. Yinglin, B. Fu and J. Wang, Distribution, sources, migration, influence and analytical methods of microplastics in soil ecosystems, *Ecotoxicol. Environ. Saf.*, 2022, **243**, 114009.
16 Z. Qaiser, M. Aqeel, W. Sarfraz, Z. F. Rizvi, A. Noman, S. Naeem and N. Khalid, Microplastics in wastewaters and their potential effects on aquatic and terrestrial biota, *Case Stud. Chem. Environ. Eng.*, 2023, **8**, 100536.
17 Y. Feng, C. Tu, R. Li, D. Wu, J. Yang, Y. Xia, W. J. Peijnenburg and Y. Luo, A systematic review of the impacts of exposure to micro-and nano-plastics on human tissue accumulation and health, *Eco-Environ. & Health*, 2023, **2**(4), 195–207.
18 M. Garcia and M. Campen, *Nanoplastics in the human brain and their change in abundance over time*, Nature Portfolio Heidelberger Platz 3, Berlin, 14197, Germany, 2025, vol. 31, pp. 1077–1078.
19 A. Kaushik, A. Singh, V. K. Gupta and Y. K. Mishra, Nano/micro-plastic, an invisible threat getting into the brain, *Chemosphere*, 2024, **361**, 142380.
20 J. Papac Zjačić, S. Tonković, A. Pulitika, Z. Katančić, M. Kovačić, H. Kušić, Z. Hrnjak Murgić and A. Lončarić Božić, Effect of aging on physicochemical properties and size distribution of PET microplastic: influence on adsorption of diclofenac and toxicity assessment, *Toxics*, 2023, **11**(7), 615.
21 Y. Wang, C. Liu, F. Wang and Q. Sun, Behavior and mechanism of atrazine adsorption on pristine and aged microplastics in the aquatic environment: Kinetic and thermodynamic studies, *Chemosphere*, 2022, **292**, 133425.
22 H. Luo, C. Liu, D. He, J. Xu, J. Sun, J. Li and X. Pan, Environmental behaviors of microplastics in aquatic

