Environment and Natural Resources Journal

Volume 23
Issue 3
2025

Assessment of Microplastic Pollution Load and Ecological Risk Index in Surface Water and Sediment Matrices in the Mangrove Ecosystem along Butuan Bay, Southern Philippines

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ARTICLE INFO

Received: 29 Apr 2024
Received in revised: 13 Jan 2025
Accepted: 16 Jan 2025
Published online: 7 Mar 2025
DOI: 10.32526/ennrj/23/20240122

Keywords:
Mangrove ecosystem/ Emerging pollutants/ Marine microplastics/ Southern Philippines

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ABSTRACT

Microplastics have garnered attention for their ubiquitous presence across various ecosystems, yet investigations into their occurrence in mangrove environments, particularly in the Philippines, remain minimal and increasingly necessary. This study seeks to establish a foundational understanding of microplastic distribution in Philippine mangrove forests, with a special focus on Butuan Bay. Surface water and sediment samples were collected from mangrove habitats in Butuan City, Buenavista, and Nasipit along Butuan Bay, in the Southern Philippines. Results indicated that Buenavista (BMS) exhibited the highest microplastic concentrations, with mean abundances of 322.22±103.41 MPs/m^3 in surface water and 88.89±50.33 MPs/kg in sediments. Both blue and transparent microplastics were prevalent, constituting 24.2% and 25.7% of surface water and 22.6% and 25.7% of sediments, respectively. Microplastics predominantly fell within the 101-250 µm range (46% in surface water and 45.7% in sediments), with films and fragments comprising 69% of surface water MPs and 76.1% of sediment MPs. Ten polymer types were identified, with polypropylene (PP) being the most abundant (31.5% in surface water and 51.7% in sediments). The assessment of the pollution load index (PLI) indicated that MP pollution levels were classified as slightly polluted (hazard level I), and ecological risk index (RI) posed varying degrees across the studied mangroves, ranging from minor danger (hazard level I) to extreme danger (hazard level V). Microplastics were observed to pose ecological risks within these mangrove areas, as indicated by the highest levels of risk shown by BMS and BCMS. Future studies should examine other surrounding waters of Mindanao, such as the adjacent Gingoog Bay, including inland freshwater bodies, to comprehensively assess MP pollution and its potential effects on marine wildlife in the region.

1. INTRODUCTION

Plastics, due to versatility and cost-effectiveness, are extensively manufactured worldwide. In 2021, global plastic production surged to 390.7 billion kg from 1.5 billion kg in 1950 (Statista, 2021; Vlasopoulos et al., 2023). Despite utility, plastics pose significant environmental concerns due to slow biodegradation. A 2017 study showed that only a fraction of the 8,300 billion kg of plastics produced between 1950 and 2015 were

Citation: Keleste EP, Fedelis JS, Opusa WFT, Inocente SAT, Banda MHT, Latayada FS, Jumawan JC, Vales TP, Seronay RA, Capangpangan RY. Assessment of microplastic pollution load and ecological risk index in surface water and sediment matrices in the mangrove ecosystem along Butuan Bay, Southern Philippines. Environ. Nat. Resour. J. 2025;23(3):196-210. (https://doi.org/10.32526/ennrj/23/20240122)

recycled, with the majority ending up in landfills and oceans (Geyer et al., 2017). Over time, discarded plastics break down into microplastics, smaller than 5mm (Arthur et al., 2009), found in various environmental compartments, including sediments, water bodies, and marine organisms (Liu et al., 2021a; Sayed et al., 2021; Zantis et al., 2021), human tissues (Ragusa et al., 2021), and blood (Leslie et al., 2022).

Microplastics (MPs), due to size, pose significant dangers as contaminants, progressing undetected through the food chain and carrying toxic heavy metals (Brennecke et al., 2016) and persistent organic pollutants (Santana-Viera et al., 2021). Urgent action is needed globally to isolate, dispose of, and prevent further environmental contamination from microplastics.

Mangrove ecosystems are among the few places with a strong tolerance to pollutants and purification capacities for heavy metals, petroleum, and other domestic sewage contaminants (Liu et al., 2022b). Mangroves prevent coastal erosion, promote shoreline protection (Meera et al., 2022), and serve as the last barrier preventing river pollutants from reaching the ocean (Liu et al., 2022b). Nonetheless, the boundary between mangrove areas and land has been identified as a microplastic (MP) accumulation hotspot (Chen, 2022).

Research indicates that mangroves act as plastic sinks (Deng et al., 2021; Martin et al., 2020), accumulating toxic metals and pollutants (Bayen, 2012). Mangroves are now considered one of the ecosystems severely threatened by microplastic pollution from marine and terrestrial sources (Prarat et al., 2024). Despite the Philippines' rich mangrove biodiversity (Garcia et al., 2013) and ranking 15th globally (Giri et al., 2011), only two studies have investigated MP presence in Philippine mangroves, particularly in sediments (Bonifacio et al., 2022; Navarro et al., 2022a). Organisms in mangrove ecosystems likely ingest MPs, which is alarming as they are food sources for nearby communities. Plastics adsorb heavy metals and pollutants (Naik et al., 2019), emphasizing the need for baseline data on microplastic pollution in mangroves to guide mitigation efforts.

Butuan Bay hosts diverse habitats, including mangroves, amid industrialized cities and municipalities. Tourism and economic growth in these areas lead to inevitable plastic pollution, endangering bay biodiversity, mainly mangroves. Only a few studies have documented microplastics in Butuan Bay mangroves, focusing on sediments (Navarro et al., 2022a) and the clam *Polymesoda erosa*, a species commonly found in the mangroves of Cabadbaran, Buenavista, and Nasipit in Butuan Bay, Mindanao Philippines (Navarro et al., 2024b). This study aims to document the microplastic presence, abundance, and types in selected mangrove sites along Butuan Bay's western portion, including Butuan City, Buenavista, and Nasipit. These sites were chosen for their extensive mangrove cover along waterways leading to Butuan Bay.

2. METHODOLOGY

2.1 Study area

The study focused on Butuan Bay in northeastern Mindanao, Philippines, an extension of the Bohol Sea, receiving water from various sources, including the Agusan River, the country's third-longest. It supports diverse habitats like mangroves. Sampling occurred at three mangrove sites along Butuan Bay: Barangay Masao (BCMS), Barangay Matabao (BMS), and Barangay Ata-atahon (NMS) chosen for extensive mangrove cover (Figure 1). Sampling in September 2022 collected nine surface water and sediment samples from each site for microplastic analysis. These mangroves provide crucial industrial, economic, and topographic benefits to the local community.

