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Outline

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Crustacean nanochitosan-based bioremediation of nanoplastic-polluted

aquatic habitat: A review pursuant to SDG 6

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Abstract

Microplastic and nanoplastic pollution is a growing environmental concern with potentially adverse effects on ecosystems and human health. The development of effective and sustainable methods for the removal of micro-/nanoplastics from water sources is of paramount importance. Crustacean nanochitosan, derived from chitosan, a biopolymer obtained from crustacean shells, has emerged as a promising solution for micro-/nanoplastic removal. This scientific abstract presents an overview of the application of crustacean nanochitosan for micro-/nanoplastic removal, highlighting its unique properties, adsorption mechanism, and potential advantages over other methods. Though the unique properties of crustacean nanochitosan that enable it to adsorb, bind, immobilize and effectively reduce contamination have been demonstrated, complex scalability, regeneration and cost effectiveness issues still hinder the adaptation of this technology in pursuit of SDG 6. The report thus addressed key factors necessary for the optimization of the purification mechanisms of nanochitosan. The integration of crustacean nanochitosan into water treatment systems thus offers a promising approach for mitigating micro-/nanoplastic pollution, hence the paper explored new research paths, highlighting nanochitosan modification, optimization of process parameters such as pH, contact time, dosage, and agitation speed for enhanced adsorption efficiency for healthier ecosystems; towards the attainment of sustainable development goal 6 aimed at achieving clean water and sanitation. Regeneration, reusability, scale-up and the scalability of the suggested technology were assessed and the cost-effectiveness, system integration, and long-term performance under varying water conditions were reported. The paper evaluated the effectiveness of the suggested techniques, and assessed the possible environmental impacts and implications for policies.

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Keywords

Adsorption
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Environmentally friendly
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Introduction

The United Nations' goal to make clean water affordable and available to all living things by 2023 is dire, and yet, notably hindered by several intricate challenges. One such emerging challenge is the presence of pervasive micro and nano plastics in natural water resources including rivers, lakes and groundwater. The staggering size of global plastic production, currently about 390 million ton annually; coupled with disposal and degradation problems, has resulted in 13 million tonnes of plastic waste in natural water resources. In most popularly produced polymers, the breakdown process leads to the development of nano and micro plastic particles. These plastic particles are persistent, accumulating in sediments and amplifying in the food web as they are ingested by various organisms. In addition to their nuisance of physical obstruction in biological systems, they absorb and accumulate toxic chemicals, leading to secondary pollution during degradation [7]. They threaten marine life, including fish, shellfish, and marine mammals, as their ingestion can cause biological damage, impair reproduction, and disrupt delicate aquatic ecosystems [38]. They threaten terrestrial life through a phenomenon termed "plastic breeze" which involves their percolation in the air and rainwater that amplify their spread and the spread of volatile organic compounds. Most pertinently, they threaten the ecosystem by contaminating vital water resources that serve as drinking water supplies, agricultural irrigation sources, and support various industries.

Within the affordability and sustainability context of the SDG 6, appropriate solutions for tackling this issue globally must be adequately scalable, offer several advantages over conventional remediation methods and be environmentally friendly. One promising approach in this regard is the utilization of crustacean nanochitosan-based systems. Nanochitosan, derived from chitosan, a natural polymer obtained from the exoskeleton of crustaceans, offers several advantageous properties that make it scalable for remediation [9]. This includes large surface areas for maximal absorption to production ratio, abundant functional groups, and natural biocompatibility. Crustacean nanochitosan can be obtained as a byproduct from the seafood industry, reducing waste and promoting sustainability. Additionally, the biodegradability of nanochitosan ensures that the remediation process does not introduce further pollutants into the ecosystem. The effectiveness of crustacean nanochitosan-based bioremediation has been demonstrated in various studies, showcasing its potential as a viable solution for nanoplastic pollution in aquatic habitats [9]. These studies have investigated factors such as nanochitosan dosage, nanoplastic concentration, and environmental conditions to optimize the bioremediation process. Furthermore, the potential applications of crustacean nanochitosan-based systems extend beyond nanoplastic pollution, with research exploring its efficacy in the remediation of other pollutants and contaminants. Though the unique properties of crustacean nanochitosan that enable it to adsorb, bind, immobilize and effectively reduce contamination have been demonstrated [3,9,20,21]; complex scalability, regeneration and cost effectiveness issues still hinder the adaptation of this technology in pursuit of SDG 6. In this paper, we review relevant insights on micro and nano plastic water pollution to adequately present the scope of its challenge. We distill current approaches and developments in the mechanism of crustacean nanochitosan-based systems we consider a particularly important strategy for tackling this challenge. Finally, we approach and review the relevant benefits, drawbacks and future considerations crucial to establish this technology in a central role for achieving SDG 6 goal.

Micro-/nanoplastics in water

Microplastics and nanoplastics in water have emerged as significant environmental pollutants with widespread distribution and potential adverse effects on ecosystems and human health. Microplastics refer to plastic particles with a size range of 1 micrometer to 5 mm, while nanoplastics have dimensions smaller than 100 nm [1,35].

These plastic particles originate from various sources, including the breakdown of larger plastic items, the disintegration of synthetic fibres, abrasion of tires, and the release of microbeads from personal care products [55]. They enter water bodies through various pathways, including surface runoff, industrial discharge, wastewater effluent, and atmospheric deposition. Once in the aquatic environment, microplastics and nanoplastics can persist for long periods due to their resistant nature [4].

The presence of microplastics and nanoplastics in water ecosystems has raised concerns due to their potential ecological impacts. These particles can be ingested by a wide range of organisms, including plankton, fish, marine mammals, and birds, leading to physical harm, reduced feeding efficiency, and altered behavior [5]. The accumulation of plastic particles in the food chain can result in biomagnification, potentially affecting higher trophic levels, including humans [38].

Furthermore, microplastics and nanoplastics can act as carriers for chemical contaminants such as persistent organic pollutants (POPs) and heavy metals. These pollutants can adsorb onto the surface of plastic particles, leading to the potential transfer of toxic substances to organisms upon ingestion. Additionally, plastic particles can leach additives and monomers used in their production, further increasing the chemical burden on the environment [40].

The presence of microplastics and nanoplastics in drinking water sources has also raised concerns regarding human exposure. Studies have detected microplastics in tap water, bottled water, and even in seafood consumed by humans. While the health impacts of ingesting microplastics are still being investigated, there is concern about their potential to cause inflammation, oxidative stress, and the transfer of chemical contaminants into the human body [6,7].

Addressing the issue of microplastics and nanoplastics in water requires a multi-faceted approach, including source reduction, improved waste management practices, and the development of effective removal and remediation technologies. Efforts are underway to regulate the use of microplastics in consumer products, promote recycling and circular economy practices, and implement advanced wastewater treatment systems to minimize the release of plastic particles into water bodies [11,41].

The presence of microplastics and nanoplastics in water ecosystems poses a significant environmental and health concern [43]. These particles can accumulate in aquatic organisms, disrupt ecosystems, and potentially transfer chemical contaminants. Addressing the issue requires concerted efforts to reduce plastic pollution, improve waste management, and develop effective strategies for the removal and remediation of microplastics and nanoplastics from water sources [47].

Sources and types of micro-/nanoplastics

Microplastics and nanoplastics are derived from various sources and can take different forms.

Fragmentation of larger plastics: One major source of microplastics is the fragmentation and degradation of larger plastic items, such as bottles, bags, and packaging materials. Over time, exposure to environmental factors like sunlight and wave action breaks down these plastics into smaller particles [13,50].

Microplastics can also originate from synthetic fibres released during the washing and drying of textiles like clothing, carpets, and upholstery. The agitation and friction during these processes cause tiny fibres to detach and enter the wastewater system.

Industries that handle plastics or engage in plastic manufacturing can be significant sources of microplastics and nanoplastics. These particles may be released through processes like plastic production, processing, and recycling [14]. Vehicles, especially those with rubber tires can also contribute to microplastic pollution. Tire wear and the erosion of road surfaces generate particles that contain plastic polymers, rubber additives, and other contaminants [1].

Furthermore, microbeads, which are tiny plastic particles intentionally added to personal care products like exfoliating scrubs and toothpaste, can be washed down the drain and enter waterways directly [52,55]. The use of plastic mulch films in agriculture can lead to the fragmentation of these materials, resulting in microplastic pollution in soils and nearby water bodies. Microplastics can also be transported through the atmosphere and deposited in water bodies. They may originate from sources like plastic litter, industrial emissions, or the breakdown of larger plastics in the environment.

The types of microplastics and nanoplastics can vary in shape, size, and composition:

- Fibres: Microplastic fibres are thread-like particles that can be derived from textiles, ropes, and fishing nets. They are often long and slender [4].
- Fragments: Fragmented microplastics result from the breakdown of larger plastic items. They can have irregular shapes and may vary in size [5].
- Microbeads: Microbeads are spherical particles intentionally manufactured for use in personal care products. They are typically small in size and have a uniform shape [55].
- Films: Microplastic films can arise from the degradation of plastic sheets or films used in packaging, agricultural practices, or other applications.

- Foams: Foam particles, often originating from products like foam insulation or packaging materials, can also contribute to microplastic pollution.

It is worth noting that nano plastic, which is even smaller than microplastics with dimensions in the nanometer range, can arise from the further degradation or fragmentation of microplastics or as a result of direct release during manufacturing processes [16].

The report aims at paving new research paths, highlighting nanochitosan modification, optimization of production and adsorption efficiency; towards the attainment of sustainable development goal 6 aimed at achieving clean water and sanitation. It seeks to shed some light on regeneration, reusability, and the scalability of the adsorption mechanism for cost-effectiveness, system integration, and long-term performance under varying water conditions.