systems: A systematic review on degradation, adsorption, toxicity and biofilm under aging conditions, *J. Hazard. Mater.*, 2022, **423**, 126915.
23 Q. Lu, Y. Zhou, Q. Sui and Y. Zhou, Mechanism and characterization of microplastic aging process: A review, *Front. Environ. Sci. Eng.*, 2023, **17**(8), 100.
24 F. Yu, Q. Qin, X. Zhang and J. Ma, Characteristics and adsorption behavior of typical microplastics in long-term accelerated weathering simulation, *Environ. Sci. Process. Impacts*, 2024, **26**(5), 882–890.
25 Q. Wang, X. Wangjin, Y. Zhang, N. Wang, Y. Wang, G. Meng and Y. Chen, The toxicity of virgin and UV-aged PVC microplastics on the growth of freshwater algae Chlamydomonas reinhardtii, *Sci. Total Environ.*, 2020, **749**, 141603.
26 F. Zha, M. Shang, Z. Ouyang and X. Guo, The aging behaviors and release of microplastics: A review, *Gondwana Res.*, 2022, **108**, 60–71.
27 Q. Fu, X. Tan, S. Ye, L. Ma, Y. Gu, P. Zhang, Q. Chen, Y. Yang and Y. Tang, Mechanism analysis of heavy metal lead captured by natural-aged microplastics, *Chemosphere*, 2021, **270**, 128624.
28 S. D. Martinho, V. C. Fernandes, S. A. Figueiredo, R. Vilarinho, J. A. Moreira and C. Delerue-Matos, Laboratory studies about microplastic aging and its effects on the adsorption of chlorpyrifos, *Polymers*, 2023, **15**(16), 3468.
29 J. Zhuang, N. Rong, X. Wang, C. Chen and Z. Xu, Adsorption of small size microplastics based on cellulose nanofiber aerogel modified by quaternary ammonium salt in water, *Sep. Purif. Technol.*, 2022, **293**, 121133.
30 Q. Liu and S. M. Khor, Emerging absorption-based techniques for removing microplastics and nanoplastics from actual water bodies, *TrAC, Trends Anal. Chem.*, 2024, **170**, 117465.
31 A. Misra, C. Zambrzycki, G. Kloker, A. Kotyrba, M. H. Anjass, I. Franco Castillo, S. G. Mitchell, R. Güttel and C. Streb, Water purification and microplastics removal using magnetic polyoxometalate-supported ionic liquid phases (magPOM-SILPs), *Angew. Chem., Int. Ed.*, 2020, **59**(4), 1601–1605.
32 E. Tiwari, N. Singh, N. Khandelwal, F. A. Monikh and G. K. Darbha, Application of Zn/Al layered double hydroxides for the removal of nano-scale plastic debris from aqueous systems, *J. Hazard. Mater.*, 2020, **397**, 122769.
33 P.-L. Yen, C.-H. Hsu, M.-L. Huang and V. H.-C. Liao, Removal of nano-sized polystyrene plastic from aqueous solutions using untreated coffee grounds, *Chemosphere*, 2022, **286**, 131863.
34 A. K. Sharma, P. Bharti, K. Chaudhary, D. Gupta and G. Agrawal, ZnO@ CoO reinforced pectin-acacia hydrogel for efficient removal of toxic dyes from wastewater, *Int. J. Biol. Macromol.*, 2026, 149986.
35 X. Liu, F. Meng and L. Luo, Recent advances in hemoperfusion adsorbents: From material innovations to emerging application systems, *Biomater. Sci.*, 2026, DOI: 10.1039/D6BM00131A.
36 T. K. Das, S. Basak and S. Ganguly, 2D nanomaterial for microplastic removal: a critical review, *Chem. Eng. J.*, 2024, **492**, 152451.
37 Z. Zhang, Y. Lu, Y. Zhao, L. Cui, C. Xu and S. Wu, Current Developments in Chitosan-Based Hydrogels for Water and Wastewater Treatment: A Comprehensive Review, *ChemistrySelect*, 2025, **10**(6), e202404061.
38 N. Delangiz, S. Aliyar, N. Pashapoor, K. Nobaharan, B. A. Lajayer and S. Rodríguez-Couto, Can polymer-degrading microorganisms solve the bottleneck of plastics' environmental challenges?, *Chemosphere*, 2022, **294**, 133709.
39 F. Yu, Z. Wu, J. Wang, Y. Li, R. Chu, Y. Pei and J. Ma, Effect of landfill age on the physical and chemical characteristics of waste plastics/microplastics in a waste landfill sites, *Environ. Pollut.*, 2022, **306**, 119366.
40 M. Malankowska, C. Echaide-Gorriz and J. Coronas, Microplastics in marine environment: a review on sources, classification, and potential remediation by membrane technology, *Environ. Sci.: Water Res. Technol.*, 2021, **7**(2), 243–258.
41 D. Burhani, V. S. Voet, R. Folkersma, D. Maniar and K. Loos, Potential of Nanocellulose for Microplastic removal: Perspective and challenges, *Tetrahedron Green Chem*, 2024, **3**, 100045.
42 K. D. Cox, G. A. Covernton, H. L. Davies, J. F. Dower, F. Juanes and S. E. Dudas, Human consumption of microplastics, *Environ. Sci. Technol.*, 2019, **53**(12), 7068–7074.
43 C. Vanetti, M. Broggiato, S. Pezzana, M. Clerici and C. Fenizia, Effects of microplastics on the immune system: How much should we worry?, *Immunol. Lett.*, 2025, 106976.
44 J. Phothakwanpracha, T. Lirdwitayaprasit and S. Pairohakul, Effects of sizes and concentrations of different types of microplastics on bioaccumulation and lethality rate in the green mussel, Perna viridis, *Mar. Pollut. Bull.*, 2021, **173**, 112954.
45 J. Chen, C. Lei, Y. Xiao, Q. Zhang and S. Shi, Impact of microplastics on human health: A critical role of gut microbiota, *Ecotoxicol. Environ. Saf.*, 2026, **316**, 120184.
46 S. L. Wright, R. C. Thompson and T. S. Galloway, The physical impacts of microplastics on marine organisms: a review, *Environ. Pollut.*, 2013, **178**, 483–492.
47 K. K. Jaiswal, S. Dutta, I. Banerjee, C. B. Pohrmen, R. K. Singh, H. T. Das, S. Dubey and V. Kumar, Impact of aquatic microplastics and nanoplastics pollution on ecological systems and sustainable remediation strategies of biodegradation and photodegradation, *Sci. Total Environ.*, 2022, **806**, 151358.
48 J. C. Prata, J. P. da Costa, I. Lopes, A. C. Duarte and T. Rocha-Santos, Environmental exposure to microplastics: An overview on possible human health effects, *Sci. Total Environ.*, 2020, **702**, 134455.
49 H. A. Leslie, M. J. Van Velzen, S. H. Brandsma, A. D. Vethaak, J. J. Garcia-Vallejo and M. H. Lamoree, Discovery and quantification of plastic particle pollution in human blood, *Environ. Int.*, 2022, **163**, 107199.

50 S. Liu, J. Guo, X. Liu, R. Yang, H. Wang, Y. Sun, B. Chen and R. Dong, Detection of various microplastics in placentas, meconium, infant feces, breastmilk and infant formula: A pilot prospective study, *Sci. Total Environ.*, 2023, **854**, 158699.

51 A. Ragusa, A. Svelato, C. Santacroce, P. Catalano, V. Notarstefano, O. Carnevali, F. Papa, M. C. A. Rongioletti, F. Baiocco and S. Draghi, Plasticenta: First evidence of microplastics in human placenta, *Environ. Int.*, 2021, **146**, 106274.

52 D. Ni, K. Yu, N. Yan, X. Chen, Q. Xie, Y. Yang, W. Jiang, Y. Yang, J. Zhang and X. Ling, Characterization of microplastics in human follicular fluid and assessment of their potential impact on mouse oocyte maturation in vitro, *Ecotoxicol. Environ. Saf.*, 2025, **291**, 117796.

53 F. Ribeiro, J. W. O'Brien, T. Galloway and K. V. Thomas, Accumulation and fate of nano-and micro-plastics and associated contaminants in organisms, *TrAC, Trends Anal. Chem.*, 2019, **111**, 139–147.

54 A. Rahman, A. Sarkar, O. P. Yadav, G. Achari and J. Slobodnik, Potential human health risks due to environmental exposure to nano-and microplastics and knowledge gaps: A scoping review, *Sci. Total Environ.*, 2021, **757**, 143872.

55 C. Shi, H. Wu, W. Wang, J. Zhao, F. Niu and J. Geng, Microplastic removal from water using modified maifanite with rotating magnetic field affected, *J. Cleaner Prod.*, 2024, **434**, 140111.

