Effects of Microplastics on the Operational Performance and Microbial Community of Activated Sludge Systems

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Abstract As emerging contaminants, the transport, fate and ecological risks of microplastics in wastewater treatment plants have become a research hotspot. This paper systematically reviews the occurrence characteristics of microplastics in wastewater treatment plants and their effects on the treatment performance and microbial communities of activated sludge systems. The results indicate that microplastics in wastewater treatment plants are predominantly fibrous, mainly composed of PE, PP, PS, and PVC, with their abundance influenced by treatment processes, geographical regions, and seasonal variations. High-concentration and small-sized microplastics significantly inhibit organic matter removal in the system. Different types of microplastics exhibit differentiated effects on nitrogen and phosphorus removal. Long-term exposure to high-concentration microplastics reduces the abundance of functional bacteria, disrupts microbial community structure, and leads to deterioration of sludge performance. In contrast, low-concentration microplastics have relatively minor effects on the system, and some microplastics may serve as microbial carriers influencing community succession.

Key words Microplastics; Activated sludge; Operational performance; Microbial community

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Plastic products are widely used in industrial production and daily life. Improper disposal leads to a large amount of plastic waste entering the environment, where it gradually breaks down into small particles or fragments through physical, chemical, and biological processes. When the particle size is less than 5 mm, it is defined as microplastics. Wastewater treatment plants are major collection points for microplastics in aquatic environments. Microplastics that are not completely retained after treatment are discharged into natural water bodies with the effluent, making wastewater treatment plants a secondary source of microplastic pollution in the environment[1]. Conventional wastewater treatment processes can remove over 90% of microplastics, but most of them are enriched in sludge[2-3], causing continuous exposure stress to the activated sludge system. Microplastics can affect the removal of organic matter and the efficiency of nitrogen and phosphorus removal in wastewater. Their effects are regulated by multiple factors, including microplastic type, particle size, concentration, and process conditions[4-6].

This paper systematically reviews the occurrence characteristics of microplastics in wastewater treatment plants, as well as their effects on organic matter degradation, nitrogen and phosphorus removal processes, and microbial community structure in wastewater. It summarizes the limitations of current research and prospects future research directions, aiming to provide a reference for assessing the ecological risks of microplastics and ensuring the stable operation of wastewater treatment systems.

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Occurrence Characteristics of Microplastics in Wastewater Treatment Plants

In wastewater treatment plants, microplastics are predominantly fibrous in shape, followed by film-like, fragmented, and granular forms. The most common color is transparent, while white, black, and blue also present. The highest proportion of microplastics falls within the particle size range of 100 – 500 μm, while those larger than 1 mm account for ≤30%. The main types of microplastics are polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC), and small amounts of polyethylene terephthalate (PET) and polyamide (PA) are also detected[7-9].

The abundance of microplastics is influenced by factors such as sludge dewatering processes, geographical regions, and seasonal variations. Filter pressing can retain more microplastics in sludge compared with centrifugation[10]. Kong[11] found that the concentration of microplastics in wastewater treatment plants in Jinan was higher than that in Lanzhou and Kaifeng. In domestic wastewater, microplastic concentrations are highest in summer and lowest in winter. In industrial wastewater, the highest concentrations occur in spring and the lowest in summer[8].

Effects of Microplastics on the Removal of Biochemical Oxygen Demand/Chemical Oxygen Demand

Effects of microplastic concentration, particle size, and exposure time on cod removal

Low concentrations of microplastics have no significant effect on COD removal, while high concentrations significantly inhibit it. In aerobic granular sludge, enhanced biological phosphorus removal systems, and sequencing batch reactor systems, COD removal rates decrease with increasing microplastic concentrations[12-14].

Under the same concentration conditions, the length of microplastic retention time in the system does not have a significant adverse effect on COD removal. Wang *et al*. [15] found that in a sequencing batch membrane bioreactor, the addition of microplastics caused deterioration of sludge performance, leading to lower COD removal rates. However, after a period of adaptation, the sludge's COD removal capacity recovered to normal levels. Microplastic particle size shows a negative correlation with COD removal efficiency. Li[16] reported that in a sequencing batch reactor system, smaller PS microplastic particles exerted a more pronounced inhibitory effect on COD removal.

Effects of microplastics on BOD removal

In a sequencing batch biofilm reactor, low concentrations of PE microplastics have no significant effect on BOD removal. However, high concentrations of PE significantly inhibit microbial activity and intracellular carbon synthesis, thereby suppressing the biodegradation of BOD[17]. In aerobic granular sludge systems, polylactic acid (PLA) and PET microplastics at low concentrations do not significantly affect BOD removal. Nevertheless, at high concentrations, they block nutrient transfer channels within the granular sludge, markedly weakening the system's organic degradation capacity and ultimately inhibiting BOD removal[18]. In a granular sludge sequencing batch reactor, different types of microplastics exhibit varying effects on BOD removal. PET inhibits BOD removal, and the inhibitory effect intensifies with increasing PE concentration. In contrast, PE not only does not significantly inhibit BOD removal, but can also accelerate the BOD removal process to some extent[19].