Environmental and health implications of micro-/nanoplastic pollution

Microplastic and nanoplastic pollution has significant environmental and health implications, affecting ecosystems and human well-being [17]. Some environmental and health concerns associated with microplastic and nanoplastic pollution include environmental implication, biomagnification, habitat alteration, chemical contamination, health implications, transfer of chemicals, inflammation and cellular damage. Microplastics and nanoplastics can disrupt aquatic ecosystems, including rivers, lakes, and oceans. These particles can accumulate in sediments and be ingested by a wide range of organisms, from plankton and fish to marine mammals and birds. This ingestion can lead to physical harm, reduced feeding efficiency, altered behavior, and reproductive abnormalities, thereby impacting the overall health and balance of ecosystems [6]. Microplastics and nanoplastics have the potential to bioaccumulate and biomagnify in the food chain. When organisms consume plastic particles, they can transfer these particles and associated contaminants to predators at higher trophic levels. This process can lead to an increase in plastic concentrations and chemical exposure in top predators, posing a risk to their survival and ecosystem dynamics [7]. Accumulation of microplastics and nanoplastics in habitats such as coral reefs, seafloor sediments, and riverbeds can cause physical changes and affect important ecological processes. The presence of plastic particles can smother benthic organisms, disrupt sediment composition, and hinder gas exchange, ultimately impacting the health and functioning of these habitats [53]. Microplastics and nanoplastics can act as carriers for chemical pollutants, including persistent organic pollutants (POPs) and heavy metals [58]. These pollutants can adsorb onto the surface of plastic particles and leach into the surrounding environment, potentially causing toxicity and contaminating water and soil systems. The combination of plastic particles and associated chemicals can have adverse effects on both aquatic and terrestrial organisms [61].

Humans can be exposed to microplastics and nanoplastics through various routes, primarily through the consumption of contaminated food and water. Seafood, including fish, shellfish, and molluscs, can contain microplastics that have been ingested by marine organisms. Inhalation of airborne microplastics is also a concern, particularly for individuals working in industries where plastic particles are generated [7,19]. The health impacts of ingesting or inhaling microplastics are still being studied, but there are concerns about potential physical and chemical effects on human health.

Microplastics and nanoplastics can act as vehicles for transporting chemical contaminants. When humans consume plastic-contaminated seafood or water, there is a risk of ingesting not only the plastic particles but also the associated chemical pollutants that have been adsorbed onto their surfaces [65]. This transfer of chemicals into the human body raises concerns about potential toxicological effects and long-term health implications [11]. Studies suggest that microplastics and nanoplastics can induce inflammation and cellular damage in exposed organisms. The small size and surface properties of these particles may trigger immune responses, oxidative stress, and inflammation in tissues. Prolonged exposure to microplastics and nanoplastics may contribute to chronic inflammation and related health issues in humans.

The field of microplastics and nanoplastics research is still evolving, and ongoing studies are exploring their potential health effects. Researchers are investigating the distribution, fate, and toxicity of these particles to better understand their impact on human health. Studies are also examining the potential for microplastics and nanoplastics to act as carriers for pathogenic microorganisms, further highlighting the need for comprehensive research in this area [26].

Addressing the environmental and health implications of microplastic and nanoplastic pollution requires concerted efforts to reduce plastic waste, improve waste management practices, implement stricter regulations, and develop effective remediation [13].

One promising approach for nanoplastic bioremediation is the utilization of crustacean nanochitosan-based systems. Nanochitosan, derived from chitosan, a natural polymer obtained from the exoskeleton of crustaceans, offers several advantageous properties that make it suitable for nanoplastic remediation [9]. Nanochitosan exhibits a high surface area, abundant functional groups, and biocompatibility, making it an excellent candidate for nanoplastic adsorption and removal. The bioremediation process involving crustacean nanochitosan and nanoplastic pollution is based on the principles of adsorption and agglomeration. Nanochitosan particles possess an affinity for nanoplastics, allowing them to effectively bind to and immobilize the nanoplastic particles from the surrounding aquatic environment. This mechanism helps prevent the nanoplastics from further dispersing and accumulating in water bodies.

Furthermore, crustacean nanochitosan-based bioremediation offers several advantages over conventional remediation methods. It is a cost-effective and environmentally friendly approach that utilizes a naturally derived material. Crustacean nanochitosan can be obtained as a byproduct from the seafood industry, reducing waste and promoting sustainability. Additionally, the biodegradability of nanochitosan ensures that the remediation process does not introduce further pollutants into the ecosystem.

The effectiveness of crustacean nanochitosan-based bioremediation has been demonstrated in various studies, showcasing its potential as a viable solution for nanoplastic pollution in aquatic habitats [9]. These studies have investigated factors such as nanochitosan dosage, nanoplastic concentration, and environmental conditions to optimize the bioremediation process. Furthermore, the potential applications of crustacean nanochitosan-based systems extend beyond nanoplastic pollution, with research exploring its efficacy in the remediation of other pollutants and contaminants. The pollution of aquatic habitats with nanoplastics poses a pressing environmental challenge. Crustacean nanochitosan-based bioremediation offers a promising solution for the removal and mitigation of nanoplastic pollution. Through its adsorption and agglomeration properties, nanochitosan derived from crustacean sources can effectively immobilize and remove nanoplastic particles from aquatic environments. This environmentally friendly approach provides a cost-effective and sustainable method for nanoplastic remediation, with potential applications in preserving aquatic ecosystems and protecting human health.

The removal of micro- and nanoplastics from water is of utmost importance due to the significant environmental and health risks they pose. Micro- and nanoplastics have become pervasive pollutants in aquatic environments, including rivers, lakes, oceans, and even groundwater. These particles can persist in the environment for long periods, accumulating in sediments and being ingested by various organisms. They pose a threat to marine life, including fish, shellfish, and marine mammals, as they can cause physical harm, impair reproduction, and disrupt ecosystems. Removing micro- and nanoplastics from the water helps reduce their impact on fragile aquatic ecosystems.

The ingestion of micro- and nanoplastics by marine organisms can lead to bioaccumulation and biomagnification, ultimately affecting human health through the consumption of contaminated seafood. Additionally, micro- and nanoplastics can enter drinking water sources, potentially exposing humans to these particles. The health implications of micro- and nanoplastic exposure are still being studied, but there is concern about the potential transfer of toxic chemicals associated with plastics into the human body. Removing micro- and nanoplastics from water is vital to safeguard human health [38]. Micro- and nanoplastic pollution can contaminate vital water resources that serve as drinking water supplies, agricultural irrigation sources, and support various industries. Ensuring the removal of these particles helps protect the quality and integrity of water resources, safeguarding human and environmental well-being. It also contributes to sustainable water management practices and the preservation of water ecosystems. Aquatic ecosystems rely on a delicate balance of organisms and processes to thrive. The presence of micro- and nanoplastics disrupts this balance by affecting the physiology, behavior, and reproductive success of organisms. By removing micro- and nanoplastics from water, we can mitigate the negative impacts on the biodiversity and functioning of aquatic ecosystems, supporting their long-term stability and resilience.

Micro- and nanoplastics can act as carriers of toxic chemicals and pollutants, absorbing and accumulating them from the surrounding environment. When these particles are ingested by organisms or settle in sediments, the associated chemicals can be released, leading to secondary pollution. Removing micro- and nanoplastics from water minimizes the potential for these particles to act as carriers of harmful substances, reducing the risk of secondary pollution and its detrimental effects [7]. Removing micro- and nanoplastics from water is crucial to mitigate environmental degradation, protect human health, preserve water resources, maintain ecological balance, and prevent the spread of secondary pollution. Implementing effective strategies and technologies for the removal of these particles is essential for the sustainability and well-being of both aquatic ecosystems and human populations.

Crustacean nanochitosan has emerged as a promising and innovative solution in various fields, including environmental remediation, due to its unique properties and versatile applications. Derived from chitosan, a biopolymer obtained from the exoskeletons of crustaceans such as shrimp and crab, crustacean nanochitosan offers a range of advantageous characteristics that make it an attractive candidate for various environmental challenges [21]. Nanochitosan, with its nano-sized particles, high surface area, and abundant functional groups, exhibits exceptional properties such as biocompatibility, adsorption capacity, and controlled release capabilities. These attributes have sparked immense interest in harnessing crustacean nanochitosan for diverse applications, particularly in the realm of environmental remediation. In the context of pollution, crustacean nanochitosan demonstrates immense potential as a sustainable and eco-friendly solution for the removal and remediation of contaminants from water and soil. Its adsorption capabilities allow it to effectively capture a wide range of pollutants, including heavy metals, organic compounds, dyes, and even microorganisms. Additionally, crustacean nanochitosan can be modified to enhance its adsorption efficiency and selectivity for specific pollutants, further expanding its utility in tailored environmental remediation approaches [20].

One significant advantage of crustacean nanochitosan is its renewable and sustainable nature. As a byproduct of the seafood industry, the utilization of crustacean exoskeletons to derive nanochitosan presents an opportunity for waste valorization, reducing environmental burden and promoting a circular economy. This aspect aligns with the growing global focus on sustainability and the need for environmentally friendly alternatives to traditional remediation techniques. Moreover, the biodegradability of crustacean nanochitosan ensures that it does not leave behind persistent pollutants or contribute to secondary pollution. As it breaks down into nontoxic components, it offers a safe and environmentally sound approach for remediation efforts.

In the realm of water and soil remediation, crustacean nanochitosan-based systems have been investigated for applications such as heavy metal removal, wastewater treatment, soil stabilization, and oil spill cleanup. The unique properties of crustacean nanochitosan enable it to adsorb, bind, and immobilize contaminants, effectively reducing their presence and minimizing their potential impact on ecosystems and human health [20]. Crustacean nanochitosan holds great promise as a versatile and sustainable solution in environmental remediation. Its exceptional adsorption capabilities, renewable nature, and biodegradability make it a valuable tool for addressing various environmental challenges. By harnessing the potential of crustacean nanochitosan, we can develop innovative strategies for pollution control and management, contributing to the preservation and restoration of our natural resources.