56 T. Poolwong, M. Seadan, Y. Liu and S. Suttiruengwong, In *Separation of microplastic particles by flotation with ultrafine bubbles*, AIP Conference Proceedings, AIP Publishing LLC, 2023, p. 030010.

57 A. M. Joshua, P. A. D. Aznir and E. Von Lau, Understanding microplastic flotation through microbubble-microplastic interactions, *Surf. Interfaces*, 2025, **64**, 106399.

58 H. Jiang, J. Bu, K. Bian, J. Su, Z. Wang, H. Sun, H. Wang, Y. Zhang and C. Wang, Surface change of microplastics in aquatic environment and the removal by froth flotation assisted with cationic and anionic surfactants, *Water Res.*, 2023, **233**, 119794.

59 K. Chabi, J. Li, C. Ye, C. Kiki, X. Xiao, X. Li, L. Guo, M. Gad, M. Feng and X. Yu, Rapid sand filtration for< 10 μm-sized microplastic removal in tap water treatment: Efficiency and adsorption mechanisms, *Sci. Total Environ.*, 2024, **912**, 169074.

60 S. Ahmed, M. Mofijur, S. Nuzhat, A. T. Chowdhury, N. Rafa, M. A. Uddin, A. Inayat, T. Mahlia, H. C. Ong and W. Y. Chia, Recent developments in physical, biological, chemical, and hybrid treatment techniques for removing emerging contaminants from wastewater, *J. Hazard. Mater.*, 2021, **416**, 125912.

61 M. Komorowska-Kaufman and W. Marciniak, Removal of microplastic particles during municipal wastewater treatment: A current review, *Desalin. Water Treat.*, 2024, **317**, 100006.

62 X. Duan, X. Chen, L. Shi, Y. Cao, Y. Liang, C. Huang and Y. Cao, Functionality-dependent removal efficiency and mechanisms of polystyrene microplastics by a robust magnetic biochar, *J. Environ. Chem. Eng.*, 2025, **13**(2), 115509.

63 A. Ren, O. Rius-Ayra, M. Kang and N. Llorca-Isern, Durably Superhydrophobic Magnetic Cobalt Ferrites for Highly Efficient Oil–Water Separation and Fast Microplastic Removal, *Langmuir*, 2024, **40**(41), 21533–21546.

64 Y. Heo, E.-H. Lee and S.-W. Lee, Adsorptive removal of micron-sized polystyrene particles using magnetic iron oxide nanoparticles, *Chemosphere*, 2022, **307**, 135672.

65 L. Yan, J. Chen, Z. Zhang, Z. Liu, T. Ding and G. Shi, Reduced graphene oxide membrane with small nanosheets for efficient and ultrafast removal of both microplastics and small molecules, *J. Hazard. Mater.*, 2025, **487**, 137078.

66 M. N. Puteri, L. T. Gew, H. C. Ong and L. C. Ming, Technologies to eliminate microplastic from water: Current approaches and future prospects, *Environ. Int.*, 2025, 109397.

67 G. Falco, A. Fenti, S. Galoppo, S. Chianese, D. Musmarra, M. Cocca, S. Mallardo and P. Iovino, Promoting removal of polystyrene microplastics from wastewater by electrochemical treatment, *J. Water Process Eng.*, 2024, **68**, 106418.

68 P. G. Gangadharan, A. Bharti and A. Mondal, Exploring the degradation of polyethylene terephthalate microplastics from water and synthetic marine water by the electrochemical method, *J. Water Process Eng.*, 2025, **76**, 108101.

69 X. Zheng, Y. Zhang, L. Chen and Z. Wang, Synergistic coagulation-flocculation using polymeric ferric sulfate and Opuntia Milpa Alta particles for enhanced polystyrene microplastic removal, *Process Saf. Environ. Prot.*, 2025, 108061.

70 M. Sezer, M. Isgoren, S. Veli, E. Topkaya and A. Arslan, Removal of microplastics in food packaging industry wastewaters with electrocoagulation process: Optimization by Box-Behnken design, *Chemosphere*, 2024, **352**, 141314.

71 J. Hu and J. Hu, Mineralization characteristics and behavior of polyethylene microplastics through ozone-based treatment, *Chemosphere*, 2024, **349**, 140839.

72 J. Nieto-Sandoval, R. Ammar and C. Sans, Enhancing nanoplastics removal by metal ion-catalyzed ozonation, *Chem. Eng. J. Adv.*, 2024, **19**, 100621.

73 M. T. Sturm, E. Myers, D. Schober, A. Korzin, C. Thege and K. Schuhen, Comparison of AOP, GAC, and novel organosilane-based process for the removal of microplastics at a municipal wastewater treatment plant, *Water*, 2023, **15**(6), 1164.

74 K. Pacaphol, D. Aht-Ong, D. Coughlan and J. Hoogewerff, Oleo-extraction of microplastics using flotation plus sol-gel technique to confine small particles in silicon dioxide gel, *Environ. Sci. Pollut. Res.*, 2024, **31**(51), 61096–61113.

75 Z. Yang, H. Wang, Y. Li and G. Zhang, Efficient photocatalytic degradation of polystyrene microplastics in water

over core–shell BiO2− x/CuBi2O4 heterojunction with full spectrum light response, *J. Colloid Interface Sci.*, 2025, **686**, 327–335.

