



## Tracing The Fate of Microplastics in a Wastewater Pond System: Abundance, Characteristics, and Environmental Risk Assessment

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### Article Info

**Article type:**

Research Article

**Article history:**

Received: 30 November 2025

Revised: 18 February 2026

Accepted: 01 April 2026

**Keywords:***Microplastics; Wastewater treatment plant;**Polymer composition;**Removal efficiency; Iran*

### ABSTRACT

Microplastics (MPs) have emerged as a critical environmental pollutant due to their persistence, mobility, and potential toxicity. This study assessed the abundance, characteristics, polymer composition, and removal efficiency of MPs in the Zabol municipal wastewater treatment plant, which operates via a stabilization pond system. Influent and effluent samples were collected during the winter of 2024 and summer of 2025 and analyzed for size, morphology, color, and polymer type using stereomicroscopy and Fourier transform infrared (FTIR) spectroscopy. The abundance of the MPs ranged from  $17.53 \pm 0.64$  MPs/L (1 mm, winter) to  $962.7 \pm 12.86$  MPs/L (45–425  $\mu\text{m}$ , summer) in the influent and from  $5.86 \pm 0.25$  MPs/L (1 mm, summer) to  $26.24 \pm 2.09$  MPs/L (1 mm, winter) in the effluent. Film-shaped MPs dominated in both seasons, representing 54%–61% of the influent and 51%–65% of the effluent particles, while golden and transparent colors prevailed. FTIR analysis identified polyethylene (PE) and polypropylene (PP) as the major polymers, followed by polyamide (PA), polyethylene terephthalate (PET), polyvinyl chloride (PVC), and polystyrene (PS). The overall removal efficiencies were 95.57% in winter and 97.48% in summer. Although the polymer hazard index (PHI) and pollution load index (PLI) significantly decreased after treatment ( $P < 0.05$ ), the effluent samples still exhibited a moderate hazard (Level II) due to the presence of persistent dense polymers such as PVC, PS, and PU. These findings indicate that while stabilization ponds achieve substantial MP removal, fine and buoyant particles—particularly PE and PP—can escape into the environment, emphasizing the need for advanced tertiary treatment and improved source control strategies in arid regions.

**Cite this article:** Miri, M., Pakzad Toocheai, S., & Khandan Barani, H. (2026). Tracing The Fate of Microplastics in a Wastewater Pond System: Abundance, Characteristics, and Environmental Risk Assessment. *Pollution*, 12(2), 574-585. <https://doi.org/10.22059/poll.2026.407330.3217>



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Publisher: The University of Tehran Press.

DOI: <https://doi.org/10.22059/poll.2026.407330.3217>

## INTRODUCTION

Microplastics (MPs), defined as plastic particles with diameters less than 5mm, have emerged as ubiquitous environmental pollutants due to widespread plastic use and improper disposal (Saini & Sharma, 2022). Microplastics have been identified across all environmental compartments, including marine, freshwater, terrestrial, and atmospheric ecosystems (Khan A, & Bose, 2024). These particles originate from diverse sources, including the breakdown of larger plastic products, industrial processes, synthetic textiles, cosmetics, personal care products, tire wear, and household sewage (Khan & Bose, 2024; Jolaosho et al., 2025). These particles are categorized into two main types based on their origin. Primary MPs are intentionally manufactured at microscopic dimensions and are commonly used as microbeads in cosmetic products such as facial scrubs and personal care items (Cedro & Cleary, 2015; Dąbrowska

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et al., 2022). Secondary microplastics result from the degradation of larger plastic materials through environmental processes, including UV radiation exposure, mechanical stress from ocean waves, wind action, and weathering (Cedro & Cleary, 2015).

Microplastic pollution in the environment is caused by their ability to transport various toxic contaminants through various sorption mechanisms. These particles absorb persistent organic pollutants, heavy metals, antibiotics, polychlorinated biphenyls (PCBs), pesticides, and polycyclic aromatic hydrocarbons (PAHs) from the environment (Rafa et al., 2023; Weis & Alava, 2023). The physicochemical properties of microplastics, including size, structure, and functional groups, influence their pollutant absorption capacity (Rafa et al., 2023). These particles can release absorbed chemicals into the tissues of organisms that consume them, causing harmful effects on development, physiology, gene expression, and behavior (Weis & Alava, 2023).

Although wastewater treatment plants (WWTPs) are major sources of MP pollution, they are not specifically designed to remove them (Nafea et al., 2024; Komorowska-Kaufman & Marciniak, 2024). Millions of MP particles with varying characteristics enter WWTPs from household and industrial sources through sewage systems (Reddy & Nair, 2022; Nafea et al., 2024). The large volumes of effluent discharged by WWTPs result in significant MP releases despite the fact that they can achieve removal efficiencies exceeding 90-98% through primary, secondary, and tertiary treatment processes (Reddy & Nair, 2022; Nafea et al., 2024; Komorowska-Kaufman & Marciniak, 2024).

