



MICROPLASTIC RISK ASSESSMENT IN AN URBAN TROPICAL STREAM USING ACTIVE BIOMONITORING WITH NATIVE FISH

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DOI: 10.15294/jpii.v15i3.41394

Accepted: January 20th, 2026. Approved: September 29th, 2026. Published: September 29th, 2026

ABSTRACT

Microplastic pollution has been reported worldwide. However, current assessments remain limited by quantification and evaluation based on abiotic factors. Unlike passive biomonitoring, which reflects wide biological variability in wild-caught fish, active biomonitoring with caged, standardized organisms provides controlled environmental exposure. This study introduces an early warning framework by integrating active biomonitoring with a multi-index approach to evaluate the levels (Pollution Load Index), the impact on the environment (Coefficients of Microplastic Index), bioavailability in the organism (Microplastic Index), and Estimated Daily Intake (EDI) by humans of microplastic pollution in a stream threatened by urbanization. The caged native fish (*Rasbora lateristriata*) were placed at three sites along the urbanized Winongo Stream for a 28-day exposure period. The microplastics were extracted from water samples and fish organs and characterized by size, shape, color, and polymer type. This study found that small size, fiber, and black color were the dominant microplastic types in surface water and fish tissues at all sampling sites. This study identified polypropylene, polyethylene, and polyamide as the polymers. Pollution levels ranged from low to moderate, and the potential environmental impact of microplastic shape ranged from low to extreme. The Microplastics Index shows the translocation from water to the body of fish, and the Estimated Daily Intake shows that humans possibly consume microplastics by eating fish muscle. These findings highlight the potential measurable risk of dietary exposure through fish consumption, underscoring the importance of integrating active biomonitoring with ecological risk indices for assessing microplastic contamination in tropical freshwater ecosystems. Education on proper, sustainable waste management and comprehensive policies is needed to mitigate plastic pollution in aquatic environments.

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Keywords: consumption; freshwater; health risk; monitoring; *rasbora*

INTRODUCTION

Plastic pollution is still an unresolved global problem. Plastic is versatile, lightweight, durable, inexpensive, and flexible, so it is widely used in everyday life. Problems arise when users discard plastic products into the environment. The durability of plastic debris makes it hard to degrade and persistent in the environment (Koelmans et al., 2022). Increasing plastic consumption harms the environment and health (Bhuyan, 2022; Steg-

mann et al., 2022). Large plastics (> 5 cm) can decompose into tiny particles, namely mesoplastics (5 mm – 5 cm), microplastics (0.1 µm – 5 mm), and nanoplastics (< 0.1 µm). The tiny size of microplastics (MPs) and the light character of plastic debris make it easy for them to migrate in the environment (Emmerik & Schwarz, 2020), enter the bodies of organisms, and cause disorders in test animals, including oxidative stress (Zitouni et al., 2021), digestive disorders (Zheng & Wang, 2023), and even impaired immune response (Limonta et al., 2019).

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The persistence of MPs in the environment hinders progress toward the following Sustainable Development Goals. MPs in water, seafood, and food disrupt food security (SDG 2), access to clean water (SDG 6), marine ecosystems (SDG 14), and terrestrial ecosystems (SDG 15). Disrupted ecosystem function influences the causes and impacts of climate change (SDG 13) (Stoett et al., 2024). The inevitable leakage of plastic waste into terrestrial and aquatic ecosystems remains a major challenge for researchers, policymakers, citizens, other stakeholders, and the global community (Kumar et al., 2021; Walker, 2021). A comprehensive study to monitor microplastic pollution remains urgently needed to achieve a sustainable environment. In addition, increasing environmental awareness is urgently needed as a strategic component of sustainable development in addressing the global ecological crisis (Castro & Castro, 2026).

MPs have become a global problem, as evidenced by reports of their presence in various countries worldwide, especially in the marine environment (van Calcar & van Emmerik, 2019). Conversely, monitoring of MP pollution in freshwater remains limited, and freshwater systems are closer to the source of MP production than the oceans, making them more susceptible to MP contamination (Emmerik & Schwarz, 2020). Sources of MP contamination in waters include domestic activities, agricultural activities, livestock, industrial waste disposal, and surface runoff from rainfall, river flow, and wind (Dong et al., 2023). Urbanization and land-use activities surrounding the river also contribute to MP contamination in the stream (Garcia et al., 2020). MPs in the water can enter an aquatic organism through diet or the food web. The bioavailability of MPs in the organism can cause the adverse effects as described previously. Therefore, monitoring the types and abundance of plastic debris in inland waters can improve understanding of waste sources and transfer mechanisms, supporting better mitigation of plastic debris in waters (Bauer-Civiello et al., 2019; Hassan et al., 2026).

However, MP pollution in freshwater ecosystems remains largely invisible because limited ecological literacy reduces environmental awareness and limits efforts to mitigate MP. Nevertheless, global research shows that science-based educational practices can foster environmental awareness and shift public behavior toward more pro-environmental attitudes (Castro & Castro, 2026). In this context, by presenting actual research data about the stream conditions in the surrounding environment, it is hoped that it

can be an undeniable visual alarm for the public to increase ecological literacy and environmental awareness as part of actions to protect aquatic life (SDG 14) and also to maintain the sustainability of the ecosystem further.

The previous studies focused on determining pollution levels, ecological risks, and health risks, which were calculated based on MP concentrations in water or sediment (Zhao et al., 2014; Di & Wang, 2018; Xu et al., 2018; Alam et al., 2019; Sulistyowati et al., 2022; Zaki et al., 2024; Zhao et al., 2024). While these ecological risk assessments provide critical baseline data for environmental management and pollution mitigation (Agathokleous et al., 2021), they have significant methodological shortcomings, particularly in capturing the dynamic bioavailability of MPs in aquatic food webs. Standard abiotic assessments from water and sediment fail to reflect how plastic debris interacts with living tissues over time. To address this, current literature has shifted toward biomonitoring to achieve comprehensive insights into bioavailability and health risk metrics such as the Estimated Daily Intake (EDI) (Adji et al., 2022). However, most existing biomonitoring literature still has critical, unaddressed limitations and largely relies on passive biomonitoring (Jabeen et al., 2017; Wang et al., 2017; Ismail et al., 2019; Lopes et al., 2023; Maulana et al., 2023; Polt et al., 2023). Passive biomonitoring, which captures organisms directly from the environment, introduces confounding variables such as variation in species, size, age, sex, and so on, making spatial comparisons statistically weak and unreliable. More importantly, the unknown exposure duration in wild fish obscures the kinetics of MP accumulation, leaving the temporal rate of microplastic translocation into tissues unquantified. These unresolved issues justify the urgent need for active biomonitoring using a caged native fish approach, which standardizes biological traits and controls the exposure timeline, providing an accurate, comparable assessment of MP bioavailability and risk dynamics.

To achieve this, active biomonitoring using native fish can be a valuable tool for monitoring MP pollution in the river (Vieira et al., 2019). Active biomonitoring involves transplanting test animals from a reference area (non-polluted) to the research location in cages for 4-6 weeks. Pollutant accumulation in the test organism at the end of the exposure period indicates contaminants in the environment. Biological uniformity in test animals can minimize error when interpreting results from comparisons of pollution across different environments (Santana et al., 2018).

Test-animal selection is also important in biomonitoring studies. Sentinel and filter-feeder animals, with their limited mobility, are favored as test animals because they reflect local conditions (Li et al., 2019). However, the drawback is that animals tend to be demersal, or bottom-dwelling, and therefore cannot reflect water-column pollution conditions. Therefore, fish are potential test animals for biomonitoring MP pollution (Kazour et al., 2020), given that MPs are light and tend to float or drift in water, except for high-density polymers such as HDPE. Native fish are preferred because they are ecologically proven to survive at the site (Marins et al., 2020). Besides, the animals used must not be invasive. This anticipates the possibility of test animals escaping their cages and ensures they are safe and do not invade local fish.

In this case, the wader pari fish (*Rasbora lateristriata*) was selected as the test animal for this active biomonitoring study because it meets the criteria as explained previously. As a native Indonesian fish (Kusuma et al., 2016), the fish represents the ecological health of tropical urban rivers more accurately than non-native laboratory models. Wader pari fish has also been shown to absorb MPs and metals (Pb, Cd) in streams. Passive biomonitoring research by Sabilillah et al. (2023) reported that MPs were detected in the gills, GIT, and muscles of *Rasbora lateristriata* caught in the Code River, with an average of 3-5 particles in each organ, and in the Gajahwong River as many as 2-6 particles in each organ. Besides, this fish is a benthopelagic omnivore that feeds opportunistically in the water column, making it highly susceptible to ingesting suspended particles, including MPs. Although this species is a reliable model for aquatic ecotoxicology (Retnoaji et al., 2023), this study is the first to evaluate its sensitivity and suitability as a test species in an active biomonitoring study of MPs. Moreover, as a popular food source consumed by local communities (Maghfiroh et al., 2025), its selection directly bridges the gap between ecosystem contamination and human health risk assessment.

