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Advanced biomass framework for the sustainable removal and utilization of microplastics

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Microplastics (MPs) represent a pressing global environmental issue, and an estimated 49,000–53,000 tons enter the ocean annually [1]. It has been established that MPs can cause significant harm to numerous organisms, including oxidative stress, multi-organ dysfunction, DNA damage, and metabolic disorders. Moreover, the combined toxicity associated with MPs and other pollutants may pose an even more severe and lethal threat. Despite the implementation of various policies directed at curbing plastic products, enhancing waste management, and promoting environmental recycling, MPs pollution has escalated [2,3]. A number of advanced MPs removal technologies have been developed, which encompass flotation, adsorption, catalysis, and microbial engineering [4–7]. Tan's group [8] proposed a novel purification platform with a dual effect of evaporation and adsorption, prepared by *in-situ* deposition of polyethyleneimine on commercial carbon felt. The solar-driven interfacial evaporation process served to enhance MPs adsorption kinetics, with a removal ratio increase of up to 5.5 times under 1 sun relative to dark conditions. Dai and co-workers [9] constructed a heat and fluid confinement nanofiber reactor, which integrated photocatalysts in the evaporative cooling zone. This reactor was used to convert polyethylene MPs to methyl acetate (yield of 27.4 μmol g^{-1} h^{-1}) and formic acid (yield of 24.9 μmol g^{-1} h^{-1}). By customizing the interfacial evaporation, the target methyl acetate product can be separated with 100% selectivity. Although the published methodologies have generated encouraging results under ideal laboratory conditions, effective application in treating actual MPs polluted water has not been demonstrated conclusively [10]. In terms of the circular economy, the proposed treatment technologies involve complex manufacturing processes or expensive raw materials, which could introduce additional environmental issues or increased costs.

Adsorption offers a number of process advantages, including high selectivity, low cost, ease of operation with minimal secondary pollution, and facilitating the elimination of low-concentration MPs. The use of bio-based adsorbents can draw on a plentiful supply of raw materials, cost-effectiveness with minimal environmental impact, a substantial adsorption capacity, and biodegradability. Recently, numerous advanced bio-based adsorbents have emerged, representing an innovative and low-cost solution to recover full-size and low-concentration MPs from the real world effectively. For example, Deng's group [11] proposed a novel eco-friendly MPs adsorbent *via* dynamic force conversion. They fabricated a multi-level fiber framework (MFF) using a hydrogen bonding self-assembly of chitin nanofiber and cellulose microfibers. The MFF posed a highly porous interconnected structure with a rough positively charged surface that contains numerous active sites (–OH, –NH^{3+}, and –$NHCO^{-}$). These features ensured multi-level interactions, facilitating an efficient removal of various MPs of different sizes, such as polystyrene (PS), polypropylene (PP), polyethylene terephthalate (PET), and polymethyl methacrylate (PMMA) (Fig. 1a). More advanced, the hydrogen bonding self-assembly strategy can be utilized for various biomass materials with different hydrogen bond networks. Wu et al. [12] employed α-chitosan and β-chitosan with distinct native hydrogen bond networks as raw materials to reconstruct a pure chitosan nanofiber sponge, which was used to remove ~98% of MPs (80 nm to 1 μm size range) from wastewater.

In addition to modifying existing materials, a custom synthesis of bio-based MPs adsorbents represents an alternative approach. Plastic-binding peptides can selectively interact with MPs through hydrogen bonding, electrostatic interactions, van der Waals forces, and hydrophobic interactions. Advancements in protein engineering and quantum computing have enabled the development of MPs-binding peptides for various end applications. Vendrell et al. [13] applied a hybrid quantum–classical method to design peptides capable of selective MPs binding. This method integrated a variational quantum circuit (VQC) and a variational autoencoder (VAE). The VAE encoded a peptide sequence of 12 amino acids from a one-hot encoding vector into a compressed 16-dimensional latent space, where the VQC predicted the peptide affinity for MPs based on the latent representations. The VAE and VQC were jointly optimized in end-to-end training to accurately predict peptide affinity. Molecular dynamics simulations confirmed that the resultant peptide exhibited a higher affinity for PET relative to other peptides. However, they did not include an experimental