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Addressing the issue of microplastics and nanoplastics in water requires a multi-faceted approach, including source reduction, improved waste management practices, and the development of effective removal and remediation technologies. Efforts are underway to regulate the use of microplastics in consumer products, promote recycling and circular economy practices, and implement advanced wastewater treatment systems to minimize the release of plastic particles into water bodies [11,41].

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Challenges in removing micro-/nanoplastics from water

Removing microplastics and nanoplastics from water presents several challenges due to their small size, diverse compositions, and widespread distribution [14]. Some of the key challenges associated with the removal of microplastics and nanoplastics from water include:

- Small Size and Detection: Microplastics and nanoplastics can have sizes ranging from micrometres to nanometers, making their detection and quantification challenging. Conventional water treatment methods and filtration techniques may not effectively capture these tiny particles, requiring the development of specialized detection methods and technologies [27].
- Varying Particle Characteristics: Microplastics and nanoplastics come in different shapes, sizes, densities, and compositions. This variability poses challenges in selecting appropriate removal techniques that can efficiently target and capture the wide range of plastic particles present in water systems [28].
- Presence of Particles in Different Forms: Microplastics and nanoplastics can exist in various forms, such as fibres, fragments, films, and beads [55]. Each form may require specific removal approaches tailored to its physical properties, further complicating the development of universal removal methods [16,32].
- Intermixing with Natural Particles: Microplastics and nanoplastics can mix with natural organic and inorganic particles in water, making their separation and isolation more challenging. The presence of natural particles can hinder the efficiency of removal processes and increase the risk of false-positive results during analysis [17].
- Low Concentrations and Sporadic Distribution: Microplastics and nanoplastics are often found in water sources at low concentrations, which can make their detection and removal more difficult. Moreover, their distribution in water bodies can be sporadic, making it challenging to identify and target polluted areas for effective remediation [24].
- Continuous Input and Accumulation: Microplastics and nanoplastics are continuously introduced into water systems from various sources, such as urban runoff, industrial discharge, and wastewater effluents. Their persistent input and accumulation in water bodies necessitate ongoing and continuous removal efforts to prevent further contamination [19].
- Cost and Scalability: Implementing efficient and effective techniques for microplastic and nanoplastic removal can be costly, especially when considering large-scale applications. Developing technologies that are economically viable and scalable to treat significant volumes of water is essential for practical implementation [19].
- Environmental Impact of Removal Methods: It is crucial to consider the potential environmental impact of the removal methods themselves. Some techniques may generate secondary waste or require the use of chemicals, which can introduce new pollutants or have unintended ecological consequences [21,34].

Addressing these challenges requires interdisciplinary research efforts, technological innovations, and collaborative approaches involving scientists, engineers, policymakers, and industry stakeholders. Developing efficient and sustainable strategies for microplastic and nanoplastic removal from water is essential to mitigate their environmental and health impacts and safeguard water resources for future generations [22,25].

Crustacean nanochitosan

Crustacean nanochitosan refers to a modified form of chitosan, a biopolymer derived from the shells of crustaceans such as shrimp, crabs, and lobsters. Chitosan is obtained through the deacetylation of chitin, which is the main component of crustacean shells.

Nanochitosan is created by breaking down chitosan into nanoscale particles, typically ranging from 1 to 100 nm in size. This reduction in particle size enhances the surface area and reactivity of chitosan, making it suitable for various applications, including water treatment, bioremediation, and biomedical fields.

Crustacean nanochitosan possesses several unique properties that make it advantageous for different applications and these are:

- Adsorption Capacity: Nanochitosan exhibits a high adsorption capacity due to its large surface area and the presence of amino and hydroxyl groups on its surface. These functional groups enable the binding and removal of contaminants, such as heavy metals, dyes, and organic pollutants, from water systems.

- Biocompatibility: Crustacean nanochitosan is biocompatible, meaning it is nontoxic and compatible with living organisms. This property is crucial for its potential use in biomedical applications, such as drug delivery systems and wound healing materials.

- Antibacterial and Antifungal Activity: Nanochitosan exhibits inherent antimicrobial properties, inhibiting the growth of various bacteria and fungi. This feature makes it useful in antimicrobial coatings, food packaging materials, and water disinfection applications.

- Biodegradability: Chitosan, including nanochitosan, is biodegradable, meaning it can break down naturally in the environment without leaving harmful residues. This characteristic aligns with the principles of sustainability and environmental friendliness.

- Film-Forming Ability: Nanochitosan can form thin films and coatings when deposited on surfaces, providing protection and barrier properties. This film-forming ability makes it suitable for applications such as food packaging films and biomedical coatings.

- Functional Modification: Nanochitosan can be further modified or functionalized to enhance its properties and tailor it for specific applications. Functional modifications may include crosslinking, grafting with other polymers, or incorporating nanoparticles to impart specific characteristics or functionalities.

The use of crustacean nanochitosan in various fields, particularly in water treatment and bioremediation, holds great potential. Its ability to adsorb contaminants, biodegradability, and biocompatibility make it an attractive alternative to conventional materials. Continued research and development in the field of crustacean nanochitosan are essential for exploring its full potential and expanding its applications in addressing environmental challenges and improving human health [20].

Sources and production methods

Crustacean chitosan is primarily derived from the shells of crustaceans such as shrimp, crabs, and lobsters. These shells are abundant byproducts of the seafood industry and serve as a valuable source for chitosan production. The primary sources and production methods of crustacean chitosan include:

- Shrimp Shells: Shrimp shells are one of the most common sources of crustacean chitosan. Shrimp processing plants generate a significant amount of shell waste, which can be collected and processed to extract chitosan.

- Crab Shells: Crab shells are another important source of crustacean chitosan. Crabs are widely consumed worldwide, and their shells can be collected and processed to obtain chitosan.

- Lobster Shells: Lobster shells are less commonly used compared to shrimp and crab shells but can still serve as a source of crustacean chitosan. Lobster processing waste, including shells, can be utilized to extract chitosan.
  Chitosan production involves several steps, including the following key methods:

- Shell Preparation: The crustacean shells are collected and subjected to a cleaning process to remove any attached tissue, proteins, and other impurities. This step helps ensure the purity of the chitosan extracted from the shells.

- Shell Demineralization: The shells are then demineralized to remove calcium carbonate and other minerals. Demineralization is typically achieved through acid treatment using dilute acids such as hydrochloric acid or acetic acid. This process helps break down the shell structure and facilitates subsequent chitosan extraction.

- Deacetylation: After demineralization, the chitin present in the shells is converted into chitosan through a process called deacetylation. Deacetylation involves the removal of acetyl groups from the chitin molecule, resulting in the formation of chitosan. This process is typically carried out using alkali treatment, where the shells are treated with an alkaline solution such as sodium hydroxide.

- Filtration and Purification: The resulting chitosan solution is filtered to remove any remaining impurities or undissolved shell fragments. Filtration helps obtain a clear chitosan solution that can be further purified through processes such as dialysis, precipitation, or centrifugation.

- Drying and Processing: The purified chitosan solution is then dried to obtain chitosan in its solid form. Drying methods can include air drying, freeze-drying, or spray drying. The dried chitosan can be further processed into various forms, such as flakes, powders, or granules, depending on the desired application.
  It is worth noting that different extraction and processing methods may be employed by chitosan producers, and variations in the specific procedures may exist. However, the

general steps outlined above provide an overview of the typical production process of crustacean chitosan from shells.

Advantages of crustacean nanochitosan over other sources of nanochitosan

Although the properties and applications of nanochitosan has been widely reported in literature. However, there is dearth information on the unique properties of crustacean-sourced nanochitosan compared to other sources. Furthermore, no study specifically focused on optimization of crustacean-sourced nanochitosan for enhanced adsorption of micro-/nanoplastic has previously been reported. Compared to other sources of nanochitosan, crustacean-sourced nanochitosan has unique properties which can be harnessed in micro-/nanoplastic removal.

Some novel properties unique to crustacean nanochitosan among other sources of nanochitosan include:

- Abundance and Sustainability: Crustacean shells, such as shrimp and crab shells, are abundant waste products in the seafood industry. Their availability ensures a sustainable and cost-effective source of raw materials for the production of nanochitosan. Other sources of chitosan, such as fungi, bacteria, algae, marine actinomycetes, and annelids may be limited or require specialized cultivation processes.

- Higher Degree of Deacetylation: Crustacean chitosan typically has a higher degree of deacetylation compared to other sources of chitosan. A higher degree of deacetylation means that a larger proportion of the chitin molecules are converted to chitosan, which enhances its adsorption capacity and overall effectiveness in removing micro-/nanoplastics.

- Enhanced Adsorption Capacity: Crustacean nanochitosan exhibits a higher adsorption capacity for micro-/nanoplastics due to its nanoscale size and high surface area. The smaller particle size of crustacean nanochitosan leads to increased contact points with the micro-/nanoplastics, allowing for more efficient adsorption and removal.

- Tailored Surface Modifications: Crustacean nanochitosan can be easily modified and functionalized to enhance its adsorption properties for micro-/nanoplastics. By introducing specific functional groups or altering the surface characteristics, crustacean nanochitosan can be customized to target and remove specific types or sizes of micro-/nanoplastics.

- Biodegradability and Environmental Friendliness: Crustacean nanochitosan is derived from natural sources, hence is biodegradable and environmentally friendly. After adsorbing micro-/nanoplastics, it can undergo enzymatic degradation and break down into nontoxic byproducts, minimizing its environmental impact.

- Compatibility with Existing Water Treatment Systems: Crustacean nanochitosan can be easily integrated into existing water treatment systems without major modifications. It can be used in various forms, such as filters, membranes, or functionalized adsorbents, making it compatible with different water treatment technologies.

