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Microplastic Contamination and Ecological Risk in Intertidal and Subtidal Crabs - *Uca perplexa* (Decapoda, Ocypodidae) and *Sesarma huzardii* (Decapoda, Sesarmidae) from a Mangrove Estuary of the Niger Delta, Nigeria

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Abstract

Microplastics are currently the most pervasive environmental pollutant globally, permeating all environmental matrices and remotest part of the earth. Microplastic (MP) contamination assessment was carried out in two crab species, *Uca perplexa* (H. Milne Edwards, 1837) and *Sesarma huzardii* (Desmarest, 1825), inhabiting intertidal and subtidal zones of the Isaka-Bundu tidal swamp, Niger Delta, Nigeria. This ecologically sensitive mangrove estuary is subjected to extensive anthropogenic pollution - oil exploration, illegal refining, and domestic waste discharges. Crabs (n = 100), surface water, and sediment samples were collected from three stations representing varying pollution intensities and analyzed for microplastics. Microplastic quantification was performed via stereomicroscopy, followed by ATR-FTIR for polymer identification. Higher MP abundance was recorded in the sediments and intertidal habitats with female crabs generally having higher MP loads. *U. perplexa* showed marginally greater MP accumulation than *S. huzardii*. Fragments and fibres dominated MP shapes, with blue, red, and black being the most common colours. The predominant MP sizes ranged between 20–300 µm. Station 1 exhibited the highest contamination factor (CF), pollution risk index (PRI), and microplastic concentrations in both biotic and abiotic matrices. Hazard Index (HI) was uniform (21) across all sites, indicating similar polymeric risk profiles. The presence of high-risk polymers such as polyethylene and ethylene-vinyl acetate was also confirmed. Overall, the results indicated significant ecological risks posed by MPs to benthic invertebrates and indirectly to man in the estuarine system. This study stresses the urgent need for regulatory action, improved waste management, and continuous monitoring of microplastic pollution in Nigeria's coastal environments. Polymer-specific ATR-FTIR results provided the basis for ecological risk assessment calculations.

Keywords: Microplastics, estuarine pollution, *Uca perplexa, Sesarma huzardii*, Niger Delta

Introduction

Plastic pollution has emerged as a critical environmental issue of global concern (UNEP 2025), with microplastics (MPs) now being a pervasive threat across terrestrial and aquatic ecosystems (Wheatley 2024). It has also been considered as novel pollutants of concern in the aquatic ecosystems (Mvovo 2021). These synthetic particles, defined as plastic fragments less than 5 mm in size, originated from both intentional production (primary MPs) and the breakdown of larger plastic debris (secondary MPs) (Wright et al. 2013). Due to their persistence, buoyancy, and small size, MPs have infiltrat-

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ed virtually all environmental compartments, including sediments, water columns, and a wide range of aquatic organisms (Wheatley 2024). It has been reported in very remote and isolated areas like the deepsea trenches and Arctic ice sheets; showing that no part of the earth exempted (Bergmann et al. 2019). It has also been reported in different types of environmental matrices like waters (Chandra and Walsh 2024), soils and sediments (Prajapati et al. 2024), and biota (Gautam et al. 2022).

In coastal ecosystems, microplastics pose unique threats. Estuaries, mangroves, and intertidal zones act as sinks for land-based pollutants, including MPs introduced through municipal runoff, industrial discharge, illegal oil bunkering, and fishing activities (Luo et al. 2022). The Niger Delta region of Nigeria, and specifically Rivers State, is emblematic of this environmental vulnerability. This region, characterized by a dense network of mangrove creeks and significant dependence on oil and gas exploitation, has experienced escalating ecological degradation (Aransiola et al. 2024). The Isaka–Bundu tidal swamp, situated along the Bonny Estuary, illustrated these challenges; demonstrated through extensive studies (Odekina et al. 2021; Davies and Amaewhule 2022; Davies and Anyanwu 2022; Davies et al. 2022; Davies and Anyanwu 2023a, b) and its strategic location renders it a focal point for anthropogenic inputs and an optimal site for assessing microplastic pollution in coastal species.

Fiddler crabs (*U. perplexa*, H. Milne Edwards, 1837) and mangrove crabs (*S. huzardii*, Desmarest, 1825) are essential components of the ecological systems in these regions. These species play a crucial role in sediment aeration, organic matter turnover, and nutrient cycling (Mokhtari et al. 2016; Natalio et al., 2017). Nonetheless, their behaviour of dwelling in sediment and feeding on detritus enhances their vulnerability to the ingestion of microplastics (Not et al. 2020; Wu et al. 2023; Olarinmoye et al. 2024). Crabs unintentionally ingest microplastics either directly from sediments or indirectly via contaminated food sources. The ingestion of microplastics has been demonstrated to induce physiological stress, decrease feeding efficiency, hinder growth, and adversely affect reproductive outcomes in crustaceans (Zhang et al. 2023).

Studies on microplastic contamination of aquatic biota especially fish is more prevalent in Nigeria (Doherty et al. 2024; Kpakol et al. 2025). However, studies on crustaceans, especially estuarine species such as *U. perplexa* and *S. huzardii* are limited. These species are commonly distributed within mangrove and estuarine systems of tropical coastal regions. Both species are not considered endangered in Nigeria but are experiencing population decline due to anthropogenic activities and environmental degradation (Moslen et al., 2022). Considering the ecological significance of crabs and their function as bioindicators of environmental health, evaluating the level of microplastic contamination in these species offers important insights into pollution dynamics and trophic transfer potential within mangrove ecosystems.

