



OPEN Distribution characteristics of microplastics in wastewater treatment plants in mega cities—the case study of Chengdu City

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With the increasingly serious problem of microplastic pollution, wastewater treatment plants (WWTPs) have attracted much attention as a key node for intercepting microplastics into the natural environment. In this study, the distribution characteristics of microplastics and their removal efficacy in wastewater treatment processes were systematically investigated in four typical wastewater treatment plants in Chengdu. The abundance, particle size, morphology and composition of microplastics in the influent and sludge were quantitatively analyzed by improving the sampling device and combining body-view microscopy and Fourier transform infrared (FTIR) spectroscopy. The results showed that the microplastic concentration in the influent water showed significant spatial heterogeneity, with microplastic concentrations ranging from 177 to 517 particles/L. The Chengdu Cooperative Plant, which is located in the central business district, had the highest percentage of fibers at 38.5%, while the PET fibers of the Hedong Plant, which is located in the textile industrial area of Jianyang City, had a percentage of 15%. In this study, the removal rate is defined as the difference in microplastic concentrations between influent and effluent divided by the influent concentration. The removal rate of > 1 mm microplastics in the primary treatment reached 85%–92%, but the removal rate of < 0.2 mm ultrafine particles was only 37%–45%, and the percentage of < 0.1 mm particles in the secondary treatment increased inversely, revealing the fragmentation effect caused by hydraulic shear. Microplastics in sludge were dominated by PP and PE, accounting for 76%, and the percentage of small particles (< 0.2 mm) in secondary sludge was significantly higher, with a maximum of 58%. The study showed that the overall removal rate of Chengdu wastewater treatment plant reached 89.3%–94.6%, but the residual small particle size and high density microplastics (e.g., PET fibers) in the effluent still constituted a potential ecological risk. It is recommended to optimize the process for industrial source characteristics and to strengthen the control of sludge microplastics. This study provides a scientific basis for microplastics control and process upgrading in mega-city wastewater treatment plants.

Keywords Microplastics, Wastewater treatment plants, Removal rate, Particle size distribution, Mega cities

Microplastic pollution has emerged as a focal point of concern amidst the escalating spectrum of global environmental issues. Microplastics typically denote plastic fragments and particles with dimensions under 5 millimeters, originating from diverse sources such as the degradation of everyday plastic products, industrial emissions, and microbeads in personal care items, among others¹. These diminutive particles infiltrate the natural environment through multiple pathways, including surface runoff and atmospheric deposition. Subsequently, they accumulate in terrestrial, aquatic, and other ecosystems, posing significant and enduring threats to ecological integrity and biological health². Research indicates that microplastics are inadvertently ingested by numerous aquatic organisms, impairing their digestive functions, growth, and development, and in severe cases, resulting in mortality³. Furthermore, microplastics possess the capacity to adsorb environmental contaminants such as heavy metals and organic pollutants, thereby magnifying their detrimental impacts as they traverse the food chain. This amplification jeopardizes the equilibrium of ecosystems and endangers human health. The pervasive nature of microplastic pollution transcends geographical boundaries, with their presence detected in oceans, rivers, lakes, and other water bodies worldwide. Consequently, it represents a pressing global

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environmental challenge that necessitates comprehensive investigation and the implementation of effective mitigation strategies^{4–7}.

As an important part of urban infrastructure, wastewater treatment plants play a key role in addressing environmental pollution, particularly in megacities where their significance is increasingly prominent⁸. Megacities are often densely populated, industrially developed, and produce vast amounts of wastewater. Wastewater treatment plants are responsible for collecting and treating this wastewater, reducing pollutant discharges, and protecting the environmental quality of receiving waters⁹. During wastewater treatment, microplastics also enter the treatment system. Consequently, wastewater treatment plants serve as crucial barriers for intercepting and removing microplastics, preventing them from flowing into natural water bodies in large quantities¹⁰. Understanding the distribution characteristics of microplastics in various segments of wastewater treatment plants is essential for optimizing treatment processes, improving microplastic removal efficiency, and assessing their potential impact on the surrounding environment^{11–13}.

Among many cities, Chengdu, a megacity in southwest China, holds significant research value¹⁴. On one hand, Chengdu has a large population, rapid economic development, and frequent industrial and domestic activities, resulting in the generation of wastewater with complex compositions and high emissions^{15,16}. This diversity in wastewater sources and types leads to a relatively varied presence of microplastics, making Chengdu representative of the general situation in megacities. On the other hand, Chengdu has increased its investment and efforts in ecological environmental protection in recent years¹⁷ emphasizing the construction and upgrading of wastewater treatment facilities. Its wastewater treatment plant exhibits a certain degree of sophistication and representativeness in terms of operation modes and treatment processes¹⁸. By studying the distribution characteristics of microplastics in Chengdu's wastewater treatment plant, the results can provide a scientific basis for improving wastewater treatment and microplastic control strategies in Chengdu, while also offering valuable insights for other megacities facing similar challenges.

In summary, this study focuses on Chengdu's wastewater treatment plant (WWTP), employing an improved wastewater sampling device and utilizing stereomicroscopy and Fourier transform infrared (FTIR) spectroscopy to explore methods for extracting and identifying microplastics in the effluent and sludge of the WWTP. It conducts a characterization and distribution study of microplastic pollutants in the plant's inflow, outflow, and sludge, analyzes the WWTP's role in reducing the discharge of microplastic pollutants in the city, and estimates the amount of microplastics entering the rivers flowing through the city via its effluent. The study provides valuable references for wastewater treatment practices and environmental protection strategies in megacities.

Methods

Overview of the study area

As one of the important national central cities in China, Chengdu has a resident population of more than 21 million, an urbanization rate of more than 75%, and an economy that has long ranked among the top ten in China. With a large volume of industrial and domestic wastewater discharged, the construction and upgrading of wastewater treatment capacity occupies a central position in urban environmental management. Currently, Chengdu city has more than 30 wastewater treatment plants with a combined capacity of more than 5 million tons/day, some of which have adopted advanced deep treatment processes, which is one of the representatives of domestic wastewater treatment technology level. In this study, four wastewater treatment plants in Chengdu were selected as representative cases, which was principally informed by four methodological considerations, including geographic representativity with service area heterogeneity, diversity of wastewater treatment technologies, scalability of treatment infrastructure; and holistic contaminant profile analysis incorporating source variability. The geographical distribution of the four sewage treatment plants in Chengdu is shown in Fig. 1.

Chengdu Cooperation Sewage Treatment Plant (Wastewater treatment plant I): located in Chengdu PI Du District, Deyuan Town, the service area includes PI tube town, Hongguang Town, cooperation town, high-tech west west area, such as areas, service area of about 51.9 square kilometers, the service population of nearly 300,000 people, the total design scale of 100,000 tons/day, put into operation in July 2012, the treatment process for coarse and fine grating + aeration and sand + membrane grid + flocculation and sedimentation + modified Bardenpho-MBR process. This sewage treatment station mainly serves rural and small-town communities with sparse populations. The wastewater sources are mainly domestic sewage from rural and small-town areas, and the pollutant load is relatively low.