2.2 Sample collection

Transect lines were established with three sampling points spaced roughly 50 meters apart. Following Tien et al. (2020), surface water samples were manually collected using 1-liter glass bottles, capturing 20 liters within the top 50 cm. Samples were sieved through stacked metal sieves (5.0 mm and 0.25 mm) to remove debris larger than 5.0 mm (Egessa et al., 2020). Particles on the 0.25 mm sieve were rinsed, transferred to glass jars, and covered with aluminum foil. A total of 27 surface water samples (nine per site) were collected.

For sediment sampling (Masura et al., 2015), about 300 g of wet sediments were scraped up to 1 cm deep at each sampling point using a metal shovel or grab sampler. Samples were stored in glass containers covered with aluminum foil and kept in the dark until analysis. Nine sediment samples were taken from each mangrove site, totaling 27 samples overall.

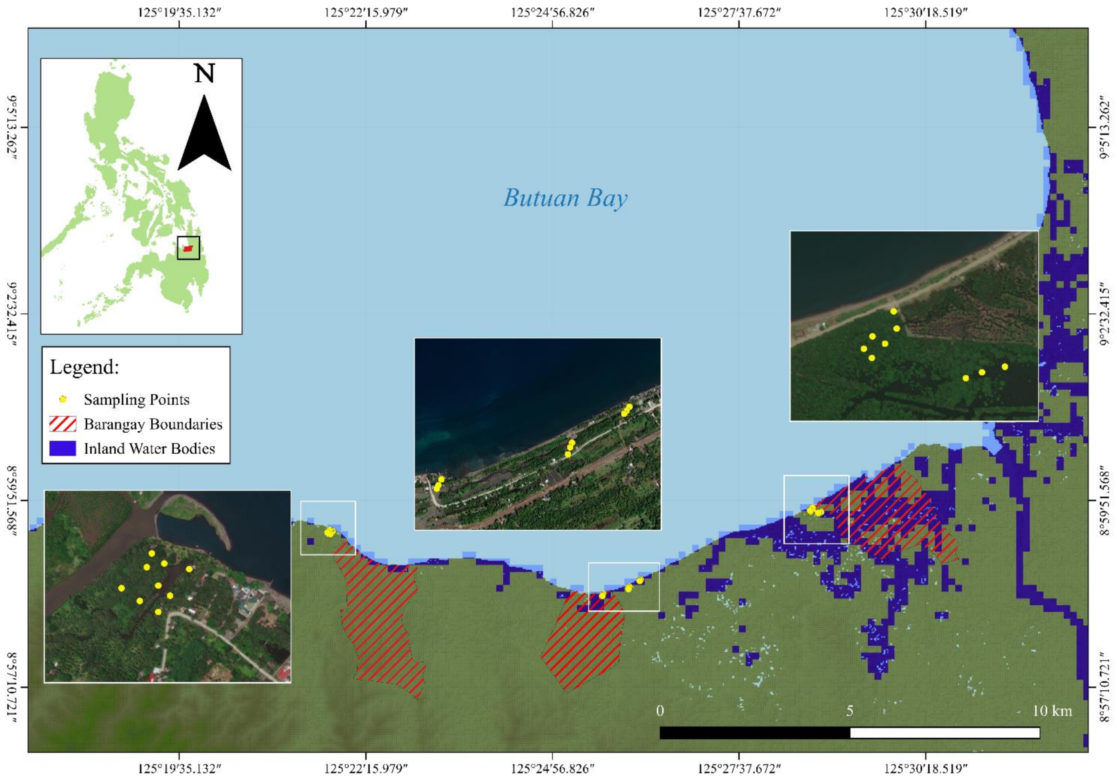

Figure 1. Study area for microplastic assessment in mangrove sites along Butuan Bay, Agusan del Norte, Philippines

2.3 Sample processing

Samples of surface waters and sediments underwent pretreatment to remove impurities and organic matter according to the methods of Inocente et al. (2023). Sediment samples were oven-dried at 90°C for 24 h (Inocente et al., 2023; Masura et al., 2015). Dried sediments (150 g) and surface water samples were digested individually in 10% KOH at 40°C for 40 h (Inocente et al., 2023; Karami et al., 2017) and 60°C for 24 h (Inocente et al., 2023; Dehaut et al., 2016) to dissolve organic material. The resulting supernatants were filtered using a 47 mm Whatman GF/C glass microfiber filter under vacuum. Density separation was conducted on unclear samples with residues by adding a 30% aqueous NaCl solution at a 2:1 ratio and constant agitation for 2 h. The solution was vacuum filtered using Whatman GF/C glass microfiber filters. Filter films were dried overnight in a clean petri dish before isolating suspected microplastics.

2.4 Identification and quantification of microplastics

Microfiber filter films were observed with an Amscope® Dissecting Microscope at 20-40X magnification. Suspected microplastics were isolated on glass slides with a clean needle and labeled. They were then counted and classified by color and morphotype following criteria by Hidalgo-Ruz et al. (2012) and Su et al. (2016a). Using an Amscope® camera connected to a Motic microscope and TCapture software (version 5.1.1.0), photographs were taken, and sizes were measured based on (Li et al., 2020a). Universal Attenuated Total Reflectance Fourier-Transform Infrared (UATR-FTIR) Spectroscopy (PerkinElmer Spectrum Two, USA) determined microplastic polymer type. Spectral data were compared to a plastics library (Jung et al., 2018) at a 0.50 correlation score for identification, considering sample size, impurities, and degradation.

2.5 Quality control

To ensure experimental accuracy, non-plastic lab equipment was prioritized, and regular station cleaning minimized sample contamination. Laboratory windows remained closed to prevent interference from dust and foreign materials. The glassware was thoroughly rinsed with distilled water and stored covered with aluminum foil to prevent airborne contamination. The experimental blank controls containing distilled water were processed following the same procedure for the collected samples. As procedural blanks, clean filters were also exposed inside the laboratory alongside filters containing samples. All samples and blanks were run in triplicates. No MPs were detected in all the blanks.

2.6 Data treatment

The experimental data were analyzed using Microsoft Excel 2016 and the PAST Statistical tool v.4.03. To determine the abundance of microplastics in the surface water and the sediments, the following formulas were used:

$$\text{MP Abundance (Surface Water)} = \frac{\text{number of confirmed microplastics}}{\text{volume of the water sample (m}^3\text{)}} \quad (1)$$

$$\text{MP Abundance (Sediments)} = \frac{\text{number of confirmed microplastics}}{\text{dry mass of the sediment sample (kg)}} \quad (2)$$

These formulas were modified and derived from by Liu et al. (2021a) and Egessa et al. (2020). The Shapiro-Wilk test was utilized to check for the normality of the data. One-way ANOVA test (with Tukey's test) or Kruskall-Wallis test (with Dunn's test) was used to test the variance between the site's mean microplastic abundances. The significance level was assigned at 0.05.