This study conducted a comparative analysis of microplastic contamination in *U. perplexa* and *S. huzardii*, collected from intertidal and subtidal zones of the Isaka–Bundu mangrove swamp in Rivers State. The objective is to characterize microplastics in water, sediment and crabs as well as evaluate the variation of contamination based on sex and habitat and assess the polymeric composition and ecological risk associated with ingesting microplastic-contaminated crabs.

Materials and methods

Study Area

The study was conducted in the Isaka–Bundu tidal swamp, situated at the upper reaches of the Bonny Estuary in Rivers State, Nigeria. This region serves as a clear example of a mangrove creek ecosystem that has been significantly impacted, experiencing substantial pollution from human activities, including oil exploration, illegal refining, and the discharge of domestic waste, alongside natural influences such as tidal fluctuations and sediment deposition. Rivers State, located in the Niger Delta region of Nigeria, is known for its rich oil resources and vast wetland ecosystems. The Isaka–Bundu swamp is particularly susceptible to contamination due to its proximity to industrial areas, residential zones, and unregulated human activities. Three representative sampling stations were selected as follows:

Station 1: Located in a region experiencing significant growth in both industrial and agricultural sectors. It is characterized by extensive mudflats, visible oil sheen, and particulate waste accumulation. This station is also close to an abandoned bunkering site, reflecting chronic pollution.

Station 2: Located adjacent to a densely populated coastal settlement. The area contains multiple visible pollution sites and is fringed by tidal mangrove vegetation, periodically flushed by estuarine tides.

Station 3: This site lies approximately 1000 meters downstream of Station 2 and captures a broader spatial profile of the swamp. It is close to an area visibly impacted by illegal refining activities and represents a transitional zone between high and moderate pollution levels.

Sampling Methods

Sampling was conducted during low tide periods to optimize accessibility to intertidal species and surface sediments.

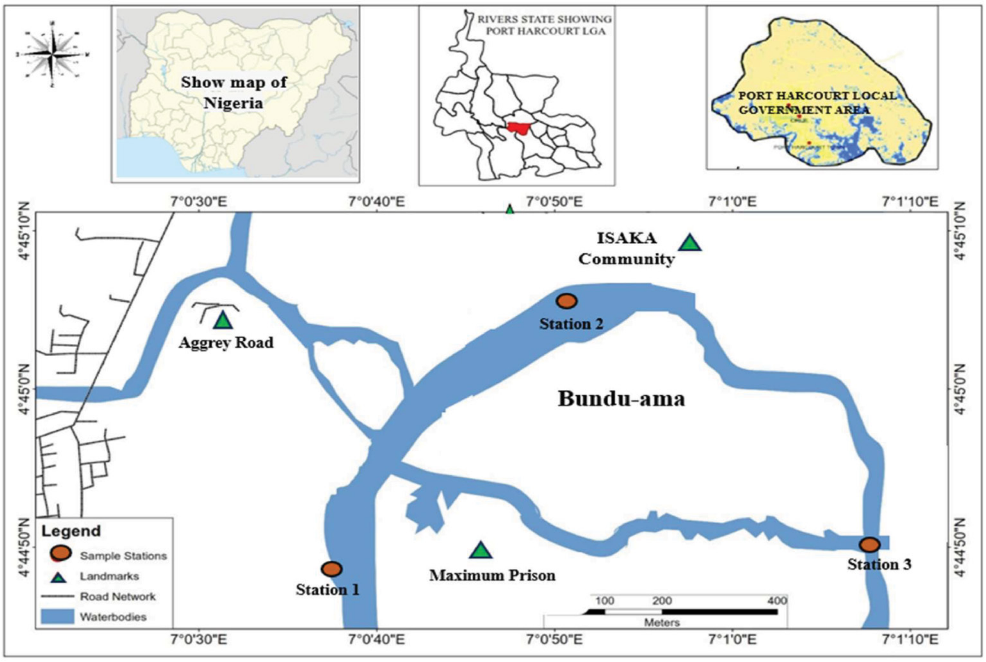

Figure 1. Showing the map of sampling sites

Crab collection

A total of 100 specimens (50 *U. perplexa* and 50 *S. huzardii*, each with 25 males and 25 females) were collected by handpicking from intertidal zones. Subtidal specimens were obtained at depths between 25–100 meters using trawl nets deployed from local fishing boats with the assistance of community fishermen.

Surface water sampling

From each station, 15 litres of surface water were collected in triplicate using sterilized glass containers. The water was sieved using a 25 µm mesh, filtered on-site, and stored in clean glass jars for transport to the laboratory. All biological and environmental samples were immediately preserved in an icebox to maintain sample integrity and reduce degradation before laboratory analysis.

Sediment sampling

At each station, five replicate sediment samples were collected using a stainless-steel sediment corer. The samples were taken at 100-meter intervals, with the core capped with a stainless-steel sheath immediately after insertion to prevent contamination or loss of surface material.

Laboratory analysis

Identification and Morphometrics of the Crab Species: The crabs were identified to lowest possible level using standard taxonomic keys. Sex differentiation was based on the presence or absence of a gonopore on the coxa of the second walking leg. A digital Vernier callipers was used to measure the shield lengths of the crabs while a precision electronic balance was used for the total wet weights.

Tissue Preparation and Digestion: Each crab was dissected to remove appendages and body tissue. The digestion process involved ten sets of samples from each species (five crabs per set), treated with 10% potassium hydroxide (KOH) and incubated at a temperature of 60°C for 48 hours in a hot air oven.

Sediment and Water Processing: Sediment and water samples were digested in the same way while the density separation was carried out using supersaturated sodium chloride (NaCl) solution. The supernatant was kept for 24 hours and subsequently filtered with Whatman filter paper (20 µm pore size) and dried at normal room temperature.