To reinforce this point, while previous studies have documented MPs' abundance in tropical rivers, they have paid limited attention to integrating active biomonitoring with ecological risk indices and human exposure assessment. This study addresses this gap by applying a field-based biomonitoring approach combined with multiple indices (PLI, CMPI, MPI, and EDI) to provide an ecosystem-to-human perspective of MPs pollution in the Winongo Stream, one of the essential streams in the Special Region of Yogya-

karta Province, Indonesia, which is increasingly threatened by urbanization and land-use changes (Fadlillah et al., 2023) and has experienced declining water quality in recent years (DLHK, 2022). As MP contamination in this stream has not been previously investigated, this study aims to evaluate the status of MP pollution by assessing: (i) surface-water contamination through MP abundance and the Pollution Load Index (PLI), (ii) the environmental impact through the Coefficient of Microplastic Impact (CMPI), (iii) the bioavailability through the Microplastic Index (MPI) and potential human health implications using Estimated Daily Intake (EDI). The MPI and EDI were determined through active biomonitoring using the Indonesian native fish *Rasbora lateristriata* as a test organism.

Previous evaluations of MP contamination have relied heavily on passive biomonitoring of wild aquatic organisms to estimate ecological and bioaccumulation risks. However, these wild-caught samples exhibit substantial biological variation in age, size, and unknown exposure duration, leaving a critical knowledge gap in the precise, time-dependent kinetics of MP bioavailability under natural river conditions. Furthermore, baseline data for the Winongo Stream are virtually nonexistent, and comprehensive risk assessments integrating environmental concentrations with multi-index biotic evaluations remain limited. To address these issues, this study introduces an active biomonitoring approach using native fish (*Rasbora lateristriata*) held in cages and regularly deployed at three stations in the Winongo Stream during a controlled 28-day exposure period. The novelty of this work lies in its pioneering integration of active biomonitoring with various ecological and dietary indices, such as the Pollution Load Index (PLI), the Microplastic Index (MPI), and the Estimated Daily Intake (EDI), to provide an explicit, standardized, and real-time risk assessment in a freshwater ecosystem. As the first empirical assessment of MPs in this vital aquatic resource, these findings provide crucial and unambiguous data to support local plastic mitigation strategies and community-driven awareness, directly advancing global efforts towards achieving the Sustainable Development Goals (SDGs), specifically SDGs 2 (Zero Hunger/Food Security), 6 (Clean Water and Sanitation), 14 (Life Below Water), and 15 (Life on Land).

METHODS

This field study was conducted from May 2024 to June 2024 (low rainfall intensity, with an

average rainfall of 4- 70 mm/month) in the Winongo Stream, Special Region of Yogyakarta, Indonesia. The determination of sampling sites is

based on MPs pollution gradients (low, moderate, high) from community activities around the Winongo Stream (Figure 1).

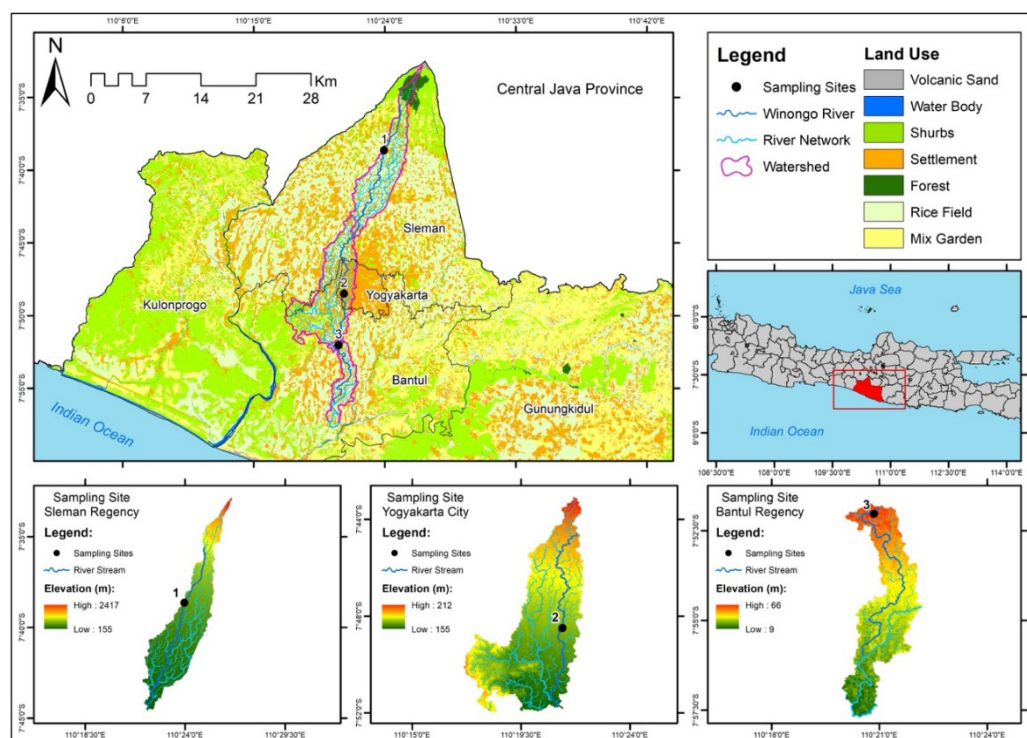


Figure 1. Study Area

Site 1 (S1), located at 7°38'36.80"S, 110°23'32.11"E. The potential pollution comes from domestic and horticultural activities. Site 2 (S2) is located at 7°48'29.81"S, 110°21'13.22"E. Residential housing is very dense, so domestic waste from household activities entering the water is estimated to be high. Site 3 (S3) is located at 7°52'2.11"S, 110°20'51.33"E. The area around the stream flow is dominated by agricultural land and residential areas. The pollution can come from domestic and farming activities. The estimated MP gradient pollution from high to low was S2, S3, and S1, respectively.

Test organism and active biomonitoring

The test organisms used in this research were adult male Indonesian native fish, wader pari (*Rasbora lateristriata*), from the Cangkringan Aquaculture Technology Development Center in Yogyakarta. The fish had a mean size of 7.79 (0.38 cm in length) and 3.91 (0.81 grams in weight). A healthy indicator of the fish is active movement. Fifty-four healthy fish, collected from the reference site, were transplanted into 1.5 m × 1 m × 1 m bamboo cages in the stream. Eighteen

fish were caged at each site (S1, S2, S3).

Sample collection

The water samples were collected on days 0, 3, 7, 14, 21, and 28 in three replicates from each of the three sampling sites (S1, S2, S3). Twenty liters of surface water (0-50 cm from the upper surface) were collected using a stainless-steel container and immediately filtered with a 54 µm stainless-steel screen. The filtrate was then washed using distilled water stored in a 100 mL glass bottle and transferred to the laboratory at 4°C until further treatment (Yan et al., 2021). Three fish were collected and stored in a cold box from each site on days 0, 3, 7, 14, 21, and 28. The samples were immediately transferred to the laboratory and stored at -20°C until further treatment. The fish's gills, muscles, and gastrointestinal tract (GIT) were separated and weighed (g) (Ukasha et al., 2024; Yan et al., 2021).

MPs extraction, visual characterization, and identification

MPs extraction

MPs extraction in water samples refers to the method developed by Yan et al. (2021) and Yin et al. (2021). In the laboratory, the water

sample was transferred to a 500 mL glass Erlenmeyer flask, 30% H_2O_2 was added up to 3× the sample volume, and the mixture was heated at 60 °C for 2 hours until the organic material was destroyed, indicated by a clear solution and the absence of MP particles.

MP extraction for fish organs refers to the method developed by Adji et al. (2022), Sabilillah et al. (2023), and Yin et al. (2021). Each previously weighed organ was transferred into a 100 mL Erlenmeyer flask, then 10% KOH was added to 3 times the sample volume. It was heated at 60 °C overnight until the organic material was destroyed, as indicated by the destruction of the organ. Add 10% KOH to 3 times the sample volume again, and extend the heating process if the organic material has not been destroyed. The condition of the sample needs to be checked regularly to ensure the KOH solution does not run out during heating.

Samples that have been destroyed and have reached room temperature were then filtered using Whatman paper (pore size 2.5 μ m). Filter paper containing MPs was stored in labeled glass Petri dishes before further characterization.

MP identification

MP identification was conducted by observation under a stereo microscope (Nikon SMZ745, Japan). MP criteria include: 1) Particle size <5 mm, 2) Homogeneous color, 3) No organic or cellular structures, and 4) Not segmented and not branched. Characterization of identified MP particles, as referred to in McNeish et al. (2018) and Adji et al. (2022), is based on size (<1.5 mm, 1.6–3.2 mm, 3.3–5 mm), shape (fiber, fragment, foam, pellet, film), and color (transparent, yellow, red, green, blue, and white). The identified particles were placed in a glass bottle, and the polymer was characterized using Fourier transform infrared spectroscopy (FTIR; Type IRPrestige-21, Shimadzu) with a wavelength range of 4000-400 cm^{-1} . The spectrum analysis was compared with the database according to Jung et al. (2018).

Quality assurance and contamination control

To maintain data accuracy in MP analysis, this study applied quality assurance (QA)/quality control (QC) referring to previous studies by Sabilillah et al. (2026) and Ukasha et al. (2024). The protocols implemented to prevent contamination and bias from the beginning, include: (1) the use of cotton laboratory clothes and coats and nitrile gloves, (2) the use of non-plastic tools, such as stainless steel for collecting samples in the field, glassware for laboratory equipment, (3) the use of ultrapure water (filtered distilled water) for making digestion solutions (10% KOH and 30% H_2O_2) and also for rinsing equipment before and after use; (4) Conditioning sterile glass petri dishes and Erlenmeyer flask that have been labeled to remain closed and immediately closed when placing the filtered sample after digestion, (5) The use of controls in the form of open petri dishes in the laboratory room during the extraction and identification process of MPs.

