EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology, 2026, 27(8), 74–86
https://doi.org/10.12912/27197050/224861
ISSN 2719–7050, License CC-BY 4.0

Received: 2026.06.14
Accepted: 2026.07.10
Published: 2026.08.01

Characteristics and pollution load index of microplastics in surface coastal waters of Makassar, Indonesia

Rahayu A. Akili[1], Mahatma Lanuru[2], Mardiana E. Fachry[2], Eymal Bahsar Demmallino[1*]

[1] Environmental Science Study Program, The Graduate School, Hasanuddin University, Makassar 90245, Indonesia
[2] Faculty of Marine and Fisheries Science, Hasanuddin University, Makassar 90245, Indonesia
* Corresponding author's e-mail: demmallino2019@gmail.com

ABSTRACT

Microplastic pollution in coastal environments has emerged as an environmental concern due to its persistence, widespread distribution, and potential ecological risks. This study aimed to quantify microplastic abundance, characterize its physical properties (shape, color, and size), and assess the pollution levels in the coastal waters of Makassar, Indonesia, using the pollution load index (PLI). Water samples were collected from six coastal stations (Barombong, Pelabuhan Soekarno-Hatta, Paotere, Tallo, Tanjung, and Untia) with three replicates per station, yielding 18 sampling points. Microplastics were isolated through vacuum filtration and identified under a stereomicroscope. Statistical analyses included Shapiro–Wilk, Levene's test, Kruskal–Wallis, Pearson correlation, Spearman correlation, and non-metric multidimensional scaling (NMDS). Microplastics were detected at all stations, with median abundances ranging from 23.33 to 76.67 particles/L. Pelabuhan Soekarno-Hatta recorded the highest maximum concentration (326.67 particles/L), reflecting strong anthropogenic influence. No significant differences in abundance were observed among stations (Kruskal–Wallis, $p = 0.4877$). Fiber-shaped microplastics dominated the samples (96.79%), followed by fragments and films. Blue was the most common color, while particles measuring 0.1–1.0 mm constituted the dominant size class (64.24%). NMDS analysis revealed spatial variation in microplastic characteristics among sampling locations. The stations with higher microplastic abundance generally exhibited higher PLI values because the index was derived from abundance-based contamination factors. Therefore, PLI was used as an integrated indicator of contamination rather than an independent variable. These findings demonstrate the influence of anthropogenic activities on microplastic distribution and provide a baseline for future coastal pollution monitoring and management in Makassar.

Keywords: microplastics, coastal waters, pollution load index, NMDS, anthropogenic activities, Makassar.

INTRODUCTION

Microplastic pollution has become one of the most pervasive environmental issues in marine and coastal ecosystems worldwide. These particles, defined as plastic fragments smaller than 5 mm, originate from both primary sources, such as cosmetic microbeads and synthetic fibers, and secondary sources resulting from the degradation of larger plastic debris (Yu and Singh, 2023; Pourebrahimi and Pirooz, 2023; Dey et al., 2024; Mathew et al., 2024). Due to their small size, microplastics are easily transported across aquatic systems, accumulate in surface waters, and enter food webs, thereby posing ecological and potential human health risks (Saeedi, 2024; Eze et al., 2024; Rakib et al., 2023; Borriello et al., 2023). In coastal zones, the accumulation of microplastics is strongly influenced by anthropogenic activities, including urban runoff, shipping, fisheries, and riverine inputs, making these areas critical hotspots for monitoring pollution dynamics (Wang et al., 2022; Jong et al., 2022; Koner et al., 2026).

Recent studies have demonstrated that microplastic distribution is highly heterogeneous and closely linked to land-based activities and hydrodynamic conditions. For example, the investigations in Indonesian riverine and coastal systems have reported increasing microplastic loads from upstream urban areas toward estuarine and coastal waters (Fitri et al., 2026; Dwiyitno et al., 2024). Similarly, the studies integrating environmental quality indices have shown that anthropogenic pressures significantly affect pollutant accumulation patterns in aquatic ecosystems (Poikane et al., 2017; Hamzah et al., 2025; Pinna et al., 2023). Advanced environmental assessment approaches, including combined analytical and statistical models, have been increasingly applied to evaluate complex pollution scenarios, as demonstrated in groundwater and wastewater systems (Alimuddin et al., 2026; Pesireron et al., 2026). These studies highlight the importance of integrating quantitative indices with spatial analysis to better understand environmental contamination processes.

In coastal environments, microplastic characterization typically includes abundance, shape, color, and size distribution, which are essential for identifying pollution sources and transport pathways (Zhang, 2017; Rodríguez-Seijo and Pereira, 2017; Luo et al., 2019; Zhou et al., 2020; Lusher et al., 2020). Fiber-shaped microplastics are often associated with textile wastewater and fishing activities, while fragments and films are linked to plastic degradation and packaging waste (Hossain et al., 2025; Ainali et al., 2026; Patidar et al., 2024). In addition, color and size distribution provide further insight into degradation stages and environmental exposure history. Despite increasing research, many studies in Indonesia remain descriptive and lack integrated pollution assessment frameworks that combine microplastic characterization with quantitative risk indices, such as the pollution load index (PLI).

Makassar coastal waters represent a highly dynamic urban–marine interface influenced by dense population activity, river discharge, shipping routes, and fishing practices. These conditions make the area particularly vulnerable to microplastic accumulation and variability in distribution. However, limited studies have comprehensively assessed both the physical characteristics of microplastics and their pollution load using standardized quantitative approaches. Most existing research focuses either on abundance reporting or isolated spatial distribution without integrating statistical analysis and pollution indexing. Therefore, the research gap lies in the lack of integrated assessments that simultaneously evaluate microplastic abundance, physicochemical characteristics, spatial variability, and Pollution Load Index in tropical urban coastal systems. The significance of this study was to provide a comprehensive baseline dataset and methodological integration for microplastic pollution assessment in Indonesian coastal waters. The aim of this study was to analyze the abundance, characterize the physical properties (shape, color, and size), and quantify the pollution load of microplastics using the Pollution Load Index in surface coastal waters of Makassar, Indonesia, supported by multivariate statistical analyses.

RESEARCH METHODS

Study area

This study was conducted in the coastal waters of Makassar City, South Sulawesi, Indonesia (5°8′–5°19′ S; 119°24′–119°28′ E). The coastal system is characterized by strong anthropogenic influence, including dense urban settlements, industrial zones, port activities, fisheries, and riverine inputs from major rivers such as the Tallo and Jeneberang Rivers. These conditions make the coastal waters a highly dynamic environment for microplastic accumulation and transport.