Effects of Microplastics on Nitrogen and Phosphorus Removal in Activated Sludge Systems

The concentration, type, particle size, and exposure time of microplastics can affect nitrogen removal efficiency in activated sludge systems. Xu[20] found that with increasing PP concentration and prolonged exposure time, the activated sludge system in a sequencing batch reactor was disrupted, leading to deteriorated nitrogen removal performance. In aerobic granular sludge systems, both low and medium concentrations of microplastics can enhance nitrogen removal efficiency. Although high concentrations of microplastics inhibit sludge growth, they can still promote the denitrification process[18]. In a simultaneous nitrification and denitrification phosphorus removal system, higher microplastic concentrations exert a more pronounced inhibitory effect on total nitrogen removal[21]. Different types of microplastics exhibit varying degrees of inhibition on nitrogen removal. In an anaerobic ammonia oxidation system, the order of inhibitory effects is PVC > PE > PET[22]. In the nitrification process of biological nitrogen removal, PS exhibits the strongest inhibitory effect, followed by PVC, while PP and PE show slight promoting effects[23]. The smaller the particle size, the more pronounced the impact on nitrogen removal. In sequencing batch reactors and heterotrophic nitrification-aerobic denitrification batch experiments, nano-sized microplastics exhibited significantly stronger inhibitory effects on nitrogen removal than micro-sized ones[24-25].

Different types of microplastics exhibit significant differences in their effects and mechanisms on phosphorus removal at various concentrations. In aerobic granular sludge systems, PLA and PET microplastics can promote total phosphorus removal, with higher concentrations producing more pronounced effects. This is mainly achieved by enhancing the abundance of phosphorus-accumulating organisms to strengthen biological phosphorus removal. Once microplastic exposure ceases, the system's phosphorus removal capacity returns to its original level[18]. In contrast to the promoting effects of the aforementioned two types of microplastics, PE nanoplastics exhibit a clear inhibitory effect on phosphorus removal. High concentrations of PE can significantly inhibit the anaerobic phosphorus release and aerobic phosphorus uptake processes in activated sludge, interfering with key enzyme activities in polyphosphate metabolism and intracellular substance metabolism, thereby reducing the overall phosphorus removal efficiency of the biological wastewater treatment system[14,26]. Furthermore, low concentrations of PLA microplastics show no significant effect on the phosphorus removal efficiency of microalgae-bacterial granular sludge systems, while high concentrations significantly reduce phosphorus removal efficiency by disrupting sludge structure, reducing extracellular polymeric substances, and inhibiting the activity of phosphorus-accumulating organisms[27].

Effects of Microplastics on the Microbial Community in Activated Sludge Systems

Effects of microplastic concentration, exposure time, particle size and type on microbial community characteristics in activated sludge systems

In sequencing batch activated sludge systems and aerobic granular sludge systems, low concentrations of microplastics generally do not cause significant inhibition of the microbial community. However, high concentrations of microplastics can significantly reduce the abundance of functional bacteria such as Proteobacteria, Bacteroidetes, and *Nitrospira*, leading to structural imbalance of the microbial community and deterioration of sludge performance[12,28]. During short-term exposure to microplastics in conventional activated sludge systems, microorganisms can adapt to the stress by secreting extracellular polymeric substances, and the microbial community structure shows no significant changes[29]. However, in anaerobic activated sludge systems, long-term exposure (≥100 d) to microplastics can lead to reduced microbial community diversity and functional imbalance due to the accumulation of toxicity[30]. The stress effects of microplastics on microbial communities are negatively correlated with their particle size. In sequencing batch activated sludge systems, smaller microplastic particles cause more significant disturbance to community structure, promote cell disruption in residual sludge, and inhibit hydrolysis acidification and volatile fatty acid production[16]. Small-sized PET reduces the activity of functional bacteria and enzymes, thereby suppressing hydrolysis and acidogenesis[30].

Distinct effects of different types of microplastics on microbial communities

PE, PP and PET microplastics differ in their surface hydrophobicity, charge characteristics, and surface roughness, resulting in differentiated microbial adsorption capacities and biofilm formation characteristics. They can serve as microbial carriers to regulate community succession processes, but may also pose potential microbial safety risks[31]. In addition, PVC and polylactic acid (PLA) can severely disrupt the microbial community composition of aerobic granular sludge, leading to a decline in nitrogen removal performance by inhibiting the proliferation of denitrifying functional bacteria[32]. Furthermore, aged PA and PS can release highly toxic leachates, whose toxic effects far exceed those of the microplastics themselves. These leachates not only reduce microbial community richness and inhibit functional microbial activity, but also disrupt normal microbial metabolism in sludge, thereby affecting the stable operation of activated sludge systems[33].

Conclusions

Studies have shown that the concentration, particle size, and type of microplastics significantly influence the pollutant removal efficiency of activated sludge systems. High-concentration, small-sized microplastics inhibit COD and BOD removal as well as nitrogen removal processes, while different types of microplastics exhibit either promoting or inhibiting effects on phosphorus removal. Microplastics reduce the abundance of functional bacteria and disrupt microbial community structure. Long-term exposure can lead to functional imbalance of the community. This study elucidates the mechanisms of these effects, providing a scientific basis and theoretical support for aquatic environmental risk assessment and the optimization of wastewater treatment processes. Currently, extensive research has been conducted on the interactions between microplastics and activated sludge systems. However, several issues remain. Most studies have only examined the effects of short-term exposure to a single type of microplastic on activated sludge systems, and these studies have been conducted at the laboratory simulation level, which differs from the real-world conditions of actual wastewater treatment plants. Future research should focus on the combined pollution of multiple microplastics and long-term exposure conditions, and investigate the interactions between microplastics and activated sludge systems in the context of actual wastewater treatment plant operations.

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improvement of training quality. A closed-loop operational mechanism of "training objectives – training process – training evaluation – continuous improvement" has been established. This model is conducive to promoting the synergistic enhancement of graduate students' knowledge, ability and literacy, providing a reference for the reform of agricultural master's degree training models under the background of new agricultural science. In the future, further empirical research should be conducted to continuously improve the operational mechanisms and quality assurance system of AI-empowered graduate training.

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