A Cheap and Portable Solution for The Removal of Microplastics from Natural Waters

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Abstract. The exponential increase in plastic production has led to a significant environmental challenge due to the pervasive presence of microplastics (MPs) in aquatic ecosystems. These MPs, defined as plastic particles smaller than 5mm, have been identified as a major pollutant, ingested by a wide range of aquatic organisms and contaminating the food chain. This paper reviews the current strategies and mechanisms for the removal of MPs from freshwater and saltwater environments, highlighting the limitations of existing methods and the need for innovative solutions. A novel approach using an eco-friendly Cu/Co LDHs-based superhydrophobic sponge is proposed, offering a practical, cost-effective, and efficient method for MPs removal without the need for external energy sources or complex machinery. The study also emphasizes the importance of advanced treatment methods in wastewater treatment plants (WWTPs) to enhance the removal of smaller MP particles and suggests a multifaceted approach involving stringent source control measures and household treatments. Through comprehensive analysis and evaluation of various MPs removal techniques, this paper aims to contribute to the development of sustainable solutions to mitigate the impact of microplastic pollution on aquatic ecosystems and human health.

Keywords: Microplastics removal; microplastics extraction; layered double hydroxides (LDHs).

1. Introduction

The production of plastics has surged from 2 million tons in 1950 to 370 million tons annually by 2019, with projections suggesting a fourfold increase by 2050 [1]. This growth underscores plastics' integral role in modern society, enhancing convenience across all industries but also contributing to significant environmental challenges, notably plastic pollution. Among these pollutants are microplastics (MPs), defined as plastic particles smaller than 5mm [2]. MPs are categorized into primary MPs, designed for specific uses like skincare products or as carriers for raw plastic materials, and secondary MPs, which result from the natural degradation of plastic. While the full environmental impact of MPs is not entirely understood, their presence is widespread across the biosphere, including deep-sea sediments and both rural and urban settings, with a pronounced accumulation in aquatic environments. MPs are ingested by a wide range of aquatic organisms, contaminating the food chain. Addressing the removal of microplastics from aquatic ecosystems is a critical and urgent focus of this study.

Microplastics (MPs) are composed of various plastics, including major polymers such as polyethylene terephthalate (PET), polyurethane (PU), polystyrene (PS), polyvinyl chloride (PVC), polypropylene (PP), and polyethylene (PE). Research has highlighted MPs' toxicity; for instance, diclofenac MPs significantly inhibited Pseudokrichneriella subcapitata algae growth by over 50% under certain conditions [3], and high concentrations of small PP MPs stimulated the human immune system [4]. The large surface area-to-weight ratio of MPs facilitates the absorption of toxins and pollutants. Additionally, some additives in MPs act as endocrine disruptors, posing risks to both wildlife and humans, although there is no direct evidence linking MPs to human fatalities [1]. This study proposes a strategy to mitigate microplastic pollution, emphasizing the critical need for reducing plastic waste and implementing sustainable solutions.

2. Microplastics Removal Mechanisms and Strategies

This study addresses the removal of MPs from freshwater and saltwater environments. It is acknowledged that sediment layers in riverbeds and deep oceans are significant microplastic reservoirs, with estimates of 4 billion MP fibers per km^2 in the Indian Ocean's seamount sediment [5]. While several mechanisms exist for extracting MPs from sediment, most are primarily investigative, aimed at detecting MPs rather than removing them. Techniques like density separation, though simple, have not been effectively scaled up [6,7]. Moreover, these methods, often involving sediment dredging, are labor-intensive and environmentally disruptive, rendering MP removal from sediments impractical. Consequently, focusing on the extraction of MPs from water bodies before they settle into sediments underscores the significance of this project's contribution to mitigating microplastic pollution. In this realm, the chosen mechanism must be compact, cost-effective, and dependable, necessitating operation without an external energy source or moving parts and minimizing component count.

Among physical filtration techniques for MPs, membrane bioreactors and conventional activated sludge systems utilize microorganisms for wastewater MP removal, achieving 99.4% and 98.3% efficacy, respectively [8]. The performance of activated sludge systems can be enhanced with an aeration tank to stimulate microorganisms and a sedimentation tank for further purification. However, it's important to note the potential denaturation of these systems by seawater. Sand filtration, a method employed in numerous wastewater treatment facilities, has proven to be effective, with certain configurations removing up to 100% of MPs at a manageable flow rate of 7.24 cm^3 per minute [9], compatible with the flow rates of natural water bodies.