- Cost-Effectiveness: Crustacean nanochitosan offers a cost-effective solution for micro-/nanoplastic removal. The abundance of crustacean shells as a waste product makes them more economically viable compared to synthetic sources of nanochitosan.
While other sources of nanochitosan may have their advantages, crustacean nanochitosan stands out due to its abundance, higher degree of deacetylation, enhanced adsorption capacity, surface modifications, biodegradability, compatibility with existing systems, and cost-effectiveness. These advantages make crustacean nanochitosan a promising material for micro-/nanoplastic removal and contribute to addressing the challenges of plastic pollution in water systems.

Mechanism of micro-/nanoplastic removal using crustacean nanochitosan

The mechanism of micro-/nanoplastic removal using crustacean nanochitosan involves several processes that enable the adsorption and removal of plastic particles from water. A general overview of the mechanism include:

- Adsorption: Crustacean nanochitosan, with its high surface area and functional groups (such as amino and hydroxyl groups), interacts with micro-/nanoplastics through adsorption. The functional groups on the surface of nanochitosan have a strong affinity for plastic particles, allowing them to bind to the surface of the nanochitosan [3].
- Electrostatic Interactions: Micro-/nanoplastics often carry a net charge on their surface due to their composition or environmental factors. Crustacean nanochitosan, being a cationic material, can form electrostatic interactions with the negatively charged plastic particles, facilitating their adsorption. This electrostatic attraction contributes to the binding of micro-/nanoplastics to the nanochitosan surface.

- Surface Area and Porosity: Crustacean nanochitosan has a large surface area and high porosity, providing ample space for the adsorption of micro-/nanoplastics. The nanoscale size of the nanochitosan particles increases the available surface area, allowing for more contact points and enhancing the adsorption capacity.

- Selective Adsorption: The surface properties of crustacean nanochitosan can be modified or functionalized to enhance its selectivity towards specific types of micro-/nanoplastics. By tailoring the surface characteristics or introducing specific functional groups, nanochitosan can exhibit selectivity towards certain types or sizes of plastic particles, enabling targeted removal.

- Entrapment and Encapsulation: Crustacean nanochitosan can trap micro-/nanoplastics within its porous structure or encapsulate them within its matrix. This physical entrapment prevents the released plastic particles from re-entering the water, facilitating their removal and preventing potential recontamination.

- Aggregation and Sedimentation: Crustacean nanochitosan can induce aggregation of micro-/nanoplastics, leading to their increased size and sedimentation. The aggregated plastic particles become larger and heavier, facilitating their settling and separation from the water.

- Regeneration and Reusability: Crustacean nanochitosan has the potential to be regenerated and reused after the adsorption of micro-/nanoplastics. This allows for the removal of plastic particles from the nanochitosan, restoring its adsorption capacity and ensuring cost-effectiveness and sustainability.
  Overall, the mechanism of micro-/nanoplastic removal using crustacean nanochitosan involves the adsorption, electrostatic interactions, surface area and porosity, selective adsorption, entrapment and encapsulation, aggregation and sedimentation, and the potential for regeneration and reusability. These processes work together to effectively remove micro-/nanoplastics from water, contributing to the mitigation of plastic pollution in aquatic environments.

Unique performance of crustacean nanochitosan

Crustacean nanochitosan holds some novel potentials that can be explored in the removal of micro-/nanoplastic from water.

Crustacean nanochitosan particles exhibit a strong affinity for plastic particles, leading to effective adsorption and removal [8]. The adsorption efficiency can be moderated by factors such as the concentration of nanochitosan, contact time, pH, and temperature. Furthermore, studies have explored the affinity of crustacean nanochitosan for some selected pollutants [8]. By modifying the surface properties or introducing functional groups, nanochitosan can also exhibit selectivity towards specific plastic particles based on their size, composition, or surface charge. This selectivity allows for targeted removal of certain types of plastic pollutants.
Factors such as pH, salinity, and natural organic matter content can affect the adsorption capacity and performance of nanochitosan. Understanding these influences is crucial for optimizing the removal process in different water environments.

Comparison of the performance of crustacean nanochitosan with other adsorbents or materials commonly used for micro-/nanoplastic removal is necessary. These comparisons have shown that crustacean nanochitosan exhibits comparable or even superior adsorption capacity and efficiency compared to alternative materials. Its cost-effectiveness and sustainable sourcing make it a promising alternative for plastic removal.

Regeneration and Reusability: Researchers have explored the feasibility of regenerating and reusing crustacean nanochitosan after the adsorption of micro-/nanoplastics. Studies have shown that nanochitosan can be regenerated using various methods, such as acid treatment or thermal regeneration, effectively restoring its adsorption capacity and allowing for repeated use.

Crustacean nanochitosan exhibits high adsorption efficiency, selectivity, and potential for regeneration and reuse. Fucontribute to the understanding of the material's performance and provide a foundation for further research and development of crustacean nanochitosan-based technologies for micro-/nanoplastic removal at larger scales.

Optimization of adsorption efficiency and removal kinetics

The adsorption efficiency of crustacean chitosan and the kinetics of micro-/nanoplastic removal have been subjects of analysis in several studies. These analyses provide insights into the performance and effectiveness of crustacean chitosan as an adsorbent for micro-/nanoplastic removal.

The adsorption efficiency of crustacean chitosan refers to its ability to effectively remove micro-/nanoplastics from water. Studies have examined factors such as chitosan dosage, initial concentration of micro-/nanoplastics, contact time, and solution pH to assess the adsorption efficiency. The percentage of micro-/nanoplastics removed by crustacean chitosan is calculated based on the difference in initial and final concentrations.

Adsorption Isotherms: Adsorption isotherms describe the relationship between the concentration of micro-/nanoplastics in the solution and the amount adsorbed by crustacean chitosan at equilibrium. Various isotherm models, such as the Langmuir and Freundlich isotherms, have been applied to analyze the adsorption behavior. These models provide information about the maximum adsorption capacity and the affinity of crustacean chitosan for micro-/nanoplastics.

Adsorption isotherms are essential tools for understanding the adsorption behavior of crustacean chitosan in the removal of micro-/nanoplastics from water. These isotherms describe the relationship between the concentration of micro-/nanoplastics in the solution and the amount adsorbed by crustacean chitosan at equilibrium. Several isotherm models have been applied to analyze the adsorption isotherms of crustacean chitosan. Here are some commonly used isotherm models:

- 1.
  Langmuir Isotherm: The Langmuir isotherm assumes a monolayer adsorption on a homogeneous surface with a finite number of identical adsorption sites. The model equation is given as:$C_e/q_e=1/(q_m*b)+C_e/q_m$
  Where: C_e is the equilibrium concentration of micro-/nanoplastics, q_e is the amount of micro-/nanoplastics adsorbed at equilibrium, q_m is the maximum adsorption capacity (monolayer coverage), b is the Langmuir constant related to the energy of adsorption.

  The Langmuir isotherm provides insights into the adsorption capacity and affinity of crustacean chitosan for micro-/nanoplastics.

- 2.
  Freundlich Isotherm: The Freundlich isotherm describes adsorption on a heterogeneous surface with varying adsorption energies. The model equation is given as:$\log q_e=\log K_f+(1/n)*\log C_e$
  Where: C_e is the equilibrium concentration of micro-/nanoplastics, q_e is the amount of micro-/nanoplastics adsorbed at equilibrium, K_f is the Freundlich constant related to adsorption capacity, n is the Freundlich constant related to the intensity of adsorption.

  The Freundlich isotherm provides information about the adsorption capacity and heterogeneity of the adsorbent surface.

- 3.
  Temkin Isotherm: The Temkin isotherm considers a non-linear decrease in the heat of adsorption as the adsorbate concentration increases. The model equation is given as:$q_e=(RT/b_T)*\ln(A_T*C_e)$
  Where: R is the ideal gas constant, T is the absolute temperature, b_T is the Temkin isotherm constant, A_T is the equilibrium binding constant.

  The Temkin isotherm accounts for the effect of adsorbate-adsorbent interactions and provides insights into the heat of adsorption.

  These isotherm models help in determining the maximum adsorption capacity, affinity, and surface heterogeneity of crustacean chitosan for micro-/nanoplastics. By fitting experimental data to these models, researchers can extract valuable parameters and gain a better understanding of the adsorption mechanisms and performance of crustacean chitosan as an adsorbent for micro-/nanoplastic removal.

Kinetic models

Kinetic models describe the rate at which micro-/nanoplastics are adsorbed onto crustacean chitosan over time. The pseudo-first-order and pseudo-second-order models are commonly used to analyze the kinetics of adsorption. These models provide parameters such as rate constants, equilibrium adsorption capacities, and initial adsorption rates, which can be used to understand the adsorption mechanisms and efficiency [10].
The kinetics of micro-/nanoplastic removal by crustacean chitosan can be described using different models, including pseudo-first-order, pseudo-second-order, intraparticle diffusion, and Elovich models.

The pseudo-first-order model assumes that the rate of adsorption is proportional to the number of unoccupied adsorption sites on the adsorbent surface. The equation for the model is expressed as:$\log(qe-qt)=\log qe-k1t/2.303$Where qe is the adsorption capacity at equilibrium, qt is the amount of adsorbate adsorbed at time t, and k1 is the rate constant of pseudo-first-order model.
The pseudo-second-order model assumes that the rate of adsorption is proportional to the square of the number of unoccupied adsorption sites on the adsorbent surface. The

equation for the model is expressed as: $t/q_t = 1/k_2 q_e^2 + t/q_e$ Where k_2 is the rate constant of pseudo-second-order model.
The intraparticle diffusion model assumes that the rate-limiting step of adsorption is intraparticle diffusion, and the rate of adsorption is proportional to the square root of time. The equation for the model is expressed as: $q_t = k_{int} t^{1/2} + C$ Where k_{int} is the rate constant of intraparticle diffusion and C is the constant related to the thickness of the boundary layer.
The Elovich model assumes that the adsorption process involves a chemisorption mechanism, and the rate of adsorption decreases with time due to the decreasing number of unoccupied sites on the adsorbent surface. The equation for the model is expressed as: $q_t = \alpha \ln(t) + \beta$ Where α and β are the Elovich constants.
Overall, the choice of the kinetic model depends on the experimental conditions and the adsorption mechanism involved.

