Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 11, No. 07, July, 2025

Linking the Tourism Activity to the Occurrence and Distribution of Microplastics

Nadda Khalila Chairunnisa [1], Moh. Awaludin Adam [2], Sonny Kristianto [3], Dining Aidil Candri [1], Husna Shofi Talbia [4], Maya Aprilia [4], Tuti Mutia [5], Heni Masruroh [5], Aditya Prana Iswara [6*], Wisnu Prayogo [7]

[1] *Department of Biology, Universitas Mataram, Mataram, 83115, Indonesia.*

[2] *Research Center for Marine and Land Bioindustry, National Research and Innovation Agency, Lombok, 83352, Indonesia.*

[3] *Department of Forensic Science, Postgraduate School, Universitas Airlangga, Surabaya, 60115, Indonesia.*

[4] *Department of Biotechnology, Sumbawa University of Technology, Sumbawa, 84371, Indonesia.*

[5] *Department of Geography, Universitas Negeri Malang, Malang, 65145, Indonesia.*

[6] *Department of Disaster Management, Postgraduate School, Universitas Airlangga, Surabaya, 60115, Indonesia.*

[7] *Department of Environmental Engineering, Chung Yuan Christian University, Taoyuan, 320, Taiwan.*

Received 23 December 2024; Revised 21 May 2025; Accepted 26 May 2025; Published 01 July 2025

Abstract

Tourism-driven activities have increasingly contributed to marine microplastic (MPs) pollution, particularly in island ecosystems. This study assesses the abundance, characteristics, and spatial distribution of MPs in Gili Trawangan, Indonesia, by analyzing samples from coastal water, sediments, and fish across three zones: a seaport, recreational beach, and mangrove area. Standardized filtration, density separation, and FTIR spectroscopy were used to identify MPs types and polymers. Results show the highest MPs concentrations in coastal water at recreational beaches (19.25 particles/L), sediment at seaports (23.15 particles/kg), and fish near seaports (17.5 particles/individual), indicating elevated risks of bioaccumulation. Fragments and fibers were the dominant forms, with prevalent polymers including PS, PE, and LDPE, mostly in black, blue, and red colors. The mangrove area exhibited lower MPs levels due to its natural filtration capacity but still showed MPs presence in biota. This multi-compartment approach highlights a clear link between tourism intensity and MPs contamination. The findings provide new insights for designing localized interventions, including waste reduction strategies and regulatory measures. By integrating ecological and anthropogenic factors, this study supports the development of sustainable tourism policies to mitigate MPs pollution and protect coastal biodiversity.

Keywords: Microplastics; Tourism Impact; Polymer Type; Gili Trawangan; Coastal Ecosystems.

1. Introduction

MPs, defined as plastic particles smaller than 5 mm in diameter, have garnered significant scientific and public attention due to their pervasive presence in aquatic ecosystems and the associated environmental health risks. While numerous studies have assessed MPs abundance in oceans, rivers, and coastal regions, few have explicitly linked tourism activities to MPs pollution. Most tourism-related research has traditionally focused on habitat alteration, threats to

* Corresponding author: aditya.prana@pasca.unair.ac.id

http://dx.doi.org/10.28991/CEJ-2025-011-07-010

wildlife, or changes in water quality, whereas the distinct contribution of tourism to MPs contamination remains relatively underexplored. Tourism substantially escalates the use of single-use plastics and other plastic-based products in many island destinations, potentially exacerbating environmental contamination, mainly where inadequate waste disposal and management infrastructure [1, 2]. Exposure to sunlight, wave dynamics, and mechanical abrasion leads to the fragmentation of larger plastic debris into MPs, creating extensive ecological hazards for marine life [3, 4]. Previous investigations conducted on various tourist islands globally, including Oahu (Hawai‘i) [5], Maldives [6], Saint Martin's (Bangladesh) [7], Holbox (Mexico) [8], Saint Mary's (India) [9], the Caribbean Islands (Puerto Rico) [10], Gujarat (India) [11], Nansha Island (China) [12], and the Black Sea Beaches (Turkey) [13], have consistently demonstrated that MPs contamination correlates strongly with residential and coastal tourism activities. However, most of these studies are restricted to single environmental compartments, such as sediment sand or coastal water, or focus on a limited number of parameters, such as MPs abundance or polymer type. Furthermore, specific tourism activities, including recreational sports or port-related operations, and their potential impacts on MPs across various environmental compartments, particularly fish, have been infrequently examined. Mangrove ecosystems remain inadequately studied in this context despite their established role in trapping plastic debris before it reaches open water. Given that mangrove habitats serve as critical nurseries for juvenile fish and other organisms [14, 15], MPs contamination in these environments may have significant implications for local trophic dynamics.

Indonesia, characterized by its extensive coastline and archipelagic geography, faces considerable challenges related to marine plastic pollution [16]. Island destinations are particularly susceptible to increased plastic waste generation driven by rapid tourism growth. Gili Trawangan Island exemplifies this vulnerability, where burgeoning tourism infrastructure, including hotels, restaurants, and maritime activities, significantly contributes to MPs pollution, posing a serious threat to local marine ecosystems. Although prior studies have addressed plastic waste issues on Gili Trawangan, comprehensive assessments focusing on MPs remain scarce. There has been limited effort in examining multiple environmental compartments simultaneously, such as coastal water, sediments, and fish, about specific local tourism activities. Understanding how different anthropogenic sources affect MPs distribution and characteristics in various mediums is essential because MPs can severely impact marine organisms by causing physical obstructions or introducing toxic chemicals through leaching and adsorption processes [14-17]. This contamination threatens biodiversity and poses potential health risks to humans through consuming contaminated seafood [18, 19]. In tourist-intensive areas, the extensive use of disposable plastics, such as food packaging, beverage containers, and single-use utensils, exacerbates this ecological risk. Additionally, visible plastic pollution significantly diminishes the aesthetic appeal of tourist destinations, potentially reducing visitor satisfaction and indirectly impacting the local economy [20, 21]. Identifying key sources and distribution pathways of MPs pollution is crucial for informing effective interventions, including targeted improvements in waste management systems, plastic bans, and educational campaigns to raise public awareness. Addressing these research gaps, this study investigates MPs contamination on Gili Trawangan Island within a tourism-intensive context, adopting a comprehensive, multi-compartmental approach. Unlike previous research limited to single environmental mediums, this study concurrently examines MPs presence in coastal water, sediments, and marine organisms across three distinct zones: the seaport, recreational beach, and mangrove areas. Each zone is characterized by unique human activities, enabling the identification of specific sources of plastic waste and their accumulation patterns within local ecosystems. The seaport is a critical hub for passenger and cargo transport, thus presenting significant potential for plastic pollution from maritime activities. The recreational beach area, populated by hotels, restaurants, and various tourist facilities, is a primary source of single-use plastic debris that readily fragments into MPs. Although the mangrove area experiences less direct human interaction, it remains susceptible to plastic debris transported by ocean currents or tides from more actively frequented island regions.

By adopting this three-zone approach, the study investigates variations in MPs abundance, composition, and polymer types across distinct coastal environments. Port and shipping activities are potential sources of industrial polymers, while tourist zones contribute MPs through discarded packaging materials and personal care products containing microbeads. Mangrove ecosystems, characterized by intricate root systems, function as natural traps for fine plastic particles and influence sedimentation dynamics [12]. Including fish samples offers insight into the trophic transfer of MPs, as previous studies have shown that fish can ingest plastic particles, especially those that mimic natural prey in size or coloration [4, 22]. The findings from this study hold valuable implications for mitigating the ecological and human health risks associated with MPs. Significantly, this research advances MPs monitoring methodologies by directly correlating localized tourism pressures with MPs contamination patterns. It integrates data gathered over 44 months (see Table 1) and introduces new environmental variables to support a more nuanced understanding of MPs distribution, polymer characteristics, and ecological resilience in coastal systems. These insights can inform the development of integrated waste management frameworks and targeted educational outreach initiatives led by local governments, industry stakeholders, and environmental organizations. Such measures are critical to preserving ecological integrity while maintaining the tourist appeal of island destinations. This study establishes a clear connection between tourism-driven activities and MPs pollution on Gili Trawangan Island, Indonesia. The research comprehensively assesses MPs sources, accumulation patterns, and potential ecological consequences through a multi-compartment analysis of coastal water, sediments, and fish across seaports, recreational beaches, and mangrove areas. The results support actionable recommendations for policymakers and environmental managers to balance ecological sustainability with socio-economic development. The Methods section elaborates on the study area, sampling protocol, analytical techniques, and statistical procedures used to quantify MPs abundance and characterize particle properties. The Results and Discussion section presents key patterns in MPs occurrence, composition, and site-based comparisons. In contrast, the Conclusion and Recommendations section consolidates these findings, underscores the urgent need for improved waste regulation, and outlines future research priorities. This study addresses the multi-faceted nature of MPs pollution and its links to human activity. It provides a critical evidence base for formulating adaptive environmental management strategies in plastic-impacted island ecosystems.

