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Original Article

Impact of Fengal cyclone on spatial and seasonal variation of microplastics contamination in surface waters along the Ennore Coast, southeast coast of India

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Abstract
Microplastic pollution has emerged as a major environmental concern in rapidly urbanising and industrialised ecosystems. This study investigated the spatial and seasonal distribution and ecological risk assessment of microplastics in the Ennore coastal waters of southeast India covering Thalankuppam, Kattupalli, and Ennore Beach across six sampling seasons from monsoon 2024 to post-monsoon 2026. Microplastics were isolated, followed by stereomicroscopic characterisation based on shape, colour, and size. Polymer composition was confirmed using ATR–FTIR spectroscopy, and ecological risk was assessed using the contamination factor (CF), pollution load index (PLI), polymer hazard index (PHI) and potential ecological risk index (PERI). Microplastic abundance ranged from 85 to 215 particles L^{-1}, with the highest seasonal recorded during post-monsoon 2025 (185 particles L^{-1}) and the lowest during summer 2025 (95 particles L^{-1}). Spatially, Kattupalli (110–215 particles L^{-1}) consistently recorded the highest microplastic abundance. Fragments and foam were the dominant morphotypes, while black and blue particles predominated among the colour classes. The 0.5–1 mm size fraction was the most abundant, suggesting extensive secondary fragmentation. ATR–FTIR analysis identified polyethylene (28–32%) and polypropylene (15–18%) as the dominant polymers, indicating packaging materials, fishing gear, and urban plastic waste as major sources. Risk assessment revealed moderate to considerable contamination (CF: 2.12–3.04), low pollution load (PLI: 1.46–1.78), very high polymer hazard (PHI: 5789–7293) and minor ecological risk (PERI: 57.89–72.93). These findings provide baseline information for monitoring microplastic pollution and support effective management strategies for the Ennore coastal ecosystem.

Keywords: bio magnification; coastal pollution; cyclone Fengal; ecological risk assessment; Ennore Coast; microplastics

1 | INTRODUCTION

Microplastics (MPs), defined as plastic particles smaller than 5 mm, have emerged as one of the most widespread pollutants in aquatic environments due to the rapid increase in global plastic production and inadequate waste management practices (Gao *et al*. 2021). Global plastic production has reached approximately 430.9 million tonnes annually (Plastics Europe 2025), resulting in the continuous release of plastic debris into terrestrial and aquatic ecosystems. Owing to their persistence, widespread occurrence, and resistance to degradation, microplastics have become a major environmental concern. Based on their origin, microplastics are classified as primary microplastics, which are intentionally manufactured at microscopic sizes, and secondary microplastics, which are generated through the fragmentation of larger plastic materials by physical, chemical, and biological processes (Veerasingam *et al*. 2021). They occur in various forms, including fragments, fibres, films, foams, and irregular particles, and consist predominantly of polymers such as polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), polyamide (PA), and polyvinyl chloride (PVC) (Chen and Chen 2020). These particles are extensively distributed in oceans, estuaries, coastal waters, beaches, and seabed sediments (Jualaong *et al*. 2021). Microplastics present in coastal environments primarily originate from terrestrial runoff, tourism, maritime transport, fishing, aquaculture, sewage discharge, stormwater, industrial effluents, and riverine inputs (Li *et al*. 2018, 2020; Rahman *et al*. 2020; James *et al*. 2021). Their distribution is strongly influenced by environmental factors such as tides, waves, currents, rainfall, and wind patterns (Karthik *et al*. 2018; Gao *et al*. 2021). Due to their small size, microplastics are readily ingested by aquatic organisms, causing physical injury, oxidative stress, DNA damage, neurological disorders, reduced growth and reproductive performance, while also acting as vectors for persistent organic pollutants (POPs), thereby increasing ecological and human health risks (Lima *et al*. 2015; Liu *et al*. 2019; Prata *et al*. 2020; Sánchez-Hernández *et al*. 2021).

Cyclone Fengal, a severe cyclonic storm that made landfall along the Tamil Nadu–Puducherry coast on 30 November 2024 with sustained wind speeds of 70–90 km h^{-1}, caused intense rainfall, widespread flooding, and substantial damage to coastal ecosystems (India Meteorological Department 2024). The cyclone significantly altered coastal hydrodynamics, enhanced terrestrial runoff, and increased the transport of sediments, nutrients, and plastic debris into adjacent estuarine and marine environments, potentially influencing the spatial distribution and accumulation of microplastics along the Ennore Coast (Bhuvana *et al*. 2024; Kanmani *et al*. 2026). Therefore, the present study aimed to (i) assess the spatial and seasonal distribution of microplastics in surface water, (ii) characterize microplastics based on their shape, size, colour, and polymer composition, (iii) evaluate the ecological risk assessment in the selected sites. The findings provide baseline information on cyclone-induced microplastic contamination and support future environmental monitoring and management of the Ennore coastal ecosystem.

