Potential for Using Algae to Reduce Microplastics in the Environment

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Abstract: As the global demand for plastics and their products continues to rise, the problem of plastic pollution is becoming more serious. Among them, microplastics as a new type of pollutants are not only harmful to the environment, but also have potential risks to human health. Focusing on algae, this paper systematically describes the potential of algae to reduce microplastics, both in terms of degrading microplastics and synthesizing bioplastics, distinguishing them from traditional methods. On the one hand, algae can immobilize microplastics in water through adsorption and interception and formation of heterogeneous aggregates, and accelerate the degradation of microplastics through the enzymes they produce. Another aspect, algae contain proteins and carbohydrate-based polymers that can be used to synthesize bioplastics, as well as elements that can act as binders in the production of bioplastics. This paper also explores existing problems and future directions to provide insights into algal degradation of microplastics.

1 Introduction

According to the United Nations, from the 1950s to 2022, the global production of plastics has reached a cumulative total of 10 billion tons. Besides, the world is still producing plastics at a rate of 400 million tons per year. This is expected to reach 33 billion tons by 2050 [1]. This growth is largely driven by global economic development, increased demand for consumer goods, and expanding industrial uses. However, this growth has been accompanied by a relative lag in the development of plastic waste treatment technologies. Currently, plastic wastes are still dominated by indiscriminate disposal and landfills, causing environmental pollution, ecosystem damage, climate change and other problems. In addition, long-term exposure to plastics causes them to break down chemically and physically, creating microplastics, which have serious potential risks to human health. Therefore, it is crucial to find a suitable method to reduce microplastics in the environment.

Currently, the traditional treatment methods for microplastics are physical separation and chemical degradation. The physical separation method is less efficient and selective to the size of microplastics, while the chemical method is affected by many factors and has the risk of secondary pollution. Therefore, most scholars are now favoring new and environmentally friendly methods over the traditional ones, among which algae stands out with its unique advantages. It has been shown that it is capable of repeatedly eliminating MP, minimizing aquatic environmental hazards and reducing energy consumption; moreover, microalgae can

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thrive on abundant waste resources and exhibit high lipid accumulation without competing with food sources, making them a better option for supplying biomass for the manufacturing of bioplastics [2].

This paper aims to summarize the possibilities of microplastic reduction by algae in terms of both plastic degradation and synthetic bioplastics. The paper discusses the current status and progress of microplastics by describing them and their relevance in aquatic environments as well as the hazards they pose to humans to emphasize the urgent need to reduce microplastic pollution. The advantages and mechanisms of microplastic removal by algae are then discussed. Subsequently, numerous approaches are used to assess algae's potential as a source of bioplastics, including combining microalgae with other materials and genetically modifying strains of microalgae that produce biopolymers. This review also highlights the challenges and limitations of the study, providing relevant information about the connection between microalgae and plastics.

2 Microplastics in aquatic environments

Any artificial solid plastic particles or polymer matrices that are insoluble in water and have a particle size less than 5 mm are known as microplastics (Mps), which typically ranges from 1 μm to 5 mm [3]. Microplastics can be divided into primary and secondary categories based on the method of generation; according to the size, they are classified into macroscopic (>25 mm), mesoscopic (525 mm), microscopic (15 mm), and nanoscopic (1 μm~1 mm); and according to the shape, they are classified into fibers, particles, fragments, films, and foams [4].

In general, primary microplastics are plastic particles with a particle size of less than 5 mm before they enter the environment. Cleaners and cosmetics, air spray media, pharmaceutical carriers, and primary plastic manufacture particles are some of the major categories into which the sources of primary microplastics can be broadly divided [3]. Secondary microplastics, on the other hand, are tiny plastic particles made from the decomposition of large plastic fragments by various factors such as degradation, photo-oxidation and other environmental factors. It is mainly derived from various plastic products and wastes associated with human activities.