76 A. Sharara, M. Samy, M. Mossad and M. G. Alalm, Enhanced depolymerization of microplastic debris in water by a hybrid ZnO-based photocatalysis-persulfate activation system, *J. Water Process Eng.*, 2025, **72**, 107633.

77 T. Gupta, S. Chakraborty and S. Bhattacharya, Application of membrane bioreactor in microplastic and nanoplastic removal from water, in *Membrane Bioreactor Technology: An Innovative Water Treatment Process*, Elsevier, 2026, pp. 277–303.

78 M. V. A. Corpuz, S. Cairone, M. Natale, A. Giannattasio, V. Iuliano, A. Grassi, A. Pollice, G. Mannina, A. Buonerba and V. Belgiorno, Sustainable control of microplastics in wastewater using the electrochemically enhanced living membrane bioreactor, *J. Environ. Manage.*, 2024, **370**, 122649.

79 S. Lv, K. Cui, S. Zhao, Y. Li, R. Liu, R. Hu, B. Zhi, L. Gu, L. Wang and Q. Wang, Continuous generation and release of microplastics and nanoplastics from polystyrene by plastic-degrading marine bacteria, *J. Hazard. Mater.*, 2024, **465**, 133339.

80 A. P. Dubey and A. K. Thalla, Bioprospecting indigenous bacteria from landfill leachate for enhanced polypropylene microplastics degradation, *J. Hazard. Mater.*, 2025, **487**, 137139.

81 X. Yu, Y. Zhang, S. Chen, S. Chen, C. Wan, Y. Wang, L. Zou, L. Peng, L. Ye and Q. Li, Study on the degradation efficiency and mechanism of polystyrene microplastics by five kinds of edible fungi, *J. Hazard. Mater.*, 2025, **492**, 138165.

82 J. Liu, D. Zhao, X. Wu, D. Wu, N. Su, Y. Wang, F. Chen, C. Fu, J. Wang and Q. Zhang, Synergistic dual-defect band engineering for highly efficient photocatalytic degradation of microplastics via Nb-induced oxygen vacancies in SnO 2 quantum dots, *J. Mater. Chem. A*, 2025, **13**(6), 4429–4443.

83 Z. Ning, X. Duan, Y. Li, X. Zhao and L. Chang, Degradation of polyvinyl chloride microplastics via electrochemical oxidation with a CeO_2–PbO2 anode, *J. Cleaner Prod.*, 2023, **432**, 139668.

84 Y. Zhang, S. Fu and L. Chen, Enhanced removal of polystyrene microplastics through coagulation using polyaluminum ferric chloride with Opuntia Milpa Alta particles, *J. Environ. Chem. Eng.*, 2024, **12**(5), 113802.

85 E. W. Gabisa and C. Ratanatamskul, Effects of operating conditions on removal of microplastics (PET, PP, PS) from wastewater by electrocoagulation systems and kinetics of chromium removal in the presence of microplastics, *J. Water Process Eng.*, 2024, **61**, 105313.

86 M. Simon, A. Vianello and J. Vollertsen, Removal of> 10 μm microplastic particles from treated wastewater by a disc filter, *Water*, 2019, **11**(9), 1935.

87 H. Jiang, Y. Zhang, K. Bian, C. Wang, X. Xie, H. Wang and H. Zhao, Is it possible to efficiently and sustainably remove microplastics from sediments using froth flotation?, *Chem. Eng. J.*, 2022, **448**, 137692.

88 T. Mani, S. Frehland, A. Kalberer and P. Burkhardt-Holm, Using castor oil to separate microplastics from four different environmental matrices, *Anal. Methods*, 2019, **11**(13), 1788–1794.

89 M. A. Hanif, N. Ibrahim, N. A. Hayazi, F. A. Dahalan, U. F. M. Ali, A. A. Jalil and A. Syafiuddin, Enhancement of microplastics and nanoplastics removal via filtration method using surface-engineered palm kernel shell biochar, *Sep. Purif. Technol.*, 2025, **360**, 130596.

90 M. Han, Z. Wang, Z. Xie, M. Hou and Z. Gao, Polydopamine-modified sodium alginate hydrogel for microplastics removal: Adsorption performance, characteristics, and kinetics, *Int. J. Biol. Macromol.*, 2025, **297**, 139947.

91 S. L. Loo, L. Vásquez, A. Athanassiou and D. Fragouli, Polymeric hydrogels—a promising platform in enhancing water security for a sustainable future, *Adv. Mater. Interfaces*, 2021, **8**(24), 2100580.

92 D. Yang, *Recent advances in hydrogels*, ACS Publications, 2022, vol. 34, pp. 1987–1989.

93 O. Duman, T. G. Polat, C.Ö Diker and S. Tunç, Agar/κ-carrageenan composite hydrogel adsorbent for the removal of Methylene Blue from water, *Int. J. Biol. Macromol.*, 2020, **160**, 823–835.

94 K. Chaudhary, A. K. Sharma, P. Bharti and G. Agrawal, Reduced graphene oxide embedded carrageenan/acacia-based hybrid hydrogel nanocomposite for the efficient entrapment of safranine and methylene blue dyes, *J. Mol. Liq.*, 2025, 128718.

95 A. A. Aboomeirah, M. F. Kabil and H. M. E.-S. Azzazy, Polyvinyl alcohol-chitosan-polyethylene glycol-glycerol incorporated with Peganum harmala loaded in lipid nanocapsules as an elastic nanocomposite surgical sealant to control bleeding, *Int. J. Biol. Macromol.*, 2024, **280**, 135987.