2 | METHODOLOGY

2.1 Study area

Surface water samples were collected from three sampling sites along the Ennore coast (Figure 1) Three sampling stations were selected along the Ennore coastal region: Thalankuppam (Station I; 13.225773°N, 80.320042°E), a traditional fishing village with extensive mangrove vegetation; Kattupalli (Station II; 13.239928°N, 80.315878°E), located near the sea mouth of Ennore Creek, where estuarine waters enter the Bay of Bengal; and Ennore Beach (Station III; 13.231843°N, 80.331292°E), an industrialised sandy coast influenced by thermal power plants, fertilizer industries, coal handling facilities and North Chennai Port. Samples were collected from each station from monsoon 2024 to post-monsoon 2026. The geographical location of the study area was noted by using a standard GPS in Android phone (Realme 12+ pro - GPS Map Camera: Geo Tagging Application).

2.2 Sample collection

Surface water samples were collected at three sampling sites across six seasons: monsoon 2024, post-monsoon 2025, summer 2025, pre-monsoon 2025, monsoon 2025 and post-monsoon 2026. Surface water samples were collected using a plankton net with a mesh size of 48 µm, which was operated at the minimum speed to prevent damage. To achieve uniform filtration, the net was dragged horizontally at the water's surface (2–3 m depth) for one km from the shoreline by using a fishing FRP boat with low towing speed (Keerthika *et al.* 2022a; Ashik *et al.* 2026). MP abundance was represented as particles per litre (particles L^{-1}) using the following formula:

$$\text{MP abundance} = \text{MP counted} / (V \times 1000)$$

Where, V in m³ is converted to litres by multiplication by 1000.

2.3 Extraction of microplastics

Water samples collected in triplicate from the cod end at each station were transferred to pre-cleaned containers, preserved with 4% buffered formalin and transported to the laboratory. Organic matter was digested using 30 mL of 30% H_2O_2 per litre of sample for 24 hr, followed by density separation with saturated zinc chloride ($ZnCl_2$). The supernatant was vacuum-filtered through glass-fibre filters, which were dried at 40°C in a hot air oven. Water and sediment samples were analysed in triplicate to ensure reliable extraction efficiency (Qiu *et al*. 2016; Sathish *et al*. 2020; Keerthika *et al*. 2022b; Ashik *et al*. 2026).

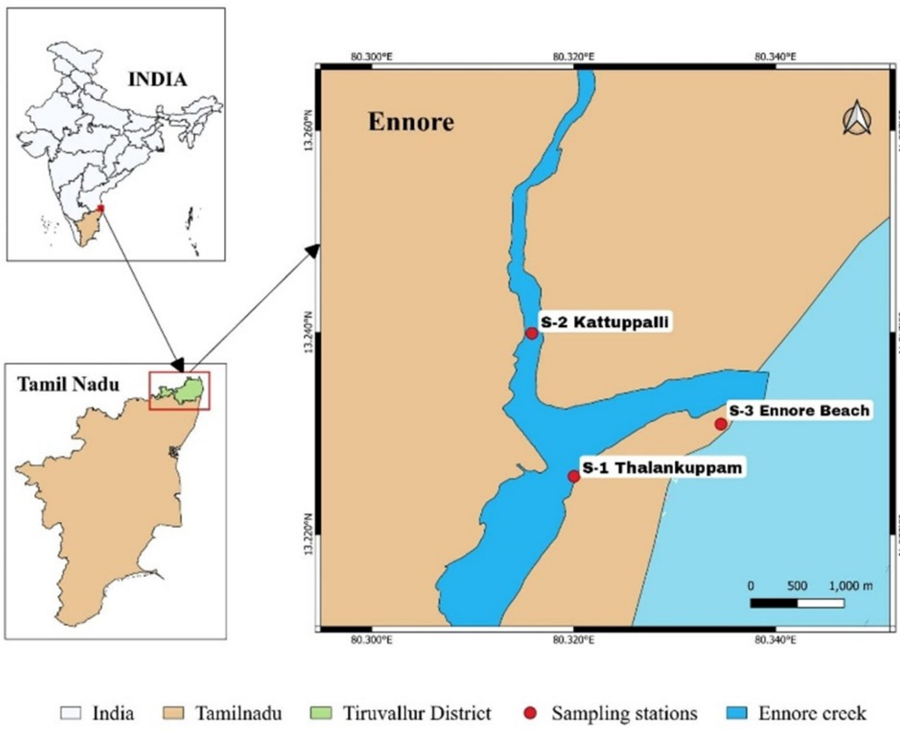

FIGURE 1 Study area map of three sampling sites along the Ennore Coast of southeast India.

2.4 Quantification and characterisation of microplastics

Dried filters were examined under a stereomicroscope (40–80×) to quantify and classify microplastics based on shape (fragment, fibre, foam, film and irregular), size (0.5–1, 1–2, 2–3, 3–4 and 4–5 mm) and colour (blue, black, white, transparent, green, red and yellow). Representative particles were photographed, measured using image-analysis software calibrated with a micrometre scale, and microplastic abundance was expressed as particles L^{-1} (Keerthika *et al.* 2022b; Ashik *et al.* 2026).