2.7 Ecological risk assessment

This study assessed the potential ecological risks associated with MP pollution in these mangroves along Butuan Bay using the pollution load index (PLI_i) and the ecological risk index (RI). The PLI_i (Tomlinson et al., 1980; Yang et al., 2023) was calculated based on Equations (3) to (5):

$$C_f^i = \frac{C_s^i}{C_b^i} \quad (3)$$

$$PLI_i = \sqrt{C_f^i} \quad (4)$$

$$PLI_{zone} = \sqrt[n]{PLI_1 \times PLI_2 \times \ldots \times PLI_n} \quad (5)$$

Where; C_f^i is the ratio of the MP concentration at each sampling site (C_s^i) and the background MP concentration (C_b^i). The background MPs used in this research have the lowest concentration observed in the studied mangrove areas due to the lack of available data for background MP concentration for mangrove waters and sediments in the southern part of the Philippines to be used as reference. The PLI_{zone} represents the MP pollution load index for mangroves along Butuan Bay and is calculated as the square root of the product of PLI_i obtained from all sampling sites. Moreover, by employing the Håkanson method (Hakanson, 1980; Peng et al., 2018) as a guide, the toxicity response factor (Tr^i) was computed, along with the ecological risk factor (Er^i), and the ecological risk index (RI) for the environment via Equations (6) to (8):

$$Tr^i = P_n \times S_n \quad (6)$$

$$E_r^i = Tr^i \times C_f^i \quad (7)$$

$$RI = \sum_{i=1}^{n} Er^i \quad (8)$$

Where; Tr^i represents the toxicity response factor corresponding to each polymer constituent, and as described by the Lithner approach (Lithner et al., 2011), this factor is calculated by multiplying the percentage of each MP polymer type in the total sample at each sampling site (P_n) by the hazard score associated with the polymer type (S_n) (Lithner et al., 2011). S_n is the hazard score for each polymer type of MP. The hazard score values for polypropylene (PP), polyethylene terephthalate (PET), general purpose polystyrene (GPPS), polyvinyl chloride (PVC), poly (methyl methacrylate) (PMMA), ethylene vinyl acetate (EVA), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyamide 6 (NY6), and polyamide 66 (NY66) were 1, 4, 0, 10 001, 1 021, 9, 11, 11, 50, and 63, respectively (Lithner et al., 2011; Yang et al., 2023; Prarat et al., 2024). The sum of the ecological risk factors for each plastic polymer is the environment's ecological risk index (RI). The criteria for the risk level of MP pollution are presented in Table S2.

3. RESULTS AND DISCUSSION

3.1 Microplastic abundance and distribution in surface water and sediments

Over 96% of the collected surface water and sediment samples in this study contained microplastics, signifying the prevalent distribution of microplastics in three mangrove areas in Butuan Bay. No confirmed microplastics were detected in all experimental blank controls used in the study.

Microplastics were found in 26 of 27 surface water (SW) samples from three mangrove sites in Butuan Bay. Among the 439 suspected microplastics isolated, 124 (28%) were confirmed via UATR-FTIR analysis. BMS had the highest concentration at 322.22±103.41 MPs/m^3, followed by NMS at 250±114.56 MPs/m^3 and BCMS at 116.67±106.07 MPs/m^3 (Table 1). Statistical analysis revealed significant differences in mean microplastic abundances between mangrove sites ($p<0.05$), particularly between Butuan City, Buenavista, and Nasipit.

On the other hand, microplastics were present in 26 of 27 sediment (Sed) samples from selected mangrove sites in Butuan Bay. Among 442 suspected microplastics extracted, about 52% (230 particles) were confirmed. BMS had the highest abundance at 88.89±50.33 MPs/kg, followed by NMS at 55.56±30.91 MPs/kg and BCMS at 25.93±20.93 MPs/kg (Table 1), matching surface water findings. Statistical analysis revealed significant differences in mean abundance between mangrove areas ($p<0.05$), particularly between Butuan City and Buenavista.

Table 1. Microplastics abundance in surface water and sediments of Butuan Bay Mangroves

Sampling area	Number of suspected MPs		Number of confirmed MPs		Abundance of confirmed microplastics (MPs)	
	SW	Sed	SW	Sed	No. of MPs/m^3 surface water	No. of MPs/kg sediment
Butuan City (BCMS)	140	142	21	35	116.67±106.07	25.93±20.93
Buenavista (BMS)	137	176	58	120	322.22±103.41	88.89±50.33
Nasipit (NMS)	162	124	45	75	250.00±114.56	55.56±30.91
Total	439	442	124 (28%)	230 (52%)	229.63±135.35	56.79±43.53

Variations in microplastic abundance among sites suggest environmental and anthropogenic influences (Ronda et al., 2023; Syversen and Lilleng, 2022). In one study (Zhou et al., 2020), microplastics were most prevalent in tourist-heavy mangrove areas, correlating with Buenavista's high microplastic levels. Anthropogenic activities, including waste dumping and proximity to tourist sites and fishing grounds, likely contribute. Larger plastic debris, such as packaging and clothing, was commonly found during sampling. Furthermore, there is a positive correlation between the distance from populated centers and the abundance of plastics found in mangrove areas (Garcés-Ordóñez et al., 2019).

The high microplastic concentration in Buenavista's sediments may result from denser microplastics settling from surface waters (Deng et al., 2021). Floating microplastics may sink due to increased density from organism biofouling (Kowalski et al., 2016). Sediments are significant microplastic sinks (Martin et al., 2020).

Surface water microplastic abundance (229.63±135.35 MPs/m^3) in Butuan Bay mangrove sites was three times higher than in Chabahar Bay, Iran, and Kingston Harbour, Jamaica (Aliabad et al., 2019; Rose and Webber, 2019), but thirty-six times lower than in Beibu Gulf, China (Li et al., 2020b) (Table 2). Sediment microplastic abundance (56.79±43.53 MPs/kg) in Butuan Bay was higher than in Iran and Singapore (Naji et al., 2019; Nor and Obbard, 2014) but lower than in Jinjiang Estuarine and Beibu Gulf, China, and Colombian mangrove habitats (Deng et al., 2020; Garcés-Ordóñez et al., 2019; Zhang et al., 2020). Comparable to 2022 data in Cabadbaran City, Buenavista, and Nasipit, Butuan Bay (Navarro et al., 2022a) (Table 3). Nearby Panguil Bay reported microplastic occurrence (62.72±18.31 MPs/m^2) (Bonifacio et al., 2022). Variances in global mangrove microplastic reports reflect local conditions and anthropogenic impacts.