MPs assessment

MPs assessment in this study was based on MPs abundance (Equations 1 and 2), Pollution Load Index (Equations 3 and 4), Coefficient of Microplastic Impact (Equation 5), Microplastic Index (Equation 6), and Estimated Daily Intake (Equation 7). The indices used in this study are screening-level tools rather than absolute risk predictors, as they provide a comparative framework to identify spatial patterns, relative contamination levels, and potential exposure pathways of MPs across sites, rather than definitive thresholds of ecological or human health risk. Given the current limitations in standardized methodologies and dose–response relationships for MP toxicity, these indices are best interpreted as early-warning indicators that support environmental monitoring and management, while highlighting the need for more refined risk assessment approaches in future studies. Table 1 presents the MP assessment formula used in this study.

Table 1. The Formula of Microplastic Assessment

No	Equation	Evaluation criteria	References
The formula of ecological risk assessment			
Equation 1	MPs abundance MPs abundance in the surface water	A lower abundance value indicates lower MP contamination, and vice versa.	(Adji et al., 2022)
Equation 2	MP abundance in the fish organ		

Equation 3	Contamination Factor (CF)	(Yan et al., 2021)
	CF _i - the quotient of the MP concentration at each site; C _i – the MP concentration; C _{oi} - the minimum MP concentration	
Equation 4	Pollution Load Index (PLI)	The hazard impact was classified into four levels (I <10, II =10–20, III =20–30, and IV > 30).
	CF _{1,2...n} is the result of the Contaminant Factor calculation. n is the number of samples.	
Equation 5	The coefficient of MPs Impact (CMPI)	CMPI categorization includes low (0.0001-0.1), average (0.11-0.5), maximum (0.51-0.8), and extreme (0.81-1). (Saikia & Handique, 2024)
Equation 6	Microplastic index (MPI)	A lower MPI index value indicates a lower level of MP contamination, and vice versa. (Patterson et al., 2019)
	MPSB is the MP concentration in soft body tissue (Number of MPs/g) in the GIT at the end of exposure time (Day 28), subtracted from the baseline (Day 0)	
The formula for health risk assessment		
Equation 7	Estimated Daily Intake (EDI)	(Sabilillah et al., 2023)
	In this study, MPs concentration is derived from the identified MPs in the muscle at the end of exposure time subtracted from the baseline (D28-D0)	

Statistical analysis of data

All statistical analyses were conducted using SPSS version 26.0 (IBM Corp., Armonk, NY, USA). Statistical significance was set at $p < 0.05$. Prior to statistical testing, data were checked for normality using the Shapiro–Wilk test and for homogeneity of variance using Levene's test. For surface water, individual water samples collected independently at distinct points within each sampling site ($n = 3$) were treated as independent replicates. For the biomonitoring experiment, individual fish (*Rasbora lateristriata*) analyzed from each site ($n = 3$ per sampling time) were treated as independent biological replicates (experimental units) to evaluate individual variation in MP abundance across tissues (gills, GIT, and muscle).

MP abundance in the water and fish tissue samples was analyzed using a factorial Two-Way Analysis of Variance (ANOVA) to determine the simultaneous effects of spatial and temporal variables. The exact statistical model included two fixed factors: Sampling Site (three levels: S1, S2,

S3) and Exposure Duration (six levels: Days 0, 3, 7, 14, 21, 28), along with their interaction effect (Site $\times$ Duration). When the data did not meet parametric assumptions, a log transformation was applied to meet normality and homogeneity of variance requirements before running the Two-Way ANOVA. For significant values, a Tukey post-hoc test was performed for pairwise comparison.

Pollution Load Index (PLI) was calculated using the daily geometric average formula, and the trend was presented visually to determine the pollution load category status. CMPI was calculated descriptively, while MPI and EDI were analyzed using One-Way ANOVA to compare values at the end of the exposure period (Day 28). For significant differences, a Tukey post-hoc test was also performed for pairwise comparisons. Data were visualized in GraphPad Prism, and MP characteristics were shown using a Sankey diagram (online version via sankeymatic.com).

RESULTS AND DISCUSSION

Microplastic abundance in the surface water

MPs were detected in water samples from three sites. There were 2,603 MP particles collected from all sampling sites, with an average abundance of 2.41 ± 1.54 items/L. Figure 2 shows the comprehensive comparison of MP contamination in the Winongo Stream during

the study period. MP abundance varied distinctly over time among the three sampling sites (Figure 2a). This finding was supported by the results of a two-way ANOVA that confirmed the significant interaction between site and time ($F(10, 36) = 4.437$, $p < 0.001$, $\eta^2 = 0.552$), proving that the temporal fluctuation of MP abundance in the surface water was highly dependent on localized, site-specific events over time.

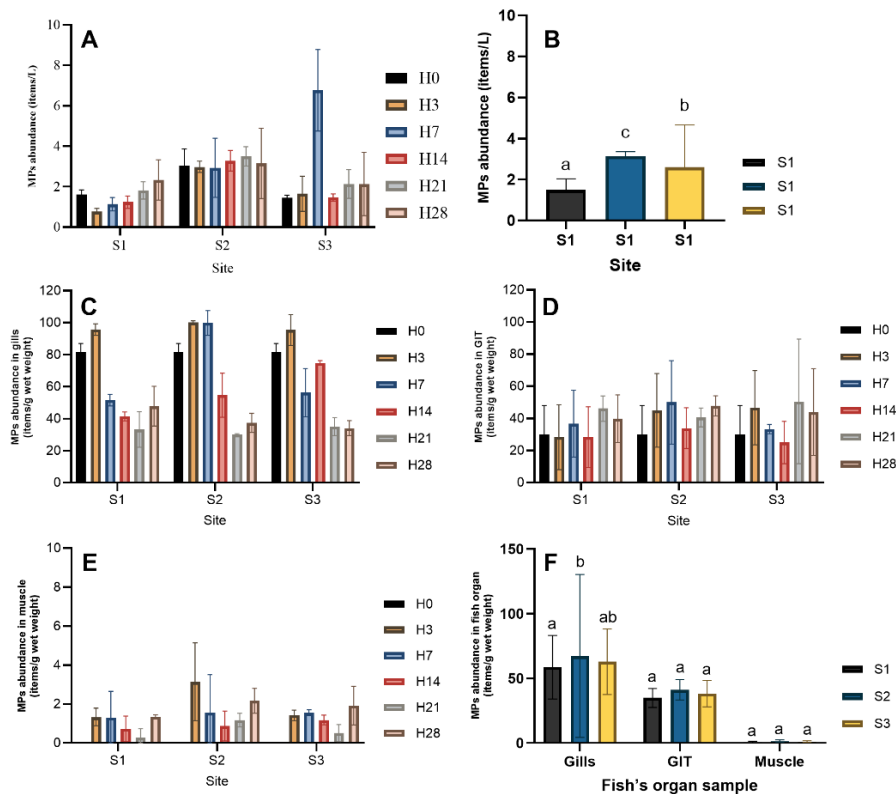


Figure 2. Comparison of Microplastic Abundance in the Winongo Stream Across Different Sampling Sites Over a 28-day Study Period: (A) Surface water; (B) Cumulative Abundance in Sample Water; (C) Gills; (D) GIT; (E) Muscle; (F) Cumulative Abundance Between Organs

Error bars in Figure 2 represent the standard deviation ($n = 3$ for each abundance, and $n=18$ for cumulative abundance). Letters a, b, c in images (B, F) show the results of the Tukey post-hoc test after a two-way ANOVA shows significant differences ($p < 0.05$). The Tukey post-hoc test shows a clear gradient in overall mean MP abundance across sites, from highest at S2 to S3 to S1 (Figure 2B). This result is also in accordance with the value of the main effect of the sampling site ($F(2,36) = 19.946$, $p < 0.001$, $\eta^2 = 0.526$). The main effect of time periods ($F(2, 36) = 3.082$, $p < 0.001$, $\eta^2 = 0.300$) also shows that sampling time affects MP abundance in the water. These results confirm that population density along the river influences the MP pollution gradient in the Winongo

Stream, consistent with the considerations used to select sampling sites in this study.

Figure 2A shows that MP abundance in the surface water fluctuates. However, the site near the urban area (S2) shows a relatively stable trend, indicating consistent MP input over time. Consistent with previous reports by Bauer-Civiello et al. (2019), Yin et al. (2021), and Zaki et al. (2024), this study also observed the highest MP abundance in the densely populated urban area. Improper waste management in densely populated areas remains a source of MP contamination, as domestic activities release MPs into the nearby stream through wind transport. Another source of MP contamination to the stream may come

from atmospheric deposition (Owowenu et al., 2023) and from intentional rubbish thrown away by residents, as observed at the research location during sampling.