At the moment, microplastics can be detected in a variety of environmental contexts, such as the air, freshwater, wastewater, ocean, food, tap water, and bottled water [5], and most of the microplastics in the environment end up in the oceans in a variety of forms. Taken together, microplastics are mainly found in aquatic environments, including freshwater and brackish water. Although the concentration of microplastics in the oceans varies greatly depending on a variety of factors such as sea area, geographic location, and human activities, according to research, the five largest seas in the world have an average abundance of 2.76 items/m^3 of microplastics, with overall concentrations ranging from 0.002 to 62.50 items/m^3. The Atlantic Ocean had the highest average microplastic concentration of 4.98 items/m^3, while the Southern Ocean had the lowest average microplastic concentration [6]. The average concentration of floating microplastics at the sea surface off China was 0.27 items/m^3. Among them, the concentration of microplastics is higher than that in the offshore waters around estuaries, bays and islands due to special topographic conditions and the influence of human activities.

In aquatic habitats, microplastics can upset ecosystems by interfering with biological processes and nutrient uptake. Because of their small size, they are also easily absorbed by animals, which at certain concentrations can result in toxicological and physical risks [2].

2.1 Impacts on Aquatic Plants

Microplastics have a wide range of adverse effects on the growth and development, physiological metabolism and ecological relationships of aquatic plants. According to studies, microplastics cause oxidative stress, decrease chlorophyll content, and stunt root and shoot growth, all of which impair plant health and productivity. Additionally, the adsorption and accumulation of microplastics can drastically lower the pace of development and root activity of floating plants' belowground component. Microplastics can also stick to plant surfaces and obstruct light and vital nutrients, which hinders photosynthesis. These disruptions impair plant growth and may affect broader ecosystem functions such as nutrient cycling and water purification, thus posing a risk to the aquatic environment [7]. It has been shown that microplastic pollution poses a possible risk to aquatic ecosystems and vegetation, ranging from direct impacts on growth and physiological functions to potential ecological effects.

2.2 Impacts on human beings

Microplastics also pose a significant potential risk to human health, affecting various systems, such as the digestive system and the functioning of the liver and kidneys. Although there is little direct research on the effects of microplastics on humans, studies have shown that microplastics have toxic effects on living organisms. They can cause metabolic disorders, genotoxicity, inflammatory responses, reproductive development, etc., and may pose various potential health hazards to humans [4]. Microplastics have been shown to quickly enter the bloodstream, build up in the digestive tract, and infiltrate the majority of organs after being consumed by humans. Receptor-mediated endocytosis, cytotoxicity and phagocytosis are the major steps in the internalization of microplastics in humans. In addition, they can be internalized in the intestine through phagocytic uptake, paracellular transport and interstitial absorption in the villi. However, MPs lead to mitochondrial depolarization and decrease the mitochondrial membrane potential. In severe cases, they can even lead to mitochondrial damage and apoptosis. This causes symptoms such as inflammation, insufficient blood flow and alteration of gut microbiota in the body [8].

Microplastics are potentially harmful to many organs in the human body, as shown in Figure 1 [8]. From the eyes to the reproductive system, microplastics can negatively affect them. These effects include a variety of health problems such as cytotoxicity, metabolic disorders, inflammation, and increased risk of cancer. As an example, abnormal changes in the structure of the retina of the eye, the blood-ocular barrier, which is an important part of the retina, and abnormalities in the organization of the retina can alter the blood-ocular barrier, making it more permeable to external molecules that enter the eye. Enteric pericyte-mediated transcytosis absorbs smaller MPs components via the intestinal mucosa [8].

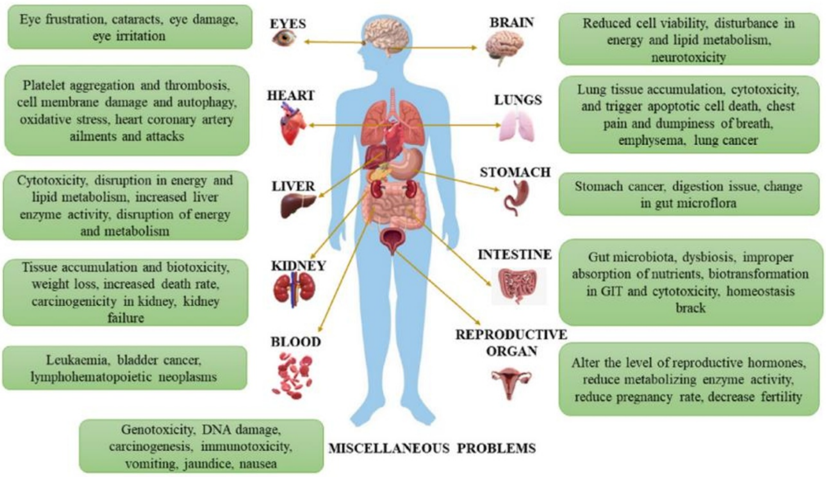

Fig. 1. The detrimental effects of microplastics on the body's organs [8].