Table 2. Comparison of microplastic abundance in surface water of mangrove areas

Study Area	MPs/m^3	Reference
Butuan Bay, Philippines	229.63±135.35	This study
Goiana Estuary, Brazil	477	Lima et al. (2016)
Kingston Harbour, Jamaica	0.76	Rose and Webber (2019)
Yunxiao Mangrove Reserve, China	275	Pan et al. (2020)
Beibu Gulf, China	399-5’531	Li et al. (2020b)
Chabahar Bay, Iran	0.14±0.06	Aliabad et al. (2019)

Table 3. Comparison of microplastic abundance in sediments of mangrove areas

Study area	MPs/kg	Reference
Butuan Bay, Philippines (Butuan City, Buenavista, Nasipit)	56.79±43.53	This study
Butuan Bay, Philippines (Cabadbaran, Buenavista, Nasipit)	53.34±21.87	Navarro et al. (2022a)
Panguil Bay, Philippines	62.72±18.31*	Bonifacio et al. (2022)
Five mangrove habitats, Iran	19.5±0.36-34.5±0.71	Naji et al. (2019)
Seven mangrove habitats, Singapore	36.8±23.6	Nor and Obbard (2014)
Six mangrove habitats, Colombia	31-2,863	Garcés-Ordóñez et al. (2019)
Jinjiang Estuarine, China	1,926±351	Deng et al. (2020)
Beibu Gulf, China	273±23-3,520±107	Zhang et al. (2020)

* MPs/m^2

3.2 Morphological characteristics of microplastics

This section details data and analyses of morphological characteristics (color, morphotype, size) and chemical composition (polymer type) of microplastics from three Butuan Bay mangrove sites in the Philippines. Identifying these characteristics and their abundance informs plastic origins and degradation pathways, which are valuable for future mitigation efforts.

3.2.1 Color

Plastics were initially colored for market appeal (Imhof et al., 2016), leading to diverse colors detected in the environment due to limited recycling. This study found 14 colors in microplastics from surface water and sediment samples: white, green, blue, brown, transparent, black, yellow, pink, gray, mixed, tan, orange, violet, and red (Figure 2).

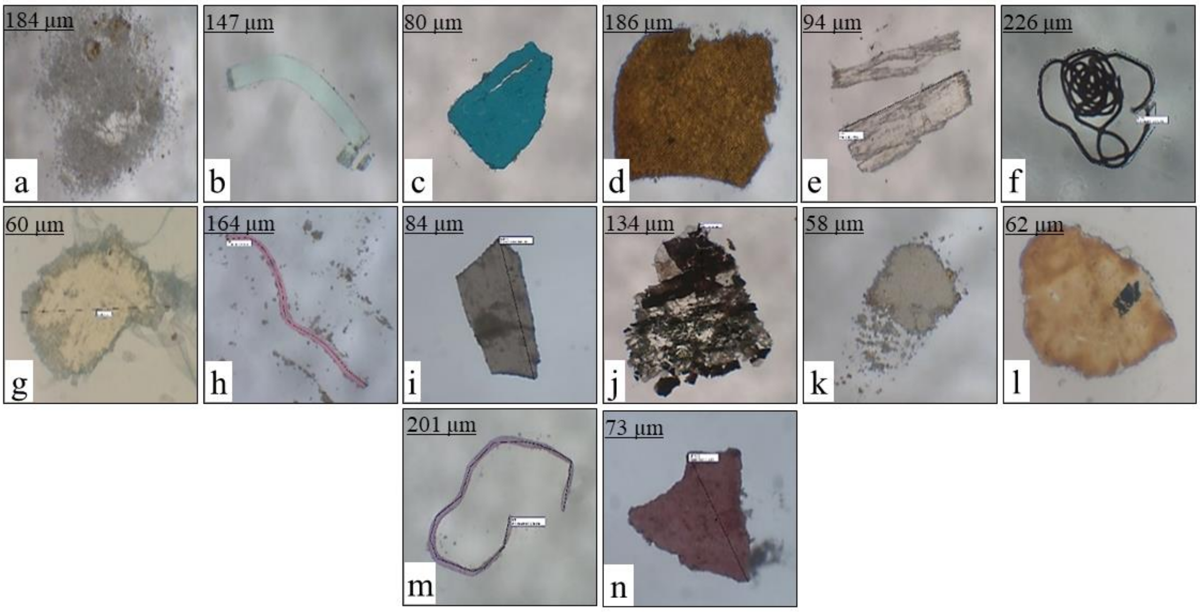

Figure 2. Varying colors, morphology, and sizes of confirmed microplastics from selected mangrove areas

Blue and transparent microplastics prevailed in both water and sediment samples, comprising 22.6% to 25.7% each, respectively (Figure 3). This color distribution aligns with findings from Singaporean coastal mangroves (Nor and Obbard, 2014), Butuan Bay sediments (Navarro et al., 2022a), and Fish Cage Water samples in Butuan and Nasipit (Similatan et al., 2023). However, the results of this study differ from those of Banda et al. (2024), who found that brown microplastics were prevalent in the water samples and white microplastics in the sediment samples of the Taguibo River, which also empties into Butuan Bay. This discrepancy can be attributed to the differing nature of the samples: while our study focuses on coastal samples, Banda et al. (2024) analyzed freshwater samples. These microplastics, mainly PP, LDPE, HDPE, and PET, likely originate from everyday items like bags, containers, and bottles.

Environmental exposure may bleach microplastics and make them transparent (Fan et al., 2019).

Microplastic colors and morphotypes serve as indicators of origin and can be bioindicators of environmental pollution (Lavers et al., 2016). Colors influence ingestion rates in biota, resembling prey colors (Wright et al., 2013). The prevalence of blue and transparent microplastics in mangroves is concerning, as Asian clams predominantly ingest them (Su et al., 2018b). Mud clams, which share similar feeding habits, are likely to consume them too. Given mud clams' status as a staple food in mangrove communities, they pose as potential vector for human microplastic ingestion.

3.2.2 Morphotype

Microplastics were categorized into six morphotypes: fiber, filament, film, foamed, granules, and fragment (Hidalgo-Ruz et al., 2012; Su et al., 2016a) (Figure 2). A fiber is slender and elongated, while a filament has a broader band. Film refers to a thin layer of plastic debris; foamed microplastics are spongy, and granules appear grainy. Fragments are thicker pieces of broken plastic debris used when a microplastic particle does not fit other categories.