Microplastic Identification: The morphological characterization of microplastics (MPs) by shape (fibres, fragments, films) and colour (e.g., blue, black, red) were carried out by examining the dried filters with a stereomicroscope while the size was determined by ocular micrometre.

Polymer Identification: A subset (10%) of isolated MPs from each characteristic group was analyzes using Attenuated Total Reflectance-Fourier Transform Infrared Spectroscopy (ATR-FTIR) while a spectral library (e.g., FLOPP, FLOPP-e), with a >70% spectral match threshold for positive MP identification was used to confirm the polymer identification.

Data analysis

The microplastic (MP) contamination in the crabs from both environments determined using the analytical procedures given bellow.

Abundance and distribution analysis

The number of MP individuals was presented as items per gram (items/g) of crab tissue weight. The mean values were recorded for stations, sexes, and habitats. The normality of MP data ($\alpha = 0.05$) was determined using the Shapiro-Wilk test. Non-parametric analytical methods were used because data were not normally distributed ($p < 0.05$). Hence, the comparison of MP contamination between intertidal and subtidal zones was carried out with Mann-Whitney U test, while the sex-based differences within habitats was carried out with Kruskal-Wallis test. The percentage composition of the MPs based on shape, size, and colour were calculated to determine the trends across species and habitats.

Statistical analysis

Microsoft Excel and PAST software (version 4.03) were used for all the statistical analysis.

Contamination control

Adequate precautionary measures were put in place to prevent any potential contamination of the samples during collection and laboratory analyses. All the MP isolates were thoroughly washed with distilled water to remove any unwanted particles from the surface sample in following processes. Metal trays, stainless steel, and glass instruments were used and adequately washed with Milli-Q water before use throughout the process. The laboratory analysis was carried out in a restricted facility with least human activity to minimize unnecessary environmental contamination. The laboratory personnel wore nitrile gloves and a white cotton coverall to avoid MP contamination from clothes made of synthetic materials. The isolated MPs were confirmed with the hot needle method. Three blanks were used at each step to determine airborne contamination. Assuming that MPs were found in the blanks, the means were calculated and subtracted from all the MPs found on each filter paper. However, there were no MPs recorded in the blanks.

Contamination factor (CF)

Contamination Factor (CF) was applied to assess the level of contamination in each station using the equation 1 below:

$$CFI = Ci/Co \quad \text{.........} (1)$$

where, Ci is the abundance of MPs in each station while Co is the minimum MPs abundance recorded in the study. The lowest MPs abundance recorded in this study was used as the Co value for calculations because of lack of existing baseline data on MP level in the environment. This allowed relative comparison of contamination levels across stations.

Polymeric Risk Assessment (Hi) and Pollution Risk Index (PRI)

The polymeric risks and toxicity levels of MPs in the environment were evaluated by calculating the hazardous scores. The potential ecological risk based on the chemical composition of the extracted MPs was calculated with equation 2 below:

$$\text{Hazard Index } (Hi) = \Sigma(pji/Ci) \times Sj \quad \text{.........} (2)$$

where, pji is the number of MP polymers identified in each station, Ci is the total MP level in each station, while Sj is the risk score given to each identified specific plastic polymer. The potential ecological risk associated with identified microplastic polymers was evaluated using the hazard scores proposed by Lithner et al. (2011). Because ATR-FTIR analysis was conducted on a representative subset (10%) of particles primarily to confirm polymer identity, polymer-specific abundance per station was not quantified. Therefore, the Hazard Index (Hi) was derived based on the confirmed presence of identified polymer types within each station rather than proportional polymer distribution. The hazard scores assigned were: polyethylene (11), polypropylene (1), ethylene-vinyl acetate (22), and polyamide (47) (Masura et al., 2015; GESAMP, 2019; Hidalgo-Ruz et al., 2021).

Pollution Risk Index (PRI)

This metric combines the contamination level with potential toxicological risks; giving a more detailed pollution profile for each station. The Pollution Risk Index (PRI) was calculated with equation 3 below:

$$PRIi = Hi \times CFi \quad \text{.........} (3)$$

where, Hi and CFi were derived from equations 1 and 2.

Percentage composition analysis

The physical and morphological characteristics (size, shape, and colour) of the MPs were recorded and categorized based on species, sex, and habitat. The percentage composition of each MP category (e.g., fibre, fragment, film; black, blue, red, etc.) was calculated. These values were compared to identify the trend of MP accumulation in the crab species and environments.

Results and discussion

Characterization of microplastics in environmental matrices (sediment and surface water)

The physical and morphological characteristics of microplastics, including shape, colour, and size are essential factors influencing their environmental behaviour, transport dynamics, and biological effects (Casagrande et al., 2024). The characterization results presented in Figures 2-4 refer exclusively to microplastics extracted from sediment and surface water samples while crab tissue data are presented separately in Tables 2 and 3.

Microplastic shape distribution

The shape of microplastics demonstrated significant spatial variability (Figures 2a-c). At Station 1, the composition was primarily comprised of fragments (48%), with fibres (35%) and films (17%). This composition indicates significant contributions from larger plastic items experiencing mechanical breakdown, likely originating from consumer plastics, packaging materials, and degraded debris (Andrady 2011). The significant proportion of fragments may suggest closeness to terrestrial sources or regions characterized by heightened human activity (Zhang et al. 2021).

Conversely, Station 2 was dominated by fibres (51%), followed by fragments (29%) and films (20%). Fibrous microplastics are generally sourced from synthetic textiles and fishing equipment, frequently entering aquatic systems via wastewater discharge and fishing practices (Carr 2017). The presence of fibres at this location may suggest that urban runoff or laundry effluent was the main source.