Table 1. Comparison of the exploration between previous research and this study

Study Site	Sampling Tool	Segmentation	Observation Objects	MPs Characteristics	Ref.
Oahu, Hawai'i	▪ Residential ▪ Tourism	▪ Beach tourism	▪ Coastal sediment	▪ Abundance	Rey et al. [5]
Maldives, Maldives	▪ Residential ▪ Tourism	▪ Coastal	▪ Coastal sediment	▪ Abundance ▪ Shape ▪ Color ▪ Polymer type	Patti et al. [6]
Saint Martin's, Bangladesh	▪ Residential ▪ Tourism	▪ Coastal	▪ Coastal sediment	▪ Abundance ▪ Shape ▪ Polymer type	Tajwar et al. [7]
Holbox, Mexico	▪ Residential ▪ Tourism	▪ Beach tourism	▪ Coastal sediment	▪ Abundance ▪ Size ▪ Shape ▪ Polymer type	Cruz-Salas et al. [8]
Saint Mary's, India	▪ Residential ▪ Tourism	▪ Beach tourism	▪ Coastal sediment	▪ Abundance ▪ Size ▪ Polymer type	Khaleel et al. [9]
Caribbean, Puerto Rico	▪ Residential ▪ Tourism	▪ Beach tourism	▪ Coastal sediment	▪ Abundance ▪ Shape ▪ Polymer type	Pérez-Alvelo et al. [10]
Gujarat, India	▪ Residential ▪ Tourism	▪ Beach tourism	▪ Coastal water	▪ Abundance ▪ Size ▪ Shape ▪ Polymer type	Upadhyay et al. [11]
Nansha, China	▪ Residential ▪ Tourism	▪ Beach tourism	▪ Coastal water	▪ Abundance ▪ Size ▪ Shape ▪ Polymer type	Tan et al. [12]
Black Sea Beache, Turkey	▪ Residential ▪ Tourism	▪ Beach tourism	▪ Sediment	▪ Abundance ▪ Shape ▪ Polymer type	Terzi et al. [13]
Gili Trawangan, Indonesia	▪ Residential ▪ Tourism	▪ Seaport ▪ Recreational beach ▪ Mangrove area	▪ Coastal water ▪ Coastal sediment ▪ Coastal biota (fish)	▪ Abundance ▪ Size ▪ Shape ▪ Polymer type	This study

2. Methods

The methodology employed in this study was systematically designed to evaluate the relationship between tourism activities and the distribution of MPs on Gili Trawangan Island, Indonesia (Figure 1). In Figure 1, the research focused on three distinct locations representing varying intensities of human activity and diverse environmental characteristics: the seaport, the recreational beach, and the mangrove area. Sampling was conducted between October and November and encompassed three different environmental compartments: coastal water, sediment, and fish. All samples were collected following standardized international protocols and appropriately preserved to maintain their integrity before laboratory analysis. Microplastics were extracted using filtration and density separation techniques and detailed characterization through stereomicroscopic observation. Further analysis was conducted using FTIR spectroscopy to identify the polymer types of MPs accurately. The spatial distribution patterns carefully informed the selection of sampling locations and techniques of MPs, which are closely associated with tourism intensity and local ecological conditions. This strategic and integrated approach enabled a comprehensive assessment of anthropogenic impacts on Gili Trawangan's dynamic coastal environment. Each stage of the research procedure is elaborated in detail in the subsequent subsections to ensure full methodological transparency and reproducibility.

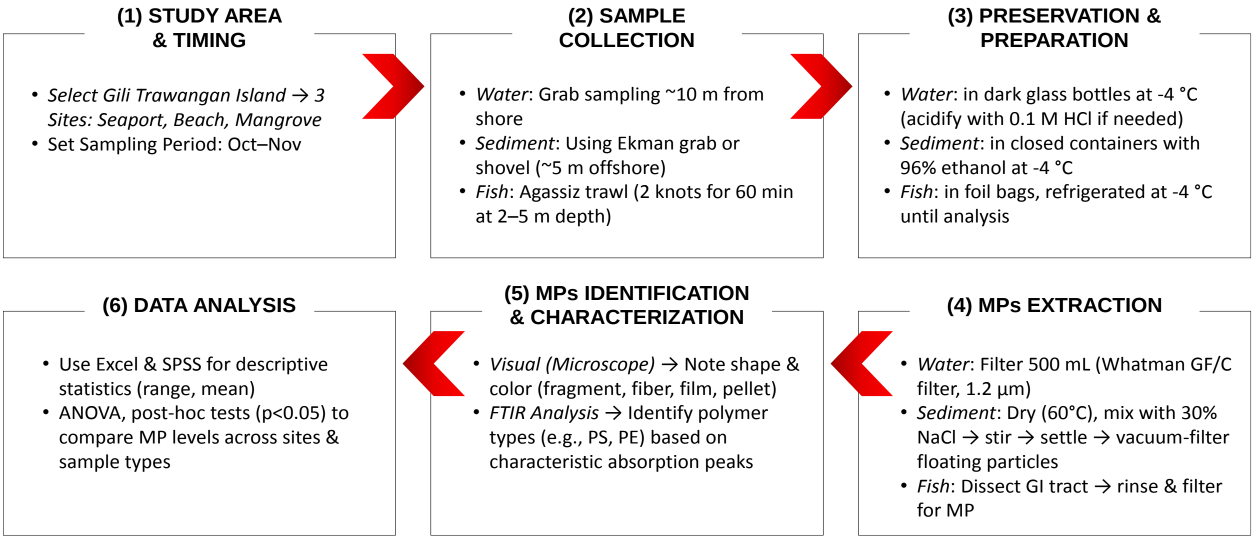

Figure 1. Flow chart procedure of this study

2.1. Location and Sampling Time

The sampling locations in this study are clearly depicted in Figure 2. Geographically, Gili Trawangan Island is strategically located northwest of Lombok Island, one of the larger islands in the southern region of Indonesia (116°00' - 116°08' E, 8°20' - 8°23' S). This island is part of the Gili Islands archipelago, which comprises three small islands: Gili Meno, Gili Air, and Gili Trawangan, the latter being the largest. With approximately 7 km of pristine coastline, white sandy beaches, and crystal-clear waters, Gili Trawangan serves as a prominent tourist destination for both domestic and international visitors. The field survey was conducted from October to November 2023. Figure 2 illustrates that Site 1 (Figure 2a; 119°29′6″ E, 34°46′7.7″ N) represents the port area that links Gili Trawangan with Bangsal Harbor. As a bustling hub for passenger and freight transport, this site exhibits high potential for plastic waste accumulation from both terrestrial and marine sources. Site 2 (Figure 2b; 119°20′3″ E, 34°46′2.84″ N) is a dynamic coastal zone surrounded by residential housing, hotels, and restaurants. This area is particularly vulnerable to MPs pollution from sources such as synthetic textile fibers released during laundering and discarded single-use plastic products. Site 3 (Figure 2c; 119°12′35″ E, 34°56′31″ N) is situated within a relatively undisturbed mangrove ecosystem. Due to its limited direct human interaction and unique ecological characteristics, this site was selected as a comparative control. The strategic selection of these three sites allows for the assessment of MPs distribution under varying levels of anthropogenic pressure. It facilitates a comprehensive evaluation of how different land-use patterns and tourism intensities influence MPs contamination in coastal ecosystems.

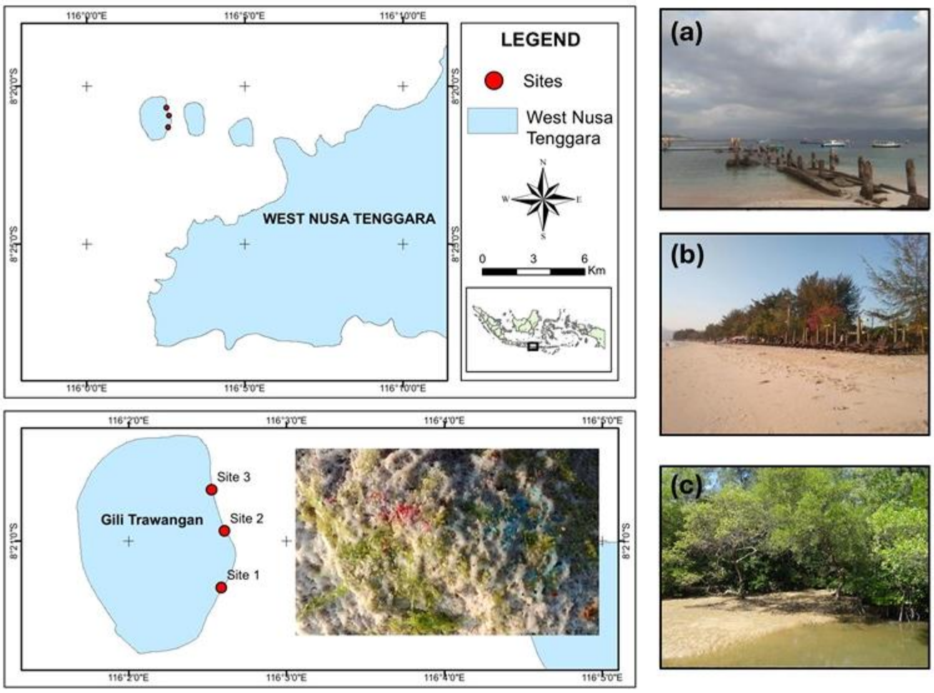

Figure 2. Map of the research locations on Gili Trawangan Island, Indonesia, indicating: (a) Seaport (site 1); (b) Recreational beach (site 2); and (c) Mangrove area (site 3)