In general, the abundance of MPs in the surface water of the Winongo Stream was detected to be lower than that of the other two streams in the waters of Yogyakarta, namely Code (12-24 items/L) (Ukasha et al., 2024) and Gajahwong (5-29 items/L) (Sabilillah et al., 2023), and also with Nanjing River, China (1.46 – 20.56 items/L) (Yan et al., 2021), but relatively similar to the abundance of the Selangor River Basin, Malaysia (1.44 items/L) (Zaki et al., 2024), Tapi-Phumduang River, Thailand (1.77 items/L) (Chinfak et al., 2021), Red River, Vietnam (0.01-0.20 items/L) (Nguyen et al., 2020). Variations in sampling techniques, preparation, identification, and MP abundance calculations reported across countries still make it challenging to compare MP abundance between locations accurately. Nevertheless, the similarity of the findings generally shows that MP abundance is related to population density around the research location.

This study detected the second-highest MP abundance in S3 downstream, with the source of MP contamination possibly coming from domestic and agricultural activities. This contrasts with MP abundance in the Brantas River, East Java (Buwono et al., 2021b), which showed the highest abundance downstream. This is because the downstream receives a lot of waste from the upstream. According to Crew et al. (2020) and Masuku et al. (2025), variations in MP abundance in surface water are influenced by proximity to point sources, particle characteristics, to-

pography, water flow, water depth, organic content, and substrate type. In this case, although the Brantas River has a wider coverage area than the Winongo stream, the water flow in the Brantas River (0.1 – 0.7 m/s) is higher than in the Winongo stream (0.1 - 0.4 m/s), so pollutant transport downstream is faster and contains more waste, including plastic debris. Therefore, understanding MP dynamics and the factors that influence them is important for mitigating pollutant contamination at the source.

In contrast, this study detected the lowest MP abundance in S1. Although population density, a potential source of MP contamination, is lower in S1 than in S2 and S3 (Figure 1), MPs in S1 may come from plantations, fishing, and tourism activities in the upper stream of S1. These results strengthen evidence that MPs are ubiquitous, reaching the upper stream (elevation $\pm$ 2.400 m above sea level), as long as human activity inseparable from plastic use is present.

Microplastic abundance in the caged fish

The MPs detected in the gills, muscle, and gastrointestinal tract (GIT) in this study show that MPs in the surface water of the Winongo Stream were available for ingestion by the caged fish over 28 days. Cumulative abundance shows that MPs were detected in the gills > GIT > muscle across all sampling sites (Figure 2.F). In line with the gradient of MPs abundance in the surface water, the highest relative abundance of MPs in the three organs was also detected in S2, S3, and S1, respectively. This finding is supported by the results of the two-way ANOVA, which are presented in Table 2.

Table 2. Statistical Analysis of Microplastic Abundance using Two-Way ANOVA

Sample	Sources	F-value	p-value	η^2
Gills	Site	5.845	0.006	0.245
	Time	93.823	<0.001	0.929
	Site $\times$ Time	9.731	<0.001	0.730
GIT	Site	0.529	0.594	0.026
	Exposure Time	1.197	0.330	0.139
	Site $\times$ Time	0.251	0.988	0.074
Muscle	Site	2.308	0.114	0.114
	Time	10.98	<0.001	0.604
	Site $\times$ Time	0.651	0.761	0.153
Water	Site	3.082	0.020	0.526
	Time	19.946	<0.001	0.300
	Site $\times$ Time	4.437	<0.001	0.552

Table 2 shows that the MP abundance in the gills was strongly affected by the main factors, which are site and exposure periods (time), and

also the interaction factor between site and exposure periods. Different sites significantly affect gill MP abundance ($p < 0,05$), with higher cumulati-

ve MP abundance in urban and suburban areas than in the relatively low-density population area (Figure 2D). The decrease in MP abundance in the gills over exposure time in this study (Figure 2C) indicates that the rate of MP elimination in the gills exceeds the absorption rate. Moreover, gill structure and continuous water exposure cause entangled MPs to accumulate; however, elimination by water is also high, resulting in fluctuations in MP abundance in the gills.

This study also observed an interesting pattern in MP abundance in the GIT. Figure 2D shows a similar trend of MP absorption and elimination in the GIT of *Wader pari* fish over 28-day exposure periods, likely related to the GIT's food-storage capacity. However, cumulatively, the abundance of MPs in the GIT was higher than the baseline and showed the same gradient as the abundance of MPs in the surface water of the Winongo Stream, namely, descriptively, the highest was detected in S2 > S3 > S1, respectively, although statistically the abundance of MPs in the GIT did not differ between stations and between exposure periods (Figure 2F). This aligns with the statistical analysis, which found no significant effect of site or exposure time on MP abundance in the GIT. The low significance in the GIT indicates efficient gastric evacuation in *R. lateristriata*, where most ingested MPs are eliminated in feces before absorption.

In contrast, the MP abundance in the muscle shows a time-dependent effect ($p < 0.001$), with the size effect reaching 0.604. These results further confirm that MP translocation between organs in natural aquatic environments is not location-dependent; rather, MPs that successfully enter the muscles are trapped and difficult to eliminate. The longer the exposure period, the greater the probability of MP translocation. The presence of MPs in the fish muscle has the potential to move to other trophic levels through the food chain, and potentially affect the health of organisms and also the consumers of muscle-contaminated MPs.

The conformity of MP characteristics in the water and the caged-fish sample

MPs in this study were also characterized by size, shape, and color. Figure 3 (A-C) shows that the identified MPs in the surface water in the Winongo Stream (S1, S2, S3) have similar characteristics, which are small size, fiber shape, and black color. The differences among the three sites are slight, mainly in the percentage of each characteristic. The dominant characteristics of MPs are small (52.88%), fiber (94.63%), and black (59.64%) in S1 (Figure 2A); small (54.51%), fiber (93.29%), and black (53%) in S2 (Figure 2B); and medium (48.72%), fiber (94.02%), and black (49.68%) in S3 (Figure 2C).

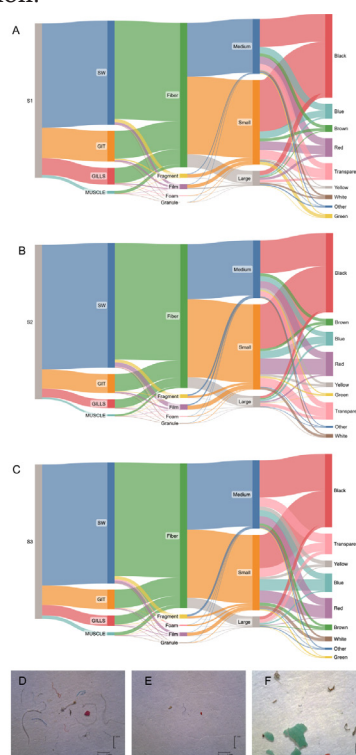


Figure 3. MP Characteristics from the Water And Fish Organs Based on Size, Shape, and Color (A: in the S1; B: in the S2; C: in the S3), MPs Visual Observation (D: in the Water Sample; E: in the Gills; F: in the GIT)

Moreover, comparing MP characteristics in water samples and biota in the study area will help isolate contamination sources and more accurately quantify contaminants in field samples (McNeish et al., 2018). In this study, the dominant MPs in the fish organs were relatively similar to the dominance of MPs in the water sample; they consist of small size (> 50%), fiber shape (> 90%), and black color (> 30%) in all sampling sites (Figure 2(A-C)). These results indicate that MPs accumulated in test animals reflect the dominant size, shape, and color of MPs in Winongo Stream surface water. The morphology of the MP particles detected in this study is presented in Figure 2 (A-C), and the visual observation of MPs detected in the water and fish samples can be seen in Figure 2 (D-F).

Figure 2 also shows that plastic debris in the environment has entered the Winongo stream and degraded into smaller sizes, reaching <1.5 mm (small), 1.6–3.2 mm (medium), and 3.3–5 mm (large). Degradation can occur through photodegradation, biodegradation, physical pressure, weathering, and other environmental factors (Tan et al., 2023). Small MPs also dominate in Surabaya River waters (Lestari et al., 2023) and the Selangor River Basin (Zaki et al., 2024). The small size of MPs increases their potential for passive absorption by aquatic organisms and translocation to the animal's organs.

By shape, fibers are the dominant MP at all sampling sites in this study, followed by film, fragments, and other shapes. The dominance of fibers has also been reported in the waters of the Code and Gajahwong Streams, Indonesia (Sabilillah et al., 2023), Surabaya River, Indonesia, Selangor River Basin, Malaysia (Zaki et al., 2024), Qinhuai River, China (Yan et al., 2021), and Tapi-Phumduang River, Thailand (Chinfak et al., 2021). The shape of MPs affects their behavior in aquatic environments. Fibers and films have high surface tension and float on the water's surface. In contrast, fragments have lower surface tension and are more likely to settle in sediments (Melkebeke et al., 2020; Xia et al., 2025). This shape also suggests that particles in the surface water of the Winongo stream came from plastic debris used in daily domestic activities. The main sources of fiber contamination include polyester, polylactide, nylon (polyamide), rayon (semi-synthetic), acrylic, and polypropylene (Rebelein et al., 2021).

Fragments are MPs resulting from the degradation of strong plastics, such as containers, pipes, and food containers. Films result from

the degradation of thin plastic sheets, including mulch, plastic bags, and plastic wrap. Styrofoam results from the degradation of packaging products, food containers, and equipment for fishing activities, and granules are primary MPs derived from microbeads deliberately made by the industry for beauty products (Adji et al., 2022; Kuroda et al., 2024; Wu et al., 2019).