2.5 Polymer identification and characterisation

Polymer composition was identified using ATR–FTIR spectroscopy (Nicolet iS5, Thermo Fisher Scientific, USA). Approximately 700 representative particles (30% of the total), including fragments, fibres, foam, film and irregular particles, were analysed over a spectral range of 4000–400 cm^{-1} with 32 scans at 4 cm^{-1} resolution. Polymer types were identified by comparison with reference spectra. Surface morphology and elemental composition were further analysed using FESEM–EDX (GeminiSEM 300, Carl Zeiss, Germany) (Hidalgo-Ruz *et al*. 2012; Jung *et al*. 2018; Veerasingam *et al*. 2021).

2.6 Ecological risk assessment of Microplastics

Ecological risk was evaluated using the contamination factor (CF), pollution load index (PLI), polymer hazard index (PHI), individual ecological risk (E_i) and total ecological risk index (RI). Hazard scores (H_i) were adopted from Ranjani *et al*. (2021), while risk indices were calculated following Dueñas-Moreno (2024). Because no uncontaminated baseline was available for the Pulicat–Ennore coastal system, the lowest observed microplastic concentration was used as the background value (C_o) for CF, E_i and RI calculations following the approach of Hakanson (1980).

2.6.1 Contamination factor (CF): The CF was determined using the equation by Hakanson (1980), where C_i is the microplastic concentration at the site and C_{oi} is the background concentration. The background MP concentration value was determined by taking the lowest MP abundance found in the water samples.

$$CF_i = C_i / C_{oi}$$

Values greater than 1 imply contamination enrichment at the site (Qiu *et al*. 2023; Paray *et al*. 2025).

2.6.2 Pollution load index (PLI_i): The PLI_i which summarises overall pollution of the study sites, was computed using the equation by Tomlinson *et al*. (1980)

$$PL_i = \sqrt{CF_i}$$

PLI values greater than 20, indicate higher pollution relative to baseline levels (Ranjani *et al*. 2021).

2.6.3 Polymer hazard index (PHI): The PHI was calculated using the equation by Lithner *et al*. (2011), which multiplies each polymer's percentage (P_n) by its hazard score (S_n), was used to calculate the PHI (Zhang *et al*. 2025).

$$PHI = \sum Pn \times Sn$$

2.6.4 The ecological risk index (E_i): The E_i was measured using the equation by Hakanson (1980) where E_i is the potential ecological hazard from a single MP polymer, T_i is the toxicity coefficient, obtained by multiplying the hazard score of each plastic polymer, C_i is the observed MP abundance at each sampling station, and C_o is the background MP concentration, taken as the lowest MP abundance recorded in the current study (Shalumon and Ratanatamskul 2023; Lee *et al.* 2024).

$$E_i = T_i \times C_i / C_o$$

2.6.5 The potential ecological risk index (PERI): PERI is calculated using the equation by Hakanson (1980) with categorical grades for ecological risk (e.g., RI < 150: low; 150–300: moderate; 300–600: high; > 600: extremely high) was computed as the sum of E_i values for each microplastic polymer (Banik *et al*. 2024; Lee *et al*. 2024).

$$PERI = \sum_{i=1}^{n} Ei$$

2.7 Quality control

To minimize background contamination, strict quality control measures were followed throughout sample processing. Water samples were stored in pre-cleaned, sealed glass vials, and all glassware and equipment were rinsed with distilled water before and after use. Filter papers were kept covered in Petri dishes, and procedural blanks containing deionised water were processed alongside samples using identical analytical procedures. No microplastics were detected in the blanks, confirming the absence of laboratory contamination and the reliability of the results (Ashik *et al*. 2026).

2.8 Data analysis

The microplastics count in water were expressed in MP L^{-1} and the shape, colour, size and polymers were expressed in percentage. MPs distribution in terms of size, shape, and colour as well as MPs abundance in water between the sampling locations in different seasons. To identify the significant differences One way ANOVA test was used. The statistical analysis was performed using the SPSS software (Version 25) and the significance level was $p < 0.05$.

3 | RESULTS

3.1 Seasonal microplastic abundance

The overall seasonal mean MP concentrations ranged from approximately 95 to 185 particles L^{-1}, with the highest abundance recorded during post-monsoon 2025 (185 particles L^{-1}) and the lowest during summer 2025 (95 particles L^{-1}) with significant difference $p = 0.025$. Spatially, Kattupalli (station II) consistently exhibited the highest MP abundance, followed by Thalankuppam (station I) and Ennore Beach (station III) (Figure 2, 3 and 4) with significant difference ($p = 0.01$). Moderate MP concentrations during monsoon 2024 were attributed to monsoon-driven runoff transporting plastics from urban, industrial, and riverine sources into the estuary (Li *et al*. 2019).