Six sampling stations were selected using a purposive sampling approach to represent different levels of anthropogenic pressure: Barombong, Pelabuhan Soekarno-Hatta, Paotere, Tallo, Tanjung, and Untia. Each station reflects distinct environmental settings, including residential coastal areas, river mouths, fishing ports, and industrial-urban interfaces. Sampling was conducted in September 2024. A map of the sampling locations is provided in Figure 1.

Sampling design and water collection

Surface water samples were collected from six stations with three replicates per station, resulting in a total of 18 sampling units. Water sampling was carried out using a Van Dorn Water Sampler to ensure sample integrity and avoid contamination from surrounding water layers.

The sampler was deployed at a depth of approximately 0–40 cm below the water surface and

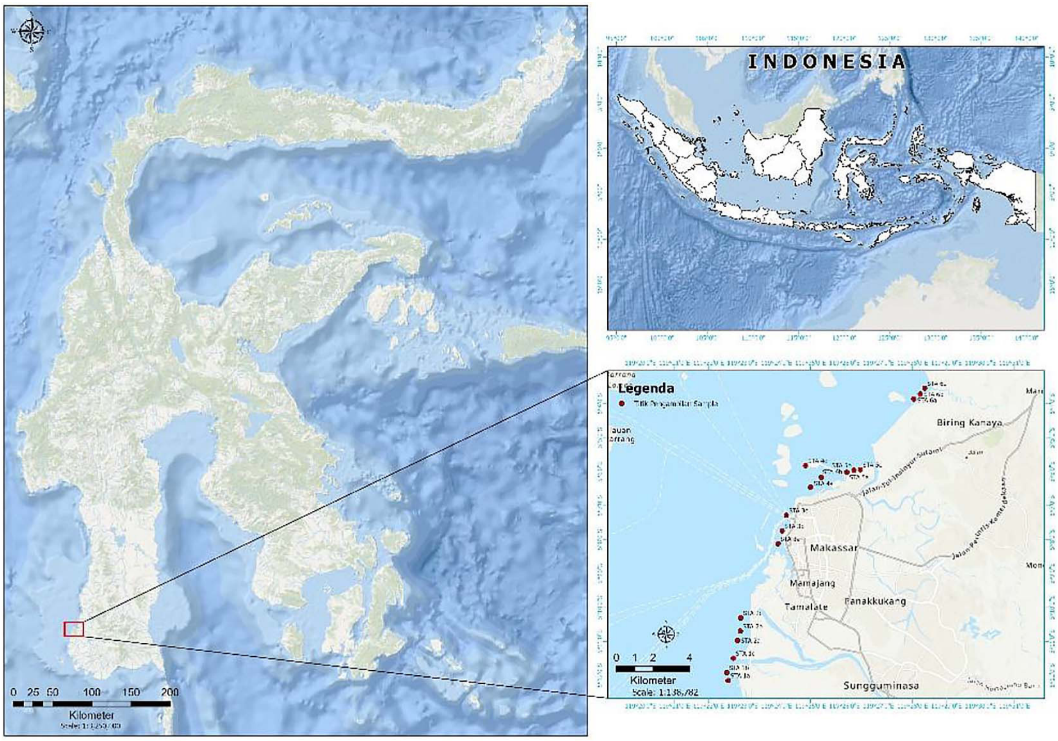

Figure 1. Sampling locations

closed automatically to collect discrete water samples. Each sample (425 mL) was transferred into pre-cleaned glass bottles and stored in a cooler box during transportation to the laboratory. In the laboratory, the samples were filtered to obtain 300 mL of usable filtrate for microplastic extraction. All samples were stored at 4°C prior to analysis to minimize biological degradation and contamination.

Microplastic extraction and identification

Microplastics were isolated from surface water samples using a vacuum filtration system (Rocker 410) equipped with Whatman cellulose filter membranes (0.45 µm pore size, 47 mm diameter). Each 300 mL sample was completely filtered without subsampling to ensure full particle recovery. Filter residues were transferred to sterile Petri dishes and stored under contamination-controlled laboratory conditions to minimize airborne interference and maintain data reliability.

Microplastic identification and characterization were conducted using a stereomicroscope (Euromax SB-1902) at 35× magnification. Filter membranes were systematically examined using a grid-based scanning approach to ensure complete coverage and reduce counting bias. Suspected particles were documented using a Dino-Eye AM7025X digital microscope camera and classified according to standardized protocols (Frias and Nash, 2019; GESAMP, 2016). Classification was based on shape (fiber, fragment, and film), color (blue, black, red, green, and transparent), and size. Particle size was measured using ImageJ software (version 1.52a) and categorized into three classes: <0.1 mm, 0.1–1.0 mm, and 1.0–5.0 mm. The classification framework used in this study is presented in Table 1.

Microplastic particles were identified based on morphological characteristics, including shape, color, texture, and the absence of visible biological structures. No spectroscopic confirmation using Fourier transform infrared spectroscopy (FTIR) or Raman spectroscopy was performed; therefore, particle classification should be considered presumptive microplastic identification. Nevertheless, visual sorting followed strict morphological criteria to minimize potential misclassification of natural or synthetic non-plastic materials.

To improve analytical reliability, each suspected particle was independently examined by two trained analysts, and only particles with agreement between both observers were included in the final dataset. Discrepant observations were jointly re-evaluated until consensus was reached. Representative microphotographs of the identified particles were captured to document morphological characteristics and support classification transparency. These images illustrate the typical features of fiber, fragment, as well as film microplastics and are presented in the figure or supplementary section as qualitative validation of the identification process.

Contamination control

Strict contamination control measures were implemented during field sampling and laboratory processing to minimize airborne and procedural contamination. All sampling equipment was rinsed with tap water, followed by ultrapure water (Onelab Waterone™) before use, while glassware and Petri dishes were sterilized, sealed, and kept covered until analysis. Sample exposure to open air was minimized throughout laboratory procedures to reduce the deposition of airborne microplastic particles.

Laboratory surfaces, instruments, and work areas were routinely cleaned using lint rollers (Micromate Lint Roller), and researchers wore cotton laboratory coats during sampling and analysis. These procedures were consistently applied to all samples to ensure data integrity and analytical reliability. The complete contamination control protocol used in this study is summarized in Table 2.

Microplastic abundance calculation

Microplastic abundance in surface water samples was quantified to determine the concentration of particles across different sampling stations. The calculation was based on the ratio of observed microplastic particles to the volume of filtered water samples. This approach allows standardized comparison of microplastic concentrations among all study sites, regardless of variations in sample volume. The abundance of microplastics was calculated using Equation 1 as follows:

$$C = \frac{N}{V} \quad (1)$$

where: C – microplastic concentration (particles/L or particles/m³), N – number of microplastic particles observed, V – volume of filtered water sample (L or m³).

This equation provides a quantitative measure of microplastic distribution in surface coastal waters and serves as the basis for subsequent statistical and pollution load analyses.