96 K. Salma-Ancane, A. Sceglovs, E. Tracuma, J. K. Wychowaniec, K. Aunina, A. Ramata-Stunda, V. Nikolajeva and D. Loca, Effect of crosslinking strategy on the biological, antibacterial and physicochemical performance of hyaluronic acid and ε-polylysine based hydrogels, *Int. J. Biol. Macromol.*, 2022, **208**, 995–1008.

97 H. Tiwari, A. K. Sharma, P. Bharti and G. Agrawal, CuO-integrated hydrogel network of gelatin and gellan gum for the efficient sequestration of rhodamine B and crystal violet, *Int. J. Biol. Macromol.*, 2025, 146016.

98 M. A. L. Huaman, J. Vega-Chacón, R. I. H. Quispe and A. C. V. Negrón, Synthesis and swelling behaviors of poly (2-hydroxyethyl methacrylate-co-itaconic acid) and poly (2-hydroxyethyl methacrylate-co-sodium itaconate) hydrogels as potential drug carriers, *Results Chem.*, 2023, **5**, 100917.

99 Y. Gao, S. Zong, Y. Huang, N. Yang, H. Wen, J. Jiang and J. Duan, Preparation and properties of a highly elastic galactomannan-poly (acrylamide-N, N-bis (acryloyl) cysteamine) hydrogel with reductive stimuli-responsive degradable properties, *Carbohydr. Polym.*, 2020, **231**, 115690.

100 K. Homma, A. C. Chang, S. Yamamoto, R. Tamate, T. Ueki and J. Nakanishi, Design of azobenzene-bearing hydrogel with photoswitchable mechanics driven by photo-induced phase transition for in vitro disease modeling, *Acta Biomater.*, 2021, **132**, 103–113.

101 G. Sennakesavan, M. Mostakhdemin, L. K. Dkhar, A. Seyfoddin and S. J. Fatihhi, Acrylic acid/acrylamide based hydrogels and its properties-A review, *Polym. Degrad. Stab.*, 2020, **180**, 109308.

102 H. Nasution, H. Harahap, N. F. Dalimunthe, M. H. S. Ginting, M. Jaafar, O. O. Tan, H. K. Aruan and A. L. Herfananda, Hydrogel and effects of crosslinking agent on cellulose-based hydrogels: A review, *Gels*, 2022, **8**(9), 568.

103 P. Yadav, S. Singh, S. Jaiswal and R. Kumar, Synthetic and natural polymer hydrogels: a review of 3D spheroids and drug delivery, *Int. J. Biol. Macromol.*, 2024, **280**, 136126.

104 B. S. Kaith, A. Singh, A. K. Sharma and D. Sud, Hydrogels: synthesis, classification, properties and potential applications—a brief review, *J. Polym. Environ.*, 2021, **29**(12), 3827–3841.

105 S. Mondal, K. Baghel, S. Cho, H. Lim and J. Lee, Efficient removal of amine-modified polystyrene nanoplastics utilizing poly (N-isopropylacrylamide)-sodium carboxymethyl cellulose hydrogel beads: Parametric optimization and mechanistic insights, *Sep. Purif. Technol.*, 2025, **363**, 132035.

106 A. K. Sharma, B. S. Kaith, K. Chandel and A. Singh, Chemically modified chitosan-sodium alginate as chemosensor adsorbent for the detection of picric acid and removal of biebrich scarlet, *Int. J. Biol. Macromol.*, 2020, **147**, 582–594.

107 A. M. Gutierrez, E. M. Frazar, M. V. X. Klaus, P. Paul and J. Z. Hilt, Hydrogels and hydrogel nanocomposites: enhancing healthcare through human and environmental treatment, *Adv. Healthcare Mater.*, 2022, **11**(7), 2101820.

108 X. Li, Q. Xia, Y. Leng, X. Cai and D. Nie, Lignin/Poly (vinyl alcohol) Hydrogel for Detecting and Effectively Removing Microplastics, *Langmuir*, 2025, **41**(25), 16506–16518.

109 N. Maldonado and P. Amo-Ochoa, Advances and novel perspectives on colloids, hydrogels, and aerogels based on coordination bonds with biological interest ligands, *Nanomaterials*, 2021, **11**(7), 1865.

110 F. Khan, M. Atif, M. Haseen, S. Kamal, M. S. Khan, S. Shahid and S. A. Nami, Synthesis, classification and properties of hydrogels: Their applications in drug delivery and agriculture, *J. Mater. Chem. B*, 2022, **10**(2), 170–203.

111 C. Munyiri, E. Madivoli, J. Kisato, J. Gichuki and P. Kareru, Biopolymer based hydrogels: crosslinking strategies and their applications, *Int. J. Polym. Mater. Polym. Biomater.*, 2025, **74**(7), 625–640.

112 M. Grosjean, L. Guth, S. Déjean, C. Paniagua and B. Nottelet, Dynamic and Degradable Imine-Based Networks for 3D-Printing of Soft Elastomeric Self-Healable Devices, *Adv. Mater. Interfaces*, 2023, **10**(17), 2300066.

113 M. T. I. Mredha, J. Y. Na, J.-K. Seon, J. Cui and I. Jeon, Multifunctional poly (disulfide) hydrogels with extremely fast self-healing ability and degradability, *Chem. Eng. J.*, 2020, **394**, 124941.