Unity Town Sewage Treatment Plant (Wastewater treatment plant II): located in unity town flower hedge village 1 community, by the former unity town sewage treatment plant, unity town second sewage treatment plant, nine dao yan end sewage treatment station merger upgrading and transformation, covers an area of about 34.24 acres, serving a population of about 150,000 people, collection of sewage range is mainly for the unity of the township, the community of shidi, bao hua village, shiqiao village, changhe village and other areas, the design capacity of 34,000 m³/d, sewage treatment adopts AAO + high density sedimentation tank + deep bed denitrification filter + ultraviolet disinfection process, the remaining sludge treatment adopts centrifugal dewatering process, the treated tail water is discharged to Mou Zhuyan through pipeline, and the dewatered sludge is entrusted to the third-party with sludge disposal qualification unit for treatment. This sewage treatment station covers the airport and the surrounding high-density commercial and industrial areas. Wastewater mainly comes from transportation, commercial and industrial activities, with a wide variety of pollutants and a high load.

Airport Phase I Wastewater Treatment Plant (Wastewater treatment plant III): put into operation in 2007, located in Jiang'an Village, Xihanggang Street Office, Shuangliu District, Chengdu City, with a treatment capacity of 49,900 m³/d, adopting the wastewater treatment process of "AAO + mechanical filtration + activated coke adsorption + deep-bed filtration tank". The wastewater treatment plant mainly serves suburban areas and satellite

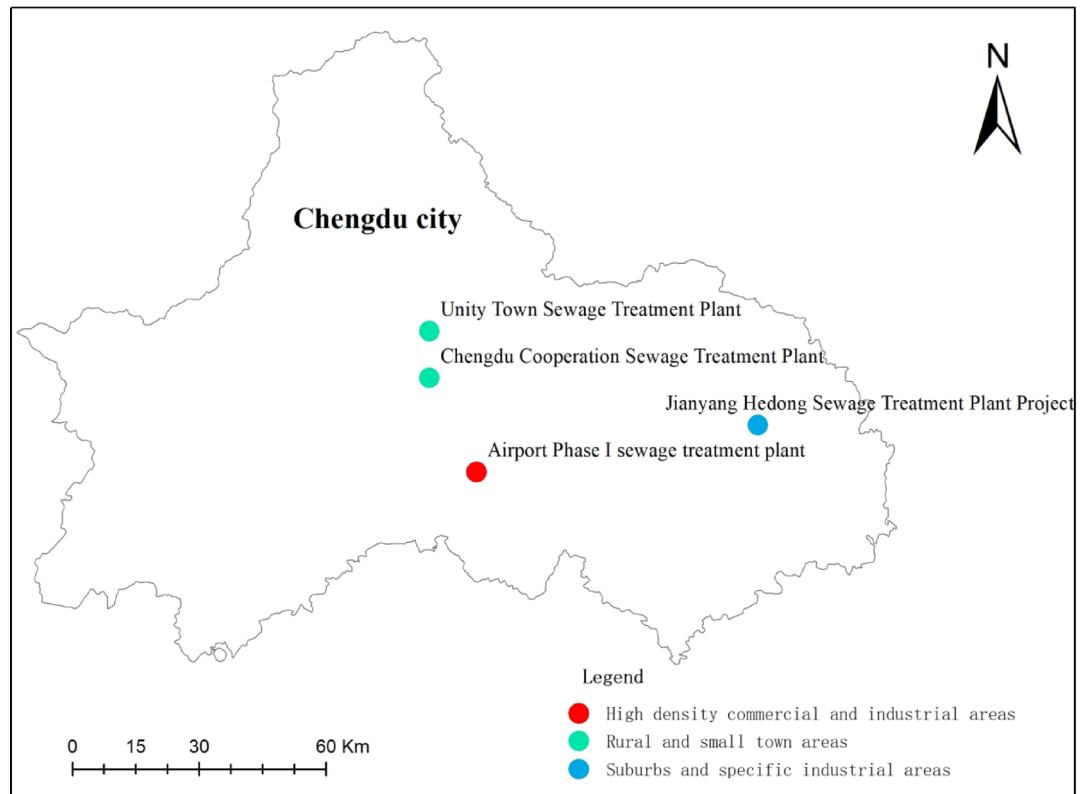


Fig. 1. The geographical distribution map of four sewage treatment plants in Chengdu.

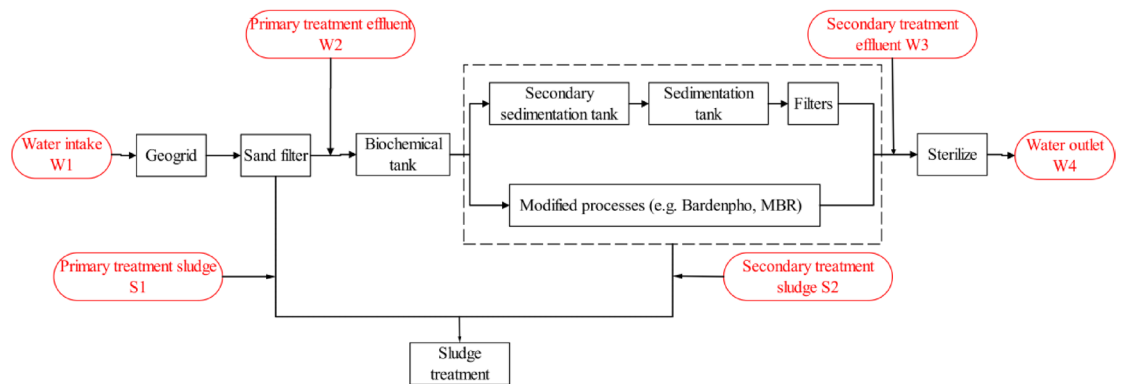


Fig. 2. Wastewater treatment process flow diagram and sampling points.

cities, especially specialized industrial zones such as high-end equipment manufacturing parks. The wastewater includes both domestic sewage and industrial wastewater, with high pollutant loads and complex compositions.