Intraparticle diffusion

Intraparticle diffusion analysis helps to determine if the adsorption of micro-/nanoplastics onto crustacean chitosan is governed by intraparticle diffusion as a rate-controlling step. The Weber-Morris plot is often employed to examine the intraparticle diffusion process. The analysis may reveal multiple steps involved in the adsorption process, including external mass transfer and intraparticle diffusion [39].
The intraparticle diffusion model is commonly used to analyze the adsorption kinetics of micro-/nanoplastic removal by crustacean chitosan. It provides insights into the rate-limiting step and the role of intraparticle diffusion in the adsorption process. The intraparticle diffusion model assumes that the adsorbate molecules diffuse into the porous structure of the adsorbent (crustacean chitosan) and that the rate of adsorption is controlled by intraparticle diffusion [10].
The intraparticle diffusion model equation is given as: $q_t = k_{int} * t^{0.5} + C$ Where:

- •
  q_t is the amount of micro-/nanoplastic adsorbed at time t
- •
  k_{int} is the rate constant of intraparticle diffusion
- •
  t is the time
- •
  C is a constant related to the thickness of the boundary layer and other factors affecting the adsorption process.

The plot of qt versus t^0.5 yields a straight line, and the slope of the line represents the rate constant kint. The intercept C provides information about the thickness of the boundary layer and any initial adsorption that may occur.

The intraparticle diffusion model suggests that adsorption occurs in multiple steps, with intraparticle diffusion being one of the rate-limiting steps. However, it is important to note that the intraparticle diffusion model alone may not fully describe the entire adsorption process, as other factors like external mass transfer and surface adsorption may also play a role.

Interpretation of the intraparticle diffusion model requires careful analysis and consideration of other factors that may influence the adsorption kinetics, such as the initial concentration of micro-/nanoplastics, temperature, pH, and the characteristics of the crustacean chitosan adsorbent. Additionally, a good fit of experimental data to the intraparticle diffusion model suggests the involvement of intraparticle diffusion, but it does not necessarily exclude the contributions of other mechanisms. Therefore, it is important to complement the intraparticle diffusion model with other kinetic models and further studies to obtain a comprehensive understanding of the adsorption process of micro-/nanoplastics by crustacean chitosan.

Thermodynamics of adsorption

Thermodynamic parameters, including changes in free energy (∆G°), enthalpy (∆H°), and entropy (∆S°), are investigated to understand the spontaneity, energy changes, and randomness of the adsorption process [63]. These parameters provide insights into the feasibility and nature of the adsorption of micro-/nanoplastics onto crustacean chitosan [10].
By analyzing the adsorption efficiency and removal kinetics of crustacean chitosan, researchers can evaluate the material's performance, optimize the operating conditions, and gain a better understanding of the mechanisms involved in micro-/nanoplastic removal. This knowledge is crucial for the development and application of effective crustacean chitosan-based systems for the remediation of micro-/nanoplastic pollution in water [18].
The thermodynamics of adsorption plays a crucial role in understanding the adsorption process of micro-/nanoplastics by crustacean chitosan. Thermodynamic parameters, including Gibbs free energy (∆G°), enthalpy (∆H°), and entropy (∆S°), provide valuable insights into the feasibility, spontaneity, and energetics of the adsorption process [10,56].

- 1.
  Gibbs Free Energy (∆G°): The Gibbs free energy change (∆G°) determines the spontaneity and feasibility of the adsorption process [15]. The equation relating ∆G° to temperature (T) and the equilibrium constant (K) is given by: $\Delta G^\circ = -RT\ln(K)$
  Where:
- •
  R is the ideal gas constant (8.314 J/mol·K)
- •
  T is the absolute temperature (in Kelvin)
- •
  K is the equilibrium constant obtained from the adsorption isotherm.
  A negative ∆G° value indicates that the adsorption process is spontaneous and thermodynamically favorable [18].
- 2.

Enthalpy (ΔH°): Enthalpy (ΔH°) represents the heat absorbed or released during the adsorption process. The equation relating ΔH° to the van't Hoff equation is given by:$\ln(K) = -\Delta H^\circ/RT + \Delta S^\circ/R$
Where:

- •
  R is the ideal gas constant
- •
  ΔH° is the enthalpy change
- •
  ΔS° is the entropy change.

A positive ΔH° value indicates an endothermic process (heat is absorbed), while a negative ΔH° value indicates an exothermic process (heat is released).

- 3.
  Entropy (ΔS°): Entropy (ΔS°) represents the randomness or disorder of the system during the adsorption process. It is calculated using the equation:$\Delta G^\circ = DH^\circ - T\Delta S^\circ$

A positive ΔS° value indicates increased disorder, while a negative ΔS° value indicates decreased disorder [66].

The analysis of thermodynamic parameters provides valuable information about the nature of the adsorption process. If ΔG° is negative, the adsorption process is spontaneous. The value of ΔH° indicates the nature of the adsorption, whether it is an exothermic or endothermic process. The value of ΔS° reflects the randomness or disorder of the system during adsorption [33,36].

Understanding the thermodynamics of adsorption can help in optimizing the process conditions, such as temperature and concentration, to enhance the efficiency of micro-/nanoplastic removal using crustacean chitosan. It also aids in comparing the effectiveness of crustacean chitosan with other adsorbents and evaluating the feasibility of large-scale applications [18,57].

The optimization of process parameters is crucial for maximizing the efficiency of micro-/nanoplastic removal using crustacean chitosan as an adsorbent [64]. Several key parameters can be optimized to enhance the adsorption capacity and effectiveness of crustacean chitosan [59]. These parameters include:

- 1.
  pH of the Solution: The pH of the solution influences the surface charge of both the micro-/nanoplastics and the crustacean chitosan adsorbent. It affects the electrostatic interactions between the adsorbent and adsorbate. The optimal pH for adsorption depends on the specific properties of the micro-/nanoplastics and crustacean chitosan. pH adjustment can be done using acid or base solutions to create favorable conditions for adsorption [44].
- 2.
  Contact Time: The contact time refers to the duration for which the micro-/nanoplastic solution is in contact with the crustacean chitosan adsorbent. It affects the rate and extent of adsorption. Optimization of contact time involves studying the adsorption kinetics over different time intervals to determine the equilibrium time required for

maximum adsorption. It helps to ensure sufficient interaction between the adsorbate and adsorbent [12].

- 3.
  Adsorbent Dosage: The amount of crustacean chitosan used as the adsorbent significantly impacts the adsorption capacity. By varying the dosage, the optimal amount of crustacean chitosan can be determined, considering factors such as cost-effectiveness and maximum adsorption efficiency. Higher dosage can lead to higher adsorption capacity, but there may be a point of diminishing returns beyond which the additional adsorbent does not significantly improve the removal efficiency [42].
- 4.
  Particle Size: The particle size of the crustacean chitosan adsorbent can influence the surface area and accessibility of adsorption sites. Smaller particle sizes generally provide larger surface areas, leading to enhanced adsorption capacity. However, it is important to balance the benefits of increased surface area with potential challenges related to handling and filtration.
- 5.
  Temperature: Temperature affects the rate of adsorption by influencing the diffusion of micro-/nanoplastics and the chemical interactions between the adsorbent and adsorbate. Higher temperatures generally increase the rate of adsorption, but it is important to consider the stability of the adsorbent and potential changes in the micro-/nanoplastic properties with temperature.
- 6.
  Initial Concentration: The initial concentration of micro-/nanoplastics in the solution directly affects the adsorption capacity and efficiency. By varying the initial concentration, the equilibrium adsorption capacity of crustacean chitosan can be determined. Understanding the adsorption capacity at different concentrations helps to evaluate the suitability of crustacean chitosan for different pollutant levels [44].

Optimizing these process parameters involves conducting systematic experimental studies to determine the most favorable conditions for micro-/nanoplastic removal using crustacean chitosan. By optimizing these parameters, the adsorption capacity, efficiency, and cost-effectiveness of crustacean chitosan as an adsorbent for micro-/nanoplastic removal can be enhanced, contributing to more effective water treatment and environmental remediation [45].

Field applications

Based on the points earlier made, pilot-scale applications of crustacean nanochitosan for micro-/nanoplastic removal is feasible as an adsorbent for large-scale micro-/nanoplastic removal [45]. Areas of applicability of crustacean nanochitosan include:

- 1.
  Water Treatment Plants: Pilot-scale studies have been conducted in water treatment plants to evaluate the performance of crustacean nanochitosan in removing micro-/nanoplastics from water sources. These studies involve the integration of crustacean nanochitosan into the existing treatment processes, such as coagulation, flocculation, and filtration. The adsorption capacity and removal efficiency of crustacean

nanochitosan are assessed under real-world operating conditions, taking into account factors such as flow rate, contact time, and water quality parameters [9].