2.2. Sample Collection, Preservation, and Preparation Techniques

Sampling was conducted on water, sediment, and several fish at the three research locations to represent affected aquatic biota, aiming to identify the overall distribution of MPs. Water samples were collected using a grab sampling method with dark glass containers sized 1 L. Before sampling, the containers were rinsed multiple times with coastal water from the site. Sampling occurred approximately 10 m from the shore, adhering to SNI 6964.8:2015 standard. The collected water samples were preserved at -4°C and transported to the laboratory [23]. For chemical analysis, samples were separated by container and maintained by adding 0.1 M HCl until the water pH reached 2. MPs separation from the water samples was performed by filtering 500 mL of water using Whatman® GF/C filter paper with 1.2 mm pores [24]. Sediment sampling utilized an Ekman grab sampler for beach sediment and a shovel for rocky sands at depths of about 5 m from the shore [25, 26].

Collected sediment were preserved in 96% ethanol in closed dark glass containers and stored at -4°C [23]. Each sediment sample was processed following methods introduced by Wang et al. [27], with modifications from Peng et al. [28]. One kilogram of wet sediment was dried at 60°C for 48 hours in an oven. After drying, 100 g of sediment was taken in duplicate and dissolved in 400 mL of 30% NaCl solution. The mixture was vigorously stirred for ten minutes and then allowed to settle until no visible material floated in the supernatant. Floating material in the supernatant was filtered using a vacuum pump over Whatman® GF/C filter paper. Fish samples were captured using a new Agassiz trawl made of polypropylene, measuring 2.2 × 0.65 × 4 m with a mesh size of 20 mm. Fish were caught at each location at about 2 knots for 60 minutes at depths of 2-5 m. A total of 120 dominant fish were collected, comprising six different species: (1) A. hexanema, (2) C. stigmatias, (3) O. rubicundus, (4) C. lucidus, (5) C. semilaevis, and (6) T. kammalensis. The fish were then sealed in foil bags and transferred to a refrigerator at -4°C. All fish samples were stored for no more than three days before dissection analysis.

2.3. MPs Identification

The BRUKER Alpha II FTIR spectrometer, version 8.2, was employed to identify functional groups and predict the chemical composition of the samples. In vibrational spectrophotometry, three primary techniques are commonly used: FTIR Transmission, Attenuated Total Reflectance (ATR), and Diffuse Reflectance Infrared Fourier Transform (DRIFT). As noted by Walenna et al. [29], FTIR is particularly effective for confirming various types of synthetic polymers that originate from the degradation of plastic waste and resemble MPs. According to Zhang et al. [30], the infrared spectrum spans wavelengths ranging from 14,000 cm^{-1} to 10 cm^{-1} and is divided into three distinct regions: the near-infrared region (14,000–4,000 cm^{-1}), which is sensitive to overtone and combination vibrations; the mid-infrared region (4,000–400 cm^{-1}), which is associated with fundamental molecular vibrational transitions and is most informative for identifying functional groups; and the far-infrared region (400–10 cm^{-1}), which is used to analyze molecular structures involving heavier atoms and typically requires specialized instrumentation.

The FTIR technique is based on the interaction between infrared radiation and matter, whereby the sample absorbs specific frequencies corresponding to the vibrational modes of its molecular bonds. The sample characteristics influence the amount of energy absorbed and transmitted, and the remaining infrared radiation is directed to a detector. The resulting signal is then processed and displayed as a spectrum, typically represented by peaks corresponding to distinct vibrational modes [31]. For sample preparation, the material was finely ground, mixed with potassium bromide (KBr) in a 1:200 ratio, and then pressed into pellets. The FTIR spectra were recorded using the Bruker Tensor 27 instrument over 400 to 4,000 cm^{-1}, with a spectral resolution of 2 cm^{-1} [5–12].

2.4. Data Analysis

The collected data were systematically analyzed using Microsoft Excel 2013 and IBM SPSS Statistics version 25 to accurately assess the concentrations of MPs in coastal water, sediment, and fish samples from various designated sites. The analysis included detailed computations of descriptive statistics such as range, mean, and standard deviation, complemented by graphical representations to facilitate more explicit visual interpretation and insight. A one-way analysis of variance (ANOVA) was conducted at a 95% confidence level to examine differences in MPs concentrations across sampling locations and among different types of MPs. Where significant differences were detected, post hoc tests were applied to determine specific pairwise group differences. This analytical framework ensured a rigorous and statistically robust evaluation of the data, allowing for the identification of spatial trends and variations in MPs contamination.

3. Results & Discussion

3.1. Quality of Coastal Water at Gili Trawangan Island

Table 2 presents the results of a comprehensive water quality assessment conducted at three locations: Site 1, Site 2, and Site 3. The data reveal notable differences in key physicochemical parameters, reflecting each site's varying environmental conditions and anthropogenic influences. The analysis focused on critical indicators, including ammonia (NH_3), phosphate (PO_4^{3-}), nitrate (NO_3^-), water temperature, dissolved oxygen (DO), turbidity, and salinity. Site 1 recorded an NH_3 concentration of 0.17 mg/L, a PO_4^{3-} level of 0.0062 mg/L, and a NO_3^- concentration of 0.0025 mg/L. Site 2 exhibited markedly higher levels of these nutrients, with NH_3 at 0.42 mg/L, PO_4^{3-} at 0.0325 mg/L, and NO_3^- at 0.0091 mg/L, suggesting a more substantial influence of anthropogenic inputs, particularly from residential runoff. Site 3 showed intermediate nutrient levels, with NH_3 at 0.22 mg/L, PO_4^{3-} at 0.0088 mg/L, and NO_3^- at 0.0023 mg/L, potentially moderated by the natural buffering capacity of the surrounding mangrove ecosystem. Water temperature remained relatively stable between Sites 1 (26.79°C) and 2 (26.80°C), while Site 3 exhibited a lower temperature of 23.42°C, likely attributable to the shaded conditions provided by dense mangrove cover.

Dissolved oxygen concentrations were notably low at Sites 1 (2.76 mg/L) and 2 (2.94 mg/L), both falling below the recommended threshold of >5.0 mg/L for healthy aquatic ecosystems, indicating potential organic pollution and elevated biological oxygen demand. Conversely, Site 3 demonstrated a comparatively higher DO level of 3.52 mg/L, suggesting improved water quality and ecological function. Salinity also varied substantially across the sites. Site 2 recorded the highest salinity at 42.25‰, likely influenced by its proximity to the port and elevated evaporation rates that concentrate dissolved salts. Site 1 exhibited moderate salinity (29.51‰), whereas Site 3 showed significantly lower salinity at 9.16‰, reflecting the freshwater input typical of mangrove habitats. These observed variations underscore the spatial heterogeneity of water quality and highlight the influence of local environmental factors and human activities, such as waste discharge and urban runoff, on aquatic ecosystems [24–28].

Table 2. Coastal water quality testing on Gili Trawangan Island

Water Parameter		**Location**			***Standard**
		Site 1 (Seaport)	**Site 2 (Recreational beach)**	**Site 3 (Mangrove area)**	
Water temperature	T_{water} (°C)	26.79	26.80	23.42	-
Total dissolved solids	TDS (mg/L)	643	840	221	-
Dissolved oxygen	DO (mg/L)	2.76	2.94	3.52	>5.0
Ammonia	NH_3 (mg/L)	0.17	0.42	0.22	-
Nitrate	NO_3 (mg/L)	0.0025	0.0091	0.0023	0,008
Phosphate	PO_4 (mg/L)	0.0062	0.0325	0.0088	0.015
Salinity	(%)	29.51	42.25	9.16	-

*Decree of the Minister of State for the Environment of Indonesia No. 51 of 2004 Concerning the Marine Water Quality Standards.

Furthermore, turbidity measurements obtained using a total dissolved solids (TDS) meter provided additional insights into water quality, revealing distinct variations among the sampling sites. Site 1 exhibited a turbidity level of 643 mg/L, Site 2 recorded the highest value at 840 mg/L, while Site 3 showed significantly lower turbidity at 221 mg/L. The elevated turbidity observed at Site 2 may indicate a higher concentration of suspended particulate matter in the water column, which is frequently associated with increased MPs levels. When compared with the established water quality standards outlined in the Decree of the Minister of State for the Environment No. 51 of 2004, several measured parameters fell below acceptable thresholds. In particular, the low DO concentrations at Sites 1 and 2 raise concerns regarding organic pollution and potential ecosystem stress. Additionally, the elevated nutrient levels at Site 2, especially ammonia and phosphate, could contribute to eutrophication, thereby exacerbating water quality degradation if left unmanaged.