Hedong Sewage Treatment Plant Project in Jianyang City (Wastewater treatment plant IV): located in Changchun Village, Pingquan Town, Jianyang City, with a total design scale of 99,600 m³/d, the sewage treatment scope is the domestic sewage in Hedong Area, Dongcheng New Area, Dongxi Area, Fuxingba Area, and High-end Equipment Industrial Park, adopting the sewage treatment process of “coarse grille + inlet elevation + fine grille aeration and sand sedimentation tank + AAO biochemical tank + secondary sedimentation tank + high-efficiency sedimentation tank + deep-bed filter + ultraviolet disinfection”. Sedimentation tank + deep bed filter + ultraviolet disinfection” sewage treatment process. The wastewater treatment plant covers the western urban area of Chengdu and several surrounding towns, which have a high level of urbanization. The wastewater is characterized by complex mixtures, including domestic sewage from urban areas, commercial wastewater, agricultural runoff from rural areas, and some local industrial wastewater.

Integrating the above four wastewater treatment plants process flow, their processes all cover the four basic units of pretreatment, biochemical treatment, deep treatment and sludge treatment, the specific process flow diagram and sampling points are shown in Fig. 2. Referring to the five key characteristics of wastewater treatment

plants listed in the study by Ayankoya Yemi Ayankunle et al.¹⁹ the key parameters of the four wastewater treatment plants in this study are shown in Table 1.

Sample collection and processing

Sample collection

In this study, water and sludge samples were collected from four wastewater treatment plants (WWTPs) at different treatment stages (Fig. 1). For each plant, four water samples were collected: influent (W1), primary effluent (W2), secondary effluent (W3), and final effluent (W4). Two sludge samples were collected: primary sludge (S1) and secondary sludge (S2). In total, 16 water samples and 8 sludge samples were obtained.

At each water sampling point, 3 L of raw influent or effluent was collected in pre-cleaned stainless steel containers. For sludge, ~40 g of fresh sludge was collected and immediately sealed in glass jars. All samples were kept at 4 °C and transported to the laboratory within 48 h. To reduce variability, three replicates were collected per sampling point, and the average value was used for analysis. Stainless steel or glass instruments were used throughout sampling to prevent plastic contamination, and field blanks were included to check for potential airborne contamination²⁰.

Sample handling

Samples were collected from surface water using plankton nets, filtered, and rinsed with deionized water before being immediately stored in glass containers. They were then transported to the laboratory for analysis²⁰. A grading sieve system consisting of 4-mesh, 5-mesh, 6-mesh, 10-mesh, 18-mesh, 35-mesh, 75-mesh, and 150-mesh sieves was used to separate the particles into nine size segments: <0.1 mm, 0.1–0.2 mm, 0.2–0.5 mm, 0.5–1 mm, 1–2 mm, 2–3 mm, 3–4 mm, 4–5 mm, and >5 mm. The glass containers in which the rinse solution was kept were rinsed at least 3 times and then the rinse solution was transferred to a dispensing sieve. Due to the limitations of the sieve aperture, particles smaller than 0.1 mm were excluded from the pretreatment, while particles larger than 5 mm were too large to be considered microplastics (≤ 5 mm) and were manually rejected. In this study, density separation combined with wet peroxide digestion was employed²¹. Sodium chloride and sodium iodide were used as the density separation salt solutions to remove inorganic substances, based on the density of the salt solution and the type of digestant. Hydrogen peroxide and nitric acid were utilized as the digestion reagents to eliminate organic substances. In the collection and treatment process for microplastic particles, for the water samples collected, all samples in this experiment were filtered using a glass fiber filter with a pore size of 45 μm (Whatman GF/C). Firstly, saturated salt solution was poured into the beaker and mixed with the samples, ultrasonicated for 2 min, stirred the mixture for 30 min, settled for 24 h, collected the supernatant, and the above steps were repeated three times^{22,23}. According to the actual situation of the organic content in the sample, 30–50 mL of 30% hydrogen peroxide (H_2O_2) and 65% nitric acid were added to the dried sample in the ratio of 1:1, and then placed in the environment at a temperature of 60 °C for 72 h. The aim was to effectively remove the organic components in the sample through this chemical digestion process, so as to reduce the interference of the sample with the subsequent analysis of microplastics. After the degradation of the organic matter, a density separation method was used to further separate and enrich the microplastics. The specific procedure involves adding saturated sodium chloride (NaCl) or sodium iodide (NaI) solution (containing residues) to the digested mixture (containing residues) after digestion, until the total volume reaches approximately 500 mL. Ultrasonic stirring is performed for 5 min to ensure thorough dispersion of particles, followed by magnetic stirring for 30 min. The mixture is then transferred to a modified separation funnel and left to stand for 24 h. Collect the floating microplastics from the upper layer. The remaining residue is mixed again with saturated NaCl or saturated NaI solution, and the flotation steps are repeated twice, totaling three flotation cycles, to maximize microplastic recovery efficiency. The collected supernatant is vacuum-filtered through a 45 μm stainless steel filter (or glass fiber filter, Whatman GF/C). The filter is rinsed multiple times with ultra-pure water to completely remove residual salts. The filter containing microplastics is carefully placed in a clean glass petri dish and stored at room temperature in the dark to dry. Specifically, sodium chloride (NaCl) and sodium iodide (NaI) high concentration salt solution was selected, and the difference in density between microplastics and other impurities was utilized to float microplastic particles in the upper layer of the solution by means of solution flotation, thus realizing the separation from other impurities and obtaining relatively pure microplastic particles.

As for the treatment of sludge samples, the overall process is roughly similar to that of water samples. In this study, four sludge samples were obtained from four wastewater treatment plants, and each sludge sample was divided into four equal parts, and 10 g was taken from each part, which were digested by different density

Feature	plant I	plant II	plant III	plant IV
Population Equivalents	300,000	150,000	150,000	210,000
Flow rate(m^3/day)	100,000	34,000	49,900	99,600
Mechanical Treatment Process	Grid + aeration sand settling + flocculation sedimentation	Grid + aeration sand settling + flocculation sedimentation	Coarse screen + fine screen aeration grit chamber	Coarse screen + fine screen aeration grit chamber
Biological Treatment Process	Improved Bardenpho-MBR	AAO + ultraviolet disinfection	A/A/O	A/A/O + ultraviolet disinfection

Table 1. Key parameters of four wastewater treatment plant.

separation + wet peroxidation methods. Considering the density of salt solution and the type of digestant, sodium chloride and sodium iodide were used as the density separation salt solution in this experiment; hydrogen peroxide and nitric acid were used as the digestion reagents. Firstly, the saturated salt solution was poured into the beaker and the sample for mixing, ultrasonication was performed for 2 min, the mixture was stirred for 30 min, and settled for 24 h. The supernatant was collected, and the above steps were repeated for three times; the digestion solution was added into the supernatant after density separation, and the mixture was placed in the reaction under the condition of 60 °C for 72 h, in order to fully digest the organic matter in the extract; the digested sample was filtered with a 0.45 µm microporous glass fiber filter membrane (GF/C, Whatman). The separation and digestion conditions of microplastics in four groups of sludge were shown in Table 2.