Pollution load index (PLI) assessment

PLI was applied as a relative contamination indicator to evaluate spatial differences in microplastic pollution across sampling stations. In this study, PLI was calculated using a standardized normalization approach based on the mean concentration of all sampling stations, rather than the minimum value, to improve methodological robustness and reduce sensitivity to extreme values. The contamination factor (CF_i) was calculated as:

$$CF_i = \frac{C_i}{C_0} \quad (2)$$

where: C_i represents the microplastic concentration at each station and *C_mean* represents the mean concentration across all stations. *PLI* was then derived as:

$$PLI = \sqrt{CF_i} \quad (3)$$

This modified formulation allows a more stable comparative assessment of relative pollution intensity within the study area. It should be noted that the PLI used in this study is a relative site-specific index, and is not intended as an absolute

Table 1. Classification criteria of microplastic particles

Parameter	Category
Shape	Fiber (line), fragment, film
Color	Blue, black, red, green, transparent
Size	<0.1 mm; 0.1–1.0 mm; 1.0–5.0 mm

Table 2. Contamination control procedures applied in the study

Procedure	Description
Equipment rinsing	Tap water followed by ultrapure water (Onelab Waterone™)
Sterilization	Glassware and Petri dishes sterilized and sealed before use
Surface cleaning	Laboratory surfaces cleaned using lint rollers (Micromate Lint Roller)
Personal protection	Cotton laboratory coats worn during all procedures
Exposure control	Minimal exposure of samples to open air during processing

ecological risk indicator or for direct comparison with heavy-metal-based PLI studies.

Statistical and multivariate analysis

Prior to analysis, data normality was tested using the Shapiro–Wilk test, while homogeneity of variance was assessed using Levene's test. Because not all datasets met parametric assumptions, non-parametric Kruskal–Wallis tests were applied to assess differences in microplastic abundance and PLI among stations. Pearson correlation analysis was used to examine the relationship between microplastic size and abundance, while Spearman correlation was used to evaluate the relationship between microplastic abundance and PLI. Multivariate spatial patterns of microplastic characteristics (shape and color) across stations were analyzed using non-metric multidimensional scaling (NMDS). All statistical analyses were performed using RStudio and Microsoft Excel, with a significance level of $p < 0.05$.

Quality assurance and quality control (QA/QC)

To ensure data reliability and minimize contamination bias, quality assurance and quality control (QA/QC) procedures were applied throughout sampling and laboratory analysis. All glassware and sampling equipment were rinsed with tap water followed by ultrapure water before use, while laboratory surfaces were regularly cleaned, and analyses were conducted in a controlled indoor environment to reduce airborne contamination.

Procedural blanks (n = 3) were prepared by filtering ultrapure water using the same vacuum filtration system and analytical procedures as the environmental samples. No microplastic particles were detected in the blanks, indicating negligible contamination during sample processing. All suspected microplastic particles were examined under a stereomicroscope and independently verified by two analysts. Any discrepancies were resolved through joint re-evaluation to ensure consistency in shape, color, and size classification.

All 300 mL samples were filtered completely without subsampling to maximize particle recovery. However, microplastics smaller than the 0.45 µm filter pore size may not have been fully retained. In addition, recovery efficiency tests using spiked reference particles were not conducted; therefore, the reported abundances should be considered conservative estimates, as potential particle losses during filtration and sample processing could not be quantified. Future studies should incorporate recovery experiments to improve analytical accuracy and enable correction of abundance estimates.

Uncertainty and analytical limitations

This study acknowledged several sources of uncertainty associated with microplastic identification and quantification. Particle classification was based solely on visual examination without spectroscopic confirmation of polymer composition, which may result in the misclassification of natural fibers or other non-plastic materials with similar morphological characteristics. Consequently, uncertainty remains regarding the exact polymer composition and classification accuracy of some particles.

Although procedural blanks were used to minimize contamination, recovery efficiency experiments using spiked reference particles were not performed. Therefore, potential particle losses during sample processing, filtration, and microscopic examination could not be quantified, which may affect absolute abundance estimates. Future studies should incorporate recovery assessments and spectroscopic techniques, such as FTIR or Raman spectroscopy, to validate particle identification, improve analytical accuracy, and strengthen the reliability of microplastic monitoring in coastal environments.

RESULTS AND DISCUSSION

Microplastic abundance in surface coastal waters

Microplastics were detected at all sampling stations in the coastal waters of Makassar, indicating widespread contamination throughout the study area. Abundance showed clear spatial variability, with median values ranging from 23.33 to 76.67 particles/L and a maximum concentration of 326.67 particles/L recorded at Pelabuhan Soekarno-Hatta (Table 3). The high abundance and variability observed at this station likely reflect intensive anthropogenic activities, including port operations, shipping traffic, and associated waste inputs. Similar patterns have been reported in urbanized coastal and estuarine environments, where ports often act as microplastic

Table 3. Microplastic abundance in surface coastal waters of Makassar (particles/L)

Station	Min	Q1	Median	Mean	Q3	Max
Barombong	26.67	28.34	30.00	77.78	103.34	176.67
Pelabuhan Soekarno	56.67	61.67	66.67	150.00	196.67	326.67
Paotere	33.33	41.67	50.00	45.55	51.67	53.33
Tallo	30.00	31.67	33.33	91.11	121.67	210.00
Tanjung	16.67	20.00	23.33	62.22	85.00	146.67
Untia	36.67	56.67	76.67	92.22	120.00	163.33

accumulation hotspots due to continuous human pressure and hydrodynamic processes (Ainali et al., 2026; Luo et al., 2019; Wang et al., 2022).

In contrast, Tanjung Station exhibited the lowest median abundance (23.33 particles/L), suggesting lower direct anthropogenic influence. Nevertheless, the presence of microplastics at all stations indicates that contamination is not restricted to local sources, but is also affected by coastal circulation, riverine transport, and atmospheric deposition (Zhang, 2017). These findings support previous studies showing that microplastics can be widely dispersed across interconnected aquatic environments through both local and regional transport mechanisms (Ainali et al., 2026; Fitri et al., 2026; Jong et al., 2022; Pourebrahimi and Pirooz, 2023).

Normality testing using the Shapiro–Wilk test showed that microplastic abundance data were not normally distributed ($W = 0.7666$, $p = 0.0005$), whereas Levene's test indicated homogeneous variances among sampling stations ($p = 0.9099$). Therefore, the differences in abundance were evaluated using the non-parametric Kruskal–Wallis test. The analysis revealed no statistically significant differences among stations ($H = 4.4419$, $p = 0.4877$), indicating that although spatial variation in abundance was observed descriptively, the differences were not statistically significant. This pattern suggests that strong hydrodynamic mixing and transport processes may promote the redistribution of microplastics throughout the coastal system, resulting in overlapping concentration ranges among stations. Similar findings have been reported in coastal and estuarine environments where transport processes dominate over localized source effects, producing weak statistical differentiation despite visible spatial variability (Ainali et al., 2026; Wang et al., 2022; Zhang, 2017; Luo et al., 2019).