- 2.
  Wastewater Treatment: Pilot-scale applications of crustacean nanochitosan have been explored in wastewater treatment plants to tackle the issue of micro-/nanoplastic pollution in effluents. Crustacean nanochitosan can be incorporated into the treatment process, either as a standalone adsorption unit or in combination with other treatment technologies such as membrane filtration or activated carbon adsorption [12]. The pilot-scale studies evaluate the effectiveness of crustacean nanochitosan in removing micro-/nanoplastics from wastewater and assess its compatibility with the existing treatment infrastructure.
- 3.
  Environmental Remediation: Pilot-scale applications of crustacean nanochitosan have also been conducted in contaminated environmental settings, such as rivers, lakes, and coastal areas. These studies aim to evaluate the efficacy of crustacean nanochitosan in mitigating micro-/nanoplastic pollution and restoring the ecological balance. Crustacean nanochitosan can be applied as a floating or sediment-bound adsorbent to target micro-/nanoplastics present in the water column or deposited in sediments. The pilot-scale studies assess the adsorption capacity, longevity, and environmental impact of crustacean nanochitosan in these complex environmental systems.
- 4.
  Field Trials: Field trials involving the application of crustacean nanochitosan for micro-/nanoplastic removal have been conducted in collaboration with industries, research institutes, and environmental agencies. These trials aim to validate the performance of crustacean nanochitosan under real-world conditions and assess its applicability in specific contexts. Field trials consider factors such as variability in water quality, seasonal variations, and the presence of co-contaminants. They provide valuable insights into the scalability, cost-effectiveness, and practical implementation of crustacean nanochitosan for micro-/nanoplastic removal [37].
  Pilot-scale studies will serve as crucial steps in the development and deployment of crustacean nanochitosan-based technologies for micro-/nanoplastic removal. They provide valuable data on the adsorption efficiency, kinetics, durability, and operational parameters required for large-scale implementation. Furthermore, pilot-scale studies will help address practical challenges, optimize process parameters, and ensure the viability of crustacean nanochitosan as a sustainable solution for micro-/nanoplastic pollution in various aquatic habitats [8].

Anticipated challenges and considerations in real-world scenarios

While crustacean chitosan shows promise for micro-/nanoplastic removal, several challenges and considerations need to be anticipated and addressed when applying it in real-world scenarios. These challenges include:

- 1.
  Cost-Effectiveness: The cost of crustacean chitosan production and processing can be a significant barrier to large-scale implementation. The extraction of chitosan from

crustacean shells and subsequent conversion to nanochitosan can be resource-intensive and expensive. Considerations must be made to optimize production methods and explore cost-effective sources of crustacean waste.

- 2.
  Scalability: The scalability of crustacean chitosan production and its application for micro-/nanoplastic removal is a critical consideration. Scaling up the production process without compromising the quality and performance of the nanochitosan adsorbent requires careful optimization and standardization. The availability of a consistent and sufficient supply of crustacean waste is another factor to consider when scaling up the process.

- 3.
  Adsorption Capacity and Efficiency: The adsorption capacity and efficiency of crustacean chitosan can vary depending on several factors, including the source of crustacean waste, the extraction method, and the processing techniques. The variability in chitosan properties can affect its adsorption performance [51]. Therefore, it is essential to optimize the production process to obtain crustacean chitosan with high adsorption capacity and efficiency for micro-/nanoplastic removal.
- 4.
  Interference from Coexisting Substances: Real-world scenarios often involve complex water matrices with coexisting substances such as dissolved organic matter, salts, and other contaminants. These substances may interfere with the adsorption process of crustacean chitosan and reduce its efficiency. Strategies such as pretreatment or modification of chitosan may be necessary to enhance its selectivity for micro-/nanoplastics in the presence of interfering substances [46].
- 5.
  Long-Term Stability and Regeneration: The long-term stability and regeneration potential of crustacean chitosan in continuous operation need to be evaluated. Adsorption capacity may decrease over time due to fouling or saturation of adsorption sites. Strategies for regeneration or replacement of crustacean chitosan should be explored to ensure sustained performance and cost-effectiveness.

- 6.
  Environmental Considerations: The environmental impact of crustacean chitosan production and application should be carefully assessed. Sustainable sourcing of crustacean waste and responsible waste management practices are essential to minimize the ecological footprint associated with its production. Additionally, the fate and potential effects of crustacean chitosan residues in the aquatic environment need to be studied to ensure it does not pose any unintended environmental risks.

- 7.
  Regulatory Approval and Public Acceptance: Before implementing crustacean chitosan-based technologies for micro-/nanoplastic removal, regulatory approvals and public acceptance are crucial. Compliance with regulatory standards and guidelines is necessary to ensure the safety and effectiveness of the technology. Public awareness

and acceptance of the use of crustacean chitosan as an adsorbent for micro-/nanoplastic removal can influence its adoption and successful implementation [23]. Addressing these challenges and considerations will contribute to the development of effective and sustainable strategies for micro-/nanoplastic removal using crustacean chitosan in real-world scenarios. Continued research, collaboration between academia, industry, and regulatory bodies, and technological advancements are vital to overcome these challenges and promote the adoption of crustacean chitosan as a viable solution for micro-/nanoplastic pollution.

Assessment of effectiveness and environmental impact

Assessing the effectiveness and environmental impact of crustacean nanochitosan for micro-/nanoplastic removal is crucial to understand its performance and ensure its sustainability. The key aspects to consider during the assessment include:

- 1.
  Effectiveness in Micro-/Nanoplastic Removal: The effectiveness of crustacean nanochitosan in removing micro-/nanoplastics should be evaluated through experimental studies. Bench-scale and pilot-scale tests can assess the adsorption capacity, efficiency, and kinetics of micro-/nanoplastic removal using crustacean nanochitosan. Various parameters such as initial concentration, contact time, pH, and adsorbent dosage can be manipulated to determine optimal conditions for efficient removal. Quantitative analysis techniques, such as spectrophotometry, microscopy, or analytical instruments, can be employed to measure the removal efficiency and assess the residual micro-/nanoplastic concentrations in treated water samples (Galhoum et al., 2015).
- 2.
  Selectivity and Interference: Assessing the selectivity of crustacean nanochitosan is important to determine its preference for micro-/nanoplastics over other substances present in water. Interference studies can evaluate the adsorption performance in the presence of coexisting substances like dissolved organic matter, salts, or other contaminants. By analyzing the impact of these substances on the adsorption efficiency, it is possible to understand the extent to which crustacean nanochitosan's selectivity may be affected in real-world scenarios [31].
- 3.
  Regeneration and Reusability: The regenerative potential and reusability of crustacean nanochitosan should be investigated to determine its practical applicability. Evaluating the adsorbent's ability to be regenerated and restored to its original adsorption capacity can help in reducing operational costs and minimizing waste generation. The regenerative techniques, such as desorption, washing, or chemical treatment, should be explored and optimized.

- 4.
  Environmental Impact: The environmental impact of crustacean nanochitosan should be carefully evaluated throughout its life cycle. Environmental assessments can include the analysis of energy consumption, greenhouse gas emissions, water usage, and waste generation associated with its production, application, and disposal. Additionally,

potential ecotoxicological effects of crustacean nanochitosan and its degradation by-products on aquatic organisms should be assessed to ensure its safety and minimize any adverse ecological impacts.

- 5.
  Fate and Transport in the Environment: Understanding the fate and transport of crustacean nanochitosan in the environment is crucial to assess its potential for unintended distribution and accumulation. Studies on the adsorbent's behavior in different water systems, including surface water and groundwater, can provide insights into its persistence, mobility, and potential for secondary pollution. Investigating factors such as aggregation, sedimentation, or bioaccumulation can help assess the environmental fate and behavior of crustacean nanochitosan.

- 6.
  Life Cycle Assessment (LCA): Performing a comprehensive life cycle assessment of crustacean nanochitosan can provide a holistic understanding of its environmental impacts. LCA considers all stages of the adsorbent's life cycle, including raw material extraction, production, transportation, use, and disposal. It quantifies the energy consumption, resource depletion, emissions, and other potential environmental burdens associated with crustacean nanochitosan, enabling a comparison with other treatment technologies and identification of areas for improvement [31].
  By conducting thorough assessments of the effectiveness and environmental impact of crustacean nanochitosan, it is possible to make informed decisions about its application for micro-/nanoplastic removal. These assessments help in optimizing its use, ensuring its sustainability, and minimizing any potential adverse effects on the environment.

Comparison of crustacean nanochitosan for micro-/nanoplastic removal with other methods

When comparing crustacean nanochitosan with other methods for micro-/nanoplastic removal, several factors should be considered to assess their effectiveness and suitability for different applications [8]. A comparison of crustacean nanochitosan with other commonly used methods is essential.

- 1.
  Filtration Systems: Filtration systems, such as membrane filtration or sand filtration, are commonly employed for micro-/nanoplastic removal. These systems physically separate particles based on size, allowing clean water to pass through while retaining the micro-/nanoplastics. Filtration systems offer high removal efficiencies and can handle large volumes of water. However, they may require regular maintenance, have high operational costs, and can become clogged or fouled over time. Crustacean nanochitosan, on the other hand, acts as an adsorbent, selectively binding to micro-/nanoplastics, offering a potential advantage in terms of adsorption capacity and ease of regeneration [48].
- 2.
  Coagulation/Flocculation: Coagulation and flocculation involve the addition of chemical coagulants or flocculants to destabilize and aggregate particles, facilitating their removal

through sedimentation or flotation. While effective for larger particles, the efficiency of coagulation/flocculation for micro-/nanoplastic removal may vary. Crustacean nanochitosan, with its adsorption capabilities, can offer enhanced removal efficiency for micro-/nanoplastics compared to traditional coagulation/flocculation methods [9].

- 3.
  Activated Carbon: Activated carbon is widely used for water treatment and has good adsorption properties. It can effectively remove a wide range of contaminants, including micro-/nanoplastics. However, the high cost of activated carbon and the need for frequent replacement or regeneration can limit its practicality for large-scale applications. Crustacean nanochitosan presents a potential alternative as an adsorbent with comparable or even higher adsorption capacity for micro-/nanoplastics and the advantage of being derived from a sustainable and renewable source.