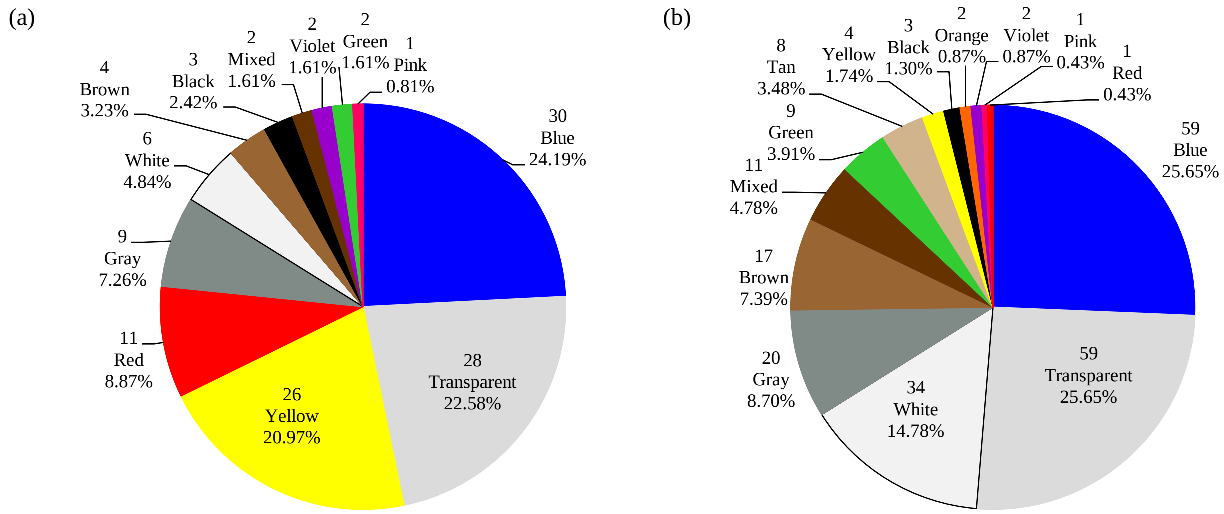

Figure 3. Color distribution of the confirmed microplastics between sample types (a) surface water and (b) sediment

Only four microplastic morphotypes (fiber, film, filament, fragment) were observed in surface water samples. At the same time, all six were found in sediment samples (Figure 4). Fragmented microplastics predominated in surface water (41.9%). In contrast, film-dominated sediment samples (39.6%) (Figure 4). Fiber and filament were third and fourth most abundant in both water and sediment samples across mangrove sites. These findings align with those from the Persian Gulf shoreline, South African estuaries, and Manila Bay River mouths (Govender et al., 2020; Nabizadeh et al., 2019; Osorio et al., 2021). Water morphotypes detected in this study differ from Similatan et al. (2023) from Nasipit samples (fiber) and Banda et al. (2024) (fiber) but agree with the Butuan water morphotypes of Similatan et al. (2023). Sediment morphotypes do not align with the results of Navarro et al. (2022a) and Banda et al. (2024). Films mainly derive from single-use plastic degradation, while fragments originate from larger plastic debris (Martin et al., 2020; Wang et al., 2019), such as containers, bottle caps, and food packaging. Proximity to human settlements suggests microplastics originate from household and business waste. The prevalence of films and fragments underscores poor plastic waste management in surrounding communities.

3.2.3 Size

Microplastic sizes were categorized as <50 µm, 50-100 µm, 101-500 µm, and >500 µm (Li et al., 2020a) (Figure 2). Most microplastics fell in the 101-500 µm range, followed by 50-100 µm, with some <50 µm and >500 µm sizes detected (Figure 5). These findings align closely with Govender et al. (2020), who found 47% and 75% of mangrove microplastics in the surface water and sediments, respectively, were <500 µm. Microplastic ingestion is heavily influenced by size and abundance, especially for benthic species (Rodríguez-Seijo and Pereira, 2017). Sizes of 50-500 µm are small enough for indiscriminate ingestion by mangrove organisms, impacting their growth and reproduction (Cole et al., 2015). Since many of these organisms are food sources, microplastics will likely enter the local food web. The prevalence of microplastics within 50-500 µm may suggest in-situ biodegradation by mangrove-endemic microorganisms (Auta et al., 2022; Kannahi and Sudha, 2013).

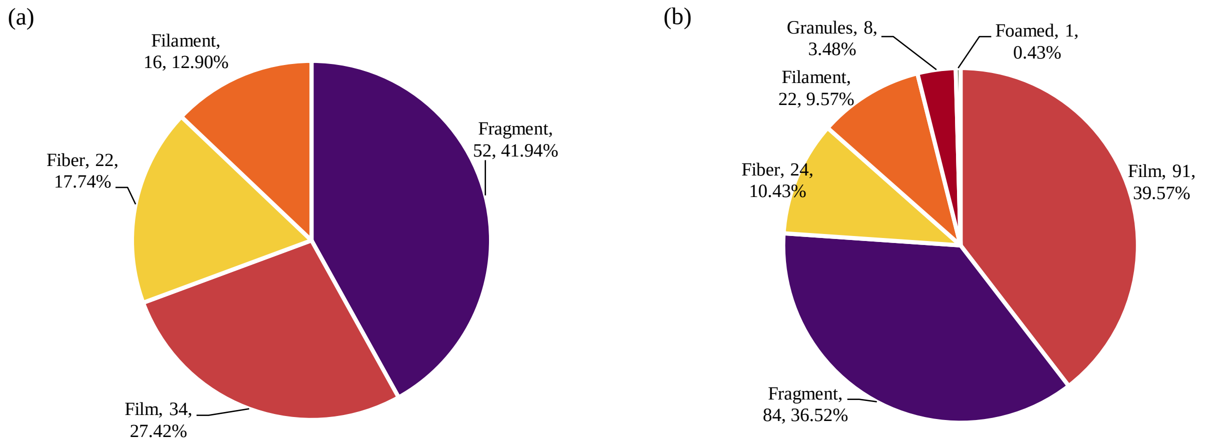

Figure 4. Morphotype distribution of confirmed microplastics between types of samples - (a) surface water and (b) sediment