The distribution pattern is illustrated in Figure 2, which shows variations in abundance ranges and maximum values among stations. Pelabuhan Soekarno-Hatta and Tallo exhibited wider interquartile ranges and higher maximum abundances, suggesting localized pollution hotspots

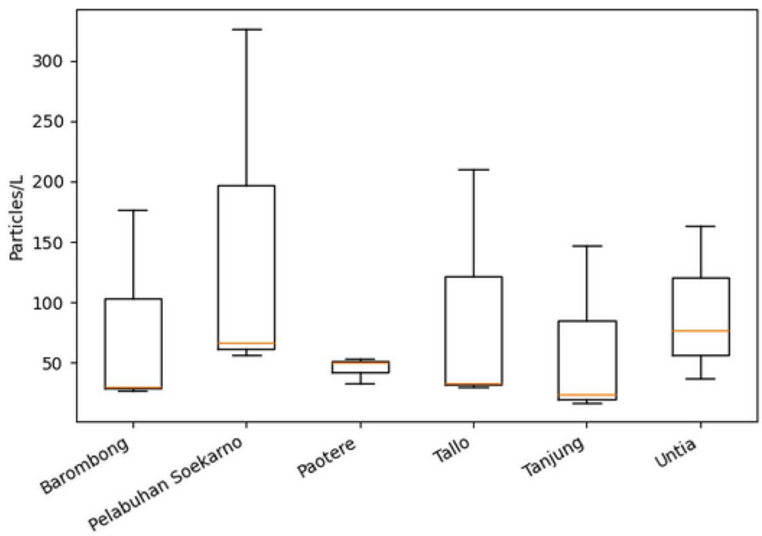

Figure 2. Boxplot of microplastic abundance in coastal waters of Makassar

associated with urban runoff, port activities, and industrial inputs (Fitri et al., 2026; Jong et al., 2022). However, the absence of significant statistical differences supports the view that coastal circulation facilitates system-wide redistribution of microplastics, a phenomenon commonly observed in dynamic coastal environments (Wang et al., 2022; Ainali et al., 2026).

Physical characteristics of microplastics

Color distribution

The microplastics identified in the coastal waters of Makassar were classified into five color categories: blue, black, red, green, and transparent. Blue particles dominated at all sampling stations, accounting for 34.8–54.2% of total microplastics, with the highest proportions recorded at Untia (54.2%; 45 particles) and Barombong (51.4%; 36 particles), and the lowest at Pelabuhan Soekarno (34.8%; 47 particles). The predominance of blue microplastics is commonly associated with synthetic fishing gear, ropes, and textile fibers widely used in coastal fisheries and maritime activities. Similar patterns have been reported in Indonesian and other coastal environments, influenced by fishing activities and domestic wastewater inputs (Hossain et al., 2025; Mathew et al., 2024; Borriello et al., 2023).

Black microplastics represented the second most abundant color category, reaching the highest proportion at Paotere (43.9%; 18 particles), followed by Tallo (32.9%; 27 particles) and Pelabuhan Soekarno (32.6%; 44 particles), while the lowest proportion occurred at Tanjung (19.6%; 11 particles). These particles are often associated with tire wear, urban runoff, and industrial discharges, reflecting strong land-based anthropogenic influences in urbanized coastal areas (Dey et al., 2024; Patidar et al., 2024). Red particles contributed a moderate proportion (11.0–21.5%), with the highest value observed at Pelabuhan Soekarno (21.5%; 29 particles) and the lowest at Tallo (11.0%; 9 particles). Green and transparent particles occurred at relatively low proportions and showed no consistent spatial pattern.

Figure 3 summarizes the spatial distribution of microplastic color fractions among sampling stations. Overall, the observed color composition indicates that both marine-based sources, particularly fishing activities, and land-based sources such as urban runoff jointly influence microplastic contamination in the study area, consistent with the findings from mixed-source coastal

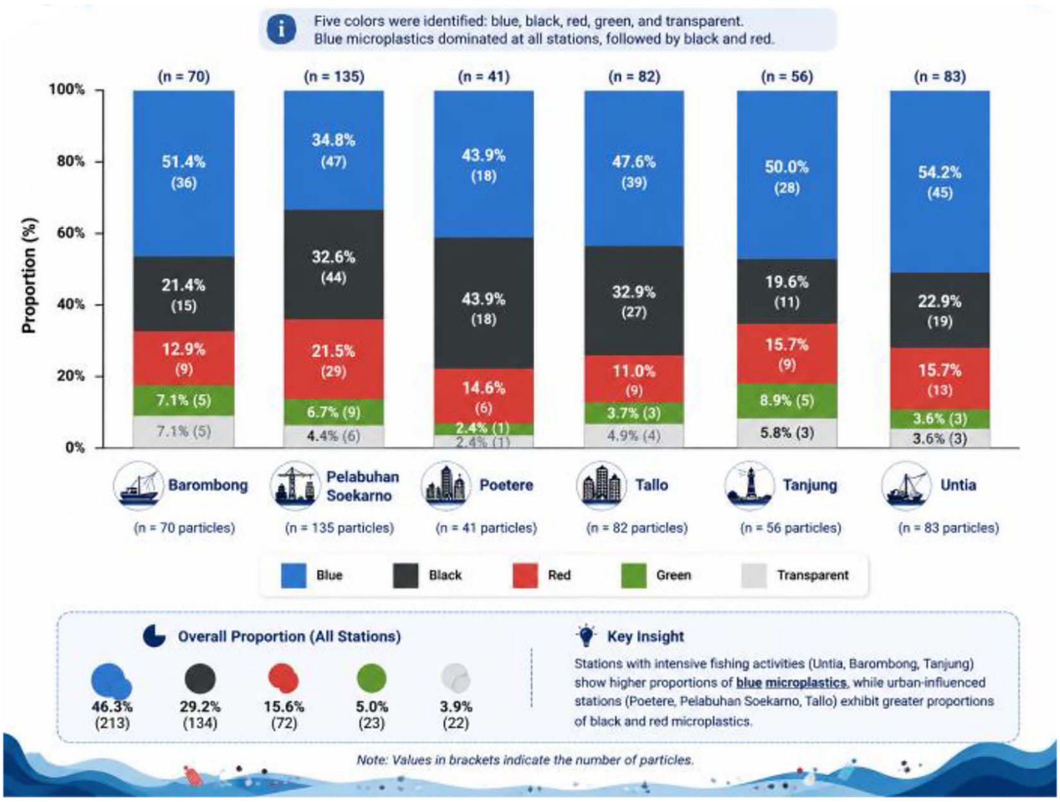

Figure 3. Proportion of microplastics colors in surface coastal waters of Makassar

environments worldwide (Yu and Singh, 2023; Pourebrahimi and Pirooz, 2023).