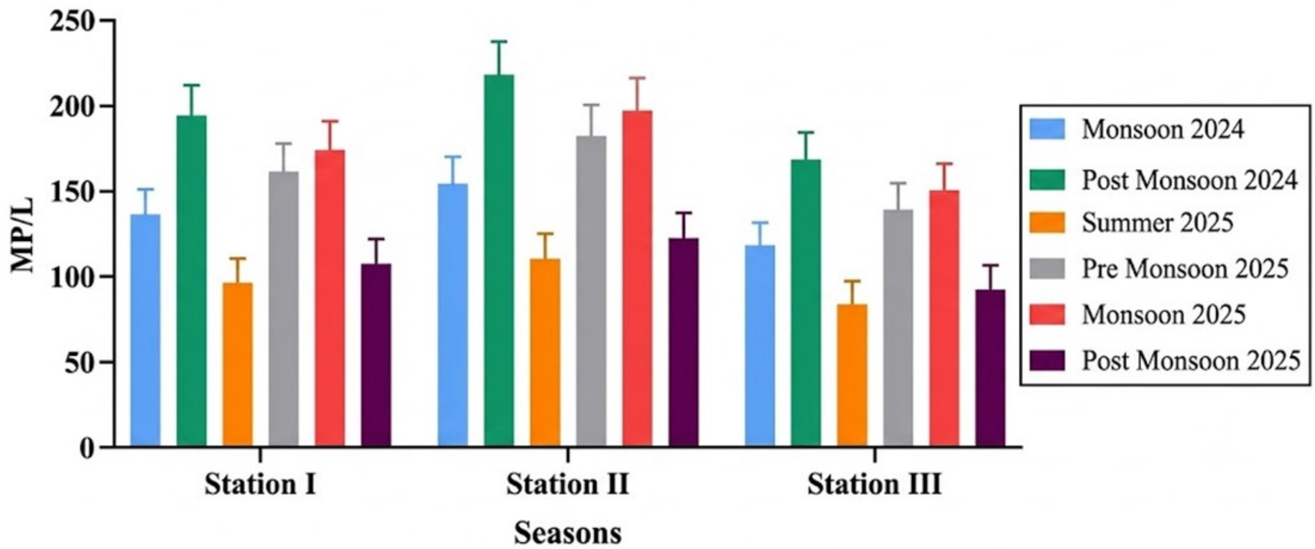

FIGURE 2 Spatial variation of microplastic (MP) abundance in water from three sampling sites along the Ennore Coast.

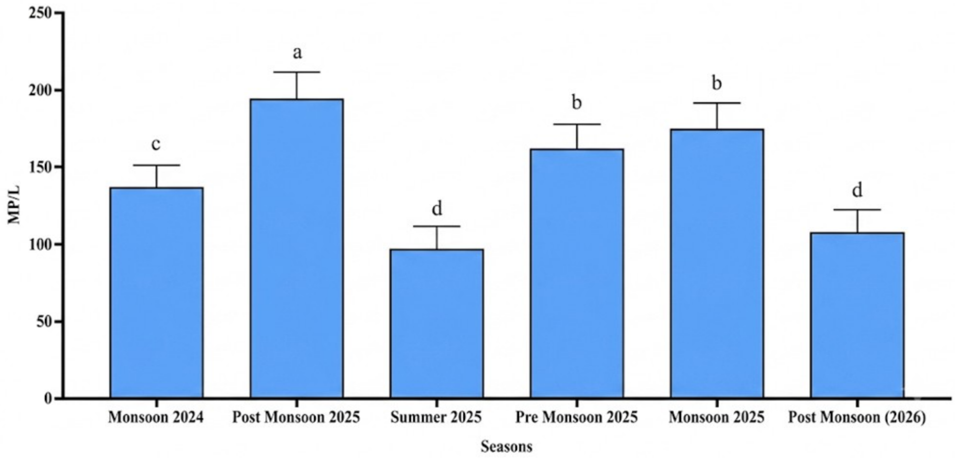

FIGURE 3 Seasonal variation of microplastic (MP) abundance in water samples from three sampling sites along the Ennore Coast of southeast India.

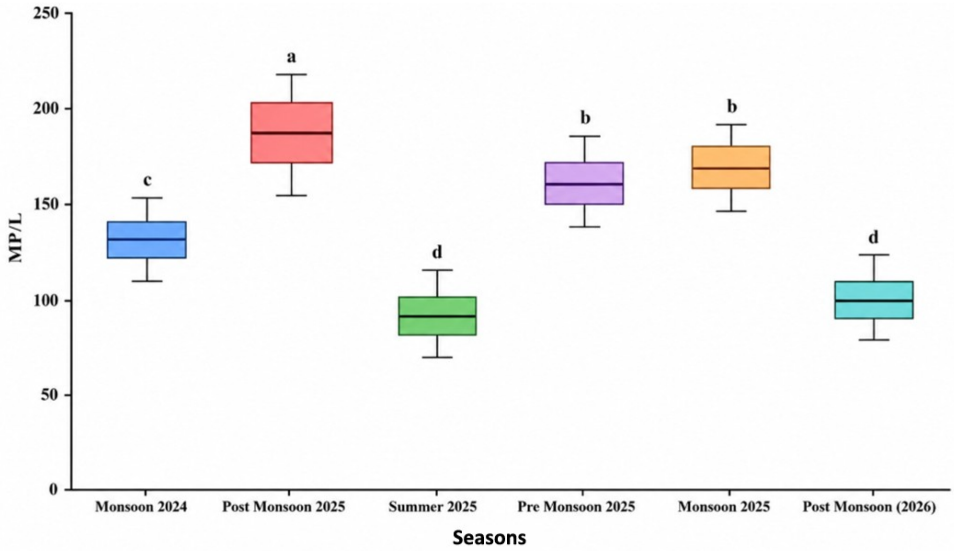

FIGURE 4 Box-Plot showing Seasonal variation of microplastic (MP) abundance in water samples from three sampling sites along the Ennore Coast of southeast India.