The correlation between turbidity and MPs concentrations is particularly significant, as elevated turbidity often reflects increased particle loading in the water, including MPs. These MPs particles originate from various sources, such as the fragmentation of larger plastic debris, the release of microbeads from personal care products, and the shedding of synthetic fibers during laundry processes. Once introduced into the aquatic environment, these particles persist and accumulate, contributing to long-term pollution and ecological risks to marine organisms. Given that increased turbidity can serve as a proxy indicator for the presence of MPs, this finding underscores the importance of further investigation into the links between plastic waste inputs, particulate matter dynamics, and overall water quality. Such insights are essential for developing effective strategies to mitigate plastic pollution and safeguard aquatic ecosystem health [3, 17].

3.2. Abundance of MPs in Different Environmental Compartments at Gili Trawangan

This study identified distinct spatial patterns in the distribution of microplastics (MPs) across coastal water, sediment, and fish around Gili Trawangan Island, with variations largely influenced by anthropogenic activity and local environmental dynamics (see Figure 3). Among water samples, the highest concentration of MPs was found at the Recreational Beach (19.25 particles/L), followed by the Seaport (16.25 particles/L), and the Mangrove Area (5.89 particles/L). The elevated levels at the Recreational Beach are consistent with findings from other tourism-intensive areas, where inadequate management of single-use plastic waste significantly contributes to MP contamination [20, 28].

Although the Seaport also showed relatively high concentrations, the values were lower than expected, possibly reflecting more effective waste management practices aimed at reducing plastic pollution from maritime sources. In sediment samples, the Seaport recorded the highest concentration (23.15 particles/kg dry weight), highlighting the role of hydrodynamic processes in MP deposition and the accumulation of waste related to shipping activities. The Recreational Beach (12.46 particles/kg) also exhibited substantial MP accumulation, likely a result of intense tourist presence—an observation consistent with findings from similar coastal environments [31–34]. In contrast, the Mangrove Area had the lowest sediment concentration (3.00 particles/kg), possibly due to the sediment-trapping function of mangrove root systems and limited direct human interference.

MPs were also detected in fish samples, with the highest abundance found in individuals collected near the Seaport (17.5 particles/fish), followed by those from the Recreational Beach (16.25 particles/fish) and the Mangrove Area (9.25 particles/fish). The elevated MP load in fish near the Seaport suggests a higher bioavailability of MPs in densely trafficked marine zones, increasing the likelihood of trophic transfer [18, 30]. These results align with previous research documenting MP ingestion by fish in areas with intense anthropogenic pressure [35–38].

The spatial distribution patterns observed in this study reflect the complex interactions among human activities, environmental conditions, and MP characteristics such as size, polymer type, and buoyancy. Notably, MPs in sediment not only serve as sinks but can also become secondary sources through resuspension in turbulent waters, thereby prolonging their environmental persistence and ecological impact [6, 11].

These findings emphasize the urgent need for targeted mitigation efforts, including stricter control of plastic waste at tourism hotspots, ongoing monitoring programs, and public education initiatives to promote sustainable plastic consumption. Continued interdisciplinary research is essential to fully understand the long-term ecological consequences of MPs and to support the development of effective, context-specific strategies for managing MP pollution in island ecosystems [15–17].

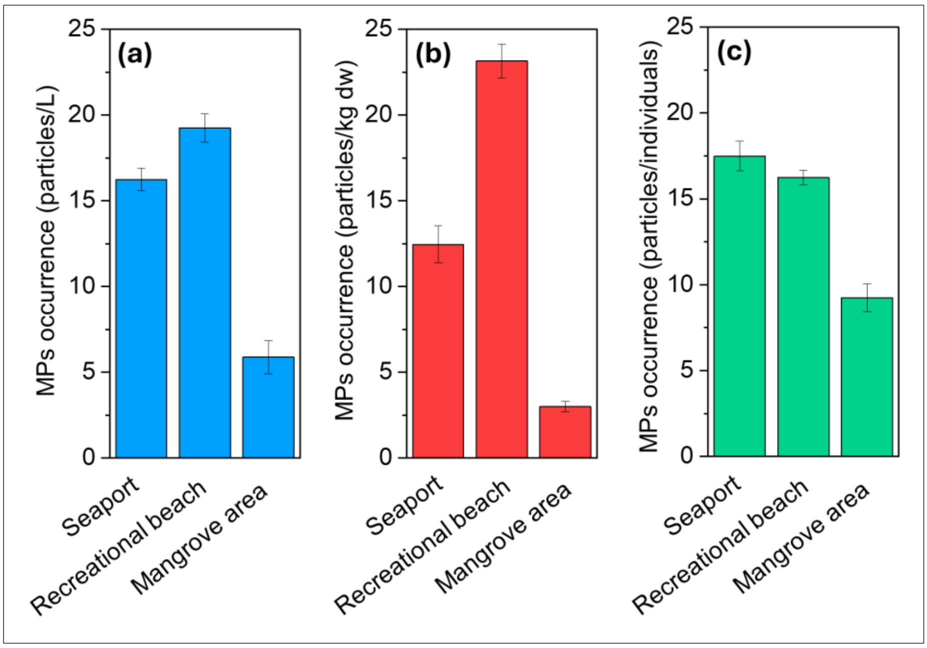

Figure 3. The abundance of MPs in (a) coastal water, (b) sediment, and (c) fish at Gili Trawangan Island

Significant differences in MPs concentrations across environmental compartments and sampling locations can be attributed to the unique ecological dynamics of each area, shaped by both anthropogenic activities and natural processes. At the Recreational Beach, intensive tourist activity contributes to substantial plastic waste generation, particularly from single-use items such as water bottles, straws, and food packaging. These materials are prone to fragmentation, forming secondary MPs that are widely dispersed in coastal waters and sediment. The frequent recreational use of the area, combined with tidal transport, results in elevated MPs concentrations, often characterized by smaller particle sizes and fibrous morphologies. In contrast, the Mangrove area functions as a natural trap for sediments. The dense root systems of mangrove vegetation effectively limit the dispersion of MPs, resulting in considerably lower concentrations in both water and sediment samples. However, the persistence of MPs within mangrove ecosystems is evident from their presence in local fish, indicating ongoing bioaccumulation and potential biomagnification through trophic levels [15, 36]. Although MPs concentrations in the water column at the seaport are lower than those at the Recreational Beach, sediments exhibit notable MPs accumulation. This pattern is likely driven by maritime operations, tidal currents, and localized runoff. Ports often act as accumulation zones for plastic debris from shipping activities, improper waste disposal, and urban discharge. These factors facilitate the deposition of MPs in port sediments, where they may persist and act as long-term reservoirs for adsorbed contaminants [8, 22].

The observed spatial heterogeneity of MPs highlights the interplay between industrial, recreational, and ecological processes as key drivers of MPs pollution. Variations in polymer types and particle sizes across environmental compartments suggest differing sources and degradation pathways. For instance, MPs found at recreational beaches are predominantly secondary fragments from consumer plastic waste, while MPs in seaport sediments are more likely to be industrial in origin. These findings underscore the importance of location-specific strategies for MPs mitigation. Enhanced waste management at recreational areas, stricter enforcement of maritime waste regulations, and protection of mangrove ecosystems as natural filtration systems are critical for reducing MPs inputs and persistence. Addressing the complex interactions between human activities and natural dynamics offers valuable insights for developing comprehensive MPs pollution control strategies [13, 25]. Moreover, implementing long-term and seasonally sensitive monitoring programs could facilitate the detection of emerging MPs hotspots, particularly in response to infrastructure development or increased tourist influx. Such monitoring efforts would also support refining policy interventions and enable adaptive management. Collaborative engagement among local stakeholders, environmental agencies, and research institutions is essential to translate scientific understanding into effective conservation practices. Ultimately, this integrative and adaptive approach enhances the potential for achieving sustainable, long-term outcomes in the fight against MPs contamination [37-40]. These efforts contribute meaningfully to global initiatives to foster environmental resilience and sustainability by bridging the gap between empirical research and practical implementation.

3.3. Characteristics of MPs at Gili Trawangan Island

3.3.1. Types and Colors of MPs

MPs analysis on Gili Trawangan reveals notable variations in particle types and colors across environmental compartments, shaped by a combination of ecological processes and anthropogenic activities. In water samples, fragments and fibers were identified as the dominant forms. Fragments are primarily derived from the degradation of larger plastic items, such as bottles, packaging materials, and fishing nets, through photodegradation and mechanical abrasion induced by UV radiation and wave action [39]. Fibers, commonly linked to textile materials and marine ropes, were particularly prevalent in areas characterized by high tourism and maritime traffic. Color analysis revealed black, blue, and red particles as the most frequently observed, indicative of widely used materials, including fishing gear, food packaging, and recreational equipment. Although less abundant, film-like MPs were also detected and are likely sourced from single-use plastic bags and snack wrappers, which are commonly discarded in tourist-heavy zones. The buoyant properties of both fragments and fibers facilitate their suspension in the water column, thereby increasing their bioavailability and potential for ingestion by pelagic organisms [40]. Fragments were the predominant form in sediment samples, likely due to their greater density and propensity to settle on the seafloor or along coastal zones [41].