Shape distribution

As shown in Figure 4, fiber (line) microplastics overwhelmingly dominated all sampling stations in the coastal waters of Makassar, accounting for approximately 96.79% of the total identified particles. Fragment and film microplastics occurred only in minor proportions, with slightly greater diversity observed at Untia, possibly due to hydrodynamic mixing and exposure to multiple pollution sources. The predominance of fibers indicates strong anthropogenic influences, particularly from wastewater discharge, textile-related effluents, and fishing activities. This pattern is consistent with the observations by Lusher et al. (2020), who reported fibers as the most common microplastic shape in marine environments because of their widespread occurrence and efficient transport within aquatic systems.

The dominance of fiber-shaped microplastics observed in this study agrees with findings from various aquatic environments worldwide. Wastewater-impacted systems have been identified as major sources of synthetic fibers released from household laundry and textile-related activities (Ainali et al., 2026; Hossain et al., 2025). In addition, fiber accumulation has been widely reported in coastal environments influenced by riverine inputs and densely populated settlements, including Indonesian coastal waters (Borriello et al., 2023; Dwiyitno et al., 2024; Fitri et al., 2026). Overall, the results suggest that both land-based wastewater inputs and marine-based fishing activities contribute to the high abundance of fiber microplastics in the coastal waters of Makassar, reflecting a common pattern of mixed-source contamination in coastal ecosystems.

Size distribution

As shown in Table 4, the microplastics in the coastal waters of Makassar were dominated by the 0.1–1.0 mm size class (64.24%), followed by particles measuring 1.0–5.0 mm, while the <0.1 mm fraction contributed the least. Tanjung and Untia exhibited the highest proportions of smaller particles, suggesting more advanced fragmentation processes associated with strong hydrodynamic conditions, wave action, and prolonged environmental exposure. In contrast, Pelabuhan Soekarno contained a relatively higher proportion of larger particles (1.0–5.0 mm), indicating proximity to primary sources such as shipping activities, port operations, and direct plastic inputs prior to extensive degradation. Similar patterns have been reported in other coastal environments, where smaller particles dominate under continuous physical abrasion and transport processes (Zhang, 2017; Wang et al., 2022). Environmental factors, including UV radiation, mechanical abrasion, and hydrodynamic turbulence, further contribute to progressive particle fragmentation (Dey et al., 2024; Mathew et al., 2024).

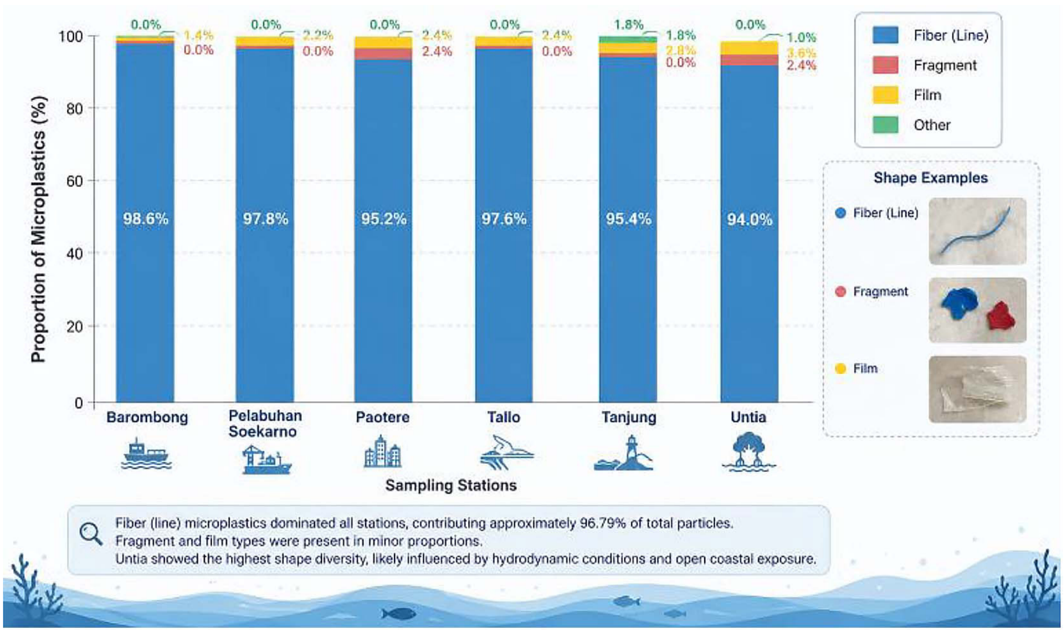

Figure 4. Shape distribution of microplastics in the coastal waters of Makassar

Table 4. Size distribution of microplastics in surface coastal waters of Makassar

Station	<0.1 mm (%)	0.1–1.0 mm (%)	1.0–5.0 mm (%)
Barombong	11.4	63.2	25.4
Pelabuhan Soekarno	7.6	56.1	36.3
Paotere	5.8	62.5	31.7
Tallo	4.9	66.8	28.3
Tanjung	3.6	73.2	23.2
Untia	1.7	70.0	28.3
Mean (%)	5.14	64.24	30.62

The predominance of the 0.1–1.0 mm fraction is consistent with the previous studies showing that microplastic size distribution is strongly influenced by transport processes and environmental residence time. Smaller particles tend to accumulate through prolonged degradation and repeated transport among riverine, estuarine, and marine environments (Ainali et al., 2026; Dwiyitno et al., 2024; Fitri et al., 2026). In addition, the particles smaller than 1 mm are considered more bioavailable and more readily incorporated into aquatic food webs, potentially increasing ecological risks (Borriello et al., 2023; Saeedi, 2024). Overall, the observed size distribution reflects an active fragmentation process driven by both anthropogenic inputs and natural hydrodynamic forces, consistent with global patterns of microplastic degradation and transport.

Relationship between microplastic size and abundance

The weak negative relationship between microplastic size and abundance (r = 0.3712) indicates that particle size alone does not strongly control microplastic abundance in the coastal waters of Makassar. Instead, microplastic distribution appears to be influenced by a combination of hydrodynamic processes and multiple anthropogenic sources. Similar studies have shown that transport mechanisms such as coastal circulation, mixing zones, and estuarine dynamics can redistribute particles of different sizes, resulting in weak or non-linear size–abundance relationships (Wang et al., 2022; Zhang, 2017; Luo et al., 2019). Although photochemical weathering and mechanical fragmentation contribute to the generation of smaller particles (Dey et al., 2024; Mathew et al., 2024), the continuous input of microplastics from various sources may obscure the direct relationships between particle size and abundance.

