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Article

Biomechanics identification and risk management strategy of volatile organic compound pollution sources integrated with machine learning algorithms

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Abstract: Microplastic pollution has emerged as a critical environmental issue, posing significant threats to aquatic ecosystems and human health. As an innovative approach, biological techniques have shown great potential in mitigating microplastic contamination in water systems. This study explores the use of biotechnological methods, such as microbial degradation and biofilm-assisted filtration, in combination with conventional water treatment processes to enhance the removal of microplastics. Focusing on Southwest China, where water pollution is exacerbated by rapid urbanization and industrial activities, the research identifies the ecological and technical challenges unique to this region. Experimental approaches include optimizing bio-coagulation using microbial consortia, assessing enzymatic degradation of common microplastic polymers, and evaluating the biomechanical interactions between biological agents and microplastic particles during water filtration. Results aim to provide insights into the efficacy and scalability of integrating biological solutions into existing water treatment frameworks. This study contributes to developing sustainable and eco-friendly strategies for addressing microplastic pollution and safeguarding water quality through biologically informed interventions.

Keywords: water environment; microplastic pollution; water treatment process; pollution removal; biomechanical interactions; biological remediation;

1. Introduction

Microplastics, plastic particles smaller than 5 mm, pose a significant health threat due to their ability to adsorb organic pollutants and release harmful additives into water, causing contamination. As a major producer and consumer of plastics, China faces severe microplastic pollution in its water environments. Evaluating microplastic pollution, assessing water treatment processes, and implementing effective waste management strategies are urgent to protect water ecosystems and ensure drinking water safety [1].

In the 21st century, rapid advancements in information technology have driven economic and technological growth, increasing demand for resources, particularly water. Recognizing the critical role of water in human survival, China has taken significant steps to protect water resources. Water protection is central to ecological progress. China's drinking water standards have evolved, with major revisions in 2006 and 2020. These updates included pollutant reclassification, emphasizing localized pollutant analysis and evaluation. This reflects the necessity of tailored strategies for pollutant management to address regional variations and enhance water quality [2].

There are many types of pollutants in water, among which microplastics are a class of pollutants that have recently started to attract much attention [3]. Primary microplastics are industrially produced microplastics with microscopic particle size at the time of production and are commonly used in personal toiletries; secondary microplastics refer to microplastics that are broken or degraded from large pieces of microplastics, such as discarded agricultural plastic sheds, car tire chips, etc. [4]. Recent studies have pointed out that the release of primary microplastics has exceeded that of secondary microplastics. Microplastics are widely present in various environments due to human activities. To date, traces of microplastics have been found in the ocean and freshwater. In China, microplastic pollution has been found in Yangtze River, Pearl River basin and Taihu Lake, and the microplastic content in more than 20 rivers and lakes in Yangtze River and Han River basin reached 1660.0 ± 639.1–8925 ± 1591/m^3; in addition, microplastics have been detected in water supply plant effluent, municipal sewage, and wastewater plant effluent, indicating that microplastics have become an integral part of the water treatment process. It shows that microplastics have become a part of water treatment process that cannot be ignored. Therefore, more and more attention has been paid to the research on ways to reduce micro plastic pollution and improve water quality [5].

The drinking water treatment process typically involves coagulation, sedimentation, filtration, and disinfection. Coagulation and sedimentation primarily target the removal of suspended solids and colloidal particles [6]. To address increasingly complex water pollution, advanced methods like the ozone-activated carbon process have been developed and widely applied to remove difficult organic pollutants. Conventional processes remain advantageous due to their low cost and minimal risk of secondary contamination.

Filtration processes, including ultrafiltration, are indispensable in water treatment plants worldwide. They primarily remove organic matter not eliminated by coagulation and sedimentation, with effectiveness influenced by factors such as filter media type, porosity, tortuosity, surface morphology, and particle characteristics. However, filtration alone has limitations, highlighting the importance of regulating water quality and particle morphology entering the filtration process to improve efficiency and minimize adverse effects.

Current water treatment processes often emphasize changes in water quality during treatment rather than controlling process dynamics or understanding particle size variations. Studying the effects of small microplastic particles on the coagulation-sedimentation process can enable targeted regulation to mitigate microplastic pollution. Given their regular shape, controllable size, and defined diameter, microplastic particles are ideal for investigating the impact of particle distribution on water treatment [7].

Southwest China, including Sichuan, Guizhou, Yunnan and Chongqing, is rich in phosphate and coal resources. It is an important base and strategic reserve for the development of China's non-ferrous metal industry. It is also an ecologically unsustainable region [8]. Due to the rapid growth of regional economy and the acceleration of urbanization, the urban discharge to the river basin is increasing, and the pressure on its own water environment is increasing. The Chengdu section of the

Tuo River is the most polluted river in Sichuan Province, with less than 30% of good water quality; the Dianchi River in Kunming City is still suffering from insufficient ecological water, eutrophication of water bodies, and damage to water ecology; the extensive phosphate mining in Guiyang City is an important reason for the V or poor V water quality of the Yangshui River in recent years; the water quality of secondary rivers in Chongqing City has been worse than the municipal level for a long time, and 1/3 of the sections in the Three Gorges Reservoir area are showing Eutrophication. In addition, the region also generally suffers from a serious shortage of water resources per capita and prominent surface runoff pollution [9].