This study found no significant differences in MP color profiles between stations. This study also reported the dominance of black MP in the waters of the Brantas River, Indonesia (Buwono et al., 2021b), the Ciliwung River, Indonesia (Wilyalodia et al., 2023), and the Qarasu River, Iran (Heshmati et al., 2021). Black plastic is the most commonly used plastic for various purposes, but its lower recycling rate makes it a larger source of total MPs than other colors (Huang & Xu, 2022). In addition, the variation in MP color detected in this study reflects people's daily plastic products, including fragmented plastic containers, plastic bags, and colorful clothing fibers (Yan et al., 2021; Haque et al., 2024). Although present at low concentrations, these variations resemble natural food, increasing the likelihood that aquatic organisms in the Winongo will ingest them.

Moreover, Figure 3D shows the various sizes, shapes, and colors of MP particles in the surface water, which enter the gastrointestinal tract (Figure 3F) or are trapped in the gills (Figure 3E). The image clearly shows the potential dangers posed by MPs, including irregular fragments with sharp ends that irritate the GIT epithelial layer. As explained by McNeish et al. (2018), the fiber's small diameter increases the opportunity for MP translocation from the digestive tract, disrupting nutrient absorption and thereby affecting health. The trapped fibers in the gills (3E) also disrupt important processes such as filtration and circulation. Lestari et al. (2023) found that *Rasbora argyrotaeni* has one of the highest levels of MPs in the Surabaya River. This omnivorous, benthopelagic fish can take up MPs from the water surface and water column.

To ensure that the detected particles are plastic debris, this study also conducted KBr-FTIR spectra to determine the polymer type. However, the particle weight limitation in this study may have led to suboptimal peak readings. Nevertheless, polymer identification according to Jung et al. (2018) shows conformity between the surface water and the fish organs (Figure 3(A-B)).

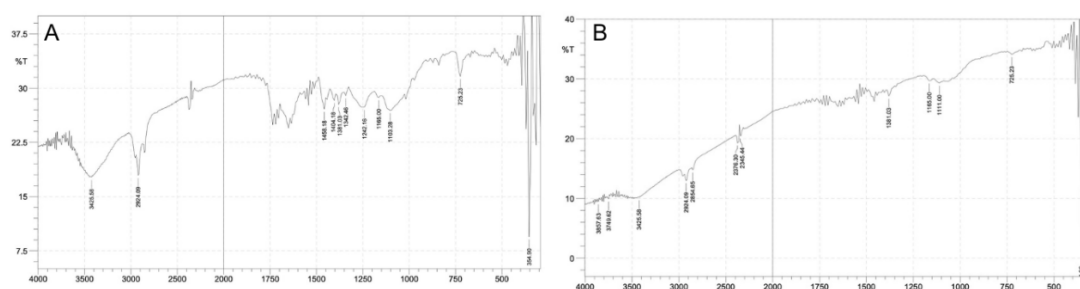


Figure 4. The FTIR Spectra: (A) Particles from Water Sample; (B) Particles from Fish Organ

The results in Figure 4A indicate that the polymers detected in the water sample are Low-density polyethylene (LDPE), Polypropylene (PP), and Polyamide (PA)/Nylon. Furthermore, the polymers of MPs from the collected organs (gills, muscles, GITs) in the three sampling sites are PP and Nylon (Figure 3B). Low-density MPs, such as PP (0.89-0.92 g/cm³) and PE (0.91-0.97 g/cm³), are commonly found in water because they float on the surface and are easily carried by river runoff. PE is the most commonly used plastic, used in food packaging, cardboard liners, shrink wrap, mulch film, squeezable bottles, and trash bins. PP products include bottle caps, container lids, duct tape, and automotive equipment. Nylon or Polyamide (1.14 - 1.15 g/cm³) is a fiber used in clothing, fishing nets, ropes, and automotive equipment (Chinfak et al., 2021; Crawford & Quinn, 2017).

MPs Risk Assessment

Pollution Load Index (PLI)

To compare MP contamination levels between sites, PLI is the preferred index because it uses the same baseline. In this study, the baseline was determined by the lowest abundance detected in the surface water of Winongo stream. Consistent with abundance, the Pollution Load

Index (PLI) trend also showed PLI in S2 > S3 > S1 (Figure 4(A-B)). The PLI level can be used to determine the priority scale for actions to reduce MP levels and the potential danger to the Winongo stream. The highest PLI indicates a potential hotspot of MP contamination in the Winongo stream: the urban area.

Figures 4A and 4B explain that although the cumulative PLI in the Winongo Stream was categorized as Minor to Moderate, the daily fluctuating PLI (Figure 4A) reached high to extreme levels. These findings serve as an early warning of MP contamination in the Winongo Stream, especially in urban areas, and necessitate action to reduce its impact.

However, PLI varies widely, driven by environmental dynamics and specific contaminant sources rather than uniform spatial gradients. For example, high-human-activity zones in China yielded elevated PLI scores (Yin et al., 2021). Spatially, peak PLI scores may align with downstream currents that facilitate waste transport, as seen in the Code River (Ukasha et al., 2024), or concentrate near localized waste treatment facilities regardless of river zoning (Yan et al., 2021). These shifting dynamics underscore that assessing MP abundance via PLI alone cannot fully capture the complexity of plastic pollution, highlighting the need for complementary, multi-index evaluations.

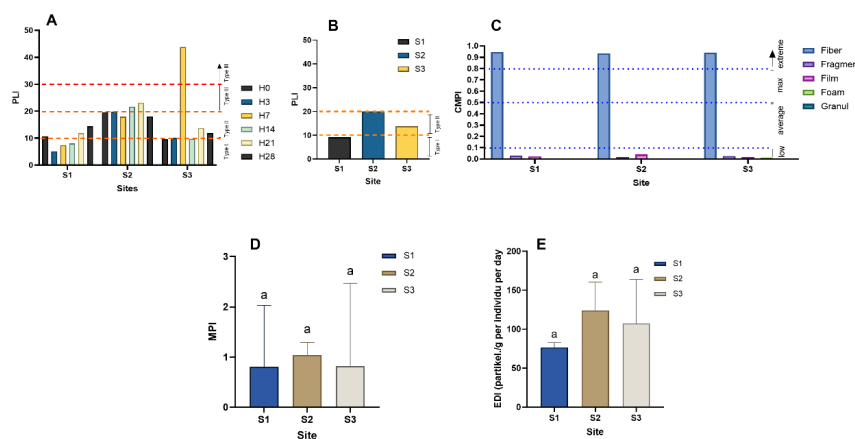


Figure 5. Microplastic Risk Assessment in the Winongo Stream

Coefficient of MPs Impact (CMPI)

In this study, the impact of MPs on the environment is also evaluated through the Coefficient of Microplastics Impact (CMPI). Variation in CMPI values between stations reflects the dominance of specific MP shapes at each site and provides details on the environmental impacts of specific MP shapes (Ashwathi et al., 2025; Bappy et al., 2025). Figure 5C indicates that, in this study, fiber is in the extreme category at all sampling sites, followed by film and fragment in the low category. Fiber shows the highest CMPI in the water and sediment of St. Mary's Island (Khaleel et al., 2023). The shape of fiber makes it easier to translocate to other matrix environments, such as the body of an organism, and affect health (Bappy et al., 2025).

Ashwathi et al. (2025) reported higher CPM values in agricultural areas, especially those using mulch. This contrasts with the results of this study. Although S3 in this study is an agricultural area, the CMPI film falls in the low category. At the time of sampling in S3, there was no significant use of mulch; the similar trend in CMPI at this site in this study indicates that urbanization pressure strongly influences MP contamination in the stream. Nevertheless, other MPs have a low environmental impact and can also be ingested by aquatic organisms. To support this, this study included active biomonitoring to evaluate potential accumulation and assess microplastic exposure in the Winongo Stream over time.

Bioavailability of MPs

PLI and CMPI provide quantitative values for MP pollution levels and the impact of MP form on the environment. Some indices can even predict health risks based on the MP polymer type. However, conventional monitoring still has shortcomings, namely its inability to determine the proportion of MP particles absorbed or the bioavailability of MPs by aquatic organisms, so the resulting risk assessment is less relevant to actual ecological conditions. To bridge this methodological gap, the Microplastic Index (MPI) integrates heterogeneous particle characteristics into a standardized risk matrix. By shifting the analytical focus from mere quantity to biologically accessible hazards, MPI provides a robust predictive framework for evaluating the actual bioavailability of MPs, thereby improving the accuracy of ecological risk assessments across environments.

Figure 4D shows that the MPI-based pollution gradient is similar to the PLI. The highest MPI was detected in S2 (1.04 ± 0.25) > S3 (0.82

(1.65) > S1 (0.80 (1.20)). Although differences between sites are not statistically significant, the similar trend to PLI in this study reflects MPs pollution in the environment. In highly urbanized coastal zones, very high MPI (around 10) directly correlated with increased MPs bioavailability and increased bioaccumulation in benthic organisms over time (Naidu et al., 2022). The study further explained that MPI successfully synthesized raw concentration data from heterogeneous matrices (water and sediment) into functional indicators of biological vulnerability, validating that bivalve condition indices and soft tissue growth dynamics were closely related to the bioaccessible fraction of MP particles rather than MP environmental abundance.