The Zabol treatment plant was built in 1996 to collect and treat wastewater from 130,000 water and wastewater subscribers and was put into operation in 2008 with the implementation of 160 kilometers of collection network and 9 pumping stations (Badiei et al., 2017). In this treatment plant, the treatment is a stabilization pond type, and raw wastewater is transferred to the stabilization ponds after aeration. Wastewater stabilization ponds (WSPs) represent one of the simplest and most cost-effective biological treatment technologies, particularly suitable for developing countries with warm climates (Shammas et al., 2009; Kadri et al., 2017). These systems operate without chemicals or advanced equipment, relying instead on natural physicochemical and biological processes including algal-bacterial symbiosis (Mahapatra et al., 2022). Waste stabilization ponds use natural purification processes to treat sewage and organic wastewater through symbiotic relationships between algae and bacteria (Lakshminarayana 1975). These systems facilitate organic matter oxidation through complex bacterial consortiums and nutrient assimilation by photoautotrophic microalgae (Rahman et al., 2012). The effluent is a valuable water resource for irrigation, particularly in arid and semi-arid regions where natural water sources are limited and nutrient-depleted (Hosetti & Frost, 1995).

The Sistan region in southeastern Iran was historically an agriculturally dependent area centered around the Hamoun Wetland. Before recent droughts (1999-2005), agriculture formed the economic foundation, with approximately 55% of the rural population directly dependent on agricultural activities for income and employment (Ebrahimzadeh & Esmaelnejad, 2013). Wheat is a major agricultural crop that plays a key role in the local economy (Shahraki et al., 2018). The region also supported livestock activities, with the Hamoun Wetland providing environmental support for cattle rearing, including the native Sistani breed (Amiri et al., 2022). Due to recent droughts in Zabol city and the dependence of most residents of the region on agricultural income, treated urban wastewater has been allocated for irrigation of nearby wheat fields due to the limited water resources in the city. Around the Zabol urban wastewater treatment plant, there are 190 hectares of agricultural land under wheat cultivation that are over 20 years old and are irrigated with raw and treated wastewater (Badiei et al., 2017). Despite the growing concern about the occurrence of microplastics in various environmental media, limited information is available on their abundance and characteristics in wastewater treatment plant influents and effluents. The influence of different treatment processes on removal efficiency

remains unclear. Therefore, this study aims to fill this knowledge gap by examining the occurrence, characteristics, and removal of MPs in the Zabol wastewater treatment plant and determining relevant pollution indices associated with these particles.

## MATERIAL AND METHODS

The study area is Zabol city, located in the Hamun-Hirmand watershed, Sistan Province (30° 5' N–31° 28' N and 61° 15' E–61° 50' E) in the southeastern part of Iran, close to the border of Iran with Pakistan and Afghanistan. The Zabol synoptic station exhibited an arid climate with an average precipitation of 55 mm/year and evaporation exceeding 4000 mm/year. The Zabol Wastewater Treatment Plant (Zabol WWTP) is located in the southwestern part of Zabol. The Zabol WWTP treatment system operates in three sequential stages: (i) aeration lagoons, (ii) stabilization ponds, and (iii) chlorination. The system comprised three stabilization ponds until the winter of 2024; however, two additional lagoons were constructed and integrated into the stabilization pond stage in the spring of 2025 to enhance the hydraulic retention time and treatment efficiency. Accordingly, wastewater samples were collected from both the plant's influent (raw wastewater) and effluent (treated wastewater) during the winter of 2024 and summer of 2025 to evaluate seasonal variations in treatment performance and microplastic characteristics.