Station 3 demonstrated a notable shift, with films comprising 43%, followed by fragments (38%) and fibres (19%). Film-shaped MPs are typically linked to plastic bags, wraps, and packaging, which are materials susceptible to fragmentation in aquatic environments. Their prevalence at Station 3 may indicate either direct littering or insufficient waste management in nearby locations (Bessa et al. 2019).

The distributions of these shapes hold ecological importance, as shape affects the likelihood of ingestion and the retention of food during digestion in aquatic organisms. For example, films are ingested more easily compared to fragments and fibres (Xiong et al. 2019) and fibres have demonstrated the ability to entangle within digestive tracts, whereas fragments and films may traverse through but can still result in internal abrasions or chemical leaching (Wright et al. 2013; Lusher et al. 2017).

Microplastic colour patterns

The colour composition of MPs further demonstrated their origin and potential for biological interaction (Figure 3). At Station 1, the primary particles consisted of blue (33%), black (28%), and red (20%). Brightly colored MPs like red and blue are more likely to be mistaken as prey by marine fauna, leading to increased ingestion (Barboza et al. 2018a).

In Station 2, the leading colours were transparent (30%), red (26%), and blue (22%). Transparent MPs may

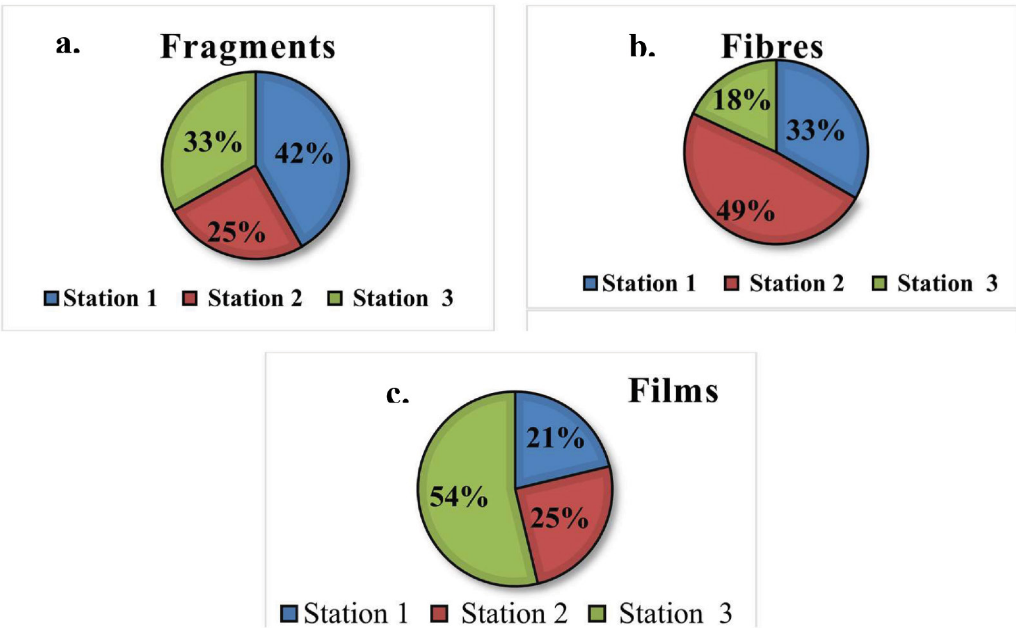

Figure 2. Distribution (%) of microplastic shapes in sediment and surface water samples across the three sampling stations.

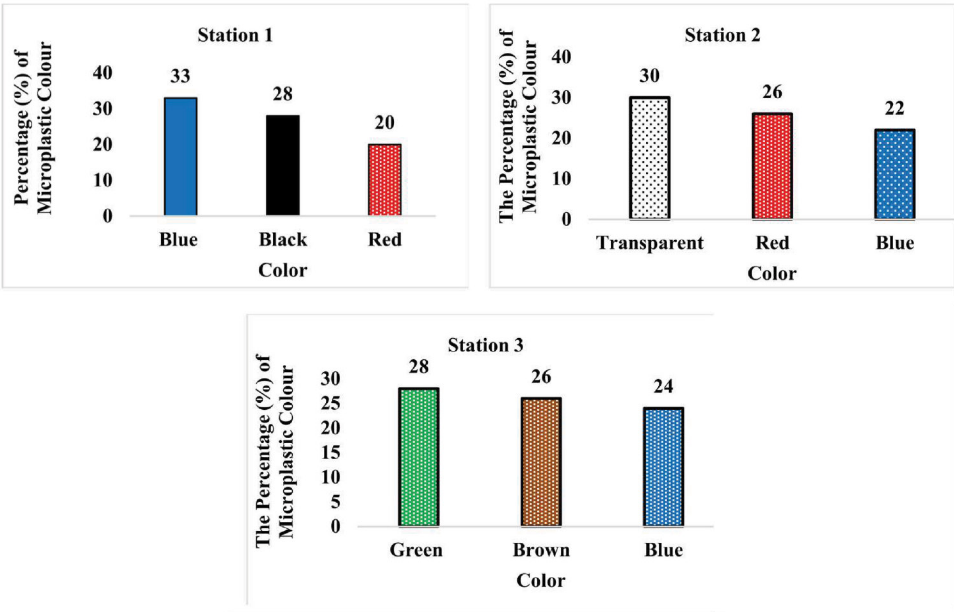

Figure 3. Microplastic colours at the three Sampling stations

result from weathered packaging materials, while red and blue again suggest the presence of consumer plastics and synthetic dyes (Osorio et al., 2021).

Station 3 was characterized by green (28%), brown (26%), and blue (24%) microplastics. Green and brown particles are often associated with agricultural plastics or degraded fishing nets (Abdipour et al. 2026), reinforcing the hypothesis of mixed-use area contamination, where both urban and artisanal sources contribute to plastic input.