Under a stereomicroscope, particles on the dried filter were systematically observed. All suspected microplastic particles were completely picked out. Individual particles were carefully transferred using tweezers onto gold plates or diamond compression cells, with precise location marking. The quantity, position, and microscopic morphology of each particle were recorded and matched with corresponding data tables. Polymer identification was conducted using Fourier-transform infrared spectroscopy (FTIR). For small particles (< 500 µm), micro-FTIR (Nicolet iN10) was used to locate particles under the microscope; background spectra were scanned first in adjacent areas, then the particles themselves were scanned with background subtraction applied. For larger particles, conventional FTIR (Nicolet iS10) with diamond compression cell attachments was used in transmission or attenuated total reflection (ATR) mode. The obtained infrared spectra were matched against a built-in polymer spectral library using OMNIC software. Particles with a Hit Quality Index (HQI) of 70% or above were identified as plastic polymers. Polymer types, spectra, and matching similarity were recorded.

Quality control

To ensure the accuracy and reliability of experimental results, a series of strict quality control measures were implemented throughout sampling and experimental processes to minimize laboratory contamination risks and improve data credibility. To avoid potential laboratory contamination affecting results, blank controls were set at every experimental stage. Blank controls contained no target samples and were processed under identical experimental conditions, including sample treatment and instrument operation, to accurately detect and quantify any external contamination. By comparing with experimental sample results, it was ensured that laboratory contamination did not influence final data quality. All experimental instruments (beakers, pipettes, filters, etc.) were made of non-plastic materials (e.g., glass or stainless steel) to avoid interference from microplastic particles possibly present in plastic materials. Before each experiment, all instruments and materials underwent strict cleaning procedures: washing with deionized water and suitable detergents, followed by three rinses with ultrapure water to ensure no residues. Cleaned instruments were dried in a dedicated clean environment to prevent cross-contamination. During the experiments, sample and environmental conditions were monitored and checked multiple times to ensure stability and controllability. Laboratory temperature, humidity, and air quality were continuously recorded and maintained within suitable ranges to prevent external contamination or degradation of microplastics. Sample exposure time during handling and storage was strictly controlled to avoid compositional changes or contamination from prolonged air exposure or improper storage. During microplastic extraction, high-power microscopes were used repeatedly to check samples, ensuring no visible contaminants remained throughout extraction and analysis. After each processing step, microscopic inspection was performed to confirm absence of contamination from the environment, operators, or instruments. All suspicious particles were recorded for further verification and exclusion. To guarantee data reliability and consistency, multiple replicate experiments were conducted. Each sample group was processed at different times and by different experimenters to ensure reproducibility and stability of results. Differences among experimental outcomes were compared to further validate method reliability and stability. Statistical methods were applied during data processing and analysis to identify possible sources of experimental error and perform corrections. All data were rigorously cleaned and preprocessed to exclude outliers or errors before analysis, ensuring authenticity and accuracy of results. To ensure measurement precision, all key analytical instruments (such as FTIR spectrometers and microscopes) were regularly calibrated and maintained. Instrument performance was confirmed by comparison with standard samples, minimizing potential impacts from instrument errors.

Microplastic detection and classification methods

In this study, microplastics were systematically detected and classified in the collected water and sludge samples, using a combination of stereomicroscopic observation and Fourier transform infrared (FTIR) spectroscopic analysis to ensure the accuracy and completeness of the classification. According to the morphology, microplastics were classified into four categories: fibers, spheres, fragments, and particles; while the colors covered black, yellow, red, blue, green, white, and transparent, and the corresponding statistical analyses were carried out. It is worth noting that, when using the spectral library for sample identification, it is particularly

Experimental group	Separation reagent	Elimination reagents	Temperature/°C
1	NaCl	30% H ₂ O ₂	60
2	NaCl	30% H ₂ O ₂ + 65% Nitric acid	60
3	NaI	30% H ₂ O ₂	60
4	NaI	30% H ₂ O ₂ + 65% Nitric acid	60

Table 2. Summary of microplastic separation and extraction conditions in sludge.

important to construct a spectral library that is closer to the characteristics of environmental samples, given that the samples in the library are idealized pure samples, while the actual environmental samples are often different from them. In addition, by identifying the functional groups in the samples, their chemical structures can be further confirmed.

Results and discussion

Spatial distribution and disparity analysis

From Fig. 3, the abundance of influent microplastics in the four sewage treatment plants in Chengdu showed significant spatial heterogeneity. The total amount of microplastics in the influent water of Chengdu Cooperative WWTP was the highest (517 particles/L), far exceeding that of the other three plants (332 particles/L in the first phase of the aerial harbor, 410 particles/L in Hedong of Jianyang city, and 177 particles/L in Tuanjie town). This difference is closely related to the functional characteristics of each plant's service area: the Chengdu Cooperative Wastewater Treatment Plant covers the central city's commercial-intensive area and receives a large amount of synthetic fiber-containing domestic wastewater (e.g., washing wastewater, clothing fiber shedding), which results in a high percentage of fiber microplastics (38.5%); whereas the service area of the Hedong Wastewater Treatment Plant in Jianyang City contains the Textile Industrial Park, which has a significantly higher percentage of PET in the effluent (15%), which may be related to the high density polyester fiber contained in industrial wastewater. In addition, the higher total amount of microplastics (332 particles/L) in the influent of the Airport Phase I WWTP may be due to its proximity to a logistics hub, which receives more packaging material fragments (e.g., film, pellets) and other microplastics of industrial origin.

From the sludge microplastic content (unit: particles/kg) in Fig. 4, the microplastic content in primary sludge of Chengdu Cooperative Wastewater Treatment Plant amounted to 677 particles/kg, and the secondary sludge rose to 808 particles/kg, indicating a high microplastic retention efficiency in the treatment process, but also reflecting a huge input load to the service area. In contrast, the lower microplastic content in the sludge of the Tuanjie Town WWTP (215 particles/kg in primary sludge) is consistent with the lower population density and less industrial activity in its service area.

In terms of removal rates, the spatial differences among the four sewage treatment plants in Chengdu were also significant. Chengdu Cooperative WWTP had the highest removal rate of 94.6%, and its primary and secondary treatment removal rates were 62.67% and 52.85%, respectively, which was closely related to the measures taken by Chengdu Cooperative WWTP to enhance the removal rate by optimizing the design of sedimentation tanks (e.g., inclined plate sedimentation) and extending the aeration time. The removal rates of Aviation Harbor Phase I and Tuanjie Town Wastewater Treatment Plant were 91.6% and 91%, respectively, and that of Hedong Wastewater Treatment Plant in Jianyang City was the lowest of the four at 89.3, which indicates that urban wastewater treatment plants play an important role in reducing urban microplastic pollutants from entering into rivers and groundwater. However, the higher microplastic residual of 44 particles/L in the effluent of Hedong Wastewater Treatment Plant in Jianyang City may be related to the design of its treatment process, and the shorter retention time of the secondary treatment in Hedong Plant in Jianyang City may have resulted in the insufficient retention of small particle-size microplastics (<0.1 mm).