3 Technologies to reduce microplastics using algae

Taken together, microplastics have become a problem that mankind cannot ignore and must address. Microplastics are generated by human beings in their production, living and other activities, and are discharged directly or indirectly into the environment, which ultimately has various effects on various organisms in the natural world as well as on human beings themselves. These effects include adverse effects on physiological metabolism, growth and development, and various functions. Therefore, it is necessary to reduce the amount of microplastics in water bodies.

From the point of view of nature, the mainstream methods of removing microplastics are mainly divided into physical separation, chemical degradation and biodegradation. Physical separation is mainly through sieving, filtration and other ways to separate microplastics and other substances, although the method is simple and fast, its removal efficiency is low, and it is difficult to remove nanoscale microplastics. The degradation of microplastics by chemical reagents under specific conditions may produce secondary pollution, and there are many limitations, such as the anode material, initial solution pH, electrolyte concentration, MPs species, etc. in the electroflocculation technology will have an impact on the removal effect. The biodegradation method has shown great potential under certain conditions, especially algae as a natural biodegradation pathway, which is gradually put on the research agenda due to its low cost, easy cultivation and non-toxicity.

Algae play an important role in the ecosystem as primary producers and as the basis of the aquatic food web. Algae themselves are easy to cultivate and collect, simpler and less costly to process than traditional wastewater treatment. Although not much research has been done on microplastic degradation based on algae, the use of algae to reduce microplastics is a highly promising approach, both in terms of environmental friendliness and sustainability.

Algae are a very widespread and diverse group of plants, ranging from the tropics to the poles and even in extreme environments such as hot springs and salt lakes. In aquatic ecosystems, they play a crucial role in energy transmission and material cycling because of their basic structure and reliance on photosynthesis for autotrophic development, which transforms solar energy and inorganic carbon into bioenergy and organic carbon [9]. In addition, algae participate in the carbon and nitrogen cycles in the ecosystem, which is essential for maintaining ecological balance.

Although microplastics can affect the growth and health of aquatic plants such as algae, etc., to a certain extent, algae, especially microalgae, contribute to the removal of microplastics from water bodies. Studies have shown that some marine macroalgae are able to capture and retain microplastics in seawater through adhesion, embedding, encapsulation and entanglement [9]. Moreover, the chemical bonds of plastic polymers are broken by the enzymatic activities of microalgae, aiding in the biodegradation of plastic waste. Microplastics interact with microalgae in a variety of ways, including adhering to the surface of microalgae or forming clusters. These interactions are influenced by factors such as the size of the microplastic, the nature of the surface, and the species of microalgae involved [8]. In addition, it has been shown that algae have potential for synthesizing bioplastics.

3.1 Degradation

Algae can intercept, catch, and entangle microplastics in wastewater. They can also create heterogeneous aggregates with algae, which lowers the free suspension of microplastics [10]. Compared to endotoxic bacterial and fungal strains, microalgae can photosynthesize without the need for an organic carbon source, which gives them a unique advantage in water treatment applications to differentiate and degrade biological contaminants effectively. Many non-toxic algae form biofilms on plastic surfaces, are present in contaminated water bodies, and promote phytoplankton adhesion to plastic through extracellular polysaccharides. Enzymes produced by microalgae, such as lipases, esterases, and cellulases, promote biodegradation of plastics. In particular, microalgae can flourish on the surface of PET and produce key PETase enzymes, significantly accelerating the biodegradation of PET. In addition, genetic modification, such as the modification of Chlamydomonas reinhardtii to produce PETase, can further enhance the degradation ability of microalgae, which effectively promotes the decomposition of plastics by causing pores and cavities on the surface of plastics [11].