The pronounced increase during post-monsoon 2025 coincided with the aftermath of cyclone Fengal, whose intense rainfall, flooding and storm surges enhanced runoff, sediment resuspension and fragmentation of larger plastics into secondary microplastics (Keerthika *et al*. 2022b; Bhuvana *et al*. 2024). MP abundance declined during summer 2025 because of reduced runoff and enhanced sedimentation (Sarkar *et al*. 2026), increased again during Pre-monsoon and monsoon 2025 through terrestrial inputs and resuspension, and decreased during post-monsoon 2026, indicating gradual recovery. The consistently higher MP abundance at Kattupalli reflects its proximity to Ennore Creek, industrial complexes, thermal power stations and stormwater outlets, whereas lower concentrations at Ennore Beach were likely due to tidal flushing and wave-driven dispersion. These observations agree with previous studies identifying estuarine systems as effective sinks for microplastics (Li *et al*. 2019; Keerthika *et al*. 2022a; Zhang *et al*. 2025). Mak *et al*. (2020) further reported substantial increases in coastal microplastics following tropical cyclones, supporting the influence of Cyclone Fengal on the elevated MP concentrations observed in the present study.

3.2 Characteristics of MP particles

3.2.1 Microplastic shape composition: Fragments were the dominant shape at Thalankuppam (35%) and Ennore Beach (38%), whereas foam predominated at Kattupalli (40%). The high abundance of fragments indicates extensive weathering and secondary fragmentation of larger plastic debris through prolonged UV exposure, wave action and mechanical abrasion (Banik *et al*. 2024). Fibres accounted for 15%, 12% and 28% at Stations I, II and III, respectively, and were mainly associated with fishing nets, synthetic ropes, laundry effluents and textile fibres. Irregular particles contributed 18%, 10% and 18%, suggesting degradation of composite and multilayer plastics, while film was the least abundant morphotype (2%, 8% and 4%, respectively), originating primarily from deteriorated plastic bags and packaging films (Wang *et al*. 2022). Overall, the predominance of fragments and foam reflects the influence of urban litter, industrial activities and fishing operations, indicating that secondary microplastics are the major contributors to MP pollution along the Ennore coast. The distribution of microplastic (MP) shapes varied among the three Ennore sampling stations (Figure 5).

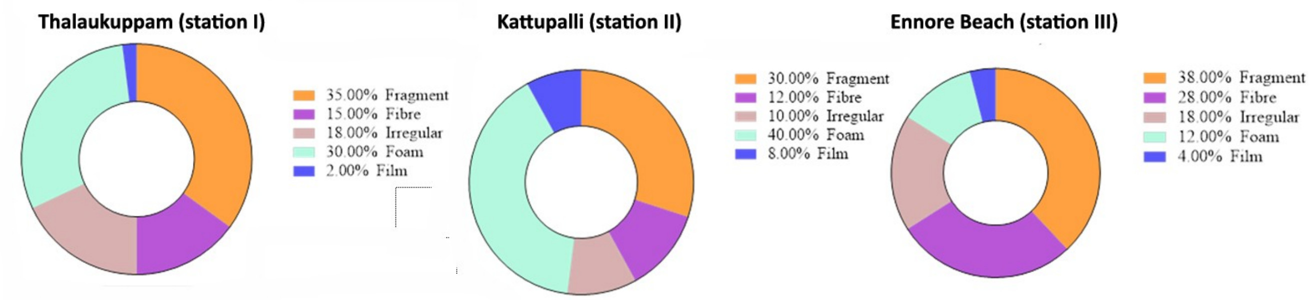

FIGURE 5 Microplastic shapes of three sampling sites along the Ennore Coast.

3.2.2 Microplastic colour composition

Black was the dominant colour at all three stations, accounting for 35% at Thalankuppam, 36% at Kattupalli and 40% at Ennore Beach (Figure 6). Black MPs are commonly associated with tyre wear particles, industrial residues, fishing gear coatings and weathered plastic materials transported through urban runoff (Selvam *et al*. 2021). Blue was the second most abundant colour (20%, 28% and 28%, respectively), indicating inputs from fishing nets, ropes and synthetic fibres (Chandran *et al*. 2025). Green MPs represented 16%, 10% and 9%, while transparent particles accounted for 12%, 10% and 8%, mainly originating from degraded packaging films and single-use plastics (Arisekar *et al*. 2025). White MPs constituted 8%, 10% and 7%, whereas red (4%, 2% and 4%) and yellow (5%, 4% and 4%) occurred in relatively lower proportions. Overall, the predominance of black and blue MPs highlights the influence of industrial activities, urban runoff and fishing-related sources in the Ennore coastal environment.