Electrocoagulation emerges as a promising method for MPs removal in aquatic environments, achieving over 82% efficacy through a series of physical-chemical reactions in three stages [10]. Initially, metal cations produced by the metal anode form micro coagulants under an electric field. These charged coagulants capture suspended particles, leading to the aggregation of MPs into flocs. As collisions continue, the flocs grow, allowing for MP removal via physical (e.g., filtration) and chemical methods [11].

Absorption techniques, utilizing chemically synthesized sponges, graphene, and biochar, have also been effective in extracting MPs from water. Notably, a biodegradable green sponge, developed through the chemical crosslinking of plant proteins, exhibits high mechanical strength and an absorption rate of 81.2%, thanks to active side chains on amino acid residues. This sponge also offers advantages in reusability and biodegradability [12]. Despite these innovations, a sponge based on Cu/Co-layered double hydroxides (LDHs) demonstrates superior efficiency in removing MPs and other pollutants. Their application in extraction and filtration MPs will be discussed in this study.

3. LDHs as Adsorber for MP Filtration

The absorption of MPs using an eco-friendly Cu/Co LDHs-based superhydrophobic sponge represents a practical approach, surpassing other mechanisms in simplicity and efficiency. Unlike methods requiring power sources, pumps, or large aeration tanks, this sponge operates without necessitating water flow through it, offering advantages in terms of weight and versatility compared to sand filters. A 9cm x 6cm x 1cm coated sponge can remove nearly 100% of polypropylene (PP) and polyethylene (PE) MPs at a concentration of 40 mg/L within one minute [13]. Its reusability is notable, with performance maintained after pressing out effluent and cleaning. The sponge's durability, superhydrophobicity, high salt tolerance, and antibacterial properties make it ideal for oceanic applications, facing high salinity, strong currents, and potential colonization by organisms.

The required materials for the synthesis of LDHs in the above study include dopamine hydrochloride, hexadecyltrimethoxysilane, Tris-HCl, NaOH, $CuCl_2 \cdot 2H_2O$, $Co(NO_3)_2 \cdot 6H_2O$, ethanol, and a polyurethane sponge. The fabrication process, encompassing polymerization, oxidation, and siliconization, which is straightforward and scalable. Despite Dopamine hydrochloride being the costliest material at £332.00 per 100 grams (as of 24/02/2024), only 0.1 grams are needed for a single sponge, with the remaining materials being relatively inexpensive. This cost-effectiveness facilitates the mass production of these sponges for the proposed filtration applications.

The filter, intended for use in natural waters with currents and tides, harnesses these movements for self-filtration, eliminating the need for pumps or large tanks. Its design, inspired by a windsock, allows it to swivel and capture the current efficiently. The design comprises three main components: The filter design features a mesh-equipped mouth with an optimized profile to prevent organism entry and reduce drag and turbulence, enhancing durability and ensuring proper orientation specific to each environment. The funnel-shaped body, made from fabric supported by a wire frame for cost efficiency, is designed to be protected from eddy currents by the mouth, though it may require reinforcement or a transition to a more durable material due to the aquatic environment's demands. The sponge is contained within a nonreactive PVC coupling, facilitating straightforward installation or removal. This novel design necessitates comprehensive testing to verify its effectiveness [14].

An alternative deployment involves multiple sponges linked to a central buoy system, suitable for both flowing and stagnant waters. Sponges can be left to absorb MPs and later collected by a vessel for replacement, offering a cost-effective solution. This approach necessitates a specially designed casing to maximize the sponge's surface area and ensure submersion, facilitating MP diffusion into the hydrophobic sponge. Existing waterway structures, such as navigational buoys, offer a platform for integrating filters to remove MPs from aquatic environments. This approach could extend to various navigational aids, enhancing MP removal efforts. Additionally, dedicated filtration setups, like ropes adorned with sponges floated downstream in rivers, provide a practical method for MP capture, allowing easy retrieval and sponge replacement. The affordability and portability of these sponges enable their use by both governmental bodies and individual consumers for MP removal in diverse water bodies, from rivers to private ponds [15]. For filter maintenance, a protocol involving secure storage in watertight containers, and transportation to a central facility for waste extraction, sponge cleaning, and reuse is proposed. The wastewater generated during this process should undergo thorough filtration, with the resultant waste disposed of responsibly, ensuring pollutants are not reintroduced into the environment.