Lighter particles, such as films and fibers, were less commonly found in sediments unless physically trapped by sediment compaction or retained by structures such as mangrove root systems. Like water samples, the dominant colors observed in the sediment were red, blue, and black, reflecting the influence of packaging waste and marine debris from fishing activities. Port areas exhibited a higher prevalence of industrially derived MPs, including plastic pellets and irregular fragments, suggesting localized inputs from maritime operations, industrial runoff, and shipping activities. Fibers and fragments were frequently detected in biota, particularly in fish collected near the Seaport and Recreational Beach. Fibers are likely ingested when mistaken for natural food sources such as algae or aquatic vegetation. At the same time, fragments may enter the food web through direct ingestion or trophic transfer from smaller contaminated organisms. The predominance of blue, black, and red MPs in fish tissues closely mirrors the color distributions observed in the surrounding water and sediments, indicating consistent environmental exposure pathways [42]. Polymer analysis further identified a range of compositions, including PE, PP, and PS, with variations across sampling sites reflecting the diversity of consumer and industrial plastics introduced into marine environments. Moreover, physical processes such as wave action and nearshore currents significantly influence the transport and redistribution of tiny plastic fragments along the coastline, exacerbating the risk of MPs accumulation in ecologically sensitive habitats. These findings underscore the multifactorial origins, complex transport pathways, and ecological implications of MPs contamination in coastal systems, particularly in regions subject to intense tourism and maritime activity [39, 42-44].

3.3.2. Polymer Types of MPs

The characterization and quantification of MPs were conducted using FTIR spectroscopy to identify the polymer types present in samples collected from coastal water, sediment, and fish at three distinct locations: the seaport, recreational beach, and mangrove area (n=9). Randomized sampling was employed to ensure representativeness across environmental compartments (Figure 4). Each polymer exhibited distinctive absorption spectra, allowing for precise identification based on characteristic wavenumber peaks. For example, PS was identified in water samples by absorption peaks at 3919.37 cm^{-1} and 3334.14 cm^{-1}. In comparison, PE was detected at 2229.00 cm^{-1}, and LDPE exhibited multiple peaks ranging from 2166.81 to 1969.06 cm^{-1}. PS was also consistently detected in sediment and fish samples, including seaweed, where it was identified at 3327.40 cm^{-1}. These consistent detections across different environmental media and sampling locations underscore MPs' environmental persistence and mobility, driven by anthropogenic pressures and natural transport mechanisms. The FTIR spectra for MPs from Gili Trawangan across coastal water, sediment, and fish samples can be seen in Figure 5. The predominance of PS across all sites likely reflects its extensive use in packaging and consumer goods. At the same time, the frequent detection of LDPE corresponds to the widespread presence of single-use plastic products, particularly in areas with intense recreational activity. At the Recreational Beach, elevated MPs concentrations were associated with high visitor density and inadequate waste management. Furthermore, the synergistic effects of UV radiation and mechanical abrasion from wave action likely accelerated the fragmentation of larger plastic debris into MPs. Conversely, the Mangrove Area exhibited lower MPs concentrations in coastal water and sediment. This pattern is attributed to the natural filtration capacity of mangrove root systems, which can trap and retain particulate matter.

However, the detection of MPs in fish samples from this area indicates the persistence of these contaminants in the food web, suggesting ongoing bioaccumulation and the potential for biomagnification [15]. At the Seaport, MPs concentrations in sediments exceeded those in surface waters, a pattern likely influenced by maritime activity and hydrodynamic conditions that facilitate the deposition of plastic particles. Sediment samples from this site commonly contained industrial polymers such as PS and PE, indicating localized contributions from port operations, urban runoff, and shipping-related sources. The observed variability in polymer types across environmental compartments highlights the diversity of MPs sources and degradation pathways. Secondary MPs derived from the breakdown of larger plastic debris were especially prominent at the Recreational Beach, whereas primary or industrial-origin MPs were more prevalent at the Seaport. These findings illustrate the complex interactions between plastic waste and environmental variables, including particle density, hydrodynamic forces, and habitat characteristics, all of which influence MPs distribution and fate [41]. Overall, the results emphasize the need for site-specific approaches to MPs pollution mitigation. Recognizing the distinct contributions of tourism, maritime activities, and ecological features across different coastal settings is essential for developing effective and targeted management strategies.

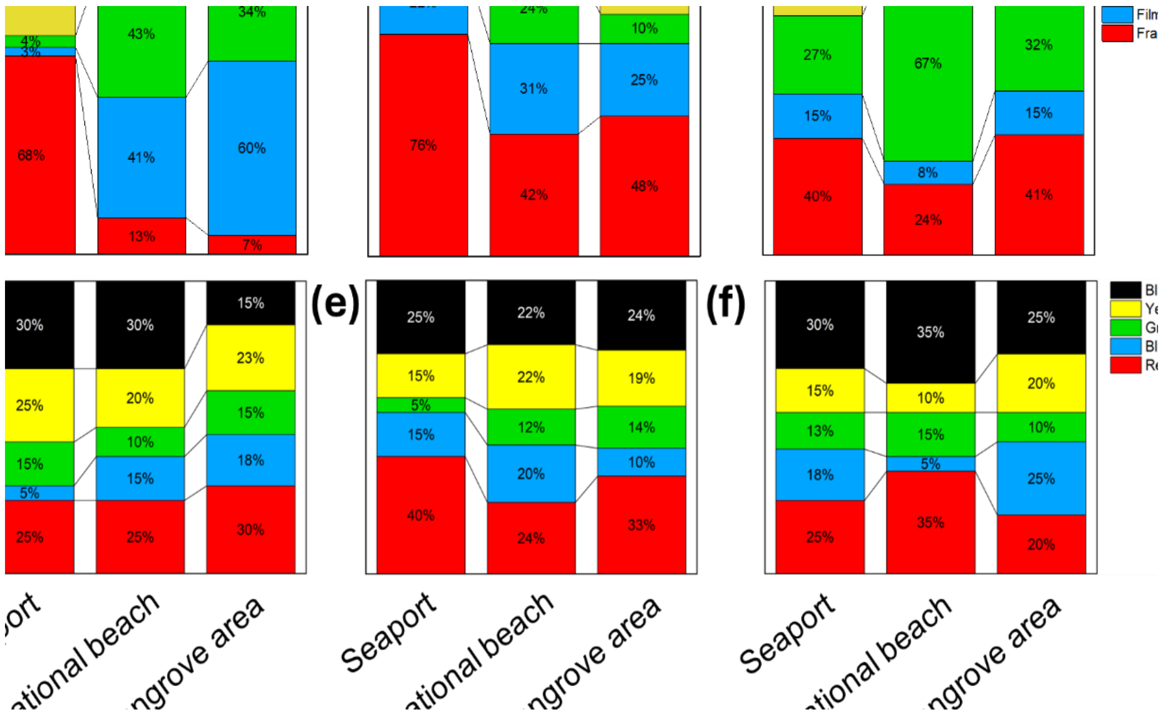

Figure 4. Types and colors of MPs found: (a) & (d) coastal water, (b) & (e) sediment, (c) & (f) fish