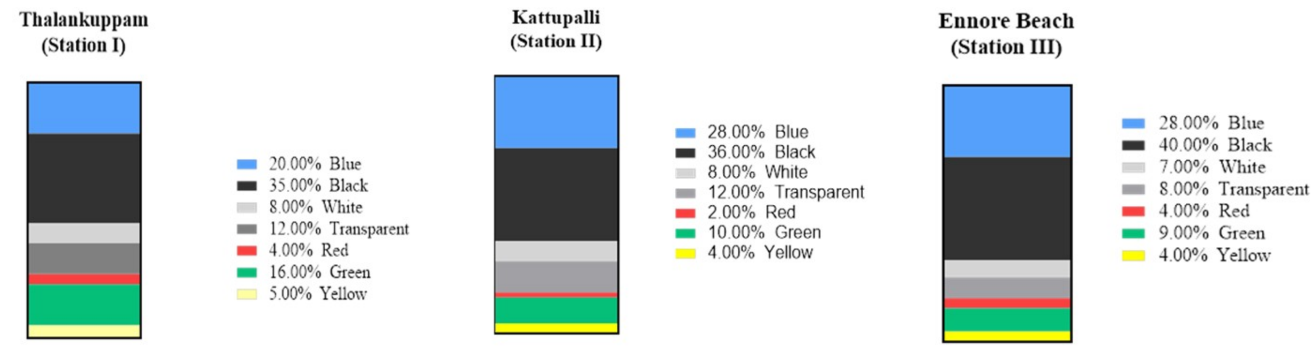

FIGURE 6 Microplastic colours of three sampling sites along the Ennore Coast of southeast India.

3.2.3 Polymer composition: ATR–FTIR analysis identified six major polymer types (PE, PP, PS, PA, PU and PVC) across the three Ennore sampling stations (Figure 7). Polyethylene (PE) was the dominant polymer, accounting for 28% at Thalankuppam (station I), 31% at Kattupalli (station II) and 32% at Ennore Beach (station III), reflecting its widespread use in packaging materials, fishing gear and household plastics, together with its high buoyancy and persistence in coastal waters (Andrady 2011). Polypropylene (PP) was the second most abundant polymer (17%, 15% and 18%), followed by polyurethane (PU) (23%, 27% and 18%), indicating inputs from consumer products, fishing activities and industrial materials (Peng *et al*. 2023; Arisekar *et al*. 2025). Polystyrene (PS) (10–15%), polyvinyl chloride (PVC) (9–13%) and polyamide (PA) (7–9%) occurred in lower proportions and were mainly associated with packaging waste, drainage infrastructure, fishing nets and synthetic fibres (Martinho *et al*. 2022; Prabu *et al*. 2026). Overall, PE and PP predominance indicates major contributions from packaging waste, fishing activities and urban plastic litter along the Ennore Coast.

3.2.4 Microplastic size composition: Microplastic size distribution was dominated by the 0.5–1 mm fraction at all stations, accounting for 38% at Thalankuppam, 45% at Kattupalli and 38% at Ennore Beach, followed by the 1–2 mm fraction (21–30%) (Figure 8). Larger particles (4–5 mm) were least abundant (6–8%), indicating progressive fragmentation of plastic debris. The predominance of particles < 2 mm suggests advanced weathering and enhances their bioavailability for trophic transfer in coastal organisms (Li *et al*. 2019; Costa *et al*. 2020; Kutralam-Muniasamy *et al*. 2021).

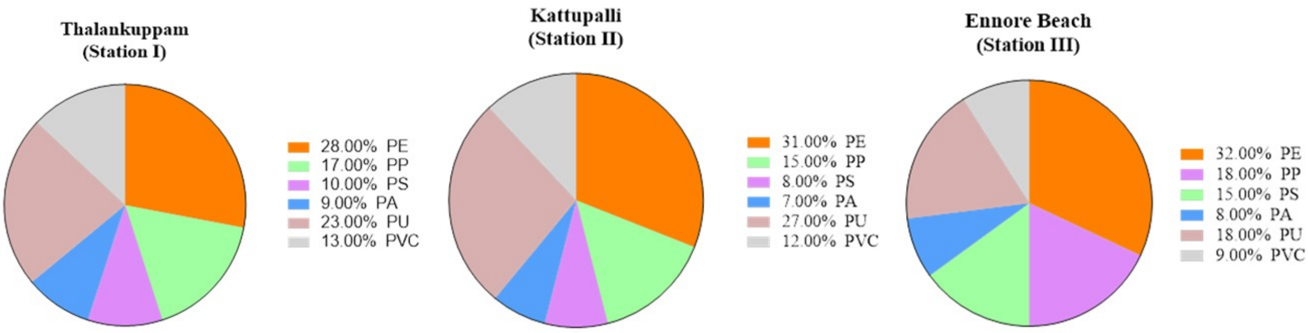

FIGURE 7 Microplastic polymer types of three sampling sites along the Ennore Coast of southeast India. PE – Polyethylene, PP – Poly-propylene, PA – Polyamide, PS – Polystyrene, PU – Polyurethane and PVC – Polyvinyl chloride.