Color impacts biological uptake and potential ecotoxicity as organisms are often visually attracted to colors resembling natural food items, especially under turbid or low-light conditions (Savoca et al. 2016; Zhao et al. 2022). Furthermore, colored plastics may contain or adsorb hazardous additives and persistent organic pollutants, which could leach upon ingestion (Rochman et al. 2015; Zhao et al. 2022).

Microplastic size distribution

Microplastic size classes across stations revealed a predominance of small particles (<500 µm), supporting concerns about their bioavailability to a wide range of aquatic taxa (Figure 4). At Station 1, 20–100 µm MPs accounted for 55%, followed by 300–500 µm (30%), indicating intense fragmentation and degradation processes in the environment. Station 2 showed a slightly different pattern: 100–300 µm (47%) and 20–100 µm (38%), suggesting ongoing degradation but potentially with less advanced weathering than at Station 1. Station 3 was similar, with 100–300 µm (50%) and 20–100 µm (40%) indicating high proportions of MPs within a size

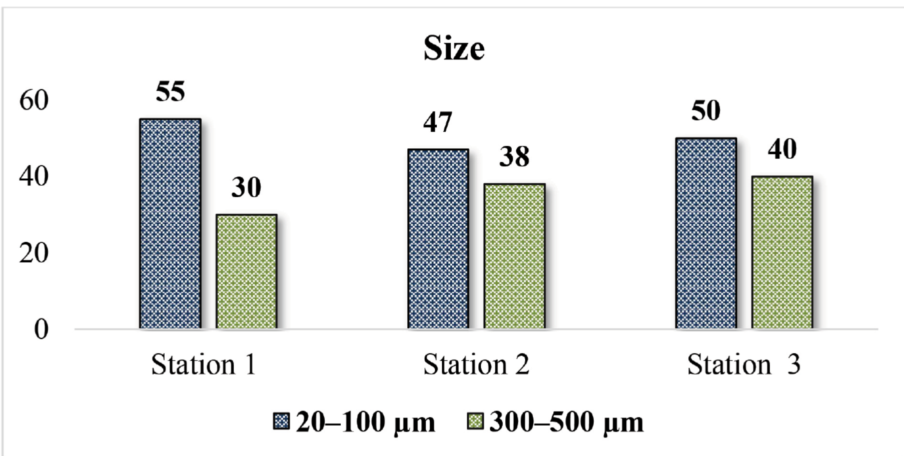

Figure 4. Microplastic characteristics by size at the three sampling stations

range that is easily ingestible by filter feeders, larvae, and small invertebrates (Lu et al. 2016). Olarinmoye et al. (2024) recorded higher mean length (669 µm) and width (802.8 µm) in crabs in mangrove tidal mudflats in Lagos, Nigeria. Microplastics measuring between 20 and 100 µm are especially concerning because of their capacity to traverse biological membranes, infiltrate tissues, and accumulate in essential organs, which may lead to oxidative stress and inflammation in affected organisms (Barboza et al. 2018a; Zhang et al. 2021). The significant presence of these smaller particles at all stations indicates a considerable ecotoxicological risk in both benthic and pelagic systems (Issac and Kandasubramanian 2021).

Microplastic concentration in sediment and surface water

The average concentrations of microplastics (MPs) in surface water (items/l) and sediment (items/kg) across three sampling stations are presented in Table 1. The data clarify the environmental distribution of microplastics and their potential exposure routes for benthic and pelagic organisms within the study area.

Surface water microplastic loads

The concentrations of surface water MP exhibited a comparable trend, with the peak concentration observed at Station 1 (14.5±2.0 items/l), followed by Station 3 (12.2±1.8 items/l), and the minimum at Station 2 (10.3±1.5 items/l). These values were comparable to related study in estuarine and coastal systems that reported water concentrations from single-digit to hundreds items/l (Hossain et al. 2023). This is an indication of a rise in plastic inputs, probably stemming from urban runoff, industrial discharges, or regions of waste accumulation (Bessa et al. 2019; Zhang et al. 2021).

Although the loads of MP in surface water were significantly lower than those found in sediment, their existence continues to pose ecotoxicological risks to planktonic organisms, fish larvae, and filter-feeding species that reside in or feed within the water column (Wright et al. 2013; Barboza et al. 2018b). The difference in the two media can be attributed to a number of factors. For example, Radford et al. (2024) observed that though most common microplastic types can be suspended in water, others that are dense tend to sink to the bottom. Also natural processes like aggregating with organic matters or biofouling could make some the suspended ones to be dense and sink to the bottom (Koelmans et al. 2016; Zhang et al. 2021). On the other hand, local hydrodynamics enhance the removal of microplastics from water column (Owowenu et al. 2025). The elevated MP levels observed in the surface water at Station 1 may be associated with restricted tidal flushing, surface runoff, or closeness to waste discharge points, which could facilitate MP accumulation in the upper water layer (Zhao et al. 2015). The lower concentrations observed at Station 2 may indicate a higher degree of hydrological dilution (Owowenu et al. 2025) or a decrease in anthropogenic contributions.

Although the concentrations of microplastics in the surface water are reduced, these particles continue to be bioavailable to neustonic and pelagic fauna, acting as carriers for chemical contaminants that attach to their surfaces (Rochman et al. 2015). Their mobility and persistence add complexity to risk assessments and underscore the necessity for integrated management strategies that address both water and sediment compartments.

Sediment microplastic loads

MP concentrations in sediment were consistently higher than those in surface water across all stations, demonstrating the established tendency of microplastics to accumulate in benthic environments due to their density, aggregation with organic matter, and sedimentation processes (Koelmans et al. 2016; Zhang et al. 2021).