These findings support the view that microplastic dynamics in coastal ecosystems are governed by interconnected environmental and anthropogenic factors, rather than by particle size alone. In interconnected aquatic systems, continuous transport and pollutant exchange can homogenize size distributions across habitats (Ainali et al., 2026). Likewise, studies in Indonesian coastal environments have shown that anthropogenic pressure and hydrological connectivity exert stronger influences on microplastic distribution than particle-size characteristics (Fitri et al., 2026). Furthermore, all size fractions contribute to environmental exposure, with smaller particles (<1 mm) posing greater ecological concern because of their higher bioavailability and potential transfer through food webs (Borriello et al., 2023). Therefore, the absence of a strong size–abundance relationship suggests that microplastic contamination in Makassar is driven by the combined effects of multiple pollution sources, environmental transport, and ongoing degradation processes within a dynamic coastal system.

Spatial pattern of microplastic characteristics (NMDS analysis)

The non-metric multidimensional scaling (NMDS) results presented in Table 5 and Figure 5 reveal clear spatial differentiation in microplastic characteristics (shape and color) among the six sampling stations in Makassar coastal waters. Pelabuhan Soekarno was positioned furthest along NMDS1 (−0.3249), indicating a distinct microplastic composition likely associated with intensive port activities and continuous anthropogenic inputs. Untia showed strong separation along NMDS2 (−0.2970), suggesting a different pollution signature influenced by open-coastal hydrodynamics and mixed marine–terrestrial sources. In contrast, Paotere and Tanjung clustered closely

Table 5. NMDS coordinates of sampling stations based on microplastic characteristics (shape and color)

Station	NMDS1	NMDS2
Barombong	0.0361	-0.0427
Pelabuhan Soekarno	-0.3249	0.0691
Paotere	0.1968	0.1006
Tallo	-0.0035	0.1641
Tanjung	0.1352	0.0058
Untia	-0.0396	-0.2970

in the ordination space, reflecting similar microplastic compositions that may be related to comparable land-use patterns and moderate anthropogenic pressure. These patterns are consistent with the studies demonstrating that hydrodynamic transport and estuarine mixing processes generate spatially heterogeneous microplastic distributions even over relatively small geographic scales (Zhang, 2017; Wang et al., 2022). The observed clustering further highlights the influence of anthropogenic activities and environmental connectivity on microplastic composition. Previous studies have shown that the differences in local pollution sources, hydrological connectivity, and exchanges among riverine, estuarine, and marine environments can produce distinct microplastic assemblages across coastal systems (Luo et al., 2019; Ainali et al., 2026). Similar patterns have also been reported in Indonesian coastal waters, where fisheries, urban runoff, and river discharge strongly influence spatial variability in microplastic composition (Fitri et al., 2026). Therefore, the NMDS results indicate that the microplastic pollution in Makassar is highly site-specific, reflecting variations in anthropogenic pressure, land-use intensity, and coastal hydrodynamic conditions.

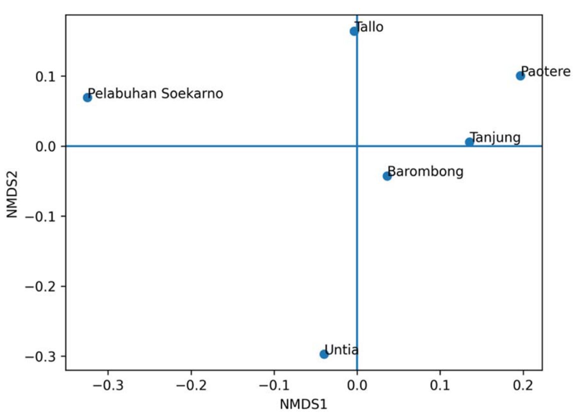

Figure 5. NMDS ordination of microplastic characteristics

Environmental implications of microplastic pollution

The PLI values in surface coastal waters of Makassar ranged from 1.00 to 4.43 across all sampling stations, indicating widespread microplastic contamination in the study area. As presented in Table 6, Pelabuhan Soekarno had the highest median PLI (2.00) and maximum value (4.43), reflecting strong anthropogenic pressure from port activities, shipping traffic, and continuous waste input. In contrast, Paotere showed lower variability and more stable values (median 1.73; max 1.79), indicating more consistent but moderate pollution sources. These spatial differences are consistent with Wang et al. (2022), who reported that the estuarine and coastal systems with high human activity tend to accumulate more pollutants due to continuous input and retention processes. Similarly, Luo et al. (2019) and Zhang (2017) found that microplastic pollution in urban coastal areas is strongly influenced by hydrodynamic transport and local anthropogenic discharges, resulting in spatially uneven but persistent contamination.

Figure 6 further illustrates the distribution of PLI across stations, showing a clear gradient of pollution intensity, with Pelabuhan Soekarno consistently having the highest values. Although all stations are classified as "low pollution" (PLI < 10), all PLI values above 1 indicate that microplastic contamination is present across the entire study area. This pattern is consistent with Ainali et al. (2026), who showed that interconnected river–estuary–marine systems allow continuous redistribution and accumulation of microplastics, creating a baseline level of contamination. Similar findings by Fitri et al. (2026) in Indonesian coastal waters highlight that urban runoff, fisheries, and port activities are key drivers of spatial variation in contamination. In addition, Borriello et al. (2023) and Eze et al. (2024) emphasized that persistent microplastic presence may contribute to ecological risks through food web transfer and potential human exposure. Overall, the results suggest low acute risk but indicate widespread chronic contamination in the Makassar coastal system.

Microplastic presence was detected at all sampling stations, with PLI values between 1.00 and 4.43, showing variability in pollution intensity across locations. Although the Kruskal–Wallis test ($p = 0.4877$) showed no significant differences in microplastic abundance among stations, spatial patterns and index results still indicate

Table 6. Pollution load index (PLI) values across sampling stations in Makassar coastal waters

Station	Min	Median	Max
Barombong	1.26	1.34	3.26
Tanjung	1.00	1.18	2.97
Pelabuhan Soekarno	1.84	2.00	4.43
Paotere	1.41	1.73	1.79
Tallo	1.34	1.41	3.55
Untia	1.48	2.14	3.13