Particle size distribution characteristics of microplastics

The current size classification of microplastics is mainly based on two technical paths: physical screening and microanalysis. In the physical screening method, microplastic particles are classified by passing them through sieves with different aperture sizes, but the method has significant limitations due to the diversity of particle

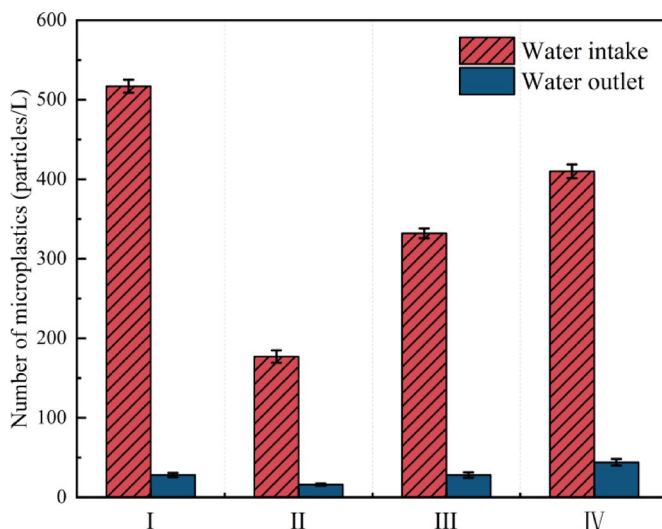


Fig. 3. Microplastic content of inlet/outlet water. Experimental conditions: 30% hydrogen peroxide (H_2O_2) and 65% nitric acid were added to the dried samples in the ratio of 1:1 in a volume of 30-50mL.

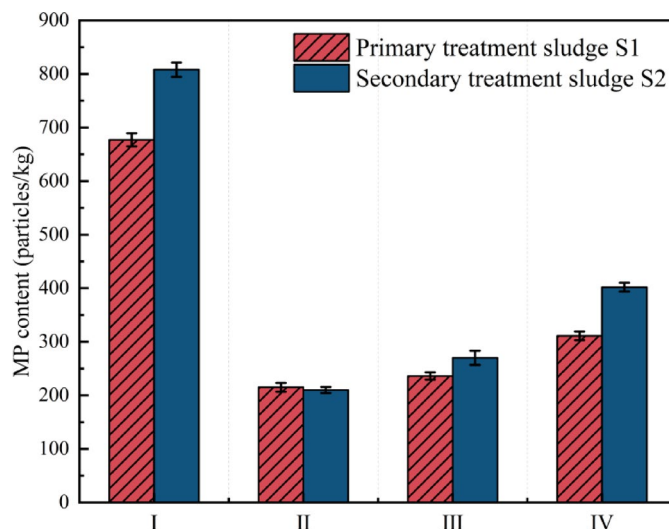


Fig. 4. Sludge microplastic content. Experimental conditions: Each sludge sample was equally divided into four portions, 10 g of each portion was taken and dissolved by different density separation + wet peroxide method (Table 2).

morphology²⁴. In contrast, microscopic imaging techniques enable more precise morphological measurements and have thus become the dominant analytical tool. Research data showed that wastewater treatment systems have a significant particle size-selective retention effect on microplastics. The proportion of large particles above 500 μm in influent samples can be up to 70%^{24,25}, whereas more than 90% of microplastics in effluent samples have particle sizes smaller than 500 μm , with about 60% of them concentrated below 100 μm ^{26,27}. It is worth noting that there is a systematic bias of sampling mesh specifications on the detection results, and larger mesh sizes (e.g., 500 μm) may lead to a large number of missed detections of small-sized particles²⁴ which suggests the need to strictly standardize the specification parameters of the sampling equipment in the study to ensure the comparability of the data.

The particle size of microplastics was categorized into <0.1, 0.1–0.2, 0.2–0.5, 0.5–1, 1–2, 2–3, 3–4, 4–5 mm, >5 mm, and the particle size distribution of microplastics in the sludge from different wastewater treatment plants is shown in Fig. 5. From Fig. 5, it can be seen that the particle size distribution of microplastics in the sewage treatment plant in Chengdu presents a significant “small particle size dominant” feature. The test data show that the proportion of microplastics <0.5 mm in the influent water is 65%–78%, of which the proportion of <0.1 mm is 21%–34%. Fiber microplastics in the very small particle size section (<0.1 mm) enrichment phenomenon is prominent, such as unity town wastewater treatment plant influent fiber <0.1 mm accounted for 42%, may be related to the release of ultrafine synthetic fibers in the washing wastewater²⁸. The particulate microplastics, on the other hand, were mostly distributed in the range of 0.2–0.5 mm (48%–55%), which might originate from cosmetic abrasive particles or mechanical abrasion of plastic products²⁹.

In terms of the removal mechanism of the wastewater treatment process, there are significant limitations in the retention efficacy of conventional processes for small particle size microplastics³⁰. Primary treatment units (e.g., grids and sedimentation tanks) show high removal efficiencies (85%–92%) for large-size microplastics (>1 mm), with a typical case showing that the percentage of >1 mm particles in the influent of the Chengdu Cooperative Plant was reduced from 12 to 2% after treatment. However, for ultrafine particles <0.2 mm, the removal rate could only reach 37%–45%. Although the secondary biological treatment further removed some residual particles, the effluent test results showed that the percentage of <0.1 mm particle size increased from 21 to 29% in the influent. This phenomenon reveals the existence of a dual mechanism of action in the biological treatment unit: the hydraulic shear action of the activated sludge method may lead to the fragmentation of large particles, while the microbial flocs have a limited adsorption capacity for nanoscale particles, forming a paradox of selective removal of particle sizes³¹. The ecological risk may be exacerbated by the high residual rate of small particle size microplastics (especially <0.1 mm). These particles can easily penetrate biofilm barriers, be ingested by aquatic organisms and enriched along the food chain³² and have a large specific surface area, making them more susceptible to the adsorption of heavy metals and organic pollutants (e.g., polycyclic aromatic hydrocarbons (PAHs))³³. Existing processes need to be targeted to enhance membrane filtration (e.g., 0.1 μm ultrafiltration) or electroflocculation to improve retention of small-sized microplastics³⁴.