The highest sedimentary MP load was also recorded at Station 1, measuring 875±130 items/kg, followed by Station 3 at 720±105 items/kg, and Station 2 at 645±95 items/kg. These values were comparable to related study in estuarine and coastal systems, that reported sediment loads from tens to thousands items/kg (Hossain et al 2023). This indicated a rise in plastic inputs, probably stemming from urban runoff, industrial discharges, or regions of waste accumulation (Bessa et al. 2019; Zhang et al. 2021).The elevated MP levels observed at Station 1 suggest a significant localised input of plastic pollutants, potentially originating from industrial runoff, domestic discharge, or riverine inflow. The increased MP levels suggest variability in the distribution of microplastics, likely influenced by sediment granulometry and hydrodynamic processes (Van Cauwenberghe et al. 2013). Stations 2 and 3, although moderately loaded, demonstrated a notable presence of microplastics, underscoring the pervasive problem of plastic contamination in aquatic sediments, even in areas remote from direct human influence. The notable presence of microplastics in sediment aligned with findings from multiple estuarine and coastal ecosystems, where benthic zones serve as key repositories for plastic debris (Drummond et al. 2020). This has important implications for sediment-dwelling organisms such as *U. perplexa* and *S. huzardii*, which are continuously in contact with these contaminated substrates and may experience chronic exposure through ingestion or dermal contact (Lusher et al. 2017; Olarinmoye et al. 2024).

Sediment-water interface dynamics

The noted difference between sediment and surface water microplastic concentrations highlights the dynamic balance at the sediment-water interface, where resuspension, deposition, and biological activity govern microplastic exchange (Wright et al., 2013). Fine particles with a high surface area may remain suspended for extended periods in the water column, whereas heavier or biofouled particles are more prone to settling and becoming incorporated into sediments (Koelmans et al. 2016). Consequently, it is essential to monitor both compartments concurrently to achieve a comprehensive understanding of MP pollution.

Table 1: MP Concentration in Sediment (items/kg) and Surface Water (items/l)

Station	Mean ± SD (Sediment in kg)	Mean ± SD (Surface Water in l)
1	875 ± 130	14.5 ± 2.0
2	645 ± 95	10.3 ± 1.5
3	720 ± 105	12.2 ± 1.8

Microplastic contamination in intertidal habitats

The results of microplastic (MP) contamination analysis in two intertidal crab species, *U. perplexa* and *S. huzardii*, across three intertidal stations revealed notable differences in MP ingestion patterns influenced by species, sex, and site location (Table 2).

Across all stations, *U. perplexa* consistently exhibited higher microplastic loads than *S. huzardii*, irrespective of sex. At Station 1, male *U. perplexa* recorded an MP mean of 16.4±2.7 items/g, while female individuals recorded 18.2±3.1 items/g. In contrast, male *S. huzardii* at the same station recorded a lower mean of 15.1±2.5 items/g, with females slightly higher at 16.9±2.8 items/g. This trend persisted across Stations 2 and 3, though with slightly reduced concentrations. The findings suggest that *U. perplexa*, due to its sediment-burrowing feeding habits and increased deposit-feeding activity (Walker et al. 2021), may have a greater tendency to ingest more microplastics within the benthic substrate compared to *S. huzardii*, which demonstrates a more generalist foraging behaviour (Zhao et al. 2015).

Female crabs of both species consistently consumed larger amounts of microplastics than their male counterparts across all stations. At Station 3, female *U. perplexa* recorded a mean of 15.2±2.3 items/g of MPs, whereas males recorded 13.6±2.1 items/g. At Station 3, female *S. huzardii* recorded a mean weight of 13.1±2.0 items/g, in contrast to males, which had a mean weight of 11.8±1.9 items/g. The identified sex-based disparity may suggest physiological or behavioural differences, including heightened foraging rates in females, especially during pre-moult or reproductive periods marked by increased energy requirements (Savoca et al. 2016; Walker et al. 2021). Additionally, female crabs often exhibit broader movement patterns during feeding, potentially increasing their exposure to microplastics (Van Cauwenberghe et al. 2015).

Station 1 consistently exhibited the highest microplastic abundance across both species and sexes, suggesting that localised factors such as proximity to pollution sources, hydrodynamic retention, or sediment composition may affect microplastic accumulation (Zhang et al. 2021). Reduced MP loads recorded at Station 2 (male *S. huzardii*: 9.7±1.6 items/g) and Station 3 (male *S. huzardii*: 11.8 ± 1.9 items/g) could suggest differences in tidal flushing rates, sediment composition, or levels of human impact in the stations.

The observed variations between and within species underscore the complex relationships among ecological behaviour, physiology, and environmental exposure in shaping microplastic bioaccumulation. Previous studies demonstrated that benthic organisms, particularly deposit feeders, show heightened vulnerability to microplastic ingestion due to their direct interaction with sediment (Wright et al. 2013; Lusher et al. 2017). The considerable variations observed among groups suggest individual variability, which is likely attributable to differences in ingestion rates or retention capacities influenced by factors including size, gut physiology, or moulting status (Lu et al. 2016). The findings have considerable ecological implications.