Estimated Daily Intake (EDI) and Potential On Human Health Implication

The detection of MPs in the muscles of caged fish in S1, S2, and S3 for 28 days in the Winongo Stream suggests the potential for MP transport to other animals or humans that consume fish from the stream. As a source of protein needed for human growth, MP contamination, whether in the form of single pollutants or interactions with other pollutants in the natural environment, can cause health problems in fish and pose a danger to humans who eat the fish (Bhuyan, 2022; Erdoğan, 2025). This study uses fish consumption rates from BPS (2025). In 2024, Indonesians consumed an average of 360 grams/week of fresh fish and 41 grams/week of preserved fish. Based on Koelmans et al. (2022), MP in the natural environment averages 12.5 mg. Therefore, the population is estimated to consume 76.71–124.22 MP particles per person per day, equivalent to 0.58–1.52 mg of MP particles per person per day. Figure 4E compares EDI across the three sites. Figure 4E shows that S2 has the highest EDI. This result is consistent with MP abundance in surface water and GIT, PLI scores, and MPI. Sites with high levels of contamination and MP bioavailability tend to have higher EDI and may pose a greater health risk.

As another index-based assessment, EDI also varies between regions. The EDI in this study is higher than that in the Southeast Black Sea, which reached 0.17 MPs/g in scallops *Flexopecten glaber* (Onay et al., 2026). Estimated daily seafood intake in some countries, such as China, India, Korea, the UK, Malaysia, Iran, Hong Kong, and Spain, ranges from 0.06 to 598 particles/day, with the highest EDI estimated for green mussels (Heo et al., 2025). However, the data were collected through passive biomonitoring, and

the exact exposure duration at each location is unknown. In this case, the EDI value from active biomonitoring is more relevant for describing actual environmental conditions because the test animals and exposure duration are known with certainty.

In addition, increased human exposure to MP is driven by other MP-contaminated foods such as salt and sugar (Makhdoumi et al., 2023), shellfish (Ukasha et al., 2024), and others (Lusher et al., 2017). MP inhalation is another source of MP ingestion in humans and should be considered (Zhang et al., 2020). So far, MPs have been detected in human lung tissue (Amato-Lourenço et al., 2021), the placenta (Ragusa et al., 2021), and sputum (Huang et al., 2022). MPs can also interact with other chemical compounds, such as metals (Mn, Zn, Cu, Cd), Bisphenol A (BPA), Polychlorinated biphenyls (PCBs), and Polycyclic aromatic hydrocarbons (PAHs), thereby increasing their harmful effects. Unused chemical compounds that enter the body through MPs can bind to proteins and hormone receptors, disrupting metabolic processes (Crawford & Quinn, 2017).

However, reported effects of MP exposure in animal models result from experimental studies with MP levels far exceeding those in the environment; therefore, they are not relevant for assessing the risk of MP exposure in humans. So far, no regulations govern food safety standards for MP parameters because these synthetic particles are not considered a significant threat to human health (Gamarro & Coztanzo, 2022). Future research should move beyond abundance-based assessments by integrating chemical characterization of plastic additives and co-occurring contaminants, examining the long-term and multi-generational effects of chronic MPs exposure on freshwater organisms, and developing standardized methodologies that incorporate effect sizes and uncertainty metrics into ecological risk assessments. Such efforts will be critical for strengthening cross-study comparability and building a more comprehensive understanding of how MPs influence freshwater ecosystem functioning, resilience, and their implications for environmental management and public health. Moreover, strengthening solid waste management and wastewater treatment, implementing source-control measures such as reducing single-use plastics and improving textile waste handling, and incorporating MP monitoring into routine water-quality assessment programs are essential steps to protect aquatic biodiversity and sustain ecosystem services that support domestic, agricultural, and fisheries activities.

CONCLUSION

This study's results add to data on MP abundance in natural environments, showing the highest abundance in urban areas. The uniformity of the test fish in active biomonitoring reflects the real-time state of MP contamination in organisms and provides more accurate comparative data between locations. Although pollution levels are relatively low, the bio-availability of MPs in fish organs indicates potential exposure through food consumption, and they may also affect human health. This study shows that integrating active biomonitoring with ecological risk indices provides an effective early-warning framework for assessing MP contamination in tropical freshwater ecosystems. The consistency of site severity across all indices, by tracing MPs from surface water (PLI, MPs abundance and characterization) to aquatic biota (MPI) and further to potential human exposure pathways (EDI), provides a basis for ecosystem-based management in river systems increasingly affected by urbanization and land-use change. Beyond its site-specific relevance, the study underscores the broader need for preventive, upstream-oriented policies to mitigate MP pollution, to support the achievement of SDGs 2, 6, 14, and 15. These are food security, clean water, life below water, and terrestrial life.

ACKNOWLEDGEMENTS

The authors thank the Indonesia Endowment Fund for Education (LPDP), the Indonesian Education Scholarship (BPI), and the Center for Higher Education Funding and Assessment, Ministry of Higher Education, Science, and Technology of the Republic of Indonesia, for their funding support.

REFERENCES

- Adji, B. K., Octodhiyanto, I., Rahmayanti, R., & Nugroho, A. P. (2022). Microplastic pollution in Rawa Jombor Reservoir, Klaten, Central Java, Indonesia: accumulation in aquatic fauna, heavy metal interactions, and health risk assessment. *Water, Air, and Soil Pollution*, 233(4).
- Agathokleous, E., Iavicoli, I., Barceló, D., & Calabrese, E. J. (2021). Ecological risks in a 'plastic' world: A threat to biological diversity? *Journal of Hazardous Materials*, 417(March), 0–2.
- Alam, F. C., Sembiring, E., Muntalif, B. S., & Suendo, V. (2019). Microplastic distribution in surface water and sediment river around slum and industrial area (case study: Ciwalengke River, Majalaya district, Indonesia). *Chemosphere*, 224, 637–645.
- Amato-Lourenço, L. F., Carvalho-Oliveira, R., Júnior, G. R., dos Santos Galvão, L., Ando, R. A., &

- Mauad, T. (2021). Presence of airborne microplastics in human lung tissue. *Journal of Hazardous Materials*, 416.
- Ashwathi, C., Warriar, A. K., Murmu, M., Priyadarshini, U., & Prabhu, S. (2025). Microplastic and trace element contamination in coastal agricultural soils of southern India: a comparative risk assessment of mulched and unmulched fields. *Environmental Geochemistry and Health*, 47(10).
- Bappy, M. M. M., Rahman, M. M., Bhuiyan, M. T., Rahman, M. M., Banik, P., Nur, A. A. U., Yu, J., Arai, T., Paray, B. A., Ngah, N., & Hossein, M. B. (2025). Contamination, potential sources, and risk assessment of microplastics in surface waters of two public bathing beaches along the Northern Bay of Bengal. *Regional Studies in Marine Science*, 83.
- Bauer-Civello, A., Critchell, K., Hoogenboom, M., & Hamann, M. (2019). Input of plastic debris in an urban tropical river system. *Marine Pollution Bulletin*, 144, 235–242.
- Bhuyan, M. S. (2022). Effects of Microplastics on Fish and in Human Health. *Frontiers in Environmental Science*, 10, 1–17.
- BPS. (2024). *Statistical Yearbook of Indonesia 2024*.
- Buwono, N. R., Risjani, Y., & Soegianto, A. (2021a). Contamination of microplastics in Brantas River, East Java, Indonesia and its distribution in gills and digestive tracts of fish *Gambusia affinis*. *Emerging Contaminants*, 7, 172–178.
- Buwono, N. R., Risjani, Y., & Soegianto, A. (2021b). Distribution of microplastic in relation to water quality parameters in the Brantas River, East Java, Indonesia. *Environmental Technology and Innovation*, 24.
- Castro, J. E. Q., & Castro, M. D. P. Q. (2026). Global Research Trends in Environmental Education and Environmental Awareness: A Bibliometric analysis. *Jurnal Pendidikan IPA Indonesia*, 15(1), 29–39.
- Chinfak, N., Sompongchaiyakul, P., Charoenpong, C., Shi, H., Yeemin, T., & Zhang, J. (2021). Abundance, composition, and fate of microplastics in water, sediment, and shellfish in the Tapi-Phumduang River system and Bandon Bay, Thailand. *Science of the Total Environment*, 781.
- Crawford, C. Blair, & Quinn, B. (2017). *Microplastic pollutants*. Elsevier.
- Crew, A., Gregory-Eaves, I., & Ricciardi, A. (2020). Distribution, abundance, and diversity of microplastics in the upper St. Lawrence River. *Environmental Pollution*, 260.
- Di, M., & Wang, J. (2018). Microplastics in surface waters and sediments of the Three Gorges Reservoir, China. *Science of the Total Environment*, 616–617, 1620–1627.
- Dong, X., Liu, X., Hou, Q., & Wang, Z. (2023). From natural environment to animal tissues: A review of microplastics(nanoplastics) translocation and hazards studies. In *Science of the Total Environment* (Vol. 855). Elsevier B.V.
- Emmerik, T., & Schwarz, A. (2020). Plastic debris in rivers. *WIREs Water*, 7(1), 1–24.
- Erdoğan, Ş. (2025). Microplastic Contamination in Freshwater Fish: First Insights from Gelingüllü Reservoir (Türkiye). *Water, Air, and Soil Pollution*, 236(6).
- Fadlillah, L. N., Utami, S., Rachmawati, A. A., Jayanto, G. D., & Widyastuti, M. (2023). Ecological risk and source identifications of heavy metals contamination in the water and surface sediments from anthropogenic impacts of urban river, Indonesia. *Heliyon*, 9(4).
- Gamarro, E. G., & Coztanzo, V. (2022). Microplastics in food commodities- A food safety review on human exposure through dietary sources. In *Microplastics in food commodities*. FAO.
- Garcia, T. D., Cardozo, A. L. P., Quirino, B. A., Yofukuji, K. Y., Ganassin, M. J. M., dos Santos, N. C. L., & Fugi, R. (2020). Ingestion of Microplastic by Fish of Different Feeding Habits in Urbanized and Non-urbanized Streams in Southern Brazil. *Water, Air, and Soil Pollution*, 231(8).
- Haque, A., Holsen, T. M., & Baki, A. B. M. (2024). Distribution and risk assessment of microplastic pollution in a rural river system near a wastewater treatment plant, hydro-dam, and river confluence. *Scientific Reports*, 14(1).
- Hassan, Y. A. M., Badrey, A. E. A., Osman, A. G. M., & Mahdy, A. (2026). Distribution and Abundance of Microplastics (MPs) in the Water, Sediment, and Some Freshwater Animals, Nile River, Upper Egypt. *Water, Air, & Soil Pollution*, 237(1), 34.
- Heo, S. J., Moon, N., & Kim, J. H. (2025). A systematic review and quality assessment of estimated daily intake of microplastics through food. In *Reviews on Environmental Health* (Vol. 40, Number 2, pp. 371–392). De Gruyter Open Ltd.
- Heshmati, S., Makhdoumi, P., Pirsahab, M., Hossini, H., Ahmadi, S., & Fattahi, H. (2021). Occurrence and characterization of microplastic content in the digestive system of riverine fishes. *Journal of Environmental Management*, 299, 1–10.
- Huang, S., Huang, X., Bi, R., Guo, Q., Yu, X., Zeng, Q., Huang, Z., Liu, T., Wu, H., Chen, Y., Xu, J., Wu, Y., & Guo, P. (2022). Detection and Analysis of Microplastics in Human Sputum. *Environmental Science and Technology*, 56(4), 2476–2486.
- Huang, Y., & Xu, E. G. (2022). Black microplastic in plastic pollution: undetected and underestimated? *Water Emerging Contaminants and Nanoplastics*, 1(3).
- Ismail, M. R., Lewaru, M. W., & Prihadi, D. J. (2019). Microplastics ingestion by fish in the Pangandaran Bay, Indonesia. *World News of Natural Sciences*, 23, 173–181.
- Jabeen, K., Su, L., Li, J., Yang, D., Tong, C., Mu, J., & Shi, H. (2017). Microplastics and mesoplastics in fish from coastal and fresh waters of China. *Environmental Pollution*, 221, 141–149.
- Jung, M. R., Horgen, F. D., Orski, S. V., Rodriguez