The influent samples were collected from the primary wastewater after passing through a coarse screen through a strainer. Three 5-L and three 10-L samples were taken from the influent and effluent, respectively, using a stainless steel sampler. All sampling tools were washed thoroughly and rinsed with filtered tap water before wrapping in aluminum foil. To avoid background contamination, wastewater samples were collected from every location and stored in 2.5 L glass bottles. The collected wastewater samples were gravity filtered by consecutively passing through three stainless steel mesh screens with sizes 45  $\mu\text{m}$ , 425  $\mu\text{m}$ , and 1 mm. The sample bottles were washed three times with Milli-Q water to ensure that all samples were adequately transferred onto the stainless steel mesh screen. A 500 mL beaker was used to collect the laboratory data of all mesh screen materials after washing three times. Beakers were wrapped in aluminum foil and dried for 12 h in a 60 °C drying oven. Wet peroxide oxidation (WPO) was employed to eliminate organic matter from the samples before microplastic analysis. The Fenton reagent acted as a catalyst to enhance the oxidative degradation efficiency of hydrogen peroxide ( $\text{H}_2\text{O}_2$ ). This advanced oxidation technique is widely recognized for its efficacy in isolating MPs from complex wastewater matrices. Each sample was transferred into a clean glass beaker, and 20–50 mL of a 30%  $\text{H}_2\text{O}_2$  solution was added, followed by an equal volume of 0.05 M  $\text{FeSO}_4$  solution. The mixture was then heated to 60 °C under continuous stirring using a Hot Plate & Magnetic Stirrer (HS15-26P, Korea) until the visible organic material was completely digested and allowed to react overnight. After the WPO step, density separation was conducted by adding 20 mL of NaCl ( $\rho = 1.2 \text{ g/mL}$ ) to each sample. The mixture was allowed to stand overnight to ensure complete phase separation and flotation of microplastic particles for subsequent collection and analysis (Meng et al., 2023). The supernatant was vacuum filtered using glass microfiber filter paper with a 1.2  $\mu\text{m}$  pore size (Whatman GF/C). The filters were placed in a clean, dry glass Petri dish at room temperature for analysis (Al-Amri et al., 2024).

Microplastic particles retained on the filter papers were visually examined using a KERN OZL 466 stereo microscope with a magnification range of 7 $\times$ –45 $\times$ . Suspected microplastic particles were categorized and labeled according to their physical characteristics, including shape (fiber, film, fragment, and foam), size class (1 mm, 425  $\mu\text{m}$ , and 45  $\mu\text{m}$ ), and color (blue, white, black, pink, purple, or green). Representative particles were further photographed using a KERN ODC 825 digital camera (5.1 MP resolution) for document morphological details. After careful identification, the representative particles could be identified by Fourier Transform Infrared

(FTIR) spectroscopy (Bruker TENSOR 27, Germany) to determine polymer composition. Spectra were recorded in transmission mode within a wavenumber range of 4000–500  $\text{cm}^{-1}$ , using a resolution of 4  $\text{cm}^{-1}$  and 32 scans per sample to ensure precise polymer identification.

Strict quality control measures were implemented throughout all experimental and analytical procedures to minimize the risk of microplastic contamination. During sample collection, preparation, and analysis, laboratory personnel wore 100% cotton clothing, clean laboratory coats, and nitrile gloves. Whenever possible, the use of plastic materials was avoided; instead, glass and stainless-steel apparatus were employed. All glassware was rinsed with deionized water before use, sealed with aluminum foil during analysis, and washed weekly with acid to eliminate potential residues. The laboratory benches and fume hoods were thoroughly cleaned with 70% ethanol before and after each experimental session. Before sample processing, all filters and glass Petri dishes were examined under a stereomicroscope to ensure the absence of pre-existing fibers or particles. To evaluate laboratory contamination, procedural blanks were included in every analytical batch, and no microplastic contamination was detected in the laboratory environment.

The total hazard score, polymer risk index (PHI), and pollution load index (PLI) were determined for each sampling site within the investigated wastewater treatment plants. The hazard score assigned to each polymer type identified at each location was based on the classification proposed by Lithner et al. (2011). The total hazard score was obtained by summing the individual polymer risk values. The polymer risk index (HI), as described by Ranjani et al. (2021), accounts for the chemical toxicity of different microplastic polymers to the ecological environment and was calculated using Equation (1):

$$PHI = \sum P_n \times S_n$$

where ‘ $P_n$ ’ represents the percentage of each polymer type extracted from a given sampling point, and ‘ $S_n$ ’ denotes the corresponding hazard score for that polymer, as reported by Lithner et al. (2011).

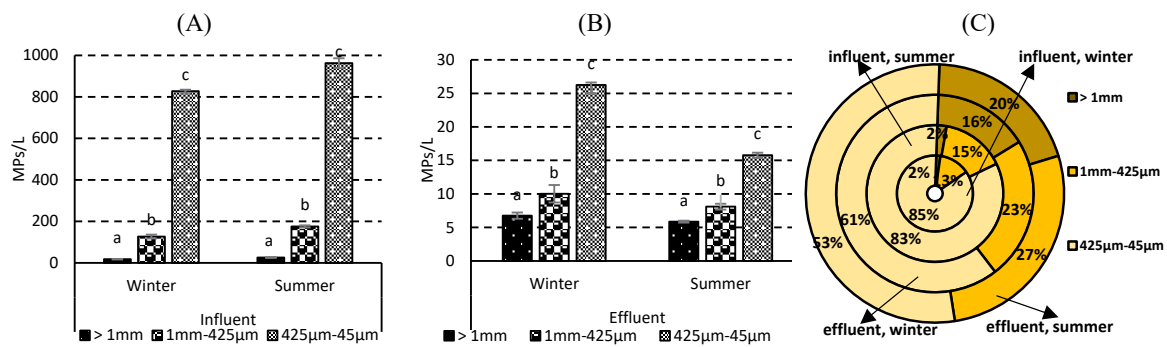
The pollution load index (PLI), introduced by Tomlinson et al. (1980) for assessing heavy metal contamination, was also applied in this study and defined according to Equation (2).