2. Microplastic contamination treatment

Among many microplastics, spherical polystyrene particles (PS particles) have a density close to that of water, are widely distributed in freshwater environments, and are second only to polyethylene particles (PE particles) in terms of commonness; therefore, spherical PS particles were used as typical microplastics for the study. Considering that millimeter-sized microplastic particles are close to the normal floc size and relatively easy to be removed in the feed water treatment process, and according to previous studies, micron-sized microplastics are comparable to coagulation for targeted removal of pollutants, especially particles of 5 μm and below have a greater impact on the flocculation process, so the study focuses on the removal of particles of 5 μm and below. Considering the size and shape of microplastics, scanning electron microscopy(SEM) and fluorescence microscopy were proposed to be used to determine the detection method by comparing the accuracy and convenience of the detection [10,11].

Prepare dispersions of 5 μm PS particles at concentrations of 6570/500mL and 2190/500mL, wash the particle counter with filtered pure water, and after the instrument readings are stable, record the average of the readings over a period of time as the number of particles in pure water (background value); for total particle count, subtract the background value from the particle counter reading to the number of microplastic particles in water. From minute 0 to minute 7, the sampling tube was placed in 500ml of dispersion solution with 6570 microplastic particles, and 2190 particles/500mL of microplastic particles were added from minute 7 onwards, and the change in particle count was counted.

3. Experimental methods

3.1. Coagulation beaker experiment

Beaker tests are performed to find the ideal amount of coagulant and, on the one hand, to study the characteristics of microplastics. Chapter 3 will provide a detailed description of the experimental process used to examine the characteristics of microplastics. The following experimental techniques can be used to determine the ideal coagulant cast amount: To ascertain the coagulation when the stirring strength is used, first ascertain the coagulation stirring circumstances based on the experiment and the actual drinking water plant connected to the principle of equal speed gradient.

$$G = \left(\frac{\varepsilon}{v}\right)^{\frac{1}{2}} = \left(\frac{N_p N^3 d^5}{Vv}\right)^{\frac{1}{2}} \tag{1}$$

where N_p the power quotient of the stirring paddle, the value of the experimentally used paddle is 1.27; *N*—stirring speed (rps); d—the diameter of the stirring paddle (m); *V*—the effective volume of the reactor (L); *ε*—the effective energy consumption per unit volume of fluid per unit time (m^2/s^3), *ν*—the kinematic viscosity of water (m^2/s^3).

From equation (2), we have.

$$N = \left(\frac{G^2 Vv}{N_p d^5}\right)^{\frac{1}{3}} \tag{2}$$

At the same time, the flow regime in the model and the prototype should be kept similar, i.e., the turbulent state should also be in the homemade reactor, with a Reynolds number of $Re \geq 1000$ during stirring, i.e.,

$$Re = \frac{Nd^2}{v} \geq 1000 \tag{3}$$

It can be obtained that the minimum stirring speed should satisfy.

$$N \geq \frac{1000v}{d^2} \tag{4}$$

In the design of the coagulation process, the mixing stage $G = 70{\sim}1000s^{-1}$ and the flocculation stage $G = 20{\sim}70s^{-1}$ were designed. In the experiment, the determination of the stirring speed was done by using equations (2) and (4) based on the design G value, drawing on the design basis in the actual process. The fast stirring speed was set to $400\ rpm(G = 250s^{-1})$, and the fast stirring time was 1 min; the slow stirring speed was $120\ rpm(G = 41s^{-1})$, and the slow stirring time was 15 min; and the sedimentation was 30 min [12].

Water samples with water quality indexes close to the water source were prepared, and the turbidity of the simulated raw water was 48–50 NTU, UV_{254} was 0.430, and pH was 7–7.2. Aluminum sulfate and polymeric aluminum chloride with different properties were used as coagulants, and were injected into different beakers according to gradient concentrations, and coagulation was started according to the established coagulation procedure. The turbidity, UV_{254}, TOC and residual Al content of the settled water were detected. According to the above indexes, the type of coagulant and the best dosage were determined.