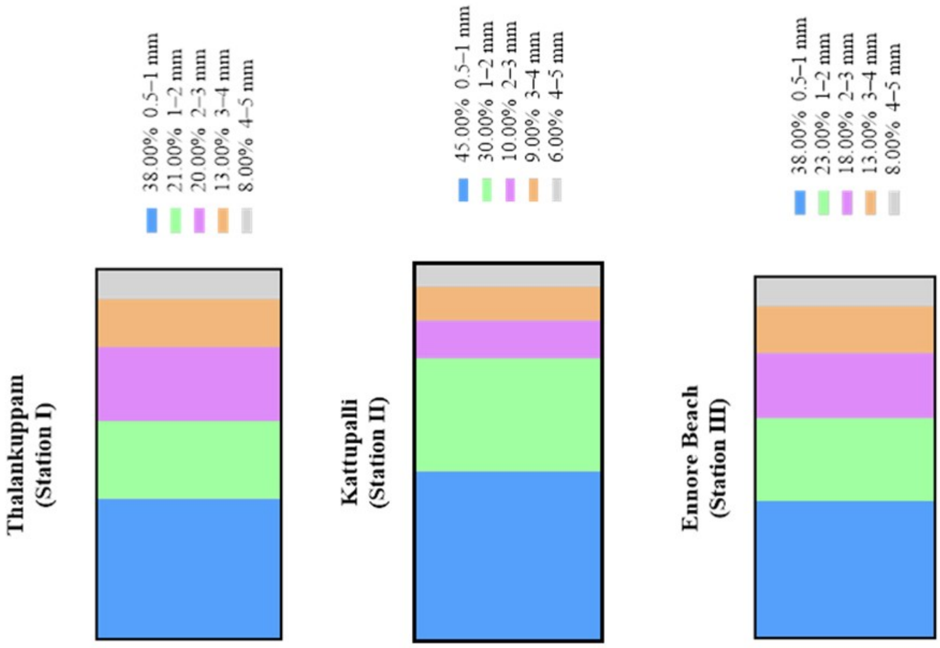

FIGURE 8 Microplastic size composition of three sampling sites along the Ennore Coast in southeast India (in mm).

3.3 Ecological risk assessment of microplastics

The contamination factor (CF) values of 3.04 at Thalankuppam, 2.84 at Kattupalli and 2.12 at Ennore Beach. The higher CF observed at Thalankuppam is likely associated with continuous inputs from urban runoff, fishing activities and restricted water circulation, which favour MP accumulation. In contrast, the comparatively lower CF at Ennore Beach reflects the influence of tidal flushing and wave-induced dispersion that reduce the residence time of floating plastics (Karthik *et al*. 2018; Dissanayake *et al*. 2021).

The pollution load index (PLI) values were 1.78, 1.69 and 1.46 for Thalankuppam, Kattupalli and Ennore Beach, respectively, placing all three stations under pollution class I (low pollution). The low PLI indicates that the overall pollution load remains limited, suggesting that continuous tidal exchange and coastal hydrodynamics partially mitigate excessive MP accumulation despite persistent anthropogenic inputs (Priyanka and Govindarajulu 2025).

The polymer hazard index (PHI) values were 7293 at Thalankuppam, 6352 at Kattupalli and 5789 at Ennore Beach, classifying all stations under rank V (very high hazard). These elevated PHI values primarily reflect the presence of hazardous polymers such as PU, PVC, PA and PS, which possess considerably higher hazard scores than PE and PP (Lithner *et al.* 2011). In Thalankuppam higher PHI values, indicated that influence of industrial activities, thermal power plants, port operations, urban drainage and fishing-related sources that characterize the Ennore coastal region (Peng *et al*. 2023; Zhang *et al.* 2025).

The potential ecological risk index (PERI/RI) values were 72.93, 63.52 and 57.89 for Thalankuppam, Kattupalli and Ennore Beach, respectively, indicating minor ecological risk (< 150) at all stations. Polymers such as PVC, PU and PS are known to contain hazardous additives and exhibit a strong affinity for adsorbing trace metals and persistent organic pollutants, thereby increasing their potential for trophic transfer and adverse biological effects in aquatic organisms (Lithner *et al*. 2011; Rochman *et al*. 2013). Ecological risk assessment of microplastics among the three sampling sites along the Ennore Coast is presented in Table 1.