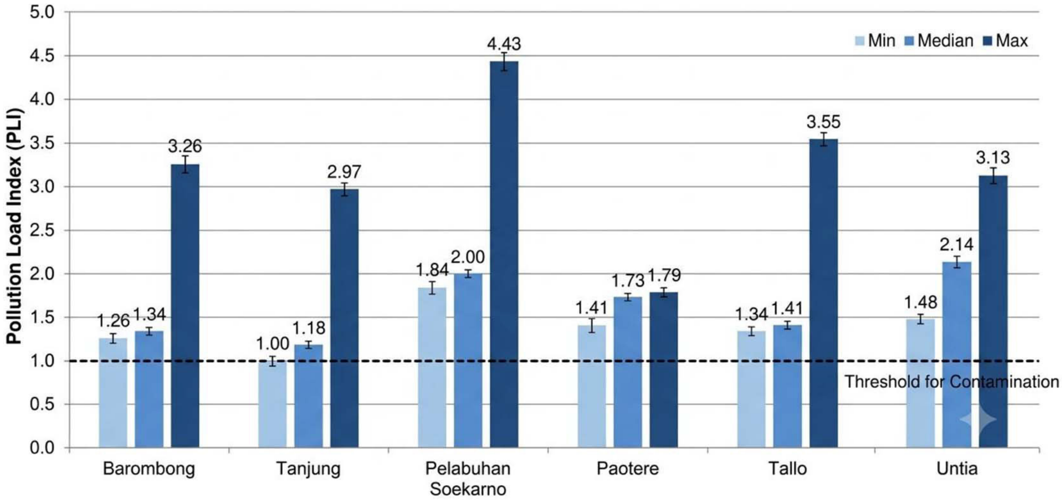

Figure 6. Distribution of pollution load index (PLI) across sampling stations in Makassar coastal waters

different levels of local anthropogenic influence. This suggests that variability is driven more by local inputs and transport processes rather than statistically distinct differences among stations. However, this finding does not indicate differences at the population level.

This study did not include toxicological assessment or exposure modeling; therefore, any interpretation of ecological or human health risks is indirect. Further studies involving bioaccumulation and toxicological endpoints are needed to better assess potential impacts. Based on the Spearman correlation analysis, which shows a very strong positive relationship ($r = 0.9896$, $p < 0.05$), Figure 6 indicates that higher microplastic abundance corresponds to higher PLI values across stations. This relationship is expected because PLI is calculated directly from abundance-based contamination factors. Therefore, PLI is used as an integrated indicator of contamination rather than an independent variable in correlation analysis. The strong correlation should be interpreted carefully because both variables originate from the same dataset, meaning the relationship is mathematical rather than ecological. Thus, it does not represent causation but structural dependence between the variables.

In this study, PLI was used as a comparative index to describe spatial differences in contamination levels. Since it is derived from microplastic abundance, correlations between PLI and abundance provide limited additional ecological meaning. Therefore, the focus of this study was on spatial distribution patterns rather than statistical relationships between these variables.

The strongest alignment was observed at Pelabuhan Soekarno, where Figure 6 shows the highest PLI values (median = 2.00; max = 4.43), reflecting high microplastic accumulation likely linked to intense port activities. In contrast, areas such as Tanjung consistently showed the lowest values (minimum = 1.00), indicating lower anthropogenic pressure. Overall, the similarity between spatial patterns and statistical results confirms that PLI is a reliable indicator for describing relative contamination intensity in the Makassar coastal ecosystem.

The PLI in this study was intended as a relative indicator to compare contamination among stations. It provides useful spatial information but should be interpreted as exploratory rather than a direct measure of environmental risk. Because it is derived from concentration data, it reflects internal variability within the dataset rather than independent ecological risk levels.

An additional limitation of this study is the absence of recovery efficiency testing. Recovery experiments are important in microplastic research to quantify potential losses during sample processing. Although procedural blanks were applied to reduce contamination, future studies should include recovery tests using reference particles of different sizes and shapes to improve data accuracy and comparability.

Finally, microplastic identification was based on visual observation, which has limitations in accurately determining polymer types. The lack of FTIR or Raman spectroscopy means that some particles may have been misclassified, including non-plastic synthetic fibers or natural materials with a similar appearance. However, visual identification remains widely used in preliminary studies when advanced instruments are not available. Therefore, the results should be interpreted as indicative of contamination patterns rather than precise polymer-specific measurements.

CONCLUSIONS

This study showed that microplastic pollution is widely present in the surface coastal waters of Makassar, Indonesia, with all sampling stations indicating detectable contamination. Microplastic abundance varied across locations, indicating spatial differences influenced by anthropogenic activities, especially at Pelabuhan Soekarno-Hatta, which recorded the highest concentrations and PLI values. Fiber-shaped microplastics dominated the samples (96.79%), with blue as the most common color and particles mainly in the 0.1–1.0 mm size range. These results suggest major contributions from textile sources, fishing activities, and ongoing fragmentation of larger plastics.

Although statistical analysis showed no significant differences in abundance among stations, multivariate analysis (NMDS) revealed clear spatial differences in microplastic composition. This indicates that while overall abundance is relatively similar, the composition and distribution patterns vary across locations. As expected, the stations with higher microplastic abundance generally showed higher PLI values because the index is derived from abundance-based contamination factors. Therefore, PLI is used as an integrated indicator of contamination, rather than an independent variable for correlation analysis. Overall, PLI proved to be a useful tool for comparing spatial differences in microplastic pollution, but it should be interpreted as a descriptive indicator, rather than a direct measure of environmental risk.

The observed spatial patterns reflect differences in human activities and hydrodynamic conditions across the study area. Based on this, future management should focus on continuous monitoring in urban and port-influenced areas, especially at hotspots such as Pelabuhan Soekarno-Hatta and Tallo. The efforts to reduce microplastic pollution should include improving waste management systems, strengthening wastewater treatment, and reducing plastic leakage from urban runoff and fishing activities. Integrating microplastic monitoring into routine coastal assessments using standardized indices such as PLI is also recommended to support long-term environmental evaluation.

Future research should expand to sediment and biota compartments to better understand trophic transfer and potential human health risks, as well as include higher-resolution temporal studies to capture seasonal variability in microplastic distribution. Since all results are based on visual identification, the findings should be considered semi-quantitative and interpreted with methodological limitations in mind. Future studies should incorporate FTIR or Raman spectroscopy to confirm polymer types and improve analytical accuracy in assessing microplastic pollution in the Makassar coastal ecosystem.