The sludge particle size distribution characteristics further verified the differences in the retention mechanisms of different treatment units. Primary sludge was dominated by 0.2–0.5 mm particle size (52%–61%), while the percentage of <0.2 mm particle size in secondary sludge was significantly increased. In the case of the Aeroport Phase I plant, for example, the percentage of <0.2 mm particles in secondary sludge reached 58%, which was 23% points higher than that of primary sludge. This change in particle size distribution may be related to the erosion of the plastic surface by extracellular enzymes secreted by microorganisms during biodegradation, and

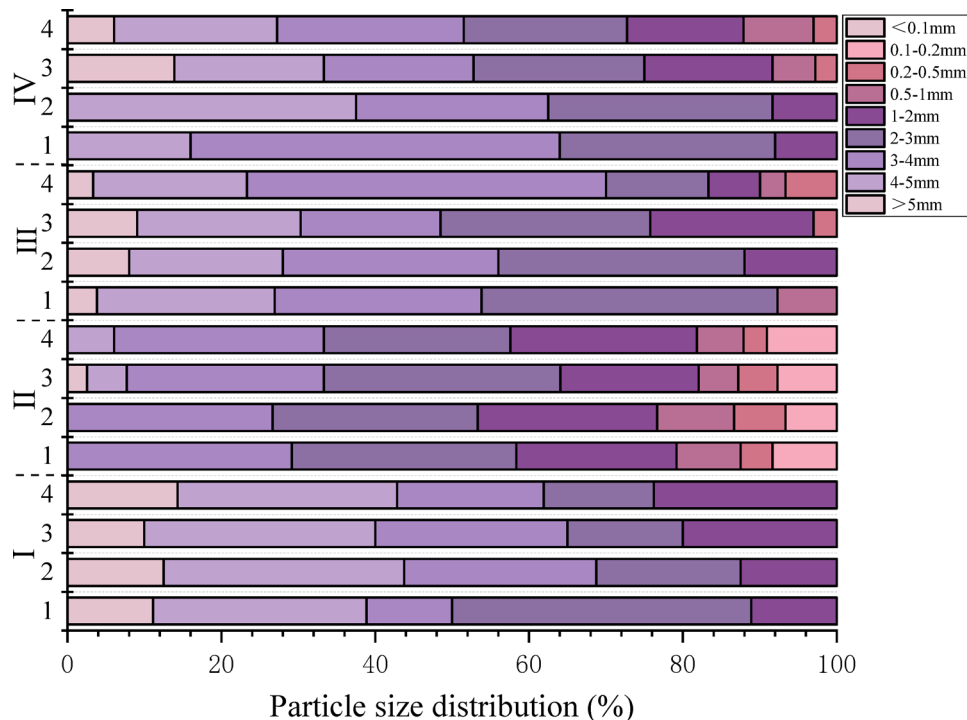


Fig. 5. Distribution of microplastic particle size at each stage of each wastewater treatment plant.

the synergistic effect of mechanical shear and biochemical degradation accelerated the particle fragmentation process³⁵.

It is worth noting that the choice of reagents for density separation had a significant effect on the detection results³⁶. It was found that the amount of PVC (density 1.3~1.5 g/cm³) detected in the samples treated with NaCl solution (density 1.19 g/cm³) was 19%~27% lower than that of NaI solution (density 1.85 g/cm³). This suggests that conventional assays may underestimate the actual loading of high-density, small-size microplastics due to incomplete density separation, and that the detection bias is particularly significant for plastic types with densities greater than 1.2 g/cm³. This methodological issue suggests the need to optimize the assay process to ensure the integrity of the particle size distribution data.

Types and compositional characteristics of microplastics

To address the challenges of quantitative analysis of microplastics in sludge matrices, a color feature-based sorting - spectroscopy coupled detection system was established in this study. According to the polymer color correlation principle proposed by Corradini et al. (2019), primary classification of microplastics was first achieved by visual sorting. Subsequently, Fourier transform micro-infrared spectroscopy (μ -FTIR) was used for precise identification: after transferring the target particles from the filter membrane to the diamond pressure cell using a YYS-110E biomicroscope, background correction, scanning of the characterized area and spectral acquisition were accomplished in a NICOLET spectrometer system (detection limit 50 μ m). By comparing the standard polymer spectral library, we focused on the analysis of the spectral peak characteristics of the main plastic components, such as polyethylene (PE), polypropylene (PP), polystyrene (PS), etc., and finally realized the analysis of the composition of microplastics in the sludge samples.

The study of microplastic pollution characteristics and treatment efficacy in Chengdu wastewater treatment plant (Fig. 6) shows that the distribution of its type presents the remarkable characteristic of “fiber dominant, film residual”. Detection data show that the influent microplastics in the form of fibers (43%) and particles (35%) as the main form, film (12%) and flakes (10%) accounted for a relatively low percentage. The treatment process shows an obvious type-selective removal pattern: fiber type is easy to be intercepted by the grid and precipitation adsorption, the removal rate of 94.6–97.8%; and film type due to the high flexibility, easy to penetrate the filtration unit, the residual rate of the effluent in the water (such as unity town wastewater treatment plant film accounted for 31%). To further illustrate the morphological diversity of microplastics observed in the samples, representative microscopic images are provided in Figure 7, which show four typical categories: fibrous, flaky, filmic, and granular microplastics.

Micro-infrared analysis revealed the spatial differentiation characteristics of microplastic polymers in sludge. As shown in Fig. 8, the standard spectrum of pure polymer showed that polyethylene (PE) showed characteristic C-H bond stretching vibration peaks at 2925 cm⁻¹ and 2857 cm⁻¹, and 1470 cm⁻¹, 1380 cm⁻¹ and 720 cm⁻¹ corresponds to its crystalline phase vibration mode; the characteristic absorption of polypropylene (PP) is concentrated in the intervals of 1165 cm⁻¹, 1156 cm⁻¹ (C-C skeleton vibration) and 998–895 cm⁻¹ (CH₂ rocking vibration). Based on the analysis of the characteristic spectral peaks, six major components of