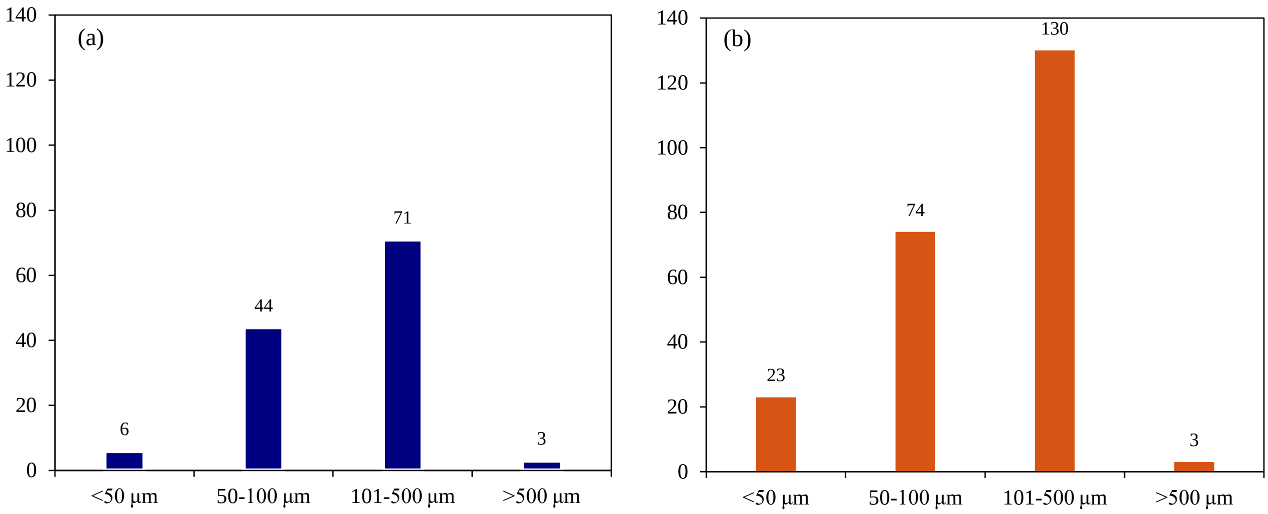

Figure 5. Size distribution and comparison of confirmed microplastics between types of samples - (a) surface water and (b) sediment

3.2.4 Polymer type

Ten polymer types of microplastics were confirmed in surface water and sediment samples via UATR-FTIR: ethylene vinyl acetate (EVA), general purpose polystyrene (GPPS), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyamide 6 (NY6), polyamide 66 (NY66), polyethylene terephthalate (PET), poly (methyl methacrylate) (PMMA), polypropylene (PP), and polyvinyl chloride (PVC). PP and LDPE were most abundant in both sample types, followed by PET and HDPE (Figure 6). Representative IR spectra of PP and LDPE show characteristic peaks (Figure 7). These findings align with Navarro et al. (2022a) on microplastics in Butuan Bay sediments. Results for water differ from Similatan et al. (2023), in which both sites (Barangay Camagong, Nasipit, and Barangay Ata-atahon, Nasipit) have EVA as the predominant polymer detected. Results also differ from those of Banda et al. (2024), who found polyacetylene and regenerated cellulose fibers to be the predominant polymers in water samples. PP, widely produced globally, likely originates from everyday items like bags, containers, and packaging (Geyer et al., 2017; Grand View Research, 2022; Jones et al., 2020; SpecialChem, 2024). The COVID-19 pandemic likely contributed to PP microplastics, especially from disposable masks (DFMs), known to release and capture microplastics (Chen et al., 2021). LDPE, HDPE, and PET, also predominant, originate from various products like bags, bottles, and packaging (Jones et al., 2020). Other polymers (EVA, GPPS, PVC, PMMA, NY6, NY66) likely come from diverse sources such as foam, electrical equipment, and textiles (Amann and Minge, 2011; Jones et al., 2020; ScienceStruck, n.d.).

It should be noted that the polymer types detected are all common plastic polymers widely used in various applications. The prevalence of these polymer types may reflect the economic and social activities, as well as the consumption preferences of the population around these sampling sites. The Philippines is often referred to as having a "sachet economy", characterized by a heavy reliance on small, single-use packages for standard household products such as shampoos, powdered drinks, and other daily necessities. These sachets are typically composed of polyethylene (PE), low-density polyethylene (LDPE), and polypropylene (PP) (Ahmed et al., 2023; Allahvaisi, 2012). This widespread use of sachets is driven by economic factors (Ang and Sy-Changco, 2007), such as affordability and convenience, which cater to the needs of consumers who prefer or can only afford to purchase products in smaller quantities (Manalo and Manalo, 2022; Gomez et al., 2023). Additionally, the cultural preference for such packaging formats contributes to the high prevalence of these plastic polymers in the environment.

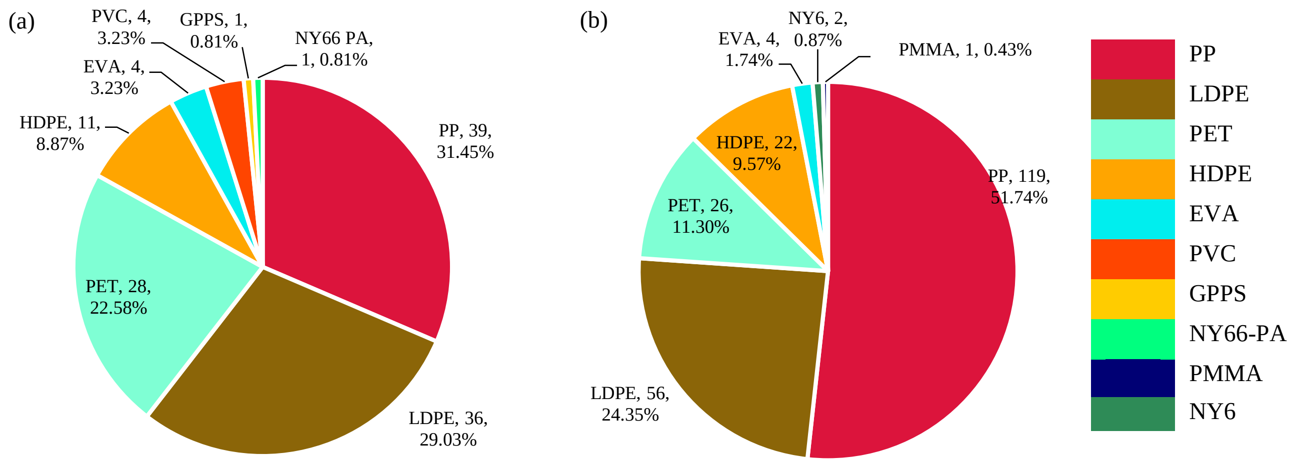

Figure 6. Microplastic polymer type distribution and comparison of the confirmed microplastics between sample types - (a) surface water and (b) sediment