REFERENCES

1. Ainali, N.M., Bikiaris, D.N. and Lambropoulou, D.A. (2026). Microplastics across interconnected aquatic matrices: a comparative study of marine, riverine, and wastewater matrices in Northern Greece, *Applied Sciences*, *16*(2), 772. https://doi.org/10.3390/app16020772
2. Borriello, L., Scivicco, M., Cacciola, N.A., Esposito, F., Severino, L. and Cirillo, T. (2023). Microplastics, a global issue: human exposure through environmental and dietary sources, *Foods*, *12*(18), 3396. https://doi.org/10.3390/foods12183396
3. Dey, S., Veerendra, G.T.N., Babu, P.S.S.A., Manoj, A.V.P. and Nagarjuna, K. (2024). Degradation of plastics waste and its effects on biological ecosystems: a scientific analysis and comprehensive

review, *Biomedical Materials & Devices*, *2*(1), 70–112. https://doi.org/10.1007/s44174-023-00085-w

4. Dwiyitno, D., Schwanen, C., Januar, H.I., Ariyani, F., Irianto, H.E. and Schwarzbauer, J. (2024). Microplastic profile in the sediment of Jakarta Bay estuary, Indonesia: characterization based on size fraction and the potential risk to the ecosystem, *Regional Studies in Marine Science*, *73*, 103465. https://doi.org/10.1016/j.rsma.2024.103465
5. Eze, C.G., Nwankwo, C.E., Dey, S., Sundaramurthy, S. and Okeke, E.S. (2024). Food chain microplastics contamination and impact on human health: a review, *Environmental Chemistry Letters*, *22*(4), 1889–1927. https://doi.org/10.1007/s10311-024-01734-2
6. Fitri, W.E., Putra, A., Deswati, D., Nofrita, N. and Syamsuardi, S. (2026). First multi-estuary assessment of microplastics along the West Sumatran coast, Indonesia: spatial patterns, polymer composition, and anthropogenic drivers, *Regional Studies in Marine Science*, 105126. https://doi.org/10.1016/j.rsma.2026.105126
7. Hossain, M.I., Zhang, Y., Haque, A.N.M.A. and Naebe, M. (2025). Fibrous microplastics release from textile production phases: a brief review of current challenges and applied research directions, *Materials*, *18*(11), 2513. https://doi.org/10.3390/ma18112513
8. Jong, M.-C., Tong, X., Li, J., Xu, Z., Chng, S.H.Q., He, Y. and Gin, K.Y.-H. (2022). Microplastics in equatorial coasts: pollution hotspots and spatiotemporal variations associated with tropical monsoons, *Journal of Hazardous Materials*, *424*(Pt C), 127626. https://doi.org/10.1016/j.jhazmat.2021.127626
9. Koner, S., Azhagesan, A., Kanimozhi, S. and Chandrasekaran, N. (2026). Flood-driven microplastics pollution and its ecotoxicological footprint in shallow marine habitats, *Frontiers in Marine Science*, *13*, 1784937. https://doi.org/10.3389/fmars.2026.1784937
10. Luo, W., Su, L., Craig, N.J., Du, F., Wu, C. and Shi, H. (2019). Comparison of microplastic pollution in different water bodies from urban creeks to coastal waters, *Environmental Pollution, 246*, 174–182. https://doi.org/10.1016/j.envpol.2018.11.015
11. Lusher, A.L., Bråte, I.L.N., Munno, K., Hurley, R.R. and Welden, N.A. (2020). Is it or isn't it: the importance of visual classification in microplastic characterization, *Applied Spectroscopy*, *74*(9), 1139–1153. https://doi.org/10.1177/0003702820930733
12. Mathew, J.T., Inobeme, A., Adetuyi, B.O., Adetunji, C.O., Popoola, O.A., Olaitan, F.Y. *et al.* (2024). General introduction of microplastic: uses, types, and generation, in Shahnawaz, M., Adetunji, C.O., Dar, M.A. and Zhu, D. (eds.) *Microplastic Pollution*. Springer, Singapore, 3–21. https://doi.org/10.1007/978-981-99-8357-5_1
13. Patidar, K., Ambade, B., Younis, A.M. and Alluhayb, A.H. (2024). Characteristics, fate, and sources of microplastics contaminant in surface water and sediments of river water, *Physics and Chemistry of the Earth*, 103596. https://doi.org/10.1016/j.pce.2024.103596
14. Pinna, M., Zangaro, F., Saccomanno, B., Scalone, C., Bozzeda, F., Fanini, L. and Specchia, V. (2023). An overview of ecological indicators of fish to evaluate the anthropogenic pressures in aquatic ecosystems: from traditional to innovative DNA-based approaches, *Water*, *15*(5), 949. https://doi.org/10.3390/w15050949
15. Poikane, S., Ritterbusch, D., Argillier, C., Białokoz, W., Blabolil, P., Breine, J., Jaarsma, N.G., Krause, T., Kubečka, J., Lauridsen, T.L., Nõges, P., Peirson, G. and Virbickas, T. (2017). Response of fish communities to multiple pressures: development of a total anthropogenic pressure intensity index, *Science of the Total Environment*, *586*, 502–511. https://doi.org/10.1016/j.scitotenv.2017.01.211
16. Pourebrahimi, S. and Pirooz, M. (2023). Microplastic pollution in the marine environment: A review, *Journal of Hazardous Materials Advances*, *10*, 100327. https://doi.org/10.1016/j.hazadv.2023.100327
17. Rakib, M.R.J., Sarker, A., Ram, K., Uddin, M.G., Walker, T.R., Chowdhury, T., Uddin, J., Khandaker, M.U., Rahman, M.M. and Idris, A.M. (2023). Microplastic toxicity in aquatic organisms and aquatic ecosystems: A review, *Water, Air, & Soil Pollution*, *234*(1), 52. https://doi.org/10.1007/s11270-023-06062-9
18. Rodríguez-Seijo, A. and Pereira, R. (2017). Morphological and physical characterization of microplastics, in Rocha-Santos, T.A.P. and Duarte, A.C. (eds.) *Characterization and Analysis of Microplastics*. Comprehensive Analytical Chemistry, Vol. 75. Elsevier, pp. 49–66. https://doi.org/10.1016/bs.coac.2016.10.007
19. Saeedi, M. (2024). How microplastics interact with food chain: a short overview of fate and impacts, *Journal of Food Science and Technology*, *61*(3), 403–413. https://doi.org/10.1007/s13197-023-05720-4
20. Wang, T., Zhao, S., Zhu, L., McWilliams, J.C., Galgani, L., Md Amin, R., Nakajima, R., Jiang, W. and Chen, M. (2022). Accumulation, transformation and transport of microplastics in estuarine fronts, *Nature Reviews Earth & Environment*, *3*, 795–805. https://doi.org/10.1038/s43017-022-00349-x
21. Yu, R.-S. and Singh, S. (2023). Microplastic pollution: threats and impacts on global marine ecosystems, *Sustainability*, *15*(17), 13252. https://doi.org/10.3390/su151713252
22. Zhang, H. (2017). Transport of microplastics in coastal seas, *Estuarine, Coastal and Shelf Science*, *199*, 74–86. https://doi.org/10.1016/j.ecss.2017.09.032
23. Zhou, Q., Tu, C., Fu, C., Li, Y., Zhang, H., Xiong, K., Zhao, X., Li, L., Waniek, J.J. and Luo, Y. (2020). Characteristics and distribution of microplastics in the coastal mangrove sediments of China, *Science of the Total Environment*, *703*, 134807. https://doi.org/10.1016/j.scitotenv.2019.134807