Freshwater non-toxic cyanobacteria (Phormidium lucidum and Oscillatoria subbrevis) can colonize PE surfaces and effectively biodegrade LDPE without the need for pro-oxidant chemicals or pretreatment, according to research. These bacteria are easily isolated, fast-growing, and widely available. Additionally, algae can easily break down the polymer bisphenol A (BPA), which is used extensively in the plastics sector, into substances that do not have estrogenic properties [12].

When microalgae encounter microplastic particles in the water column, they adhere to their surfaces through physical and chemical interactions, where the chemical interactions involve extracellular polymeric substances (EPS) secreted by the microalgae. This substance, composed of polysaccharides and proteins, forms a sticky matrix that enhances adhesion. Subsequently, microalgae internalize microplastic particles into their cells through endocytosis, which is not only a survival strategy for microalgae in the face of microplastic threats but also helps to isolate microplastics inside the cells, leading to microplastic reduction [2]. Chlorella, for example, can both adsorb and internalize polystyrene microplastic particles.

In short, algae collect and immobilize microplastics and nanoplastics mainly through two pathways: direct and indirect. As shown in Figure 2, in the direct pathway, microplastics are rapidly adsorbed onto the algal surface or taken up by the cells, and the interception capacity depends on algal coverage, stem and leaf density, and the size and surface properties of microplastics. The indirect pathway, on the other hand, involves increased secretion of extracellular polymeric substances (EPS) by algae stimulated by microplastics, which promotes the formation of heterogeneous aggregates, where aggregates formed by specific algae and microplastics are larger and more viscous [10].

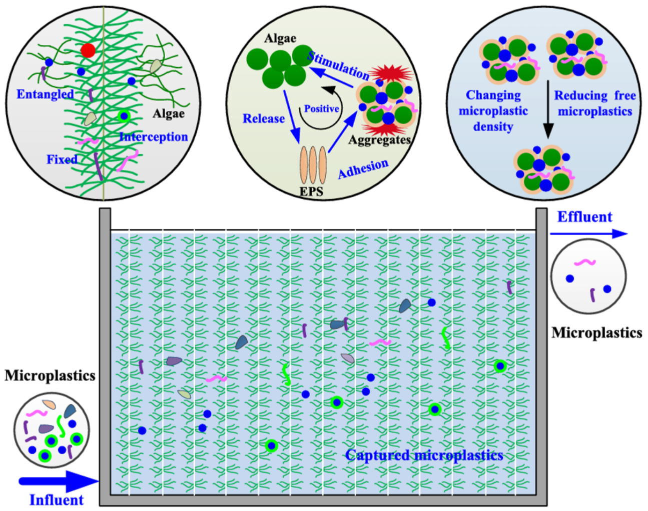

Fig. 2. Mechanisms of how algae remove microplastics during sewage treatment [9].

3.2 Synthesis of bioplastics

Bioplastics are defined as plastics made entirely or partially from biomass or renewable resources and have the same functionality as petroleum-based plastics. The production of bioplastics relies heavily on crops such as corn and wheat, as well as feedstocks such as soy protein and milk protein, but the sustainability of these feedstocks has been questioned because they may compete with human demands for land and water resources. In addition, the process of extracting compounds and polymers from plants for the synthesis of bioplastics is more difficult due to the layered structure of plant cell walls. Moreover, those microplastics made from food crops face problems of water resistance and poor mechanical properties [12].

Traditional plant feedstocks face sustainability issues and algae, as alternative materials, can circumvent these challenges and provide new solutions. In addition, algae have the ability to clean up wastewater and use carbon dioxide as a source of nutrients to produce biomass [12]. Both macroalgae and microalgae may be used for bioplastics production, with microalgae being more desirable due to their very simple structure and small size. Macroalgae contain about 50% to 76% polysaccharides on a dry weight basis and contain starch, agar, alginate, cellulose, carrageenan, fucoidan and Ulva. For the creation of bioplastics, these constituents serve as binders and have the ability to form films [13].