$$PLI = \frac{C_i}{C_o}$$

The ‘ $C_i$ ’ and ‘ $C_o$ ’ are MP concentrations at each sampling point and the minimum at the examined treatment plant, respectively. The risk index (H) was used to calculate the danger levels; these levels ranged from (I) (<10 slightly toxic) to (II) (10-100 moderately toxic) to (III) (100-1000 highly toxic), and (IV) (>1000 extremely toxic). The MP pollution load index (PLI) pollution coefficients were used to determine the three pollution categories (<1 slightly pollution, 1–2 moderate pollution, >2 highly pollution). This approach is based on the Global Harmonized System of Classification and Labeling of Chemicals (GHS) (Lithner et al., 2011; Meng et al., 2023).

The abundance of MPs in each sample was determined by relating the total number of particles collected to the corresponding sampled water volume. Results were expressed as mean  $\pm$  SE and reported in microplastics per liter (MPs/L). The removal efficiency of the microplastics in each wastewater treatment plant was assessed by comparing the MP concentrations in the influent and effluent samples. The removal efficiency was calculated using the following equation (Huang et al., 2023):

$$\text{Removal efficiency} = (E_{\text{influent}} - E_{\text{effluent}}) / E_{\text{influent}} \times 100\%$$



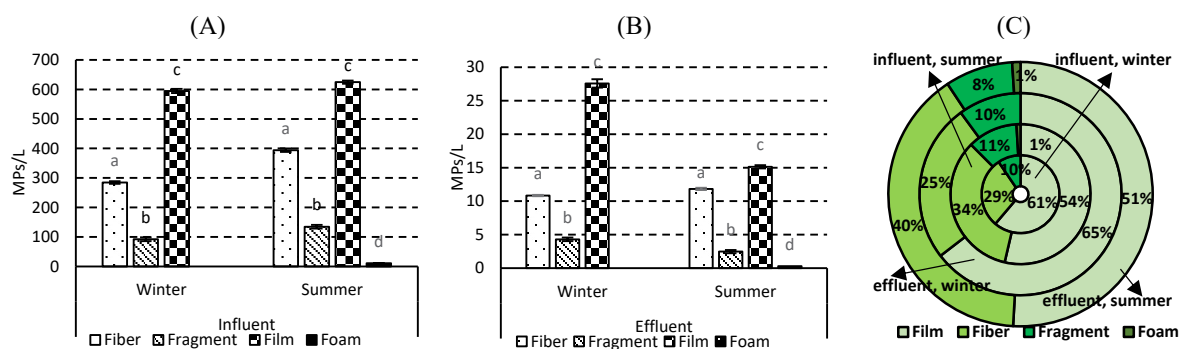
**Fig. 1.** Average comparison of MP abundance by size fractions during winter and summer: (A) influent; (B) effluent; (C) relative percentage distribution of MPs. Different letters indicate statistically significant differences ( $p < 0.05$ )

All the data, including the MPs counted by optical microscopy and characterized by FTIR, PHI, and PLI indices, were tested for normality using the Shapiro-Wilk test and for variance homogeneity using the Levene test. One-way analysis of variance (ANOVA) followed by Tukey's post hoc test was performed to evaluate statistical differences among datasets, with the significance level set at  $p < 0.05$ . The t-test is a parametric statistical test that compares the mean of two statistical groups (MP abundance between winter and summer). All statistical analyses and graphical representations were conducted using SPSS and Microsoft Excel software.

## RESULTS AND DISCUSSION

Statistical analysis revealed that the abundance of MPs in the influent of the Zabol WWTP varied markedly, ranging from  $17.53 \pm 0.64$  MPs/L (1 mm particles, winter) to  $962.7 \pm 12.86$  MPs/L (45–425 µm particles, summer) (Fig. 1 (A)). By contrast, the effluent exhibited markedly lower abundance, ranging from a minimum of  $5.86 \pm 0.25$  MPs/L (1 mm particles) in summer to a maximum of  $26.24 \pm 2.09$  MPs/L (45–425 µm particles) in winter (Fig. 1 (B)). Analysis of variance (ANOVA) confirmed a statistically significant difference ( $P < 0.05$ ) in the MP abundance among the particle size fractions in both the influent and effluent samples (Fig. 1). Microplastics within the 45–425 µm range constituted the dominant size fraction, accounting for over 80% of the total MPs in the raw wastewater and 53% and 61% of the total particles in the treated effluent during summer and winter, respectively (Fig. 1 (C)). No significant seasonal difference ( $P > 0.05$ ) was observed in the overall size distribution of the MPs, indicating consistent particle size behavior across different sampling periods (Fig. 1). The reported MP abundance in WWTP effluents varied between 0.13 and 297 MPs/L, with the highest frequency found in microplastic particles smaller than 425 µm, (Hidayaturrahman & Lee, 2019; Raju et al., 2020; Pittura et al., 2021; Takdastan et al., 2021; Kim et al., 2022; Sharifi et al., 2023), which is consistent with the present study. Therefore, conventional wastewater treatment processes are less effective in retaining fine particles because these low-density particles tend to remain suspended and are more likely to pass through subsequent treatment stages due to their lower settling velocity and flotation behavior (Carr et al., 2016; Talvitie et al., 2017).