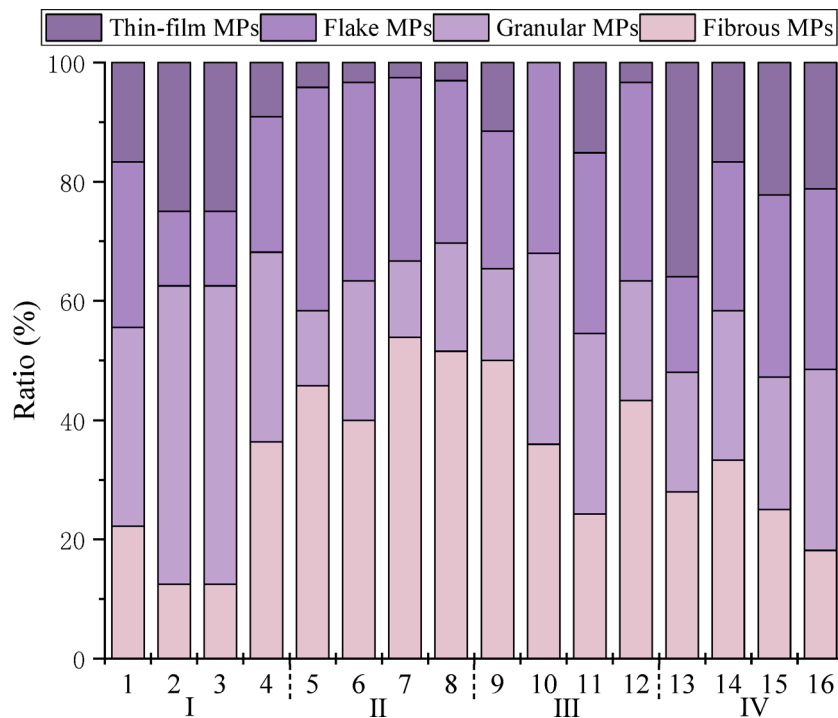


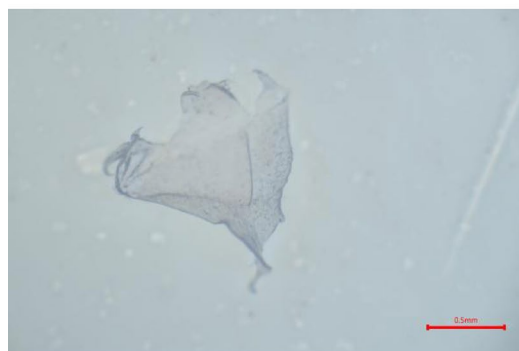
Fig. 6. Percentage of microplastic types by site.



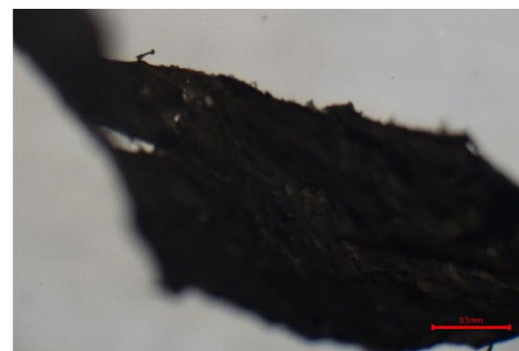
(a)



(b)



(c)



(d)

Fig. 7. Micrographs of four microplastics: (a) fibrous microplastics, (b) flaky microplastics, (c) filmic microplastics, and (d) granular microplastics.

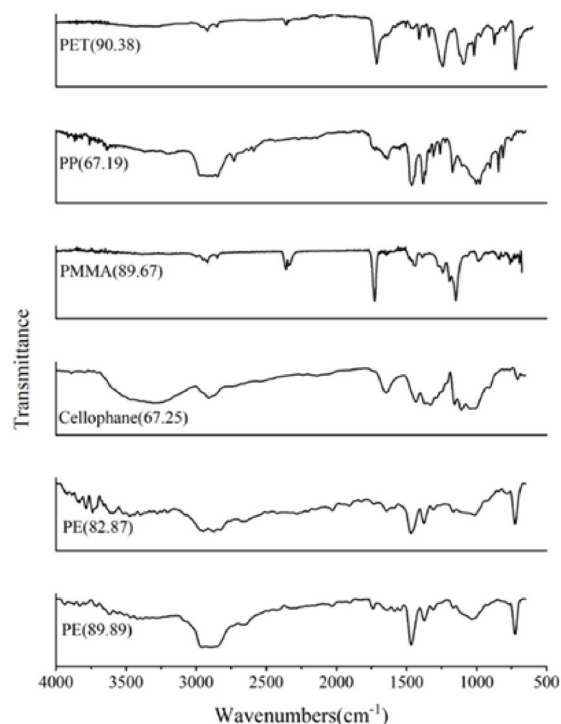


Fig. 8. FTIR spectra of microplastic pure polymers.

polypropylene (PP), polyethylene (PE), polyester (PET), ethylene-ethylene acrylate copolymer (EEA), polyvinyl chloride (PVC), and polystyrene (PS) were identified in this study, and their compositional ratios were highly consistent with the data from the study on the composition of microplastics in municipal sludge by Chen³⁷ (2021) and others. On the composition of microplastics in urban sludge. The main components of microplastics in sludge were PP and PE, which accounted for 76% of the total, which is consistent with the global pollution characteristics of municipal wastewater plants. Figure 9 demonstrates the fraction of microplastic components at each site, and it is noteworthy that polyethylene terephthalate (PET) accounted for 15% of the effluent from the Hedong Wastewater Treatment Plant in the city of Jianyang, which was significantly higher than that from other plants (average 5%). Combined with the characteristics of the plant's service area containing a textile industrial park, it is assumed that the industrial input of polyester fibers (PET-based) is the main cause. In addition, the detection of 3% polyvinyl chloride (PVC) in the sludge of the Aeroport Phase I wastewater treatment plant, which may have originated from fragments of logistic packaging materials, and the non-detection of PVC in the other plants correlates with the lack of efficiency of extraction of high-density plastics by the NaCl density separation method described in the previous section.

In addition, different types and compositions of microplastics have differentiated ecological risks. PET and PVC are difficult to degrade in the environment due to their high chemical stability, while PE is prone to adsorb organic pollutants and become a carrier of toxic substances. Of particular concern are the PET fibers remaining in the effluent of the Hedong plant in Jianyang City, which may enter the agricultural ecosystem through reclaimed water irrigation. Based on this, it is recommended that the treatment process be optimized for the characteristics of industrial source inputs: additional membrane filtration or chemical flocculation units should be installed in the downstream plant station of the textile industrial park to strengthen the retention efficiency of high-density, difficult-to-biodegrade microplastics.

Efficiency and influencing factors

Table 3 shows the removal rates for each WWTP at different treatment stages, with overall system removal rates ranging from 89.3 to 94.6%, but with significant differences in the removal contributions of different treatment stages and microplastic types. The primary treatment unit (physical interception and sedimentation) was the main removal link, contributing 58–62% of the total removal. The Chengdu Cooperative Wastewater Treatment Plant performed particularly well, with 81% fiber removal by primary treatment (199 particles/L of fiber in influent → 31 particles/L in primary treatment effluent), which was significantly higher than the other plants (68% on average). This difference is attributed to the plant's additional cyclone sedimentation tank and inclined plate sedimentation device, which strengthens the interception efficacy of fiber-based pollutants. The secondary biological treatment unit further removed 39–56% of microplastics, but less than 15% of ultrafine particles < 0.2 mm, suggesting inherent limitations in the ability of the biosorption mechanism to capture small-size contaminants.