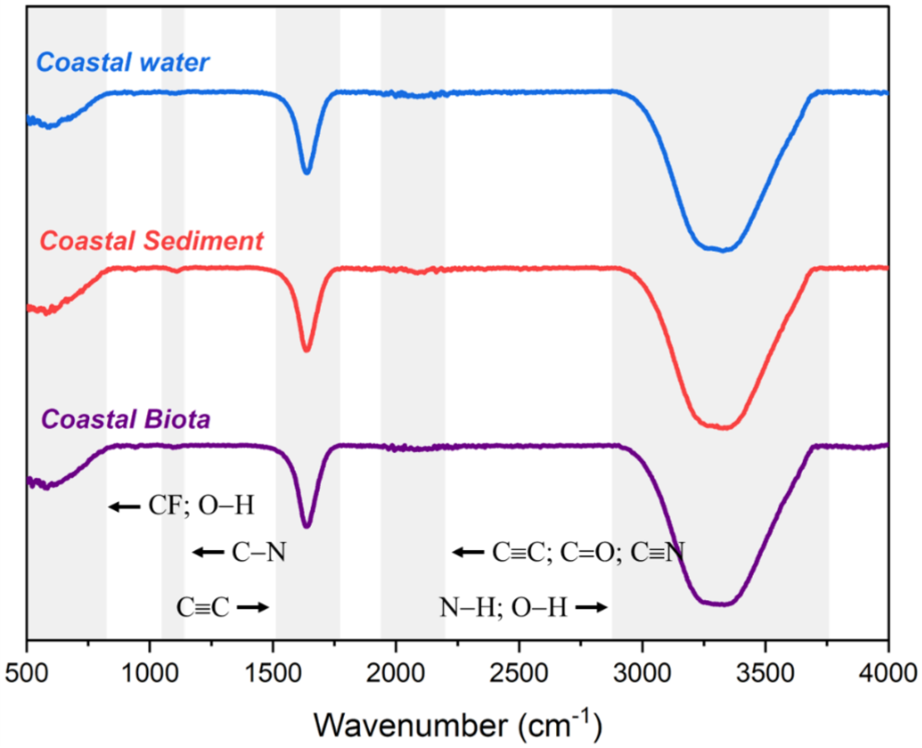

Figure 5. FTIR spectra for MPs from Gili Trawangan

3.4. Characteristics of MPs at Gili Trawangan Island

This study presents a broader and more integrated scope of analysis compared to prior research, which has typically focused on isolated or narrowly defined aspects of microplastic (MPs) contamination. For example, earlier studies on Oahu Island, Hawaii, assessed MPs abundance solely in coastal sediments, reporting concentrations between 700 and 1700 particles per square meter, with particle sizes ranging from 500 µm to 4 mm. These studies primarily identified foam, beads, and filaments in specific colors. Similarly, research conducted in the Maldives, although it characterized MPs by shape, color, and polymer type, was restricted to shallow marine sediments (up to 5 cm depth). A key limitation of such studies lies in their lack of a comprehensive, multi-compartmental analysis that includes fish—critical bioindicators of MPs' ecological impacts.

In contrast, the present study in Gili Trawangan adopts a more holistic approach by analyzing MPs across three environmental compartments: coastal water, sediment, and fish. It also incorporates sampling from locations with varying degrees of anthropogenic pressure, including a seaport, a recreational beach, and a mangrove ecosystem. This multidimensional strategy enabled detailed quantification of MPs abundance, identification of polymer types, and exploration of correlations with specific human activities. The findings showed the highest MPs concentration in coastal water at the Recreational Beach (19.25 particles/L), while the highest sediment contamination was observed at the Seaport (23.15 particles/kg dry weight). The dominant polymers identified were PS, PE, and LDPE, with black, blue, and red particles being the most frequently observed colors.

Methodologically, this research advances beyond comparable studies, such as those conducted on Saint Martin Island (Bangladesh) and Holbox (Mexico), which primarily focused on sediments without integrating biological samples like fish. The use of FTIR spectroscopy in this study enhances the precision of polymer identification, ensuring accurate characterization of MPs. Additionally, this study considers the direct effects of tourism-related activities—such as boating and beach recreation—alongside the ecological functions of mangrove systems, aspects that have often been overlooked in existing literature on MPs pollution.

Overall, this research provides valuable insights into how specific human activities influence the spatial distribution of MPs and highlights the mitigating role of natural ecosystems like mangroves. It emphasizes the urgent need for integrated plastic waste management systems and policy measures to reduce single-use plastic consumption, particularly in tourist-heavy regions—an area that has received limited attention in previous studies. Future research should incorporate long-term monitoring to assess temporal variations and further explore the ecological effects of MPs across different trophic levels (see Table 3).

Table 3. Comparison of the exploration between previous research and this study

Observation Objects	Sampling Collection and Preparation	MPs Characteristics				Ref.
		Abundance	Size	Shape	*Polymer Type	
Sediment	A 45-meter transect established, 9 quadrats (30×30 cm) placed; sieved 5 mm and 500 µm, then analyzed using a stereomicroscope (20 x/40 x).	700–1700 particles/m²	500 µm–4 mm	Foam, beads, and filaments	White, blue, red, yellow, and green	Rey et al. [5]
Sediment	Sediment collected at a depth of 5 cm, reef flat at 2–3 m, fore reef at 6–7 m; separated using a $ZnCl_2$ solution, centrifuged, and then vacuum-filtered using a 1.2 µm nitrocellulose filter; then analyzed using a stereomicroscope (30 x).	1244 particles/m²	0.01–3 mm	Filaments (49%) & Fragments (51%)	Blue (46.7%), red (19.3%), gray (11.1%), orange (9.7%), & black (8.0%)	Patti et al. [6]
Sediment	Sediment collected from a depth of about 2–5 cm; sieved with Tyler Brass sieves from 5-0.625 mm; separated using a 5 M NaCl solution and then filtered through a 5 µm cellulose nitrate filter; then analyzed using a stereomicroscope and ATR-FTIR spectroscopy.	2–49 particles/ 100 g	0.5–1 mm (57%), 1–1.5 mm (25%), & <0.5 mm (18%)	Fiber (50%), film (26%), foam (14%), & fragments (10%)	RA (32%), PA (17%), PE (16%), PP–PE (10.4%), PU (11%), PS (8%), EP (3.6%), & AL (1.6%)	Tajwar et al. [7]
Sediment	Sediment collected at a depth of 5 cm; dried in an oven (60°C for 48 hours); then sieved using a 1.13 mm mesh; separated using a $CaCl_2$ solution and washed with 0.5 N HCl to remove shells and 30% H_2O_2 to remove organic material; analyzed using a stereomicroscope (5 x /10 x)	10.58-105.81 particles/m² (average: 49.37 ± 45.55 particles/m²)	1–5 mm	Fragments (52–70%)	-	Cruz-Salas et al. [8]
Sediment	Samples separated using a $ZnCl_2$ solution; organic material in the samples was digested with 30% H_2O_2 at 50°C; then filtered using 5 mm and 0.1 mm mesh; then analyzed using a Nikon stereo microscope (40 x), FTIR-ATR spectroscopy, and SEM-EDX	7.5-217.5 particlesl/kg (average: 97,18 ± 80,49/kg)	0.1–0.3 mm (42.12%), 1–5 mm (32.48%), and 0.3–1 mm (25.40%)	Foam (41%), fragment (35%), fiber (22%), film (0.64%), & pellet (0.32%)	PS (40.51%), PE (28.30%), HDPE (15.43%), PP (6.43%), PA (4.82%), LDPE (2.57%), unidentified polymer (1.92%)	Khaleel et al. [9]
Sediment	Sediment collected from the top 2 cm layer; dried in an oven at 65°C; then extracted with an NaCl solution and sieved using a 1–0.3 mm mesh; then identified using a stereomicroscope (40 x) and ATR-FTIR spectroscopy	3–17 particles/kg dw; 432 items/m²	0.3–4.75 mm	Fiber (40%), fragment (28%), foam (27%), pellet (3%), film (2%)	PE, PP, PVC, & PS	Pérez-Alvelo et al. [10]
Coastal water	Samples towed horizontally for 30 min at a speed of about 2 knots using a neuston net (333 µm mesh); the samples pre-filtered with a 5 mm metal mesh and then vacuum-filtered using a 20 µm membrane; organic material was separated with 30% H_2O_2 at 65°C for 24 h followed by density separation using an NaCl solution; the identified using a stereomicroscope (40 x) and ATR-FTIR spectroscopy.	0.0112–0.149 items/m³ (average: 0.0556 ± 0.0355 items/m³)	0.2–3 mm	Fragments (58.4%), fibers (32.7%), plastic films (8.9%)	PP (37.8%), PE (18.3%), PPC (11.0%), PAN (6.1%), & UA (3.7%)	Upadhyay et al. [11]
Sediment	Sediment taken from a depth of about 5 cm, dried in an oven for 48 hours at 60°C, separated using a saturated NaCl solution, and then identified using a stereomicroscope (40 x) and ATR-FTIR spectroscopy	Before the tourist season: 21.4 ± 13.95 items/kg dw and after: 28.85 ± 31.97 items/kg dw	Before the tourist season: 943.01 µm and after: 2099.33 µm	Before the tourist season: foam (44.35%) and fragments (38.85%), and after: foam (58.25%) and fragments (23.78%)	Before the tourist season: PS (40.85%) and white color (33.3%); and after: PS (55.91%) and white color (48.3%)	Tan et al. [12]
Coastal water	Coastal water was collected at depths of 10 m and 15 m; filtered using a nitrocellulose membrane with a pore size of 0.45 µm; and then identified using a stereomicroscope (40 x) and ATR-FTIR spectroscopy.	25 particles/L	0.5-4 mm	Fibers (49%), fragments (33%), and films (18%)	PP, PS, PVC, Nylon	Terzi et al. [13]
Coastal water	▪ Coastal water was collected 10 m from the beach, and fish were obtained at a depth of 2–5 m; then filtered using Whatman® GF/C filter paper with a pore size of 1.2 mm.	▪ Harbor area: 23.15 particles/kg dw ▪ Tourist beach: 12.46 particles/kg ▪ Mangrove area: 3 particles/kg				
Coastal sediment	▪ Sediment was collected at a depth of about 5 m from the shoreline; oven-dried for 48 hours at 60°C; separated using a 30% NaCl solution, and filtered using Whatman® GF/C filter paper with a pore size of 1.2 mm	▪ Harbor area: 19.25 particles/L ▪ Tourist beach: 16.25 particles/L ▪ Mangrove area: 5.89 particles/L	943.01-2099.33 µm	Fragment & fiber	PS dominant with black, blue, and red colors	This study
Coastal fish	▪ Fish were taken at a depth of 2–5 m. ▪ All samples identified using a stereomicroscope (40 x) and ATR-FTIR spectroscopy.	▪ Harbor area: 17.5 particles/individual ▪ Tourist beach: 16.25 particles/individual ▪ Mangrove area: 9.25 particles/individual				

*Abbrevation: RA (Rayon), PA (Nylon), PE (Polyethylene), PP–PE Copolymer (Polypropylene–Polyethylene Copolymer), PU (Polyurethane), PS (Polystyrene), EP (Epoxy), AL (Alkyd), HDPE (High-Density Polyethylene), PA (Polyamide), LDPE (Low-Density Polyethylene), PVC (Polyvinyl Chloride), PPC (Polypropylene Copolymer), PAN (Polyacrylonitrile), UA (Urethane Acrylate).