The morphological analysis of the MPs in the influent of the Zabol WWTP showed that film-shaped particles exhibited the highest abundance ( $624.6 \pm 10.74$  MPs/L) during summer, whereas foam-like particles represented the lowest proportion ( $10.76 \pm 1.48$  MPs/L), with no foams detected in winter (Fig. 2 (A)). In the effluent, films again dominated, with abundance ranging from  $15.13 \pm 0.41$  MPs/L in summer to  $27.58 \pm 1.08$  MPs/L in winter, while foams exhibited the lowest abundance ( $0.30 \pm 0.02$  MPs/L) in summer (Fig. 2 (B)). Analysis of variance (ANOVA) revealed a statistically significant difference ( $P < 0.05$ ) among the different

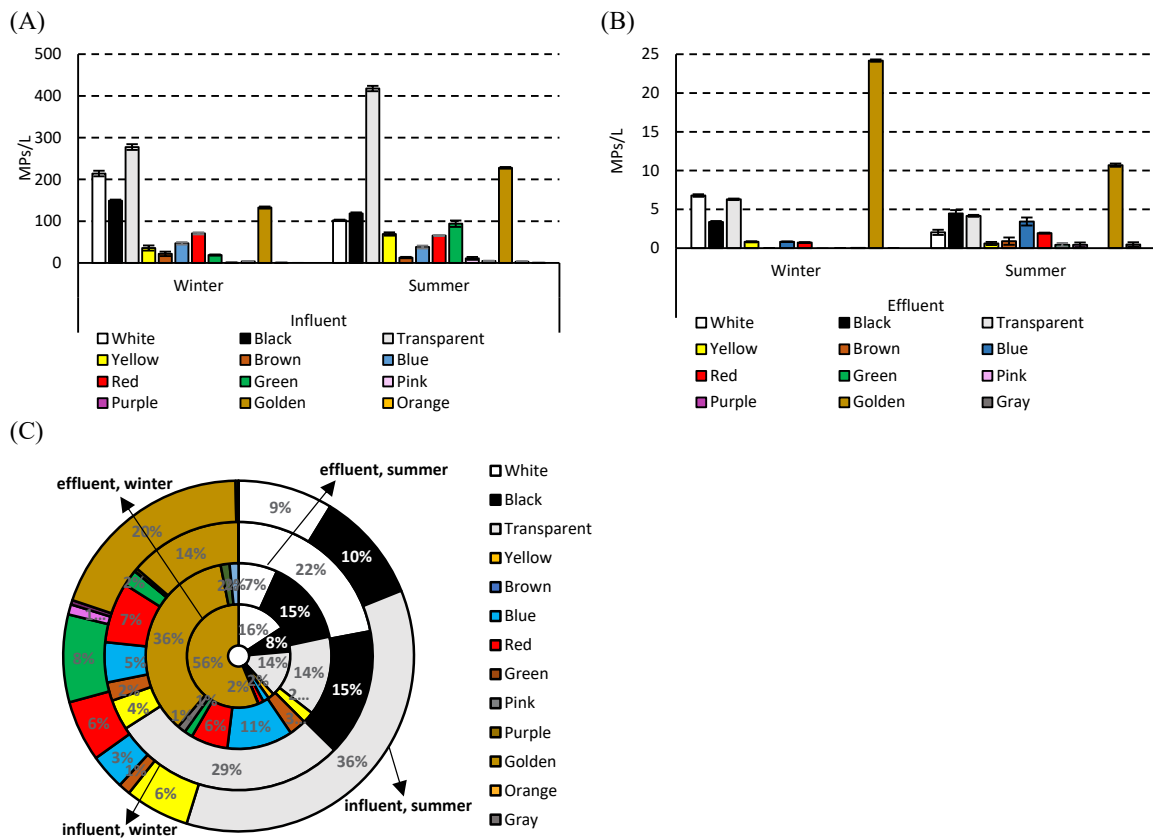


**Fig. 2.** Mean comparison of MP abundance by shape during winter and summer: (A) influent; (B) effluent; (C) relative percentage distribution of MPs. Different letters indicate statistically significant differences ( $p < 0.05$ )