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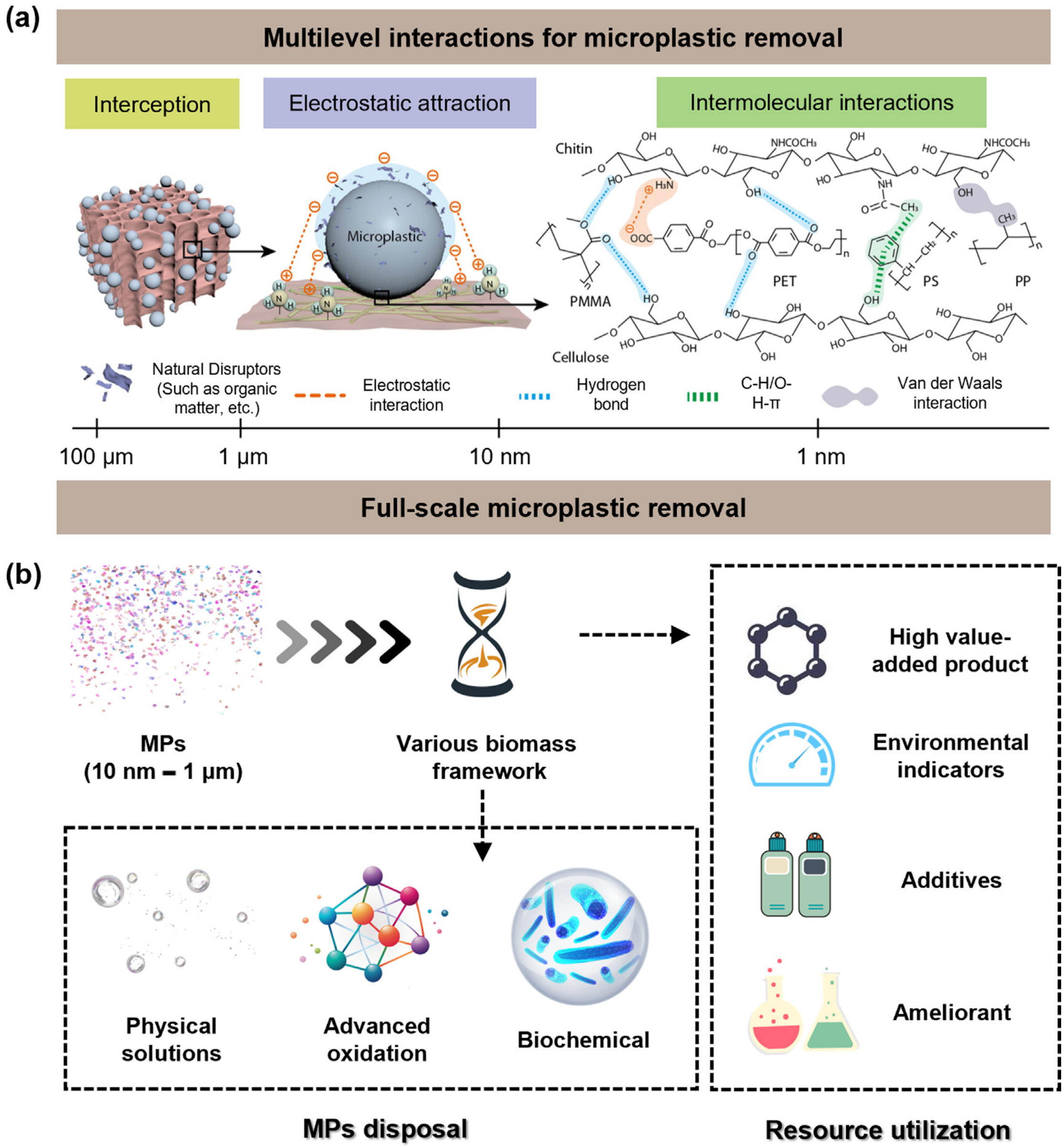