4. Conclusion and Recommendations

Research conducted on Gili Trawangan Island, Indonesia, underscores the significant influence of tourism on microplastic (MPs) pollution in marine ecosystems. The study reveals that areas with high tourism intensity, particularly recreational beaches, showed markedly elevated concentrations of MPs—recording up to 19.25 particles per liter in coastal waters and 12.46 particles per kilogram in sediments. These MPs were primarily composed of fragments and fibers, ranging in size from approximately 943.01 to 2099.33 µm. The predominant polymer types identified were PS, PE, and LDPE, most commonly found in black, blue, and red colors. These particles largely originate from the widespread use of disposable plastics associated with tourism, such as food wrappers, beverage bottles, and other single-use items.

While the seaport area showed relatively lower MP concentrations in coastal waters, it exhibited the highest contamination levels in sediments (23.15 particles/kg) and fish (up to 17.5 particles per individual), likely due to maritime operations and sedimentation processes. Conversely, the mangrove area displayed the lowest MP concentrations—5.89 particles per liter in water and 3.00 particles per kilogram in sediment—suggesting a natural filtering effect of mangrove root systems and minimal direct human impact. These spatial differences highlight how both human activities and natural environmental processes shape the distribution of MPs in coastal habitats.

The study emphasizes the persistence and ecological threat of MPs in marine environments. These particles can physically harm marine organisms through ingestion or entanglement and act as carriers for toxic substances, contributing to bioaccumulation and biomagnification across trophic levels, with potential consequences for human health. Given the ecological vulnerability and economic reliance of island destinations on marine tourism, the findings stress the urgency of implementing integrated waste management strategies and proactive regulatory measures. These efforts should focus on reducing single-use plastic consumption and improving local waste infrastructure.

Importantly, this research offers fresh insights into MP pollution dynamics by employing a comprehensive multi-compartment approach—simultaneously analyzing MPs in water, sediment, and fish. This holistic methodology provides a more complete understanding of the sources, transport pathways, and fate of MPs compared to previous studies that often examined environmental matrices in isolation.

Future research should include long-term monitoring to track temporal changes and consider a wider range of environmental and human-related variables. Moreover, integrating interdisciplinary approaches that combine ecological science with socio-economic analysis will be vital for developing targeted and effective policy responses.

Ultimately, tackling MPs pollution effectively requires coordinated action across multiple sectors. Collaboration among researchers, government bodies, tourism operators, local businesses, and the public is essential. Education and stakeholder-led initiatives to raise awareness and promote behavioral change will play a key role in encouraging sustainable tourism practices. Such collective action will help protect marine biodiversity, strengthen ecological resilience, and safeguard public health in Gili Trawangan and other vulnerable island ecosystems.

5. Declarations

5.1. Author Contributions

Conceptualization, M.A.A. and A.P.I.; methodology, S.K.; software, N.K.C.; validation, D.A.C. and W.P.; formal analysis, H.S.T.; investigation, M.A.; resources, T.M.; data curation, H.M.; writing—original draft preparation, M.A.A.; writing—review and editing, W.P.; visualization, T.M.; supervision, A.P.I.; project administration, S.K. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

The authors would like to express their gratitude to the Postgraduate School of Universitas Airlangga for the support through the Woman Empowerment in Law Enforcement Research Fund with grant number 3906/UN3.SPS/PT.01.03/2023.

5.4. Acknowledgements

We want to extend our sincere gratitude to the Research Center for Marine and Land Bioindustry, the National Research and Innovation Agency, and the Department of Biotechnology at Universitas Teknologi Sumbawa for their invaluable support in facilitating the research titled "Linking the Tourism Activity to The Occurrence and Distribution of Microplastics: A Case Study from Gili Trawangan Island, Indonesia." Your assistance has been instrumental in completing this study, and we sincerely appreciate your commitment to advancing research in marine and environmental sciences.

5.5. Conflicts of Interest

The authors declare no conflict of interest.

6. References

[1] Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., Narayan, R., & Law, K. L. (2015). Plastic waste inputs from land into the ocean. Science, 347(6223), 768–771. doi:10.1126/science.1260352.

[2] Ammendolia, J., Saturno, J., Brooks, A. L., Jacobs, S., & Jambeck, J. R. (2021). An emerging source of plastic pollution: Environmental presence of plastic personal protective equipment (PPE) debris related to COVID-19 in a metropolitan city. Environmental Pollution, 269, 116160. doi:10.1016/j.envpol.2020.116160.

[3] Moore, C. J. (2008). Synthetic polymers in the marine environment: A rapidly increasing, long-term threat. Environmental Research, 108(2), 131–139. doi:10.1016/j.envres.2008.07.025.

[4] Botterell, Z. L. R., Beaumont, N., Dorrington, T., Steinke, M., Thompson, R. C., & Lindeque, P. K. (2019). Bioavailability and effects of microplastics on marine zooplankton: A review. Environmental Pollution, 245, 98–110. doi:10.1016/j.envpol.2018.10.065.

[5] Rey, S. F., Franklin, J., & Rey, S. J. (2021). Microplastic pollution on island beaches, Oahu, Hawai. PLoS ONE, 16(2), 247224. doi:10.1371/journal.pone.0247224.

[6] Patti, T. B., Fobert, E. K., Reeves, S. E., & Burke da Silva, K. (2020). Spatial distribution of microplastics around an inhabited coral island in the Maldives, Indian Ocean. Science of the Total Environment, 748, 141263. doi:10.1016/j.scitotenv.2020.141263.

[7] Tajwar, M., Hasan, M., Shreya, S. S., Rahman, M., Sakib, N., & Gazi, M. Y. (2023). Risk assessment of microplastic pollution in an industrial region of Bangladesh. Heliyon, 9(7), 102401. doi:10.1016/j.heliyon.2023.e17949.

[8] Cruz-Salas, A. A., Alvarez-Zeferino, J. C., Ojeda-Benitez, S., Cruz-Sotelo, S. E., & Vázquez-Morillas, A. (2022). Solid waste and microplastics on the beaches of Holbox island, Mexico. Regional Studies in Marine Science, 53, 102423. doi:10.1016/j.rsma.2022.102423.

[9] Khaleel, R., Valsan, G., Rangel-Buitrago, N., & Warrier, A. K. (2022). Hidden problems in geological heritage sites: The microplastic issue on Saint Mary's Island, India, Southeast Arabian Sea. Marine Pollution Bulletin, 182, 114043. doi:10.1016/j.marpolbul.2022.114043.

[10] Pérez-Alvelo, K. M., Llegus, E. M., Forestier-Babilonia, J. M., Elías-Arroyo, C. V., Pagán-Malavé, K. N., Bird-Rivera, G. J., & Rodríguez-Sierra, C. J. (2021). Microplastic pollution on sandy beaches of Puerto Rico. Marine Pollution Bulletin, 164, 112010. doi:10.1016/j.marpolbul.2021.112010.

[11] Upadhyay, P., Ladumor, R., Gurjar, T., Kottayi, M., Doshi, A., & Pandya, P. (2025). Environmental risk assessment of heavy metals and microplastics in marine biota along Gujarat coastline, India. Marine Pollution Bulletin, 211, 117357. doi:10.1016/j.marpolbul.2024.117357.

[12] Tan, F., Yang, H., Xu, X., Fang, Z., Xu, H., Shi, Q., Zhang, X., Wang, G., Lin, L., Zhou, S., Huang, L., & Li, H. (2020). Microplastic pollution around remote uninhabited coral reefs of Nansha Islands, South China Sea. Science of the Total Environment, 725, 138383. doi:10.1016/j.scitotenv.2020.138383.

[13] Terzi, Y., Gedik, K., Eryaşar, A. R., Öztürk, R. Ç., Şahin, A., & Yılmaz, F. (2022). Microplastic contamination and characteristics spatially vary in the southern Black Sea beach sediment and sea surface water. Marine Pollution Bulletin, 174, 113228. doi:10.1016/j.marpolbul.2021.113228.