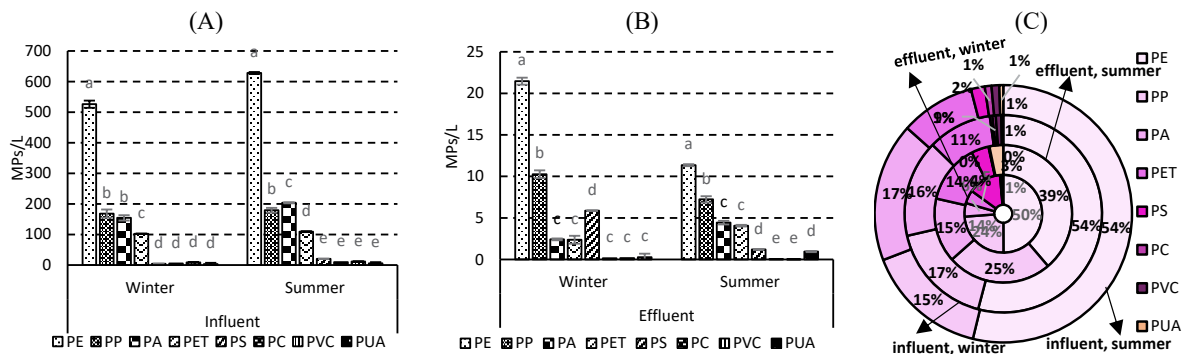
morphological categories of MPs in both the influent and effluent samples. Across both seasons, the overall morphological distribution followed the order film > fiber > fragment > foam (Fig. 2). Films accounted for 61% and 54% of the total MPs in the influent during winter and summer, respectively, and 65% and 51% in the effluent during the same seasons (Fig. 2 (C)). Consequently, film-shaped microplastics were identified as the dominant morphological type in both the influent and effluent samples. No significant seasonal variation ( $P > 0.05$ ) was observed among the morphological categories (Fig. 2). This pattern is consistent with previous findings in which films are the dominant morphology in urban wastewater treatment plants (Magni et al., 2018; Pittura et al., 2021; Wei et al., 2023), while in most studies, fibers and fragments were the dominant form of microplastics at the influent and effluent of wastewater treatment plants (Takdastan et al., 2021; Oveisy et al., 2022; Maw et al., 2022; Üstün et al., 2022). Most films are produced when plastic bags and packaging products break (Nizzetto et al., 2016). Exposure of these materials to sunlight, high temperature, and mechanical stress may lead to their rapid fragmentation and transport to wastewater treatment plants (Pittura et al., 2021).

The color distribution of the MPs in the influent and effluent of the Zabol WWTP is presented in Fig. 3. In the influent, transparent particles were the most dominant, with abundance ranging from  $417.66 \pm 11.15$  MPs/L in summer to  $277.5 \pm 10.95$  MPs/L in winter (Fig. 3 (A)). In contrast, golden MPs were the most abundant in the effluent, ranging from  $10.7 \pm 0.36$  MPs/L in summer to  $24.18 \pm 0.25$  MPs/L in winter (Fig. 3 (B)). The diversity of the MP colors was higher in summer than in winter, suggesting seasonal variation in the source inputs and plastic degradation patterns. The predominant MP colors observed in both influent and effluent samples included transparent, golden, white, black, yellow, blue, red, and green (Fig. 3 (C)). As the results show, transparent MPs in the treatment plant influent were more than other common colors by 36% and 29% in summer and winter, respectively, which followed Huang et al. (2023), Takdastan et al. (2021), and Oveisy et al. (2022). While golden MPs were the most dominant color in the treatment plant effluent by 56% and 36% in winter and summer, respectively. The results show that the removal rate of golden MPs is higher in summer than winter, despite their increased abundance at the influent, which could be due to the increase in the number of lagoons in this season. The results of this study indicate that there is more color diversity in summer, which could be due to the increased consumption of packaged foods and beverages.