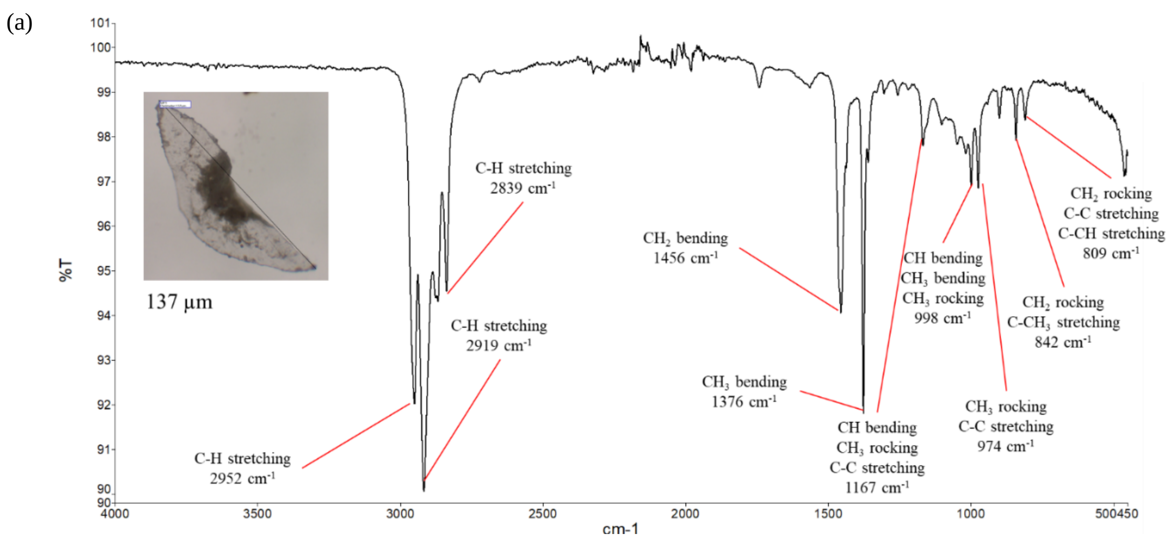

Figure 7. Representative IR Spectra of the two most dominant polymer types in the surface water and sediments of selected mangrove sites. (a) Polypropylene, and (b) Low-Density Polyethylene

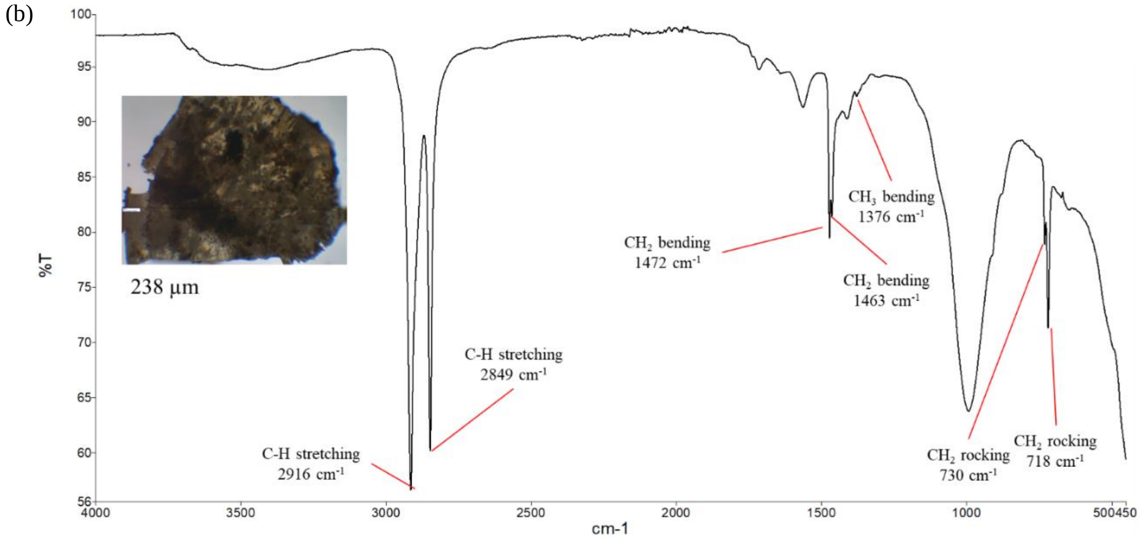

Figure 7. Representative IR Spectra of the two most dominant polymer types in the surface water and sediments of selected mangrove sites. (a) Polypropylene, and (b) Low-Density Polyethylene (cont.)

3.3 Ecological risk posed by MPs in mangrove surface waters and sediments

This study combines the PLI and RI models to assess the ecological risks of MP pollution in mangrove surface waters and sediments along Butuan Bay. As shown in Figure 8 and Table S5 (Supplementary data), the MP pollution levels in both study samples in the mangrove areas were classified as slightly polluted (hazard level I) based on the PLI_{zone} values. NMS mangroves ranked the highest among the surface water samples, followed by BCMS and BMS mangrove areas. On the other hand, BMS ranked the highest, followed by BCMS and then NMS for sediment samples. These findings were found close to the reported observations in other mangrove areas of Southern China, which reported a hazard level of I (<10), except for the Futian mangrove, which had a higher hazard level (II, 10-20) (Li et al., 2020a; Dou et al., 2021), also in both dry and wet seasons data in the southern Hainan Island, China (Yang et al., 2023), and comparable to KB, PT, and SH and lower than the MR and LB sediment sampling stations in the coastal mangroves in Eastern Thailand (Prarat et al., 2024). Although the PLI model estimates low overall microplastic (MP) pollution in this study and other areas, the ecological impact of MPs in mangrove ecosystems should not be underestimated. This is because the PLI model does not account for the potential toxicity of different polymer types.

Moreover, to investigate the ecological risk of MPs, the RI model was used considering both the MP hazard data and MP concentrations. The RI values from the studied mangrove areas for both sample types, surface waters and sediments, ranged from 737.94 to 3548.83 and 36.35 to 213.60 (Figure 8 and Table S5), respectively. Both BMS and BCMS mangroves score the highest ecological risk of MP pollution at level V (extreme danger, >1,200) due to the high abundance of MPs in surface waters, while NMS falls to the danger category at level IV (600≤RI≤1,200) also due to its high MP abundance. It is worth noting that the RI values of the sediment samples from BCMS fall only to the medium danger category level II (150≤RI<300), while BMS and NMS fall to minor danger (level I) with RI values both less than 150. This disparity of the RI values of surface water and sediment samples can be attributed to the differences in the abundance and type of polymers detected. The RI values obtained for surface water samples in this study (risk levels IV-V) were higher than those reported for southern Hainan Island (risk levels II-IV) in China for wet and dry seasons (Yang et al., 2023). However, for sediment samples, this study has low ecological risk levels, which were in the range I-II lower than those found in mangroves of Southern China (risk levels III-V) (Li et al., 2020a) and in Eastern Thailand (risk levels III-V) (Prarat et al., 2024).

Consequently, our risk assessment of MP pollution based on PLI and RI models revealed varying ecological risks to the mangrove ecosystems in Butuan Bay, Southern Philippines, with BMS and BCMS carrying the highest ecological risk. It was evident that the MP pollution in the study mangrove areas was notably widespread, and this presents the likelihood of MP ingestion by the tiny organisms, which could transfer or move up to the food chain in the mangrove food web and could lead to the bioaccumulation of MPs via biomagnification together with their associated pollutants and eventually posing health risks to human being through food consumption of mangrove animals (Parolini et al., 2023; Prarat et al., 2024).