Other LDHs have also been widely researched. A recent study reports the novel use of eco-friendly Zn-Al LDHs, synthesized via co-precipitation, for the effective removal of nanoplastics (NPDs) from aqueous environments, achieving up to 96% removal efficiency through electrostatic interactions. The adsorption capacity was influenced by the presence of anionic species, pH levels, and the ionic composition of the water, with the highest sorption observed in deionized water and the lowest in synthetic hard water due to competitive binding and decreased adsorbent stability. The findings suggest Zn-Al LDHs hold significant potential for NPDs removal in freshwater systems with low ionic concentrations, highlighting the need for further adsorbent modifications to enhance removal efficiency across various water types [16].

The LDH composites with other materials are also extensively studied. A novel high-performance capture agent for polystyrene (PS), termed three-dimensional graphene-like carbon-assembled layered double oxide (G@LDO), was developed using a precursor-calcination strategy, achieving a PS removal rate of 60–100% across a broad pH range (1–13). This unique structure, created by intercalating organic precursors with graphene-like carbon (G) and layered double oxide (LDO) and calcining under N_2 at 700°C, exhibited exceptional stability and a maximum adsorption capacity of 209.39 mg/g, adhering to the Langmuir model of monolayer adsorption. The G@LDO's effectiveness in PS removal, characterized by exothermic chemisorption and excellent reusability after five cycles, alongside DFT calculations, suggests its potential for microplastics removal in diverse wastewater conditions, particularly in acidic or alkaline effluents [17].

4. Outlook and Perspective

Addressing microplastics in wastewater treatment plants (WWTPs) necessitates focusing on several critical areas. Firstly, the potential of specific species to capture microplastics requires evaluation, considering their containment and welfare within WWTPs. Source control, including household treatments to limit microfiber release and stringent regulations, is essential for mitigating MP pollution. Moreover, the development and validation of analytical methods for MP detection in WWTPs are crucial due to current inconsistencies in measurement units and methodologies. Innovative detection techniques, such as nanocomposites, biogenic nanoparticles, and nano-sensors, show promise for pollutant identification and removal through processes like enzymatic and photocatalysis [18].

Significant MP release occurs not only from water discharges but also from sewage sludge disposal. Advanced treatment methods, beyond conventional processes, are necessary to enhance MP removal, particularly for smaller particles (<100 μm) that conventional treatments fail to capture. Membrane bioreactors and rapid sand filters have shown high efficacy, and their performance could be further improved by integrating additional membrane-based operations. Bioremediation, employing microorganisms and marine organisms, offers a viable solution for MP degradation. Finally, low-cost advanced treatments like electrocoagulation and photocatalysis are recommended for incorporation into WWTPs to better control MP pollution [18].

5. Conclusion

In conclusion, this paper has systematically explored the escalating issue of microplastics (MPs) pollution, underscoring the urgent need for effective removal strategies in both freshwater and saltwater environments. With the production of plastics projected to increase significantly, the pervasive presence of MPs poses a substantial threat to aquatic ecosystems and, by extension, human health. This study has highlighted various mechanisms and strategies for MPs removal, emphasizing the limitations of current methods predominantly focused on aqueous environments and the necessity for broader application scopes, including solid matrices and diverse food matrices.

The introduction of an eco-friendly Cu/Co LDHs-based superhydrophobic sponge presents a promising solution, leveraging its efficiency, cost-effectiveness, and ease of use without the need for external energy sources or complex machinery. This innovative approach, suitable for integration with existing waterway structures or as part of a standalone filtration system, offers a scalable and versatile option for mitigating MPs pollution. Furthermore, the study advocates for advanced treatment methods in WWTPs to address the limitations of conventional processes in capturing smaller MP particles.

Future research should focus on enhancing the specificity and efficiency of MPs removal techniques, exploring the potential of bioremediation, and developing low-cost advanced treatment methods. Additionally, addressing MPs pollution requires a multifaceted approach, including stringent source control measures, household treatments to limit microfiber release, and the establishment of rigorous regulations. By advancing the understanding and capabilities in MPs detection and removal, future work toward mitigating the environmental impact of plastic pollution and safeguarding aquatic ecosystems for future generations is crucial.

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