114 L. He, D. E. Fullenkamp, J. G. Rivera and P. B. Messersmith, pH responsive self-healing hydrogels formed by boronate–catechol complexation, *Chem. Commun.*, 2011, **47**(26), 7497–7499.

115 C. Sun, H. Jia, K. Lei, D. Zhu, Y. Gao, Z. Zheng and X. Wang, Self-healing hydrogels with stimuli responsiveness based on acylhydrazone bonds, *Polymer*, 2019, **160**, 246–253.

116 B. Hosseinzadeh and M. Ahmadi, Degradable hydrogels: Design mechanisms and versatile applications, *Mater. Today Sustainability*, 2023, **23**, 100468.

117 Y. Wu, J. Liu, R. Hu, J. Wang, X. Cai, W. Wu, X. Song, C. Zhuge, M. Huang and H. Xie, From weak to strong: the construction of dynamic reversible hydrogen bond in polyaspartic acid double network hydrogel, *Sep. Purif. Technol.*, 2025, 133023.

118 S. Shahi, H. Roghani-Mamaqani, S. Talebi and H. Mardani, Stimuli-responsive destructible polymeric hydrogels based on irreversible covalent bond dissociation, *Polym. Chem.*, 2022, **13**(2), 161–192.

119 M. M. H. Rumon, Advances in cellulose-based hydrogels: tunable swelling dynamics and their versatile real-time applications, *RSC Adv.*, 2025, **15**(15), 11688–11729.

120 S. Iskandarani, L. C. Campos, P. E. Saikaly and R. Busquets, Hybrid Wastewater Treatment: Efficiency and Challenges in Microplastic Removal, *ACS ES&T Water*, 2026, **6**(5), 2619–2636.

121 T. Patel, R. Lata, J. E. Arikibe and D. Rohindra, Towards sustainable microplastic cleanup: Al/Fe ionotropic chitosan hydrogels for efficient PET removal, *Environ. Monit. Assess.*, 2025, **197**(3), 228.

122 S. Dutta, A. Misra and S. Bose, Polyoxometalate nanocluster-infused triple IPN hydrogels for excellent microplastic removal from contaminated water: detection, photodegradation, and upcycling, *Nanoscale*, 2024, **16**(10), 5188–5205.

123 X. Li, Q. Xia, Y. Leng, X. Cai and D. Nie, Lignin/Poly (vinyl alcohol) Hydrogel for Detecting and Effectively Removing Microplastics, *Langmuir*, 2025, **41**(25), 16506–16518.

124 I. Leppänen, T. Lappalainen, T. Lohtander, C. Jonkergouw, S. Arola and T. Tammelin, Capturing colloidal nano-and microplastics with plant-based nanocellulose networks, *Nat. Commun.*, 2022, **13**(1), 1814.

125 X. Yi, R. Zhou, L. Liu, S. Xu, H. Sun, K. Ogino and Y. Fan, Preparation of nanochitin hydrogels via ice templated chemical/physical crosslinking for microplastic removal, *Int. J. Biol. Macromol.*, 2025, 144806.

126 Q. Guo, Y. Liu, J. Liu, Y. Wang, Q. Cui, P. Song, X. Zhang and C. Zhang, Hierarchically structured hydrogel actuator for microplastic pollutant detection and removal, *Chem. Mater.*, 2022, **34**(11), 5165–5175.

127 C. Sun, Z. Wang, L. Chen and F. Li, Fabrication of robust and compressive chitin and graphene oxide sponges for

removal of microplastics with different functional groups, *Chem. Eng. J.*, 2020, **393**, 124796.

128 C. Sun, Z. Wang, H. Zheng, L. Chen and F. Li, Biodegradable and re-usable sponge materials made from chitin for efficient removal of microplastics, *J. Hazard. Mater.*, 2021, **420**, 126599.

129 Z. Zhu, X. Wu and Z. Wang, Effect of polyaniline dispersibility in chitin sponge matrix controlled by hydrophilicity on microplastics adsorption, *Int. J. Biol. Macromol.*, 2023, **253**, 127292.

130 Y. Wu, S. Chen, J. Wu, F. Liu, C. Chen, B. Ding, X. Zhou and H. Deng, Revivable self-assembled supramolecular biomass fibrous framework for efficient microplastic removal, *Sci. Adv.*, 2024, **10**(48), eadn8662.

131 M. Ko, T. Jang, S. Yoon, J. Lee, J.-H. Choi, J.-W. Choi and J.-A. Park, Synthesis of recyclable and light-weight graphene oxide/chitosan/genipin sponges for the adsorption of diclofenac, triclosan, and microplastics, *Chemosphere*, 2024, **356**, 141956.

132 P. Risch and C. Adlhart, A chitosan nanofiber sponge for oyster-inspired filtration of microplastics, *ACS Appl. Polym. Mater.*, 2021, **3**(9), 4685–4694.

133 J. Xu, Y. Guo, C. Tang, Y. Qian, C. Guo, Z. Wang and L. Li, Hardwood vessel-inspired chitosan-based sponge with superior compressibility, superfast adsorption and remarkable recyclability for microplastics removal in water, *Chem. Eng. J.*, 2023, **475**, 146130.

134 R. Ma, Y. Feng, J. Yu, X. Zhao, Y. Du and X. Zhang, Ultralight sponge made from sodium alginate with processability and stability for efficient removal of microplastics, *Environ. Sci. Pollut. Res.*, 2023, **30**(47), 104135–104147.