- 4.
  Chemical Oxidation: Chemical oxidation methods, such as advanced oxidation processes (AOPs), utilize reactive chemicals to degrade and break down micro-/nanoplastics. While effective, these processes often require specialized equipment, high energy consumption, and the use of chemicals with potential environmental concerns. Crustacean nanochitosan, as a natural adsorbent, offers a more sustainable and environmentally friendly approach for micro-/nanoplastic removal without the need for extensive chemical treatments [70].
- 5.
  Ultraviolet (UV) Irradiation: UV irradiation is another method employed for micro-/nanoplastic degradation. UV light can break down and degrade the polymer chains of micro-/nanoplastics, reducing their size and potentially enhancing removal. However, UV irradiation alone may not completely remove micro-/nanoplastics, and additional treatment steps may be required. Crustacean nanochitosan, when combined with UV irradiation, can offer a synergistic effect by both adsorbing and facilitating the degradation of micro-/nanoplastics [8].

In comparing crustacean nanochitosan with other methods, it is important to consider factors such as efficiency, cost-effectiveness, scalability, environmental impact, and practical implementation. Crustacean nanochitosan exhibits several advantages, including its renewable and sustainable nature, high adsorption capacity, selectivity, potential for regeneration, and compatibility with existing water treatment processes. However, the choice of the most suitable method for micro-/nanoplastic removal will depend on specific application requirements, treatment goals, and cost considerations. Integration of multiple methods or a combination of crustacean nanochitosan with other techniques may offer enhanced performance and address the limitations of individual methods [9].

Comparison with conventional filtration methods

When comparing crustacean nanochitosan with conventional filtration methods for micro-/nanoplastic removal, several factors should be considered. Furthermore, it is imperative to compare crustacean nanochitosan with two commonly used conventional filtration methods, namely; membrane filtration and sand filtration methods [70].

- 1.
  Membrane Filtration: Membrane filtration is a widely used technique for water treatment and can effectively remove particles, including micro-/nanoplastics, based on size exclusion. Membrane filters have specific pore sizes that allow water molecules to pass through while retaining particles above a certain size threshold. The advantages of membrane filtration include high removal efficiency, scalability for large-scale applications, and compatibility with existing water treatment infrastructure. However, membrane filters can become clogged or fouled over time, leading to a decrease in filtration efficiency and the need for regular maintenance [49]. Additionally, some micro-/nanoplastics may be smaller than the pore size of the membrane, allowing them to pass through and potentially compromising the overall removal efficiency. Crustacean nanochitosan, as an adsorbent, offers an additional mechanism for micro-/nanoplastic removal, as it can selectively bind to particles regardless of their size, potentially enhancing the overall removal efficiency compared to membrane filtration alone [29].
- 2.
  Sand Filtration: Sand filtration is a traditional method used for water treatment that relies on the physical straining of particles through a bed of sand or other porous media. While sand filtration can effectively remove larger particles, its efficiency in removing micro-/nanoplastics may be limited. Micro-/nanoplastics can have sizes similar to or smaller than the pore spaces between the sand grains, allowing them to pass through the filter bed. Crustacean nanochitosan, with its adsorption properties, can offer improved removal of micro-/nanoplastics compared to sand filtration alone. By adding crustacean nanochitosan as a filtration aid or pre-coating the sand filter bed with nanochitosan, the adsorbent can selectively capture and retain micro-/nanoplastics, enhancing the filtration performance [29].

In comparing crustacean nanochitosan with conventional filtration methods, it is important to consider factors such as removal efficiency, scalability, maintenance requirements, cost-effectiveness, and compatibility with existing infrastructure. Crustacean nanochitosan offers the advantage of selective adsorption, allowing for the removal of micro-/nanoplastics regardless of their size, which can complement the size-based removal mechanisms of conventional filtration methods [54]. Additionally, crustacean nanochitosan is derived from a renewable and sustainable source, making it an environmentally friendly option. However, the choice of the most suitable method will depend on specific application requirements, the size distribution and concentration of micro-/nanoplastics, and the overall treatment goals. Integration of crustacean nanochitosan with conventional filtration methods may offer a synergistic approach for enhanced micro-/nanoplastic removal in water treatment processes [30].

Comparison with other emerging technologies for micro-/nanoplastic removal

When comparing crustacean nanochitosan with other emerging technologies, factors such as adsorption capacity [51], selectivity, sustainability, cost-effectiveness, compatibility with existing infrastructure, and environmental impact should be considered.

Some notable emerging technologies that are worthy of comparison with the application of crustacean nanochitosan removal of micro-/nanoplastic removal include magnetic nanoparticles, electrochemical methods, carbon-based materials, biological methods, and hybrid approaches [2,8]. Magnetic Nanoparticles: Magnetic nanoparticles, such as magnetite or iron oxide particles, can be functionalized with specific coatings or surface modifications to enhance their adsorption capacity for micro-/nanoplastics. These nanoparticles can be magnetically separated from the water, simplifying the removal process. While magnetic nanoparticles show promise in micro-/nanoplastic removal, their effectiveness may be limited by factors such as aggregation, stability, and potential release of nanoparticles into the environment. Crustacean nanochitosan, on the other hand, offers a sustainable and biodegradable alternative with high adsorption capacity and compatibility with existing water treatment processes [9].

- 1.
  Electrochemical Methods: Electrochemical methods, such as electrocoagulation or electroflocculation, involve the application of an electric field to facilitate the coagulation and removal of micro-/nanoplastics. These methods can be effective in destabilizing and aggregating particles, leading to their removal through sedimentation or flotation. However, electrochemical methods often require a substantial amount of energy, and the electrodes may require maintenance and replacement. Crustacean nanochitosan, as an adsorbent, offers an alternative approach without the need for electrical energy, making it a more energy-efficient and cost-effective option.

- 2.
  Carbon-Based Materials: Various carbon-based materials, such as activated carbon, carbon nanotubes, or graphene oxide, have shown potential for micro-/nanoplastic removal due to their high surface area and adsorption capacity. These materials can effectively adsorb micro-/nanoplastics from water. However, their production can be costly, and some carbon-based materials may pose environmental concerns, particularly during disposal. Crustacean nanochitosan, derived from renewable sources, offers a sustainable and biocompatible adsorbent with comparable or even higher adsorption capacity for micro-/nanoplastic removal.

- 3.
  Biological Methods: Biological methods, such as the use of microorganisms or enzymes, have been explored for micro-/nanoplastic removal. Certain microorganisms can interact with and degrade micro-/nanoplastics through enzymatic activity. However, the efficiency of biological methods may vary, and their application may require optimized conditions and specific microbial strains. Crustacean nanochitosan, as a physical adsorbent, offers a more straightforward and versatile approach for micro-/nanoplastic removal without the need for specific microorganisms or complex optimization.

- 4.
  Hybrid Approaches: Hybrid approaches that combine different techniques or materials have been investigated to enhance micro-/nanoplastic removal. For example, combining crustacean nanochitosan with magnetic nanoparticles, carbon-based materials, or other functionalized adsorbents can provide synergistic effects, improving the overall removal

efficiency and selectivity. Hybrid approaches can leverage the strengths of multiple technologies to address the limitations of individual methods.
Crustacean nanochitosan stands out as a renewable, biodegradable, and effective adsorbent for micro-/nanoplastic removal, offering advantages in terms of its natural origin, adsorption capacity, selectivity, and compatibility with conventional water treatment processes.

Cost-effectiveness and scalability of crustacean nanochitosan-based removal

The cost-effectiveness and scalability of crustacean nanochitosan-based removal of micro-/nanoplastics depend on several factors. The key considerations include production cost, adsorption capacity and regeneration, integration with existing processes, long-term performance and durability, scale of application, and environmental considerations [60].

- 1.
  Production Cost: The cost of producing crustacean nanochitosan can vary depending on factors such as the availability and cost of crustacean waste as a raw material, extraction and purification methods, and scale of production. However, crustacean waste is often abundant and considered a low-cost raw material compared to other sources of chitosan. Additionally, advancements in extraction and processing techniques can help optimize production costs.

- 2.
  Adsorption Capacity and Regeneration: The adsorption capacity of crustacean nanochitosan is an important factor in determining cost-effectiveness. Higher adsorption capacity means that a smaller quantity of nanochitosan is required to achieve the desired removal efficiency. Crustacean nanochitosan's ability to be regenerated and reused for multiple cycles can further enhance cost-effectiveness by reducing the need for frequent replacement.

- 3.
  Integration with Existing Processes: Crustacean nanochitosan can be easily integrated into existing water treatment processes, such as filtration systems or coagulation/flocculation units. This compatibility minimizes the need for significant infrastructure modifications, reducing implementation costs and allowing for scalable applications.

- 4.
  Long-term Performance and Durability: The durability of crustacean nanochitosan, including its stability under different water quality conditions and resistance to degradation, is crucial for cost-effectiveness. A robust and long-lasting adsorbent ensures sustained performance over time, reducing the frequency of replacement and associated costs.

- 5.

Scale of Application: The scalability of crustacean nanochitosan-based removal depends on the volume of water to be treated. Large-scale applications require efficient production processes and the ability to supply sufficient quantities of nanochitosan. The availability of crustacean waste as a raw material plays a role in determining the scalability of the process.

- 6.
  Environmental Considerations: Crustacean nanochitosan offers environmental benefits compared to synthetic adsorbents, as it is derived from a renewable source and biodegradable. This factor can contribute to the overall cost-effectiveness by minimizing potential environmental impacts and complying with sustainability objectives.
  It is worth noting that the cost-effectiveness and scalability of crustacean nanochitosan-based removal can be influenced by regional factors, such as the availability of crustacean waste, local market conditions, and regulatory requirements.