Persistent microplastic exposure in intertidal crabs not only threatens their digestive function, reproductive success, and energy metabolism (Barboza et al. 2018b)

Table 2. Microplastic Abundance in Crabs (g) for the Intertidal Habitat

Station	Habitat	Sex	MPs (Mean ± SD)	MPs (Mean ± SD)	Sex	MPs (Mean ± SD)	MPs (Mean ± SD)
			U. perplexa	*S. huzardii*		*U. perplexa*	*S. huzardii*
1	Intertidal	Male	16.4 ± 2.7	15.1 ± 2.5	Female	18.2 ± 3.1	16.9 ± 2.8
2	Intertidal	Male	11.3 ± 1.8	9.7 ± 1.6	Female	12.6 ± 2.0	10.9 ± 1.7
3	Intertidal	Male	13.6 ± 2.1	11.8 ± 1.9	Female	15.2 ± 2.3	13.1 ± 2.0

but also poses potential risks for higher trophic-level organisms, including fish and humans, through trophic transfer (Rochman et al. 2016). Crabs, being ecologically significant detritivores and prey species, may serve as effective bioindicators of coastal plastic pollution, particularly in sediment-dominated ecosystems.

Microplastic contamination in subtidal habitats

The analysis of microplastic (MP) contamination in subtidal populations of *U. perplexa* and *S. huzardii* revealed marked species-specific, sex-specific, and site-specific variations in MP accumulation (Table 3). Although the overall microplastic burden in subtidal zones was lower than in intertidal counterparts, the contamination patterns in subtidal crabs provide critical insight into the ecological dynamics and exposure pathways in these sediment-rich environments.

Across all three subtidal stations, *Uca perplexa* again recorded higher MP loads than *Sesarma huzardii*. At Station 1, male *U. perplexa* had a mean MP content of 13.1±2.0 items/g, compared to 12.3±2.1 items/g in *S. huzardii* males. The females of *U. perplexa* recorded a mean of 14.6±2.2 items/g, surpassing the mean of *S. huzardii* females, which was recorded at 13.5±2.3 items/g. This pattern reflected a consistent trend noted in both intertidal and subtidal zones, likely attributable to *U. perplexa*'s heightened sediment ingestion stemming from its deposit-feeding and burrowing behaviours (Walker et al. 2021). This behaviour inherently increases exposure to sediment-bound microplastics compared to *S. huzardii*, which exhibited more selective surface feeding (Zhao et al. 2015).

A comparative analysis of the stations indicated that microplastic concentrations were highest at Station 1, followed by a decrease at Station 2, and a slight increase at Station 3. For instance, *S. huzardii* males at Station 2 recorded the lowest MP burden of 6.4±1.2 items/g, while values increased to 9.4±1.5 items/g at Station 3. The observed spatial pattern suggested variations in hydrodynamics, sediment deposition rates, and localised pollution sources, which influence the distribution and bioavailability of microplastics in subtidal sediments (Zhang et al. 2021; Bessa et al. 2019).

Differences based on sex were apparent, with female crabs from both species consistently recording higher MP loads than their male counterparts at each site. At Station 2, female *U. perplexa* recorded a mean weight of 8.5±1.4 items/g, while males showed a mean weight of 7.8±1.2 items/g. In *S. huzardii*, females recorded a mass of 7.1±1.3 items/g, which was slightly higher than 6.4±1.2 items g^{-1} recorded in males. This trend aligned with previous research suggesting that females may exhibit increased foraging activity and sediment processing during reproductive phases (Savoca et al. 2016; Walker et al. 2021), consequently raising their likelihood of microplastic ingestion. Additionally, physiological traits that are specific to sex, such as gut size and metabolic rate, may influence the retention and accumulation of microplastics (Lu et al. 2016).

The levels of microplastics in the subtidal zone were lower than those in intertidal habitats; nonetheless, their presence at these levels holds ecological significance. The subtidal environment, marked by diminished exposure to tidal flushing, acts as a repository for microplastics, promoting long-term accumulation in sediment layers that consistently interact with benthic feeders like crabs (Van Cauwenberghe et al. 2013; Lusher et al. 2017). This could lead to extended exposure for resident fauna and pose a risk of trophic transfer within benthic-pelagic coupling systems (Rochman et al. 2016).

The findings highlighted the susceptibility of subtidal crabs to sedimentary microplastic pollution and confirm their potential role as bioindicators of microplastic contamination in soft-bottom marine ecosystems. Extended exposure, especially at Station 1, which showed the highest concentrations, may adversely impact physiological functions such as digestion, moulting, reproduction, and immunity, as reported in previous studies (Wright et al. 2013; Barboza et al. 2018a).

ATR-FTIR polymer identification

ATR-FTIR analysis confirmed the presence of polyethylene (PE), polypropylene (PP), ethylene-vinyl acetate (EVA), and polyamide (PA) in samples collected from all three stations. Polymer identification was accepted at a ≥70% spectral match threshold. Although polymer abundance per station was not quantified, the consistent detection of similar polymer types across stations explains the uniform Hazard Index (HI) values reported in Table 4.

Table 3. Microplastic Abundance in Crabs (items/g) for the Subtidal Habitat

Station	Habitat	Sex	MPs (Mean ± SD)	MPs (Mean ± SD)	Sex	MPs (Mean ± SD)	MPs (Mean ± SD)
			U. perplexa	*S. huzardii*		*U. perplexa*	*S. huzardii*
1	Subtidal	Male	13.1 ± 2.0	12.3 ± 2.1	Female	14.6 ± 2.2	13.5 ± 2.3
2	Subtidal	Male	7.8 ± 1.2	6.4 ± 1.2	Female	8.5 ± 1.4	7.1 ± 1.3
3	Subtidal	Male	10.7 ± 1.6	9.4 ± 1.5	Female	11.4 ± 1.9	10.2 ± 1.6

Pollution risk metrics

Contamination Factor, Hazard Index, and Pollution Risk Index

The pollution risk results determined using Contamination Factor (CF), Hazard Index (HI), and Pollution Risk Index (PRI) for the surface water and sediment in the three sampling stations are presented in Table 4. These indices offer a composite view of microplastic load, toxicity potential, and spatial variation in contamination severity.