Fig. 1. Full-scale MPs removal and application. (a) MPs removal by the MFF via multilevel interactions (physical interception, electrostatic attraction, and multiple intermolecular interactions) due to the abundance of reactive functional groups [11], reproduced with permission from Ref. [11] under a Creative Commons Attribution License 4.0 (CC BY). Copyright 2024, American Association for the Advancement of Science. (b) Diagrams for the removal and resource utilization of MPs based on the advanced biomass framework.

evaluation of the synthesized peptide performance. Further work is required to determine large-scale MPs removal efficiency, cycle stability, and competitive adsorption capabilities, as well as the biological and environmental toxicity of the designed peptides. Despite this, the utilization of advanced algorithms to enable the programmable synthesis of MPs adsorbents is indeed praiseworthy.

A number of features warrant further consideration:

(1) The disposal and utilization of MPs. Given the low concentrations of MPs in the natural environment, catalytic and microbial engineering have limited practical effectiveness in addressing associated pollution. Advanced biomass-based adsorption frameworks can serve as effective enrichment platforms to recycle and upgrade MPs (Fig. 1b) [14]. Following enrichment, a high-concentration MPs stream can be treated using microbubbles, advanced oxidation, biochemical processes, and other technologies. In terms of cycle suitability, catalytic and microbial technologies can be applied in adsorbent regeneration. Current industrial practice employs elution methods to regenerate adsorbents. However, this approach may compromise the performance of MPs adsorbents and does not represent a sufficiently rigorous approach in addressing current pollution challenges. Upgrading and transforming MPs associated with adsorbents require novel regeneration methods. Possible approaches and designs are still at the laboratory developmental stage and require appreciable fundamental research informed by industrial requirements to achieve practical engineering solutions. From the perspective of resource utilization, the enriched MPs can serve as raw materials in the production of high value-added products, such as graphene and hydrogen. When compared with conventional adsorbents, bio-based materials exhibit superior biocompatibility and degradation, ultimately enabling the complete conversion of both MPs and adsorbents. Other potential applications, notably as environmental indicators, additives, and modifiers are identified in Fig. 1b, but biological toxicity requires careful consideration.

(2) Multi-scale evaluation of biomass adsorbent practicality. In addition to performance and processing routes, scalability and production costs are important considerations. Upscaling the production of advanced adsorbents while ensuring consistent quality and performance is complex and costly, where durability and stability are crucial factors. The degradability of bio-based MPs adsorbents presents significant challenges in achieving long-term resistance to corrosion and microbial contamination in real-world environments. The overall environmental impact must be addressed. Safe disposal and life cycle assessments of bio-based MPs adsorbents are essential in considering viable broad applications.

(3) The potential value-added features of different MPs disposal techniques. Currently, no country has strictly regulated the discharge of MPs into water bodies, and MPs removal technologies have not been implemented within existing complex industrial systems. In the absence of government or regional policy support, the incorporation of MP removal modules will result in increased operating costs and an additional financial burden for companies. Consequently, enhancing the value-added benefits of MPs removal technologies is essential. Deng's group [14] has demonstrated a promising approach to converting MPs and adsorbents into composite boards using an established industrial hot-pressing method. In this process, the captured MPs, as functional adhesives, effectively bond waste wood fibers, significantly enhancing the mechanical properties and environmental stability of the composite board. In addition, the desorbed MPs can be utilized for the synthesis of functional membrane materials [12]. In the case of the battery diaphragm, this solution can earn 0.003 USD by processing 1 g of MPs.

In summary, a rationally designed biomass framework can efficiently adsorb MPs and enable complete lifecycle utilization of both MPs and adsorbents through catalytic upgrading and elution regeneration. However, large-scale and full-chain implementation of bio-based adsorbents requires further research to enable viable industrial applications.

Conflict of interest

The authors declare that they have no conflict of interest.

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