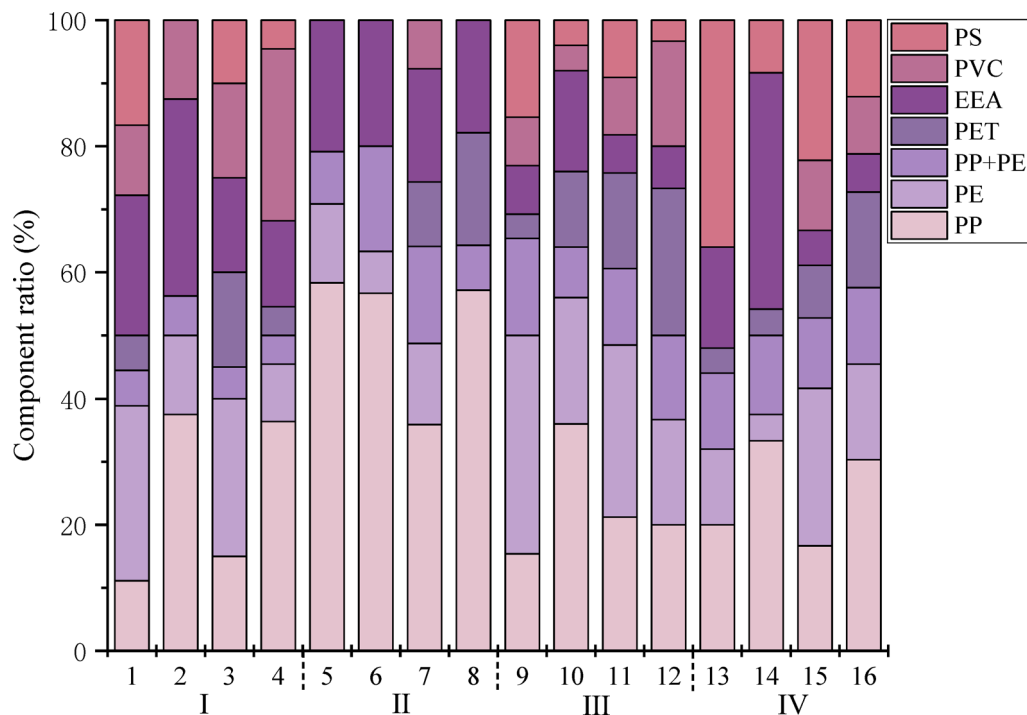


Fig. 9. Proportion of microplastic fractions by site.

Water treatment plant	Primary treatment rate	Secondary treatment rate	Total treatment rate
Chengdu Cooperative Wastewater Treatment Plant	62.67%	52.85%	94.6%
Unity Township Wastewater Treatment Plant	62.71%	39.39%	91%
Aviation Harbor Phase I Sewage Treatment Plant	57.53%	49.65%	91.6%
Hedong Sewage Treatment Plant, Jianyang City	58.54%	55.88%	89.3%

Table 3. Removal rates at various WWTPs for different treatment stages.

In addition, it was found that the treatment process parameters showed significant correlation with the removal efficiency. The hydraulic retention time (HRT) was positively correlated with the microplastic removal rate ($R^2=0.76$), and the HRT of secondary treatment in the first phase of the Aiprot wastewater treatment plant was 8 h, and the residual amount of effluent was 28 particles/L, while the HRT of the Hedong plant in Jianyang City was only 6 h, and the residual amount of effluent rose to 44 particles/L. The increase of the sludge reflux ratio (30%~50%) could enhance the retention efficiency, but at the same time exacerbate the risk of microplastic enrichment in the sludge. Although the increase of sludge return ratio (30%~50%) can enhance the retention efficiency, it also aggravates the risk of microplastic enrichment in sludge. For example, the secondary sludge at the Chengdu plant contained 808 particles/kg dry sludge, a 37% increase from the primary sludge. Although the existing process has achieved high removal efficiency, the residual small particle size and high density microplastics (e.g., PET fibers) in the effluent still pose an ecological threat. Meanwhile, microplastics enriched in the sludge (annual average 1.1~2.3 tons/plant) may trigger secondary pollution if used directly for agricultural purposes. In comparison with the world, the average removal rate in Chengdu (92%) is higher than that in Paris (82%) and Sydney (85%), but lower than that in Singapore (97%, using three-stage membrane filtration). It is recommended that mega-cities use a combination of “primary enhanced treatment + membrane bioreactors” in conjunction with a cost-benefit analysis, with a focus on improving the retention of high-density, non-degradable microplastics.

Conclusion

- (1) The microplastic input load showed significant spatial heterogeneity, with significant differences in the abundance of microplastics in the influent water of Chengdu wastewater treatment plant (177~517 particles/L), and the spatial distribution characteristics were closely related to regional functions. The influent microplastics in areas with intensive industrial activities (e.g., Hedong Factory Service Textile Industrial Park in Jianyang City) were dominated by PET fibers (15%), while the central commercial area (e.g., Chengdu Cooperative Factory) had 38.5% of fibers due to domestic wastewater input. This spatial heterogeneity reflects the decisive influence of the functional zoning of the city on the sources and types of microplastics.

- (2) The distribution of microplastics in the wastewater treatment process was characterized by significant particle size differentiation. In the primary treatment unit (physical interception), the removal rate of large particles > 1 mm reached 85%–92%, but the removal rate of ultrafine particles < 0.2 mm was only 37%–45%; in the secondary biological treatment, the percentage of microplastics < 0.1 mm rose from 21% in the influent to 29% in the effluent, revealing the fragmentation effect caused by hydraulic shear. The particle size distribution of microplastics in sludge further verified this pattern: primary sludge was dominated by 0.2–0.5 mm (52%–61%), and the percentage of < 0.2 mm in secondary sludge increased significantly (up to 58%), indicating that the biological process accelerated the enrichment of small-sized particles.
- (3) Microplastic morphology and compositional distribution characteristics are environmentally indicative. Fibers (43%) and particles (35%) dominated the influent, while films (12%) had an increased residual rate in the effluent (up to 31%) due to their high flexibility and ease of penetration into the process unit. PP and PE accounted for 76% of the sludge, consistent with global municipal wastewater plant characteristics, but the effluent from the Hedong plant in Jianyang City was unusually enriched in PET fibers (15%), pointing directly to textile industry pollutant inputs. High-density microplastics (e.g., PVC) may be underestimated due to limitations of traditional density separation methods (NaCl solution), and methodological optimization is needed to refine distribution data.

Data availability

The data are available upon reasonable request from the corresponding author.

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Conceptualization, Y.Z. and T.H.; methodology, J.R., B.W. and X.H.; validation, J.R.; formal analysis, J.R., B.W. and Y.D.; investigation, B.W. and X.H.; resources, Y.Z.; data curation, B.W. and Y.D.; writing—original draft preparation, J.R., X.H. and Y.D.; writing—review and editing, Y.Z. and T.H.; visualization, B.W.; supervision, Y.Z.; project administration, T.H.; funding acquisition, T.H. All authors reviewed the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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