3.4 FESEM–EDX

FESEM–EDX analysis revealed pronounced surface weathering of microplastics, including rough textures, cracks and irregular depressions, indicating prolonged exposure to UV radiation, oxidation and mechanical abrasion in the aquatic environment (Ashik *et al*. 2026). EDX spectra confirmed the presence of C, O, Na, Si, Al, P, Cl and Zn, with zinc (32.53 wt%) being the predominant heavy metal, followed by carbon (15.65 wt%), oxygen (35.23 wt%) and aluminium (6.12 wt%). Zinc adsorption was likely associated with antifouling coatings, tyre wear and galvanised materials (Qiu *et al*. 2023). These findings demonstrate that weathered microplastics act as efficient vectors for metal contaminants because of their enhanced surface binding sites (Figure 9; Guo *et al*. 2020).

TABLE 1 Ecological risk assessment of microplastics among the three sampling sites along the Ennore coast, southeast India.

Index	Ranking System	Thalankuppam	Kattuppalli	Ennore Beach
CF (Contamination Factor)	<1 = Low; 1–3 = Moderate; 3–6 = Considerable; >6 = Very High	3.04 (Considerable)	2.84 (Moderate)	2.12 (Moderate)
PLI (Pollution Load Index)	I = <10 (Low); II = 10–20 (Moderate); III = 20–30 (High); IV = >30 (Very High)	1.78 → Rank I (Low)	1.69 → Rank I (Low)	1.46 → Rank I (Low)
PHI (Polymer Hazard Index)	I = 0–1 (Very Low); II = 1–10 (Low); III = 10–100 (Medium); IV = 100–1000 (High); V = >1000 (Very High)	7293 → Rank V (Very High)	6352 → Rank V (Very High)	5789 → Rank V (Very High)
PERI / RI (Potential Ecological Risk Index)	<150 = Minor; 150–300 = Medium; 300–600 = High; 600–1200 = Danger; >1200 = Extreme danger	72.93 (Minor)	63.52 (Minor)	57.89 (Minor)

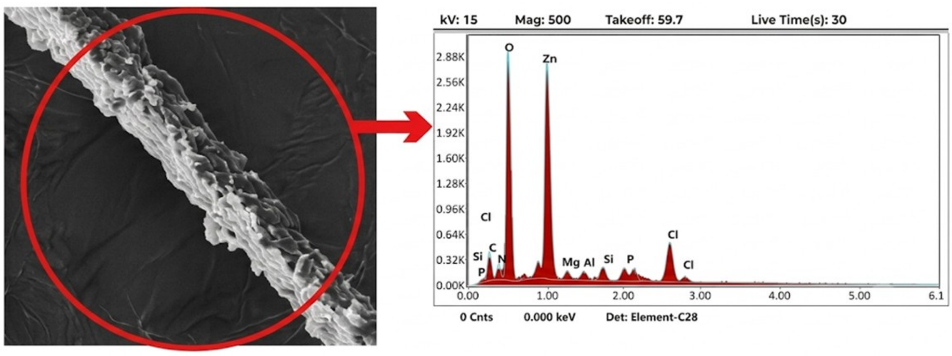

FIGURE 9 FESEM and EDX images of fragment shaped microplastics and associated heavy metals in water samples along the Ennore Coast of southeast India.

4 | CONCLUSIONS

This study assessed the spatial and seasonal distribution, characteristics, and ecological risk of microplastics (MPs) in the Ennore coastal waters, southeast coast of India. MP abundance ranged from 85 to 215 particles L^{-1}, with the highest concentrations observed during post-monsoon 2025 ((185 particles L^{-1}) and Kattupalli (110–215 particles L^{-1}), reflecting the influence of industrial activities, urban runoff, and restricted hydrodynamics. Fragments and foam were the dominant morphotypes, black was the predominant colour, and the 0.5–1 mm size class was most abundant.

Polyethylene (PE; 28–32%) and polypropylene (PP; 15–18%) was the predominant polymers, indicating packaging materials, fishing gear, and urban plastic waste as the major sources. Risk assessment revealed considerable to moderate contamination factor (CF), low overall pollution load index (PLI), very high polymer hazard index (PHI), but only minor ecological risk index (PERI). Although the current ecological risk is low, continuous anthropogenic inputs and extreme weather events such as Cyclone Fengal may accelerate MP accumulation. These findings provide valuable baseline data for long-term monitoring and sustainable management of the Ennore coastal ecosystem.

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ETHICAL APPROVAL
This study has not applicable to human or animal rights. No live specimens were used in this study.

CONFLICT OF INTEREST
The author declares no conflict of interest.

AUTHORS' CONTRIBUTION
Saleem Ashik - Writing – Original Draft, Methodology, Formal analysis and Software; Satyapriyan Aruna – Investigation, Resources, Funding acquisition and Supervision; Pandurangan Padmavathy – Conceptualization and Writing – Review & Editing; Selvaraj Sethu - Investigation and Writing - Review & Editing. Chandran Sudhan – Data curation and Visualization; Gunasekaran Gobi – Investigation and Writing - Review & Editing.

AI USE STATEMENT
The authors declare that no generative AI or AI-assisted technologies were used in the writing, data analysis, or preparation of this manuscript.

DATA AVAILABILITY STATEMENT
Data and materials will be made available on reasonable request from the first/corresponding author.

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