3.2. Coagulation reactor experiments

Based on the beaker experiment, the coagulation experiment was conducted in a 5 L reactor. Prepare the simulated raw water and coagulant, turn on the particle counter, linear light source and high-speed charge-coupled camera; turn on the power of stirring paddle, stir at 400 rpm/min until the turbidity is stable, adjust the pH of the solution to 7 with 0.1 M of $NaOH$ and HCl, then take 200 mL of the solution to measure the turbidity and UV_{254} values; then add different coagulants, fast stirring at 400 rpm/min for 1 min, then slow stirring at 120 rpm/min for 15 min, and finally settling for 30 min. Then add different coagulants and perform fast stirring at 400 rpm/min for 1 min, then slow stirring at 120 rpm/min for 15 min, and finally precipitate for 30 min, and take water samples to measure the remaining turbidity and UV_{254} values [13,14]. At the beginning of fast stirring, the acquisition and recording switches of the particle counter and flocculation image software were turned on, and at the end of slow stirring, the acquisition and recording switches of the image software were turned off.

3.3. Floc oxidation experiments

When the content of microplastics in flocs is to be examined, floc oxidation experiments are required. In addition to the adsorbed polystyrene (PS) particles in the floc, there are kaolin particles and organic matter, and the presence of organic matter can affect the observation of PS particles, so the floc is oxidized using H_2O_2 solution.

The coagulation conditions were as described before, and the floc was poured into a beaker after 24 h of continued precipitation, 500 mL of a 30% concentration of H_2O_2 solution was added, and the floc was placed in a shaker and shaken for 72 h at 80 rpm and 65 °C to fully oxidize the floc and expose the PS particles. After the temperature of the floc dropped to room temperature, 10 mL of the oxidized floc was drawn. The number of PS particles in all flocs was calculated based on the volume ratio of 10 mL sample flocs to total flocs.

3.4. Simulated sand filtration test

A quantitative filter paper with 200 μm thickness and 2.5 μm pore size was used to simulate a homogeneous filter media and filter a gradient concentration of microplastic solution. The number of particles on the filter paper and in the filtered water was examined to investigate the interception rate and penetration rate of microplastic particles by simulated sand filtration [15].

3.5. Removal rate of microplastics by coagulation

Microplastic particles undergoing coagulation without coagulant application tend to settle in water, but the settling rate does not exceed 25%, making complete removal unattainable. When coagulants are added, microplastics, as organic insoluble matter, adsorb and interact with dissolved organic matter and inorganic particles through hydrolyzed coagulants and coagulation effects, forming large flocs that settle out of the water.

During this process, fluorescent microplastics in the flocs may be obscured by kaolin and humic acid fragments, affecting observation. Some particles appear lighter in color beneath the fragments, while others at the edges may have incomplete morphology, impacting recognition by counting software. Additionally, the contrast between air-dried fragments and the background further complicates accurate counting. Therefore, oxidation of the flocculated and precipitated samples is performed prior to observation to address these issues.

In order to keep the microplastic particles from being destroyed, instead of using strong acid or alkali oxidation, hydrogen peroxide, which is a mild oxidant, was chosen as the oxidant and the method described in section 2 was used for oxidation. The PS particles in the floc after oxidation, and their morphology did not change, and they were clearer compared with that before oxidation, and their contrast with the background was more obvious, which was easy to observe and count. After counting, there were 10,649 PS particles in the floc, while the total number of PS particles in the solution before coagulation was 11,980, so the removal rate of microplastics by coagulation under this condition was 88.9%. The previous study showed that the removal rate of UV_{254} was 99.5% and the removal rate of TOC was 66.0%, both of which are dissolved organic indexes; microplastics, as large molecules and small particles insoluble organic matter, could reach 88.9% removal rate in the coagulation process, which is already a high level. That take the appropriate amount of coagulant and mixing intensity, is effective in removing microplastic particles in drinking water.

4. Conclusion

Microplastic pollution is prevalent in China's water environment, with higher levels of pollution in developed coastal areas than in the western plateau region, higher levels of pollution in freshwater systems than in coastal waters, and an unsatisfactory situation in the southwestern region. Microplastic pollution is an important research aspect in water treatment and coagulation processes. The study of the characteristics and detection methods of microplastics, the effect of microplastic particles on flocs in the flocculation process, and the removal rate of microplastics in the sludge mixing process can provide a reference for the actual control parameters of the water treatment and flocculation process, so as to control the microplastic pollution and improve the water quality.

The changes in floc morphology during flocculation can be visualized by computer simulation of the collision and sintering process of particles, and the changes in particle morphology and sintering results during flocculation can be explored by changing the initial conditions of flocculation. In-depth analysis of the mechanism of different influencing factors (e.g., flocculant type, stirring speed, reaction time, etc.) on the microplastic removal rate during flocculation can help to reveal the flocculation mechanism and optimize the treatment process.

In the discussion section, the specific influence of each factor on the microplastic removal rate can be further analyzed in depth and optimization suggestions can be made. For example, by optimizing the type of flocculant, adjusting the stirring rate and reaction time, can the removal effect of microplastics be further improved. In the conclusion part, it should be more prospective, pointing out the limitations of the study and the future research direction, such as how to further improve the removal rate, or explore more efficient treatment methods, in order to promote the development of microplastic pollution control technology.

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