Contamination Factor (CF)

The Contamination Factor (CF) evaluated the level of microplastic contamination in a specific matrix relative to a background or baseline value. CF values between 1 and 3 generally indicate moderate contamination, while values exceeding 3 suggest considerable to very high contamination (Hakanson 1980).

At Station 1, contamination factors (CF) of 1.36 (sediment) and 1.41 (water) indicate moderate contamination (CF = 1–3). Station 2 demonstrated the lowest CF values (1.00 for water and sediment), indicating baseline or minimal contamination, which may reflect reduced anthropogenic pressure or effective hydrological flushing in the area. Station 3 displayed intermediate CF levels of 1.18 (water) and 1.12 (sediment), suggesting ongoing microplastic deposition, which however, was lower than values recorded at Station 1.

The spatial differences in CF highlighted the localised variability of pollution sources, hydrodynamics, and waste management practices, all of which significantly influence microplastic accumulation patterns (Koelmans et al. 2016).

Pollution Risk Index (PRI)

The Pollution Risk Index (PRI) combined the severity of contamination with potential ecotoxicological effects to provide a thorough assessment of pollution across the site. According to established thresholds, PRI values that surpass 20 signify a considerable environmental risk (Caeiro et al. 2005).

Station 1 recorded the highest PRI values, with measurements of 29.61(water) and 28.56 (sediment), thus affirming its status as the most impacted location. The high PRI values indicated a notable presence of MP loads and the prevalence of biologically hazardous MP types, including coloured fragments and fibres under 300 µm, which have been reported at this station in prior assessments (Onyena et al. 2025). Elevated PRI scores at Station 1 may indicate heightened exposure risks for local benthic and pelagic organisms, particularly those susceptible to ingestion or dermal uptake of small particles (Lu et al. 2016; Barboza et al. 2018b).

Stations 2 and 3 recorded lower PRI values, with Station 2 exhibiting the lowest overall pollution risk of 21.00 (for both matrices). This further confirmed earlier observations of reduced MP concentrations and limited anthropogenic stress in this area (Sparks et al. 2023; Li et al. 2024). In contrast, Station 3's PRI values of 24.78 (water) and 23.52 (sediment) suggested moderate pollution risk, warranting continued monitoring, especially given the dominance of films and green-colored particles that may resemble organic material and be readily ingested (Savoca et al. 2016).

Hazard Index (HI)

The Hazard Index (HI) serves as an aggregated metric for assessing the potential non-carcinogenic risk posed by MP exposure across all stations. Interestingly, the HI value (21) remained constant in the stations (Table 4), implying that though spatial variations existed in CF and PRI, the overall hazard level based on cumulative microplastic properties remained uniformly moderate across the study area.

The uniform HI value (21) observed across stations reflects the detection of comparable polymer types in all sampling locations. Since hazard scoring was based on confirmed polymer presence rather than proportional abundance, spatial differences in polymer quantity were not considered in the HI calculation. This consistency in HI may be attributed to a similar toxicological profile of MPs in terms of shape, size distribution, and chemical additive content detected in all stations. Despite varying quantities, the types of microplastics present (e.g., dominant proportions of small-sized fibres, fragments, and films) possess comparable biological reactivity and exposure risk potential (Wright et al. 2013; Ng et al. 2018).

Nonetheless, the uniform HI value should be interpreted with caution, as it does not capture spatial

Table 4. Contamination Factor (CF), Hazard Index (Hi), and Pollution Risk Index (PRI)

Station	CF (Sediment)	PRI (Sediment)	CF (Water)	PRI (Water)	HI
1	1.36	28.56	1.41	29.61	21.00
2	1.00	21.00	1.00	21.00	21.00
3	1.12	23.52	1.18	24.78	21.00

heterogeneity in pollutant concentrations or exposure frequencies, which are critical to site-specific ecological risk assessments.

Conclusion

This research provides a comprehensive comparative analysis of microplastic contamination in two sentinel crustaceans, *U. perplexa* and *S. huzardii*, across subtidal and intertidal habitats within the Isaka–Bundu mangrove swamp. The results revealed consistent and widespread MP pollution in both environmental and biological matrices, with marked spatial differences tied to anthropogenic activity intensity. The predominance of fragments and fibres reflects secondary pollution from land-based plastics, while the abundance of small-sized MPs (20–300 µm) raises concerns about trophic transfer and bioaccumulation. Intertidal crabs harboured significantly more MPs than subtidal counterparts, and females accumulated more MPs than males, suggesting behavioural or physiological drivers of microplastic uptake.

Station 1, close to industrial discharge and bunkering activities, exhibited the highest CF and PRI values, indicating elevated contamination and ecotoxicological risk. Despite variability in MP concentration, the uniformity of Hazard Index scores across stations suggested similar polymer profiles, with hazardous polymers like polyethylene and ethylene-vinyl acetate contributing to potential long-term risks.

These findings affirm that microplastic pollution in the Bonny Estuary is not only widespread but also ecologically consequential, threatening key benthic organisms and potentially disrupting food web integrity. This study emphasized the need for urgent policy interventions, including pollution source control, community education, and enforcement of environmental regulations. A limitation of this study is that polymer-specific abundance was not quantified during ATR-FTIR analysis; therefore, future studies should incorporate quantitative spectroscopic mapping to refine polymer-based risk assessment models. Future research should focus on trophic transfer dynamics, long-term health effects on aquatic species, and the socio-economic implications of microplastic contamination in coastal fisheries and food security. The integration of polymer-specific ATR-FTIR data strengthens the ecological risk assessment framework applied in this study.

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