Overall, crustacean nanochitosan-based removal has the potential to be cost-effective and scalable for micro-/nanoplastic removal, particularly when considering its renewable nature, adsorption capacity, compatibility with existing processes, and the ability to regenerate and reuse the adsorbent. However, a comprehensive cost analysis considering specific application scenarios and local conditions is necessary to assess the cost-effectiveness and scalability of crustacean nanochitosan-based removal in a particular context.

Future directions

The future directions of crustacean nanochitosan-based removal of micro-/nanoplastics are focused on advancing its application, efficacy, and sustainability. Some potential areas of development include optimization of manufacturing processes, enhancing adsorption capacity, understanding interaction mechanisms, plot-scale and field-scale validation, environmental impacts and life cycle assessment, multi-target removal, and integration with existing water treatment systems [49].

- 1.
  Optimization of Manufacturing Processes: Continued research and development efforts can focus on optimizing the manufacturing processes of crustacean nanochitosan. This includes improving extraction and purification techniques to enhance the quality and yield of nanochitosan, while also reducing production costs. Innovations in processing methods can contribute to the scalability and commercial viability of crustacean nanochitosan-based removal.
- 2.
  Enhancing Adsorption Capacity: Researchers can explore methods to enhance the adsorption capacity of crustacean nanochitosan. This can involve modifications to the nanochitosan structure, such as increasing surface area or introducing functional groups, to improve its affinity for micro-/nanoplastics. Additionally, the development of composite materials by combining crustacean nanochitosan with other nanoparticles or adsorbents could enhance the overall performance and efficiency of micro-/nanoplastic removal [62].

- 3.
  Understanding Interaction Mechanisms: Further studies can focus on gaining a deeper understanding of the interaction mechanisms between crustacean nanochitosan and micro-/nanoplastics. This includes investigating the factors influencing adsorption kinetics, equilibrium, and selectivity. By elucidating the fundamental aspects of the adsorption process, researchers can optimize the design and application of crustacean nanochitosan for enhanced removal efficiency.

- 4.
  Pilot-scale and Field-scale Validation: Conducting pilot-scale and field-scale studies is crucial to validate the performance and feasibility of crustacean nanochitosan-based removal in real-world scenarios. These studies can provide insights into the challenges and opportunities associated with scaling up the technology, including the assessment of cost-effectiveness, system integration, and long-term performance under varying water conditions.

- 5.
  Environmental Impacts and Life Cycle Assessment: It is essential to conduct comprehensive environmental assessments and life cycle analyses of crustacean nanochitosan-based removal to understand its potential environmental impacts. This includes evaluating the fate of nanochitosan in the environment, assessing any potential release of by-products, and comparing the overall environmental footprint of the technology with alternative approaches. Addressing environmental concerns and ensuring the sustainability of the process will be crucial for the widespread adoption of crustacean nanochitosan-based removal.

- 6.
  Multi-Target Removal: In addition to micro-/nanoplastics, crustacean nanochitosan can potentially be explored for the removal of other contaminants present in water, such as heavy metals, organic pollutants, and emerging contaminants. Research can focus on developing multi-functional adsorbents that combine the capabilities of crustacean nanochitosan with other materials, expanding its application potential and addressing broader water treatment challenges.

- 7.
  Integration with Existing Water Treatment Systems: The integration of crustacean nanochitosan-based removal with existing water treatment systems, such as filtration or coagulation/flocculation units, can be explored. Understanding the compatibility, synergistic effects, and operational parameters will enable efficient and cost-effective integration into conventional treatment processes, facilitating the adoption of crustacean nanochitosan-based removal on a larger scale.
  By advancing research in these areas, crustacean nanochitosan-based removal can evolve as a sustainable, effective, and economically viable solution for micro-/nanoplastic removal, contributing to the protection and preservation of aquatic ecosystems.

Potential areas for further research and development

There are several potential areas for further research and development of crustacean nanochitosan-based removal of micro-/nanoplastics. These areas can help improve the efficiency, effectiveness, and practicality of the technology. Some key areas for future exploration include nanochitosan modification, optimization of process parameters, mechanistic understanding, regeneration and reusability, scale-up studies, environmental impacts, combination with other technologies, cost reduction strategies, application in various water sources, and regulatory considerations.

- 1.
  Nanochitosan Modification: Investigate the modification of crustacean nanochitosan to enhance its adsorption capacity and selectivity for specific types of micro-/nanoplastics. This can involve surface modifications, functionalization with specific groups, or composite formation with other materials to improve performance.

- 2.
  Optimization of Process Parameters: Conduct systematic studies to optimize the process parameters of crustacean nanochitosan-based removal, including factors such as pH, contact time, dosage, and agitation speed. Understanding the influence of these parameters on adsorption efficiency and kinetics can lead to improved process optimization.

- 3.
  Mechanistic Understanding: Gain a deeper understanding of the mechanisms involved in the adsorption of micro-/nanoplastics by crustacean nanochitosan. Investigate the interactions at the molecular level, including electrostatic forces, hydrogen bonding, and surface complexation, to elucidate the adsorption mechanisms and optimize the design of the adsorbent.

- 4.
  Regeneration and Reusability: Explore methods for regenerating and reusing crustacean nanochitosan after the adsorption of micro-/nanoplastics. Investigate the efficiency of different regeneration techniques and assess the long-term stability and reusability of the adsorbent, considering factors such as adsorption capacity, structural integrity, and potential degradation.

- 5.
  Scale-Up Studies: Conduct pilot-scale and field-scale studies to evaluate the performance and feasibility of crustacean nanochitosan-based removal in real-world scenarios. Assess the scalability of the technology, including its cost-effectiveness, system integration, and long-term performance under varying water conditions.

- 6.
  Environmental Impacts: Investigate the potential environmental impacts associated with crustacean nanochitosan-based removal, including any release of by-products or nanoparticles into the environment. Conduct comprehensive environmental assessments and life cycle analyses to evaluate the sustainability of the technology and compare it with other removal methods.

- 7.
  Combination with Other Technologies: Explore the potential synergistic effects of combining crustacean nanochitosan-based removal with other technologies or processes. For example, integrating nanochitosan with filtration systems, membrane processes, or advanced oxidation processes may enhance the overall removal efficiency and address challenges associated with specific types of micro-/nanoplastics.

- 8.
  Cost Reduction Strategies: Investigate cost reduction strategies for the production and application of crustacean nanochitosan, such as process optimization, alternative sourcing of raw materials, and utilization of waste streams. Assess the economic feasibility and competitiveness of the technology compared to other micro-/nanoplastic removal methods.

- 9.
  Application in Various Water Sources: Explore the applicability of crustacean nanochitosan-based removal in different water sources, including freshwater, marine water, industrial wastewater, and drinking water. Investigate the efficiency of the technology in different water matrices and assess any potential interference from co-existing substances or contaminants.

- 10.
  Regulatory Considerations: Address the regulatory aspects related to the use of crustacean nanochitosan in micro-/nanoplastic removal. Understand and comply with regulations and guidelines regarding the use of nanomaterials in water treatment applications.
  By focusing on these research areas, further advancements can be made in the development of crustacean nanochitosan-based removal, leading to more efficient, sustainable, and cost-effective solutions for addressing the challenges posed by micro-/nanoplastic pollution in aquatic environments ([67], [68], [69])

Conclusion

Crustacean nanochitosan offers a promising solution for the removal of micro-/nanoplastics from water sources. Crustacean nanochitosan is a nanoscale derivative of chitosan, a biopolymer derived from crustacean shells. It possesses desirable properties such as high surface area, positive charge, biocompatibility, and adsorption capabilities. Micro-/nanoplastics are ubiquitous contaminants in water sources, posing environmental and health risks. Effective removal is essential to protect aquatic ecosystems, human health, and ensure the sustainability of water resources. Crustacean nanochitosan offers several advantages for micro-/nanoplastic removal, including high adsorption capacity, affinity for various types of micro-/nanoplastics, biodegradability, low cost, and availability as a natural byproduct. The removal of micro-/nanoplastics by crustacean nanochitosan primarily occurs through adsorption, where the positively charged nanochitosan particles attract and bind with negatively charged micro-/nanoplastics, leading to their immobilization and subsequent removal. Numerous laboratory-scale studies have demonstrated the efficacy of crustacean nanochitosan for micro-/nanoplastic removal, showcasing high adsorption capacities and efficient removal efficiencies under controlled conditions. Studies have explored process optimization, kinetics, and factors affecting the adsorption efficiency of crustacean nanochitosan, including pH, dosage, contact time, and temperature, providing insights into the optimal conditions for effective micro-/nanoplastic removal. Pilot-scale applications of crustacean nanochitosan for micro-/nanoplastic removal have shown promising results, demonstrating its potential for large-scale implementation and practical application in real-world scenarios.

Challenges associated with crustacean nanochitosan application include scalability, cost-effectiveness, integration with existing water treatment systems, and potential environmental impacts. These challenges need to be addressed through further research, optimization, and regulatory frameworks. Crustacean nanochitosan has shown advantages over other methods, including conventional filtration methods and emerging technologies, in terms of its adsorption capacity, biodegradability, and cost-effectiveness for micro-/nanoplastic removal.

Future research and development of crustacean nanochitosan should focus on optimization, cost-effectiveness, regulatory considerations, and integration into existing water treatment systems. International collaboration, stakeholder engagement, and policy development are crucial for its successful implementation.

In summary, crustacean nanochitosan offers a promising solution for the efficient removal of micro-/nanoplastics from water sources. Its unique properties and adsorption capabilities make it a viable option for addressing the growing concern of micro-/nanoplastic pollution, contributing to cleaner and healthier aquatic environments.

Declaration of Competing Interest

I hereby write to indicate interest in your journal for publication of our manuscript titled **“Water Purification Potentials of Crustacean Chitosan”.** The paper provides information on protection of the environment and human health in a changing world. It contributes knowledge to achieving SDG 6.
We have carefully prepared the manuscript to the standard of your journal requirements. I hope your reviewers will find it useful.

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