FTIR spectroscopy identified various polymer types in the influent samples. Polyethylene (PE) was the predominant polymer detected in both the influent and effluent, with abundance of  $627.86 \pm 5.8$  MPs/L and  $11.35 \pm 0.2$  MPs/L, respectively, during the summer season (Fig. 4). The other detected polymers followed the order: polypropylene (PP) > polyamide (PA) > polyethylene terephthalate (PET) > polyvinyl chloride (PVC) > polystyrene (PS) > polycarbonate (PC) > polyurethane (PU) (Fig. 4 (C)). Statistical comparison of the mean polymer



**Fig. 3.** Mean comparison of MP abundance by color during winter and summer: (A) influent; (B) effluent; (C) relative percentage distribution of MPs

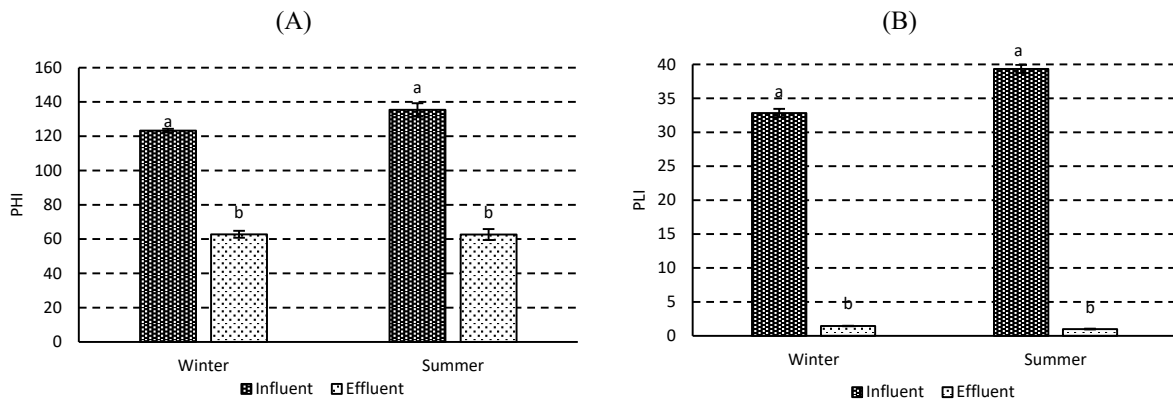


**Fig. 4.** Mean comparison of MP abundance by type of polymer during winter and summer: (A) influent; (B) effluent; (C) relative percentage distribution of MPs. Different letters indicate statistically significant differences ( $p < 0.05$ )

composition between the influent and effluent samples indicated a significant difference ( $P < 0.05$ ), indicating the selective removal of certain polymer types during treatment. However, no significant seasonal variation ( $P > 0.05$ ) was observed in the polymer distribution patterns across the sampling periods (Fig. 4 (A and B)). The predominance of PE and PP is consistent with global findings from wastewater treatment plants (WWTPs), reflecting their extensive use in personal care products, single-use packaging, shopping bags, and disposable food containers (Carr et al., 2016; Takdastan et al., 2021; Huang et al., 2023). These polymers are lightweight, chemically stable, and less dense than water ( $\rho < 1 \text{ g cm}^{-3}$ ), which facilitates their buoyancy and

**Table 1.** The removal efficiency of samples in the studied Zabol WWTP

Season	Sampling point	Abundance (MPs/L)	Removal efficiency (%)
Winter	Influent	971.96 ± 25.52	95.57
	Effluent	42.98 ± 0.62	
Summer	Influent	1166.96 ± 24.98	97.48
	Effluent	29.30 ± 0.25	

**Fig. 5.** Comparison of average PHI and PLI indices during winter and summer: (A) influent; (B) effluent. Different letters indicate statistically significant differences ( $p < 0.05$ )

persistence during wastewater transport and treatment (Bayo et al., 2016; Stride et al., 2024).

The highest abundance of microplastics (MPs) was observed in the influent, with an average abundance of  $1166.96 \pm 24.98$  MPs/L, whereas the lowest concentration was detected in the effluent during summer ( $29.3 \pm 0.25$  MPs/L). The findings of this study provide clear evidence that wastewater treatment plants (WWTPs), despite achieving relatively high removal efficiencies of microplastics (95.57% in winter and 97.48% in summer), still serve as a continuous source of MPs discharge into the environment (Table 1). The results of the present study show that the Zabol wastewater treatment plant, which uses the stabilization pond method for wastewater treatment, has increased the rate of microplastic removal despite the increase in the amount of microplastics in the summer due to the use of three lagoons in the winter and the addition of two more lagoons in the summer (five lagoons). The efficiency of microplastic removal has been reported differently in other studies, e.g., China -53.6% (Dong et al., 2022), Turkey - 71% (Vardar et al., 2021), Australia - 76.61% (Raju et al., 2020), Italy – 86% (Pittura et al., 2021), Iran – 90.87% (Takdastan et al., 2021), and South Korea - 99.8% (Kim et al., 2022). The reason for this difference could be the use of different wastewater treatment technologies, sampling points, sieve sizes, particle size and morphology, and operational parameters such as hydraulic load and sludge retention time (Kurt et al., 2022).