- C., V., Beers, K. L., Balazs, G. H., Jones, T. T., Work, T. M., Brignac, K. C., Royer, S. J., Hyrenbach, K. D., Jensen, B. A., & Lynch, J. M. (2018). Validation of ATR FT-IR to identify polymers of plastic marine debris, including those ingested by marine organisms. *Marine Pollution Bulletin*, 127, 704–716.
- Kazour, M., Jemaa, S., El Rakwe, M., Duflos, G., Hermabassiere, L., Dehaut, A., Le Bihanic, F., Cachot, J., Cornille, V., Rabhi, K., Khalaf, G., & Amara, R. (2020). Juvenile fish caging as a tool for assessing microplastics contamination in estuarine fish nursery grounds. *Environmental Science and Pollution Research*, 27(4), 3548–3559.
- Khaleel, R., Valsan, G., Rangel-Buitrago, N., & Warrier, A. K. (2023). Microplastics in the marine environment of St. Mary's Island: implications for human health and conservation. *Environmental Monitoring and Assessment*, 195(9).
- Koelmans, A. A., Redondo-Hasselerharm, P. E., Nor, N. H. M., de Ruijter, V. N., Mintenig, S. M., & Kooi, M. (2022). Risk assessment of microplastic particles. In *Nature Reviews Materials* (Vol. 7, Number 2, pp. 138–152). Nature Research.
- Kumar, R., Verma, A., Shome, A., Sinha, R., Sinha, S., Jha, P. K., Kumar, R., Kumar, P., Shubham, Das, S., Sharma, P., & Prasad, P. V. V. (2021). Impacts of plastic pollution on ecosystem services, sustainable development goals, and need to focus on circular economy and policy interventions. In *Sustainability (Switzerland)* (Vol. 13, Number 17). MDPI.
- Kuroda, M., Isobe, A., Uchida, K., Tokai, T., Kitakado, T., Yoshitake, M., Miyamoto, Y., Mukai, T., Imai, K., Shimizu, K., Yagi, M., Mituhashi, T., & Habano, A. (2024). Abundance and potential sources of floating polystyrene foam macro- and microplastics around Japan. *Science of the Total Environment*, 925.
- Kusuma, W. E., Ratmuangkhwang, S., & Kumazawa, Y. (2016). Molecular phylogeny and historical biogeography of the Indonesian freshwater fish *Rasbora lateristriata* species complex (Actinopterygii: Cyprinidae): Cryptic species and west-to-east divergences. *Molecular Phylogenetics and Evolution*, 105, 212–223.
- Lestari, P., Trihadiningrum, Y., & Warmadewanthi, I. D. A. A. (2023). Investigation of microplastic ingestion in commercial fish from Surabaya river, Indonesia. *Environmental Pollution*, 331.
- Li, J., Lusher, A. L., Rotchell, J. M., Deudero, S., Tura, A., Bråte, I. L. N., Sun, C., Shahadat Hossein, M., Li, Q., Kolandhasamy, P., & Shi, H. (2019). Using mussel as a global bioindicator of coastal microplastic pollution. *Environmental Pollution*, 244, 522–533.
- Limonta, G., Mancina, A., Benkhalqui, A., Bertolucci, C., Abelli, L., Fossi, M. C., & Panti, C. (2019). Microplastics induce transcriptional changes, immune response and behavioral alterations in adult zebrafish. *Scientific Reports*, 9(1).
- Lopes, C., Ambrosino, A. C., Figueiredo, C., Caetano, M., Santos, M. M., Garrido, S., & Raimundo, J. (2023). Microplastic distribution in different tissues of small pelagic fish of the Northeast Atlantic Ocean. *Science of the Total Environment*, 901.
- Lusher, A., Hollman, P., & Mendoza, J. (2017). Microplastics in fisheries and aquaculture: status of knowledge on their occurrence and implications for aquatic organisms and food safety. In *FAO Fisheries and Aquaculture Technical Paper* 615.
- Maghfiroh, K. Q., Retnoaji, B., Budiman, A., & Suyono, E. A. (2025). Functional feed with *Euglena* sp.: a novel approach to growth and metabolic health in *Rasbora lateristriata*. *Fisheries and Aquatic Sciences*, 28(7), 501–513.
- Makhdoumi, P., Pirsaeheb, M., Amin, A. A., Kianpour, S., & Hossini, H. (2023). Microplastic pollution in table salt and sugar: Occurrence, qualification and quantification and risk assessment. *Journal of Food Composition and Analysis*, 119.
- Marins, A. T., Severo, E. S., Leitemperger, J. W., Cerezer, C., Muller, T. E., Costa, M. D., Weimer, G. H., Bandeira, N. M. G., Prestes, O. D., Zanella, R., & Loro, V. L. (2020). Assessment of River Water Quality in an Agricultural Region of Brazil Using Biomarkers in a Native Neotropical Fish, *Astyanax* spp. (Characidae). *Bulletin of Environmental Contamination and Toxicology*, 104(5), 575–581.
- Masuku, N. B., Curtis, C. J., & Griffin, N. J. (2025). Identifying Environmental Factors Influencing the Concentration, Fluxes and Spatial Distribution of Microplastic Pollution in an Urban River: A Case Study of the Klip River, South Africa. *Water, Air, and Soil Pollution*, 236(13).
- Maulana, M. R., Saiful, S., & Muchlisin, Z. A. (2023). Microplastics contamination in two peripheral fish species harvested from a downstream river. *Global Journal of Environmental Science and Management*, 9(2), 1–10.
- McNeish, R. E., Kim, L. H., Barrett, H. A., Mason, S. A., Kelly, J. J., & Hoellein, T. J. (2018). Microplastic in riverine fish is connected to species traits. *Scientific Reports*, 8(1).
- Naidu, B. C., Xavier, K. A. M., Shukla, S. P., Jaiswar, A. K., & Nayak, B. B. (2022). Microplastics in the foreshore coastal waters, sediment, and coastal fauna of a highly populated megacity - A study on the effect of anthropogenic discharge on clams. *Marine Pollution Bulletin*, 185.
- Nguyen, B. T., Do, D. D., Nguyen, T. X., Nguyen, V. N., Phuc Nguyen, D. T., Nguyen, M. H., Thi Truong, H. T., Dong, H. P., Le, A. H., & Bach, Q. V. (2020). Seasonal, spatial variation, and pollution sources of heavy metals in the sediment of the Saigon River, Vietnam. *Environmental Pollution*, 256.
- Onay, H., Minaz, M., Emanet, M., Ceylan, Y., Gökaya, A., & Er, A. (2026). Microplastic pollution and regional risk analysis of commercially important smooth Scallop *Flexopecten glaber*