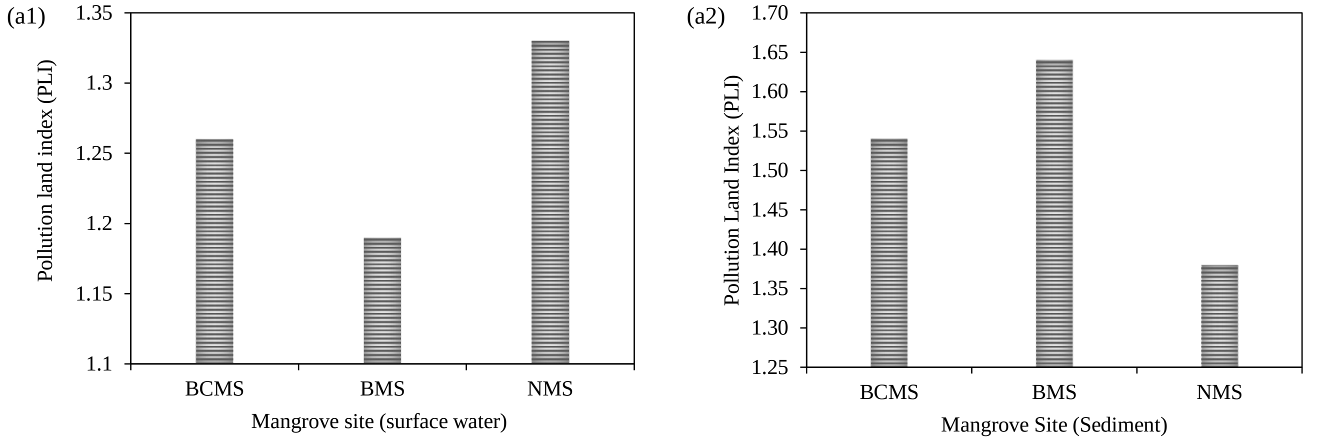

Figure 8. The pollution load index (PLI) (a1 and a2) and ecological risk index (RI) of microplastic pollution (b1 and b2) in mangrove areas located along Butuan Bay, Southern Philippines. Letters I, II, III, IV, and V indicate the risk level categories.

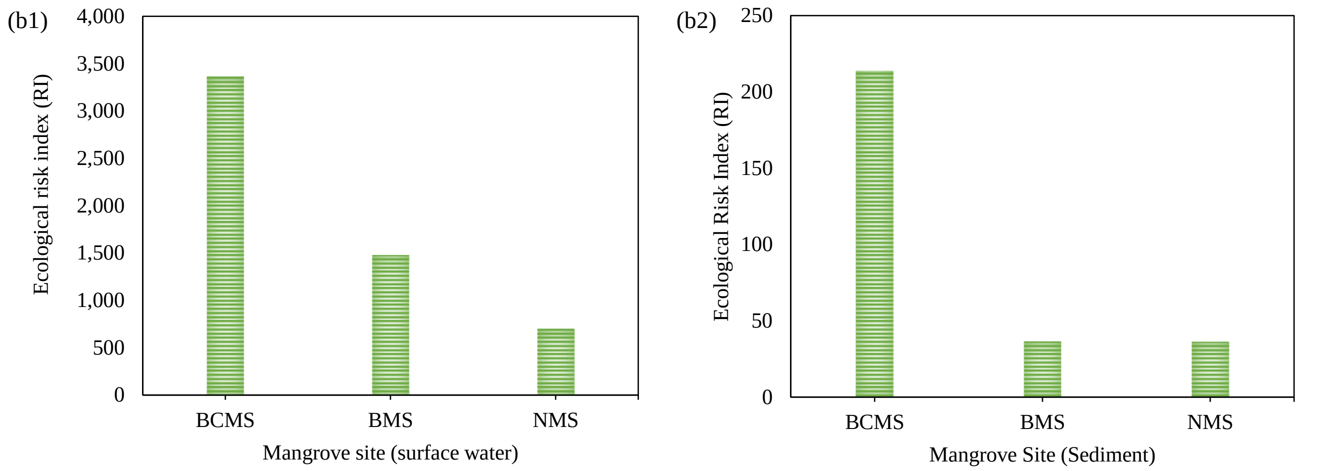

Figure 8. The pollution load index (PLI) (a1 and a2) and ecological risk index (RI) of microplastic pollution (b1 and b2) in mangrove areas located along Butuan Bay, Southern Philippines. Letters I, II, III, IV, and V indicate the risk level categories (cont.).

4. CONCLUSION

The results of this study indicate that microplastics are present in all the selected mangrove sites along Butuan Bay, Southern Philippines. This again supports the notion that mangrove areas retain microplastics from marine and terrestrial domains. The morphology of the extracted microplastics suggests that it is of secondary origin and must have come from household and business establishments around the mangroves. Additionally, the prevalence of polypropylene suggests that these microplastics hail from everyday household and establishment litter, such as pieces of discarded clothing, textiles, plastic food packaging, plastic bags, plastic cups, etc., indicating unrestrained local waste dumping of plastic waste in the area. Moreover, the dominance of blue and transparent colored microplastics is especially alarming. Asian clams, which have feeding behaviors similar to those found in mangroves, have been found to ingest them, preferably. This increases the likelihood of humans consuming microplastic as clams remain a vital food source in communities around the area. In addition, the relatively small microplastics - mostly <500 µm - found in the sites pose significant threats to the biodiversity of the living organisms in the areas. Smaller-sized microplastics mean easy and faster uptake of this type of pollutant by the biota endemic to the mangrove territories, thus affecting their growth and propagation.

Furthermore, the ecological risk assessment, based on PLI and RI models, revealed differing levels of ecological risk linked to MP pollution across studied mangrove areas. The data gathered in this study establishes baseline information for better policy formulation and stricter implementation of the existing measures countering plastic pollution in the city and municipalities involved. These findings also offer crucial baseline data for future research, assisting in point source tracing and pollution monitoring to safeguard the mangrove and coastal ecosystems.

ACKNOWLEDGEMENTS

The results published in this manuscript are part of the research project funded by the Philippine Department of Science and Technology - National Research Council of the Philippines (DOST - NRCP) through grant number E-255. The authors declare that the findings and conclusions presented herein are solely the authors' responsibility and do not necessarily reflect the official views of the funding agency. The authors are grateful for the cooperation of the Local Government Units of Butuan, Buenavista, and Nasipit for permitting this research in their respective jurisdictions, as well as Engr. Jhon Carlo C. Aporbo for his valuable help during sampling and map generation.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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