135 S. Aziz, A. Mazhar, A. Ubaid, S. Shah, Y. Riaz, T. Talha and D. Jung, A comprehensive review of membrane–based water filtration techniques, *Appl. Water Sci.*, 2024, **14**, 169.

136 X. Tang, B. Xie, R. Chen, J. Wang, K. Huang, X. Zhu, G. Li and H. Liang, Gravity-driven membrane filtration treating manganese-contaminated surface water: flux stabilization and removal performance, *Chem. Eng. J.*, 2020, **397**, 125248.

137 L. Hou, D. Kumar, C. G. Yoo, I. Gitsov and E. L.-W. Majumder, Conversion and removal strategies for microplastics in wastewater treatment plants and landfills, *Chem. Eng. J.*, 2021, **406**, 126715.

138 I. S. Al-Husaini and M. H. Al Haddabi, Recent advances in functionalized electrospun nanofiber membranes for enhanced oily water treatment, *J. Environ. Chem. Eng.*, 2025, 115391.

139 A. Dhiman, A. K. Sharma and G. Agrawal, Polymer based engineered materials for sustainable agriculture, *ACS Agric. Sci. Technol.*, 2022, **2**(4), 693–711.

140 S. N. Banitaba, S. V. Ebadi, P. Salimi, A. Bagheri, A. Gupta, W. U. Arifeen, V. Chaudhary, Y. K. Mishra, A. Kaushik and E. Mostafavi, Biopolymer-based electrospun fibers in electrochemical devices: versatile platform for energy, environment, and health monitoring, *Mater. Horiz.*, 2022, **9**(12), 2914–2948.

141 K. P. Das, P. Chauhan, U. Staudinger and B. K. Satapathy, Exploring sustainable adsorbents to mitigate micro-/nanoplastic contamination: perspectives on electrospun fibrous constructs, biochar, and aerogels, *Environ. Sci.: Adv.*, 2024, **3**, 1217–1243.

142 M. Rist and A. Greiner, Bio-based electrospun polyamide membrane–sustainable multipurpose filter membranes for microplastic filtration, *RSC Appl. Polym.*, 2024, **2**(4), 642–655.

143 S. Khademolqorani, S. N. Banitaba, A. Gupta, N. Poursharifi, A. A. Ghaffari, V. V. Jadhav, W. U. Arifeen, M. Singh, M. Borah and E. Chamanehpour, Application scopes of miniaturized MXene-functionalized electrospun nanofibers-based electrochemical energy devices, *Small*, 2024, **20**(24), 2309572.

144 J. Cui, F. Li, Y. Wang, Q. Zhang, W. Ma and C. Huang, Electrospun nanofiber membranes for wastewater treatment applications, *Sep. Purif. Technol.*, 2020, **250**, 117116.

145 E. Chamanehpour, S. Thouti, H. G. Rubahn, A. Dolatshahi-Pirouz and Y. K. Mishra, Smart nanofibers: Synthesis, properties, and scopes in future advanced technologies, *Adv. Mater. Technol.*, 2024, **9**(3), 2301392.

146 Z. Wang, C. Crandall, R. Sahadevan, T. J. Menkhaus and H. Fong, Microfiltration performance of electrospun nanofiber membranes with varied fiber diameters and different membrane porosities and thicknesses, *Polymer*, 2017, **114**, 64–72.

147 K. Juraij, S. P. Ammed, C. Chingakham, B. Ramasubramanian, S. Ramakrishna, S. Vasudevan and A. Sujith, Electrospun polyurethane nanofiber membranes for microplastic and nanoplastic separation, *ACS Appl. Nano Mater.*, 2023, **6**(6), 4636–4650.

148 A. N. Gopakumar, A. Ccanccapa-Cartagena, K. Bell and M. Salehi, Development of crosslinked polyvinyl alcohol nanofibrous membrane for microplastic removal from water, *J. Appl. Polym. Sci.*, 2024, **141**(22), e55428.

149 R. Wang, L. Zhang, B. Chen and X. Zhu, Low-pressure driven electrospun membrane with tuned surface charge for efficient removal of polystyrene nanoplastics from water, *J. Membr. Sci.*, 2020, **614**, 118470.

150 L. D. Tijing, J. R. C. Dizon, I. Ibrahim, A. R. N. Nisay, H. K. Shon and R. C. Advincula, 3D printing for membrane separation, desalination and water treatment, *Appl. Mater. Today*, 2020, **18**, 100486.

151 S. R. Barman, P. Gavit, S. Chowdhury, K. Chatterjee and A. Nain, 3D-printed materials for wastewater treatment, *JACS Au*, 2023, **3**(11), 2930–2947.

152 N. Fijoł, A. Aguilar-Sánchez, M.-X. Ruiz-Caldas, J. Redlinger-Pohn, A. Mautner and A. P. Mathew, 3D printed polylactic acid (PLA) filters reinforced with polysaccharide nanofibers for metal ions capture and microplastics separation from water, *Chem. Eng. J.*, 2023, **457**, 141153.

153 S. Jung, J. Kim, S. Park, J. Bang, H. Yun, S. Won, S. Kim, H. Lim, S.-G. Kim and J.-C. Kim, Nature-derived hydrogel for microplastic removal, *Adv. Compos. Hybrid Mater.*, 2025, **8**(5), 346.