Microalgae-based bioplastics are produced in several ways, including direct use of microalgal biomass, blending of other materials, biorefinery processing, and genetic engineering of modified microalgal strains. Microalgal biomass contains protein- and carbohydrate-based polymers that are potential components of bioplastics, among which PHA is highly prized for its biodegradability.PHB, as one type of PHA, has emerged as a novel bioplastic polymer due to its good oxygen barrier properties. There have been several examples demonstrating the use of algal biomass in bioplastic production, such as the use of algae by Dutch designers to produce bioplastic products that can completely replace traditional plastics, and the development of biodegradable materials consisting of algal agar and calcium carbonate. These bioplastic products are not only lightweight and durable, but can also be composted or used as fertilizer. There are also biodegradable plastic bottles made by mixing red algae powder with water [12].

Overall, algae as an alternative raw material, compared with traditional petroleum plastics and bioplastics, has the advantage of low price, stable nature and environmentally friendly, and has the potential for development.

4 Recommendations

Based on the extensive demand for plastics and their products in various industries, plastic pollution has become more and more serious all over the world. Algae, due to their unique advantages, have shown remarkable potential in microplastic degradation and bioplastic synthesis. However, most of the related research has been concentrated in the laboratory stage, and the industrial scale production is still facing technical and cost barriers.

The first is that algae may be affected by the toxicity of microplastics in the process of degrading them. Various pollutants (e.g. heavy metals, organic pollutants) may be adsorbed on the surface of microplastics, and these pollutants may be released during the process of microplastic adsorption by algae, causing toxicity damage to the algae themselves. Although algae are well adapted to microplastics, the effects of different types and dosages of microplastics on algae are still uncertain in practical applications. It has been shown that heavy metals adsorbed on the surface of microplastics (e.g., lead and cadmium) can be released into algal cells during the adsorption process of algae, leading to the inhibition of algal growth and even death [14]. In addition, the efficiency of microplastic degradation by algae is also affected by more factors. Different types of microplastics (e.g., polyethylene, polypropylene, etc.) respond differently to the degradation ability of algae, and the surface properties of microplastics (e.g., hydrophobicity, hydrophilicity) also affect the adsorption and degradation efficiency of algae [14]. In future studies, it is recommended to conduct more experiments on microplastic degradation by algae under different environmental conditions to explore the effects of different microplastic species and quantities on the degradation effect, and to screen and modify algal strains with efficient degradation ability to improve their degradation efficiency of microplastics by genetic engineering means or exploring the coordinated degradation system between algae and other organisms.

In addition, the transport of microalgae may carry different microbial communities and may even introduce harmful or non-native algae. Such a situation may pose a threat to the aquatic biodiversity of the new environment and destabilize the local ecosystem. The primary concern of future studies should be the possible influence of microplastics on microalgae and their ripple effects on the aquatic ecosystem overall [2].

When it comes to algal bioplastics, research is still in its experimental or early stages and cannot be widely commercialized [12]. Considerable research is still needed to identify the most suitable algae for the production of bioplastic polymers with different properties and to assess their feasibility on an industrial scale. Large-scale cultivation of algae also needs to be considered.

5 Conclusion

This paper summarizes the possibilities of algae to reduce microplastics by systematically describing the use of algae in the aquatic environment in both degrading microplastics and synthesizing bioplastics. Although microplastics are harmful to aquatic organisms, including algae and even human beings, algae, especially microalgae, can degrade microplastics in water bodies in different ways. Microalgae, which are not only free of endotoxins but also photosynthesize without the need for an organic carbon source, stand out in the choice of materials for biodegradation methods. Microalgae can immobilize microplastics in water through adsorption and interception and formation of heterogeneous aggregates, and accelerate the degradation of microplastics through the enzymes they produce. In addition, algae contain proteins and carbohydrate-based polymers that can be used to synthesize bioplastics, as well as elements that can act as binders in the production of bioplastics. Algae can therefore be used as an environmentally friendly and sustainable alternative to traditional food crops and other raw materials for the synthesis of bioplastics.

From a comprehensive viewpoint, although algae belong to the lower class of organisms, due to their unique structure and physiological advantages, they show an important potential and application prospect in the field of microplastic reduction. However, considering the variety of microplastics and their different sizes, future research should conduct more degradation experiments under different conditions and select appropriate degradation conditions to accelerate the degradation efficiency. In addition, it is necessary to consider the issues of pilot scale-up and the impact on aquatic ecosystems, so that the research results can be applied to actual production with fewer side effects.

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