[14] Horton, A. A., Walton, A., Spurgeon, D. J., Lahive, E., & Svendsen, C. (2017). Microplastics in freshwater and terrestrial environments: Evaluating the current understanding to identify the knowledge gaps and future research priorities. Science of the Total Environment, 586, 127–141. doi:10.1016/j.scitotenv.2017.01.190.

[15] Heshmati, S., Makhdoumi, P., Pirsaheb, 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, 113620. doi:10.1016/j.jenvman.2021.113620.

[16] Adam, M. A., Talbia, H. S., Ariyanti, D., Kristianto, S., Chairunnisa, N. K., Aprilia, M., Firdaus, M., Marzuki, R., Iswara, A. P., Prayogo, W., Mutia, T., & Masruroh, H. (2024). Microplastics Contamination in Environment and Marine Animals at Kodek Bay, Lombok, Indonesia. Water, Air, and Soil Pollution, 235(12), 789. doi:10.1007/s11270-024-07607-2.

[17] Provencher, J. F., Vermaire, J. C., Avery-Gomm, S., Braune, B. M., & Mallory, M. L. (2018). Garbage in guano? Microplastic debris found in faecal precursors of seabirds known to ingest plastics. Science of the Total Environment, 644, 1477–1484. doi:10.1016/j.scitotenv.2018.07.101.

[18] Hoang, T., & Mitten, S. (2022). Microplastic accumulation in the gastrointestinal tracts of nestling and adult migratory birds. Science of the Total Environment, 838, 155827. doi:10.1016/j.scitotenv.2022.155827.

[19] Muthukumar, P., & Selvam, S. (2024). Microplastic pollution in marine sea fish. In Meso and Microplastic Risk Assessment in Marine Environments: New Threats and Challenges (pp. 199–214). Elsevier. doi:10.1016/B978-0-323-90980-8.00019-4.

[20] Mamun, A. Al, Prasetya, T. A. E., Dewi, I. R., & Ahmad, M. (2023). Microplastics in human food chains: Food becoming a threat to health safety. Science of the Total Environment, 858, 159834. doi:10.1016/j.scitotenv.2022.159834.

[21] Uy, C. A., & Johnson, D. W. (2022). Effects of microplastics on the feeding rates of larvae of a coastal fish: direct consumption, trophic transfer, and effects on growth and survival. Marine Biology, 169(2), 27. doi:10.1007/s00227-021-04010-x.

[22] Blackburn, K., & Green, D. (2022). The potential effects of microplastics on human health: What is known and what is unknown. Ambio, 51(3), 518–530. doi:10.1007/s13280-021-01589-9.

[23] Leslie, H. A., Brandsma, S. H., van Velzen, M. J. M., & Vethaak, A. D. (2017). Microplastics en route: Field measurements in the Dutch river delta and Amsterdam canals, wastewater treatment plants, North Sea sediments and biota. Environment International, 101, 133–142. doi:10.1016/j.envint.2017.01.018.

[24] Barrows, A. P. W., Neumann, C. A., Berger, M. L., & Shaw, S. D. (2017). Grab: Vs. neuston tow net: A microplastic sampling performance comparison and possible advances in the field. Analytical Methods, 9(9), 1446–1453. doi:10.1039/c6ay02387h.

[25] Smith, M., Love, D. C., Rochman, C. M., & Neff, R. A. (2018). Microplastics in Seafood and the Implications for Human Health. Current Environmental Health Reports, 5(3), 375–386. doi:10.1007/s40572-018-0206-z.

[26] Wang, W., Ndungu, A. W., Li, Z., & Wang, J. (2017). Microplastics pollution in inland freshwaters of China: A case study in urban surface waters of Wuhan, China. Science of the Total Environment, 575, 1369–1374. doi:10.1016/j.scitotenv.2016.09.213.

[27] Wang, J., Peng, J., Tan, Z., Gao, Y., Zhan, Z., Chen, Q., & Cai, L. (2017). Microplastics in the surface sediments from the Beijiang River littoral zone: Composition, abundance, surface textures and interaction with heavy metals. Chemosphere, 171, 248–258. doi:10.1016/j.chemosphere.2016.12.074.

[28] Peng, G., Zhu, B., Yang, D., Su, L., Shi, H., & Li, D. (2017). Microplastics in sediments of the Changjiang Estuary, China. Environmental Pollution, 225, 283–290. doi:10.1016/j.envpol.2016.12.064.

[29] Walenna, M. A., Hanami, Z. A., Hidayat, R., Damayanti, A. D., Notodarmojo, S., Kurniaty, & Caroles, L. (2024). Examining Soil Microplastics: Prevalence and Consequences Across Varied Land Use Contexts. Civil Engineering Journal (Iran), 10(4), 1265–1291. doi:10.28991/CEJ-2024-010-04-017.

[30] Zhang, W., Zhang, S., Wang, J., Wang, Y., Mu, J., Wang, P., Lin, X., & Ma, D. (2017). Microplastic pollution in the surface waters of the Bohai Sea, China. Environmental Pollution, 231, 541–548. doi:10.1016/j.envpol.2017.08.058.

[31] Díaz-Mendoza, C., Mouthon-Bello, J., Pérez-Herrera, N. L., & Escobar-Díaz, S. M. (2020). Plastics and microplastics, effects on marine coastal areas: a review. Environmental Science and Pollution Research, 27(32), 39913–39922. doi:10.1007/s11356-020-10394-y.

[32] Yuan, W., Liu, X., Wang, W., Di, M., & Wang, J. (2019). Microplastic abundance, distribution and composition in water, sediments, and wild fish from Poyang Lake, China. Ecotoxicology and environmental safety, 170, 180-187. doi:10.1016/j.ecoenv.2018.11.126.

[33] Dowarah, K., & Devipriya, S. P. (2019). Microplastic prevalence in the beaches of Puducherry, India and its correlation with fishing and tourism/recreational activities. Marine Pollution Bulletin, 148, 123–133. doi:10.1016/j.marpolbul.2019.07.066.

[34] da Costa, J. P., Duarte, A. C., & Rocha-Santos, T. A. P. (2017). Microplastics – Occurrence, Fate and Behaviour in the Environment. Comprehensive Analytical Chemistry, 75, 1–24. doi:10.1016/bs.coac.2016.10.004.

[35] Hasan, S. S., Salam, A., Moniruzzaman, M., Bari, M. A., Aich, N., Jahan, F., ... & Parvez, S. M. (2024). Understanding the Occurrence and Fate of Atmospheric Microplastics and Their Potential Risks to Human Health: Protocol for a Cross-Sectional Analysis. JMIR Research Protocols, 13(1), e60289. doi:10.2196/60289.

[36] Roch, S., & Brinker, A. (2017). Rapid and Efficient Method for the Detection of Microplastic in the Gastrointestinal Tract of Fishes. Environmental Science and Technology, 51(8), 4522–4530. doi:10.1021/acs.est.7b00364.

[37] Liu, Y., Guo, R., Zhang, S., Sun, Y., & Wang, F. (2022). Uptake and translocation of nano/microplastics by rice seedlings: Evidence from a hydroponic experiment. Journal of Hazardous Materials, 421, 126700. doi:10.1016/j.jhazmat.2021.126700.

[38] Akdogan, Z., & Guven, B. (2019). Microplastics in the environment: A critical review of current understanding and identification of future research needs. Environmental Pollution, 254, 113011. doi:10.1016/j.envpol.2019.113011.

[39] Abd-Elkader, A., Hamed, E. S. A. E., Mahdy, A., & Shabaka, S. (2023). Microplastics in marine invertebrates from the Red Sea Coast of Egypt: Abundance, composition, and risks. Marine Pollution Bulletin, 197, 115760. doi:10.1016/j.marpolbul.2023.115760.

[40] Chemello, G., Trotta, E., Notarstefano, V., Papetti, L., Di Renzo, L., Matiddi, M., Silvestri, C., Carnevali, O., & Gioacchini, G. (2023). Microplastics evidence in yolk and liver of loggerhead sea turtles (Caretta Caretta), a pilot study. Environmental Pollution, 337, 122589. doi:10.1016/j.envpol.2023.122589.

[41] Gül, M. R. (2023). Short-term tourism alters abundance, size, and composition of microplastics on sandy beaches. Environmental Pollution, 316, 120561. doi:10.1016/j.envpol.2022.120561.

[42] Lim, C., Kim, N., Lee, J., & Yoon, Y. (2022). Potential of adsorption of diverse environmental contaminants onto microplastics. Water, 14(24), 4086. doi:10.3390/w14244086.

[43] Hidalgo-Ruz, V., Gutow, L., Thompson, R. C., & Thiel, M. (2012). Microplastics in the marine environment: A review of the methods used for identification and quantification. Environmental Science and Technology, 46(6), 3060–3075. doi:10.1021/es2031505.

[44] Agharokh, A., S. Taleshi, M., Bibak, M., Rasta, M., Torabi Jafroudi, H., & Rubio Armesto, B. (2022). Assessing the relationship between the abundance of microplastics in sediments, surface waters, and fish in the Iran southern shores. Environmental Science and Pollution Research, 29(13), 18546–18558. doi:10.1007/s11356-021-17128-8.