154 Q. Xiang, Y. Xu, J. Hou, H. Zhang, Z. Lu, M. Sun, C. Wu, H. Rao and G. Su, Sustainable Gelatin–Sodium alginate aerogel adsorbent for efficient microplastic removal in water, *Chem. Eng. Sci.*, 2025, 123265.

155 W.-p. Qiu, H.-z. Su, H. Su, S.-h. Luo, L.-s. Lai, J.-l. Zhu, Z.-l. Xu, H. Wang and P. Wen, Eco-friendly taro stem-sourced cellulose/polypyrrole hybrid aerogel: An efficient capture strategy for microplastics removal, *Chem. Eng. J.*, 2025, 168208.

156 H. Rezvani, V. G. González, Y. Majooni and N. Yousefi, Mussel-inspired Modification of Polymeric Sponges for Selective Removal of Microplastics and Nanoplastics from Water, *J. Environ. Chem. Eng.*, 2025, 120459.

157 X. Chen, H. Ma, X. Ji, R. Han, K. Pang, Z. Yang, Z. Liu and S. Peng, Engineering green MOF-based superhydrophobic sponge for efficiently synchronous removal of microplastics and pesticides from high-salinity water, *Water Res.*, 2023, **243**, 120314.

158 M. H. Sayadi and M. Nowrouzi, Biodegradable sponges made from chitin-cellulose nanofibers for sustainable removal of microplastics from aquatic environment, *J. Hazard. Mater. Adv.*, 2025, **17**, 100564.

159 S. Peng, X. Chen, X. Rong, H. Ma, C. Zhao and K. Pang, Fabrication of eco-friendly Cu/Co-LDHs-based superhydrophobic sponge and efficiently synchronous removal of microplastic, dyestuff, and oil, *J. Cleaner Prod.*, 2023, **400**, 136708.

160 L. Lv, W. Zhong and Z. Wang, Surface modification of hierarchically porous wood derived cellulose sponges with remarkable compressibility and recyclability for efficient microplastic removal, *Sep. Purif. Technol.*, 2025, 134943.

161 T. T. V. Ha, N. M. Viet, P. T. Thanh and V. T. Quan, Loofah plant—Derived biodegradable superhydrophobic sponge for effective removal of oil and microplastic from water, *Environ. Technol. Innovation*, 2023, **32**, 103265.

162 S. Singh and M. K. Biswas, Management strategies for single-use plastics: lessons to learn from Indian approach of minimizing microplastic waste, *Environ. Sci.: Adv.*, 2023, **2**(12), 1680–1695.

163 M. Calero, V. Godoy, L. Quesada and M.Á Martín-Lara, Green strategies for microplastics reduction, *Curr. Opin. Green Sustainable Chem.*, 2021, **28**, 100442.

164 A. Thacharodi, S. Hassan, R. Meenatchi, M. A. Bhat, N. Hussain, J. Arockiaraj, H. H. Ngo, A. Sharma, H. Nguyen and A. Pugazhendhi, Mitigating microplastic pollution: A critical review on the effects, remediation, and utilization strategies of microplastics, *J. Environ. Manage.*, 2024, **351**, 119988.

165 A. P. Onyena, D. C. Aniche, B. O. Ogbolu, M. R. J. Rakib, J. Uddin and T. R. Walker, Governance strategies for mitigating microplastic pollution in the marine environment: a review, *Microplastics*, 2021, **1**(1), 15–46.

166 R. C. Thompson, C. J. Moore, F. S. vom Saal and S. H. Swan, Plastics, the environment and human health: current consensus and future trends, *Philos. Trans. R. Soc., B*, 2009, **364**(1526), 2153–2166.

167 N. Singh, D. Hui, R. Singh, I. Ahuja, L. Feo and F. Fraternali, Recycling of plastic solid waste: A state of art review and future applications, *Composites, Part B*, 2017, **115**, 409–422.

168 X. Chen, Y. Wang and L. Zhang, Recent progress in the chemical upcycling of plastic wastes, *ChemSusChem*, 2021, **14**(19), 4137–4151.

169 A. Prakash and R. R. Palkar, Co-processing of plastic waste in a cement kiln: a better option, *Environ. Sci. Pollut. Res.*, 2023, **30**(10), 24804–24814.

170 Y. Zhang and G. G. Goss, The "Trojan Horse" effect of nanoplastics: Potentiation of polycyclic aromatic hydrocarbon uptake in rainbow trout and the mitigating effects of natural organic matter, *Environ. Sci.: Nano*, 2021, **8**(12), 3685–3698.

171 S. Safeer, R. P. Pandey, B. Rehman, T. Safdar, I. Ahmad, S. W. Hasan and A. Ullah, A review of artificial intelligence in water purification and wastewater treatment: Recent advancements, *J. Water Process Eng.*, 2022, **49**, 102974.

172 M. Kamali, L. Appels, X. Yu, T. M. Aminabhavi and R. Dewil, Artificial intelligence as a sustainable tool in wastewater treatment using membrane bioreactors, *Chem. Eng. J.*, 2021, **417**, 128070.

173 L. Zhao, T. Dai, Z. Qiao, P. Sun, J. Hao and Y. Yang, Application of artificial intelligence to wastewater treatment: A bibliometric analysis and systematic review of technology, economy, management, and wastewater reuse, *Process Saf. Environ. Prot.*, 2020, **133**, 169–182.