- (Linnaeus, 1758) species in the black sea. *Environmental Research*, 303.
- Owowenu, E. K., Nnadozie, C. F., Akamagwuna, F., Noundou, X. S., Uku, J. E., & Odume, O. N. (2023). A critical review of environmental factors influencing the transport dynamics of microplastics in riverine systems: implications for ecological studies. In *Aquatic Ecology* (Vol. 57, Number 2, pp. 557–570). Springer Science and Business Media B.V.
- Patterson, J., Jeyasanta, K. I., Sathish, N., Booth, A. M., & Edward, J. K. P. (2019). Profiling microplastics in the Indian edible oyster, *Magallana bilineata* collected from the Tuticorin coast, Gulf of Mannar, Southeastern India. *Science of the Total Environment*, 691, 727–735.
- Polt, L., Motyl, L., & Fischer, E. K. (2023). Abundance and Distribution of Microplastics in Invertebrate and Fish Species and Sediment Samples along the German Wadden Sea Coastline. *Animals*, 13(10).
- Ragusa, A., Svelato, A., Santacroce, C., Catalano, P., Notarstefano, V., Carnevali, O., Papa, F., Rongioletti, M. C. A., Baiocco, F., Draghi, S., D'Amore, E., Rinaldo, D., Matta, M., & Giorgini, E. (2021). Plasticenta: First evidence of microplastics in human placenta. In *Environment International* (Vol. 146). Elsevier Ltd.
- Rebelein, A., Int-Veen, I., Kammann, U., & Scharsack, J. P. (2021). Microplastic fibers — Underestimated threat to aquatic organisms? In *Science of the Total Environment* (Vol. 777). Elsevier B.V.
- Retnoaji, B., Nurhidayat, L., Pratama, S. F., Anshori, K., Hananya, A., Sofyantoro, F., & Bessho, Y. (2023). Embryonic development of Indonesian native fish yellow rasbora (*Rasbora lateristriata*). *Journal of King Saud University - Science*, 35(7).
- Sabilillah, A. M., Apriliawati, A., & Nugroho, A. P. (2026). Microplastic contamination on urban river under different precipitation rate and land use gradient. *Environmental Monitoring and Assessment*, 198(5).
- Sabilillah, A. M., Palupi, F. R., Adj, B. K., & Nugroho, A. P. (2023). Health risk assessment and microplastic pollution in streams through accumulation and interaction by heavy metals. *Global Journal of Environmental Science and Management*, 9(4), 719–740.
- Santana, M. S., Yamamoto, F. Y., Sandrini-Neto, L., Filipak Neto, F., Ortolani-Machado, C. F., Oliveira Ribeiro, C. A., & Prodócimo, M. M. (2018). Diffuse sources of contamination in freshwater fish: Detecting effects through active biomonitoring and multi-biomarker approaches. *Ecotoxicology and Environmental Safety*, 149, 173–181.
- Stegmann, P., Daioglou, V., Londo, M., van Vuuren, D. P., & Junginger, M. (2022). Plastic futures and their CO₂ emissions. *Nature*, 612(7939), 272–276.
- Stoett, P., Schrich, V. M., Elliff, C. I., Andrade, M. M., de M. Grilli, N., & Turra, A. (2024). Global plastic pollution, sustainable development, and plastic justice. In *World Development* (Vol. 184). Elsevier Ltd.
- Sulistiyowati, L., Nurhasanah, Riani, E., & Cordova, M. R. (2022). The occurrence and abundance of microplastics in surface water of the mid-stream and downstream of the Cisadane River, Indonesia. *Chemosphere*, 291.
- Tan, Y., Dai, J., Xiao, S., Tang, Z., Zhang, J., Wu, S., Wu, X., & Deng, Y. (2023). Occurrence of microplastic pollution in rivers globally: Driving factors of distribution and ecological risk assessment. *Science of the Total Environment*, 904.
- Ukasha, T., Faisal, N. U. H., Adj, B. K., & Nugroho, A. P. (2024). Active biomonitoring in streams by using multimarker approaches of mussels. *Global Journal of Environmental Science and Management*, 10(3), 1171–1196.
- van Calcar, C. J., & van Emmerik, T. H. M. (2019). Abundance of plastic debris across European and Asian rivers. *Environmental Research Letters*, 14(12), 124051.
- Van Melkebeke, M., Janssen, C., & De Meester, S. (2020). Characteristics and Sinking Behavior of Typical Microplastics including the Potential Effect of Biofouling: Implications for Remediation. *Environmental Science and Technology*, 54(14), 8668–8680.
- Vieira, C. E. D., Costa, P. G., Caldas, S. S., Tesser, M. E., Risso, W. E., Escarrone, A. L. V., Primel, E. G., Bianchini, A., & dos Reis Martinez, C. B. (2019). An integrated approach in subtropical agro-ecosystems: Active biomonitoring, environmental contaminants, bioaccumulation, and multiple biomarkers in fish. *Science of the Total Environment*, 666, 508–524.
- Walker, T. R. (2021). (Micro)plastics and the UN Sustainable Development Goals. In *Current Opinion in Green and Sustainable Chemistry* (Vol. 30). Elsevier B.V.
- Wang, Z. M., Wagner, J., Ghosal, S., Bedi, G., & Wall, S. (2017). SEM/EDS and optical microscopy analyses of microplastics in ocean trawl and fish guts. *Science of the Total Environment*, 603–604, 616–626.
- Wilyalodia, H. C., Tybeyuliana, E. V., Mahendra, A. P. D., & Rahmawati, S. (2023). Seasonal Variability on Microplastic Pollution In Water and Sediment of Ciliwung River. *CSID Journal of Infrastructure Development*, 6(2).
- Wu, P., Huang, J., Zheng, Y., Yang, Y., Zhang, Y., He, F., Chen, H., Quan, G., Yan, J., Li, T., & Gao, B. (2019). Environmental occurrences, fate, and impacts of microplastics. In *Ecotoxicology and Environmental Safety* (Vol. 184). Academic Press.
- Xia, F., Yang, W., Zhao, H., Cai, Y., & Tan, Q. (2025). Occurrence characteristics and transport processes of riverine microplastics in different connectivity contexts. *Npj Clean Water*, 8(1).
- Xu, P., Peng, G., Su, L., Gao, Y., Gao, L., & Li, D.

- (2018). Microplastic risk assessment in surface waters: A case study in the Changjiang Estuary, China. *Marine Pollution Bulletin*, 133(June), 647–654.
- Yan, Z., Chen, Y., Bao, X., Zhang, X., Ling, X., Lu, G., Liu, J., & Nie, Y. (2021). Microplastic pollution in an urbanized river affected by water diversion: Combining with active biomonitoring. *Journal of Hazardous Materials*, 417.
- Yin, K., Wang, D., Zhao, H., Wang, Y., Guo, M., Liu, Y., Li, B., & Xing, M. (2021). Microplastics pollution and risk assessment in water bodies of two nature reserves in Jilin Province: Correlation analysis with the degree of human activity. *Science of the Total Environment*, 799.
- Zaki, M. R. M., Zainuddin, A. H., Saifuddin, M. F. U., Razak, M. R., Isa, N. M., Ash'aari, Z. H., & Aris, A. Z. (2024). Microplastic Contamination and Ecological Risk Assessment in Tropical Riverine Surface Water of Selangor River Basin, Malaysia. *ACS ES and T Water*, 4(8), 3225–3234.
- Zhang, Y., Kang, S., Allen, S., Allen, D., Gao, T., & Silanpää, M. (2020). Atmospheric microplastics: A review on current status and perspectives. In *Earth-Science Reviews* (Vol. 203). Elsevier B.V.
- Zhao, S., Zhu, L., Wang, T., & Li, D. (2014). Suspended microplastics in the surface water of the Yangtze Estuary System, China: First observations on occurrence, distribution. *Marine Pollution Bulletin*, 86(1–2), 562–568.
- Zhao, W., Li, J., Liu, M., Wang, R., Zhang, B., Meng, X. Z., & Zhang, S. (2024). Seasonal variations of microplastics in surface water and sediment in an inland river drinking water source in southern China. *Science of the Total Environment*, 908.
- Zheng, S., & Wang, W. X. (2023). Disturbing ion regulation and excretion in medaka (*Oryzias melastigma*) gills by microplastics: Insights from the gut-gill axis. *Science of the Total Environment*, 857.
- Zitouni, N., Bousserhine, N., Missawi, O., Boughattas, I., Chèvre, N., Santos, R., Belbekhouche, S., Alphonse, V., Tisserand, F., Balmassiere, L., Dos Santos, S. P., Mokni, M., Guerbej, H., & Banni, M. (2021). Uptake, tissue distribution and toxicological effects of environmental microplastics in early juvenile fish *Dicentrarchus labrax*. *Journal of Hazardous Materials*, 403, 1–12.