The polymer hazard index (PHI) was calculated according to the types of polymers identified in each influent and effluent sample (Fig. 5 (A)). Statistical analysis showed that the highest PHI value ( $135.39 \pm 6.7$ ) occurred in the influent, while the lowest value ( $62.65 \pm 5.53$ ) was recorded in the effluent, both during the summer season. A significant difference ( $P < 0.05$ ) was observed in the mean PHI values between the influent and effluent of the Zabol WWTP, indicating a notable reduction in the overall hazard level following treatment. However, no significant seasonal variation ( $P > 0.05$ ) was detected between summer and winter (Fig. 5 (A)).

The Pollution Load Index (PLI)—calculated based on the total abundance of microplastics—exhibited maximum and minimum values of  $39.33 \pm 1.03$  and  $1.03 \pm 0.05$ , respectively, during summer. Consistent with the PHI results, the mean PLI differed significantly between the

influent and effluent samples ( $P < 0.05$ ), while no significant difference ( $P > 0.05$ ) was observed across seasons, suggesting stable treatment performance throughout the year (Fig. 5 (B)).

The significant reduction in both the polymer hazard index (PHI) and the pollution load index (PLI) values between the influent and effluent samples demonstrates that the stabilization pond method in the Zabol wastewater treatment effectively mitigates the overall microplastic (MP) load and associated polymer-related risks. Chemical investigations in the present study showed that polymers such as polyethylene and polypropylene, which are considered low-risk polymers (Lithner et al., 2011), were mainly found in the influent and effluent samples. Polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC) were identified as the key polymers in domestic wastewater treatment plants (WWTPs) (Alavian Petroody et al., 2020; Al-Amri et al., 2024). Due to their potential risks to humans and the environment, such as carcinogenicity, genetic defects, respiratory and eye irritations, and long-term toxicity to aquatic life, PVC and PU are classified as highly hazardous polymers (Lithner et al., 2011; Al-Amri et al., 2024). Nematollahi et al. (2025) reported that microplastics with a polymer composition of PU, PC, and PVC were present in the effluent of seven treatment plants in Tabriz, which is consistent with the results of the present study. Dense and hazardous polymers such as polyvinyl chloride (PVC), polystyrene (PS), and polyurethane (PU) tend to settle, which leads to a decrease in their abundance in the treated effluent, but they were not completely eliminated in the present study, and therefore the PHI index (PHI) shows a moderate risk level (II) for effluent samples. Therefore, Thus, the reduction in both PHI and PLI underscores the effectiveness of the stabilization pond method, but both indices category effluent samples at a moderate level (II), highlighting the need for tertiary and advanced filtration stages to minimize the discharge of persistent polymers.

## CONCLUSION

This study provides comprehensive insights into the abundance, characteristics, and removal efficiency of microplastics (MPs) in the Zabol municipal wastewater treatment plant, which operates through a stabilization pond system. Although the plant achieved high removal rates—95.57% in winter and 97.48% in summer—it still acts as a steady source of microplastic discharge into the environment. The dominant particle size range (45–425  $\mu\text{m}$ ) in both the influent and effluent indicates that smaller and lighter particles are less effectively removed by the biological processes typical of such systems. Morphological observations showed that film-shaped particles were most common, likely originating from the breakdown of packaging materials and plastic bags. Transparent and golden particles were particularly frequent, reflecting contributions from household waste such as food and snack packaging.

FTIR spectroscopy confirmed that polyethylene (PE) and polypropylene (PP) were the main polymer types in both the influent and effluent, consistent with their extensive use in everyday consumer products. The Polymer Hazard Index (PHI) and Pollution Load Index (PLI) both declined notably from the influent to the effluent, showing that the stabilization pond treatment substantially reduces the total MP loads and associated polymer-related risks. Even so, the effluent was rated as a moderate hazard (Level II–III) based on PHI, suggesting that polymers with higher toxicity potential—such as polyvinyl chloride (PVC), polystyrene (PS), and polyurethane (PU)—were only partially removed.

These findings highlight that while stabilization pond systems can achieve substantial MP removal, they are not fully efficient in eliminating fine and buoyant microplastics, particularly low-density polymers such as PE and PP. Incorporating tertiary or advanced treatment steps, such as membrane filtration or rapid sand filtration, would likely improve MP removal. At the same time, reducing the use of disposable packaging materials and strengthening local waste management are crucial steps toward preventing microplastic contamination, particularly in

arid regions where treated wastewater is reused for irrigation.

## ACKNOWLEDGEMENTS

This research was derived from an approved project conducted at the Research Institute of Zabol (Project Code: PR-RIOZ-1403-5483-1). The authors gratefully acknowledge the financial and technical support provided by the Research Institute of Zabol.

## GRANT SUPPORT DETAILS

The present research has been financially supported by the Research Institute of Zabol (Project Code: PR-RIOZ-1403-5483-1).

## CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

## LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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