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Organ-specific accumulation of microplastics in *Holothuria atra* Jaeger, 1833 (Holothuriidae) from Kepulauan Seribu, Indonesia

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ABSTRAK

Mikroplastik merupakan ancaman besar bagi ekosistem laut tropis di Indonesia. Penelitian ini mengkaji akumulasi mikroplastik secara spasial dan organ-spesifik pada Holothuria atra *yang dikoleksi dari Pulau Tidung Kecil dan Pulau Pari, Kepulauan Seribu. Sebanyak 28 individu dianalisis dengan memisahkan tentakel, kulit, dan saluran pencernaan, kemudian dilakukan degradasi menggunakan hidrogen peroksida, pemisahan densitas, pengamatan dengan mikroskop stereo, serta identifikasi polimer melalui spektroskopi Fourier Transform Infrared (FTIR). Analisis statistik dilakukan menggunakan Gamma Generalised Linear Model (GLM) dengan uji lanjut Tukey pada α = 0,05. Mikroplastik terdeteksi pada semua organ yang diperiksa di kedua lokasi pengambilan sampel. Tiga jenis mikroplastik teridentifikasi—fragmen, serat, dan pelet—dengan fragmen sebagai jenis yang paling banyak ditemukan. Konsentrasi mikroplastik tertinggi terdapat pada saluran pencernaan, khususnya pada spesimen dari Pulau Tidung Kecil. Analisis GLM menunjukkan bahwa lokasi pulau, bagian tubuh, dan jenis mikroplastik berpengaruh signifikan terhadap kelimpahan mikroplastik (p < 0,05). Analisis FTIR mengungkap dominasi polietilena (PE) dan polipropilena (PP), yang mengindikasikan sumber kontaminasi terkait limbah domestik dan aktivitas perikanan. Temuan ini menegaskan kerentanan* Holothuria atra *terhadap paparan mikroplastik dan menunjukkan potensinya sebagai organisme yang dapat digunakan dalam pemantauan polusi mikroplastik di ekosistem pesisir tropis.*

Kata kunci: FTIR, mikroplastik, pencemaran laut urban, teripang

ABSTRACT

Microplastics represent a major threat to tropical marine ecosystems in Indonesia. This study investigated the spatial and organ-specific accumulation of microplastics in Holothuria atra collected from Pulau Tidung Kecil and Pari, Kepulauan Seribu. A total of 28 individuals were analyzed by separating the tentacles, skin, and digestive tract, followed by hydrogen peroxide degradation, density separation, stereomicroscopy, and polymer identification using Fourier Transform Infrared (FTIR) spectroscopy. Statistical analysis was performed with a Gamma Generalised Linear Model (GLM) and Tukey post hoc tests at α = 0.05. Microplastics were detected in all examined organs at both sampling locations. Three microplastic types were identified—fragments, fibres, and pellets—with fragments being the most abundant. The highest microplastic concentration occurred in the digestive tract, particularly in specimens from Pulau Tidung Kecil. GLM analysis showed that island location, body part, and microplastic type significantly influenced microplastic abundance ($p < 0.05$). FTIR analysis revealed the predominance of polyethylene (PE) and polypropylene (PP), suggesting contamination sources linked to domestic waste and fishing activities.

These findings highlight the susceptibility of *Holothuria atra* to microplastic exposure and suggest its potential utility in monitoring microplastic pollution in tropical coastal ecosystems.

Keywords: FTIR, microplastics, sea cucumber, urban marine pollution

INTRODUCTION

As an archipelagic country, Indonesia faces numerous environmental challenges, one of the most significant of which is plastic pollution in coastal and marine ecosystems. Based on data from the Jakarta Open Data database, plastic accounted for about 74% of anthropogenic litter in rivers and 87% in holding facilities by mass, with its proportion slightly increasing downstream, and it was estimated that around 9.9 g/person/day of plastic waste was released into Jakarta's surface waters during the rainy season and subsequently collected by floating booms (Sari et al., 2022). Plastic waste drifting from the Jakarta mainland can be transported by ocean currents to the surrounding small islands (Assuyuti et al., 2018). Plastic waste such as plastic bags, beverage bottles, household plastic packaging, and plastic raffia strings is found on the small islands around Jakarta (Assuyuti et al., 2018). A portion of plastic waste transported through marine environments to small islands undergoes fragmentation into smaller particles known as microplastics (Jambeck et al., 2015).

Microplastics are generally defined as solid polymeric particles ranging from 1 µm to 1000 µm in size that are insoluble in water and highly persistent in the environment (Bermúdez & Swarzenski, 2021). Based on their origin, microplastics are classified into primary and secondary microplastics. Primary microplastics are intentionally manufactured in microscopic sizes for use in products such as cosmetics, personal care products, and industrial abrasives. In contrast, secondary microplastics are formed through the fragmentation and degradation of larger plastic debris due to physical, chemical, and biological processes, including ultraviolet radiation, mechanical abrasion, and microbial degradation (Darabi et al., 2021; Yang et al., 2021; Huang et al., 2020). Secondary microplastics are the most dominant form in marine environments and are commonly found in the form of fibres, fragments, and pellets, reflecting their diverse sources and degradation pathways (Li et al., 2018b).

Microplastic particles can enter marine ecosystems directly from coastal areas through currents, waves, and tidal dynamics (Lebreton et al., 2017; Humaerah & Rasyid, 2024; Kane et al., 2020). Furthermore, the size, shape, and density of microplastics also significantly influence their transport (Kooi et al., 2017; Zhou et al., 2025). The widespread distribution of microplastics poses a significant threat to marine ecosystems due to their persistent nature and resistance to biological degradation. Microplastics often accumulate in sediments over decades or even centuries (Andrady, 2017). Marine sediments serve as the primary reservoir for microplastics, thereby increasing the likelihood of exposure for benthic organisms, particularly benthic sediment feeders that ingest sediment as part of their feeding strategy (Wright et al., 2017; de Sá et al., 2018). Studies in the Kepulauan Seribu further indicate that environmental pressures also affect higher trophic and habitat-dependent organisms which are closely linked to habitat

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quality and ecosystem integrity in coastal waters (Fauziah et al., 2018; Nabila et al., 2025).

Sea cucumbers (family Holothuriidae) are benthic deposit-feeding organisms that inhabit sandy and muddy substrates, feeding by ingesting large quantities of sediment to extract organic matter, a process that also makes them particularly vulnerable to microplastic exposure while contributing to nutrient recycling and sediment bioturbation in marine ecosystems (Fang et al., 2018; Idris et al, 2022; Shukhairi et al., 2024). Due to their feeding behaviour and close association with sediments, sea cucumbers may ingest microplastics that accumulate in the substrate, resulting in the internal accumulation of microplastics within their digestive system. In addition, microplastics may adhere to external tissues, including the mouthparts and integument, reflecting multiple exposure pathways. The ingestion and accumulation of microplastics may cause adverse physiological effects, including digestive obstruction, reduced feeding efficiency, oxidative stress, and potential transfer of toxic substances associated with plastic particles (Yang et al., 2021; Idris et al., 2022). Studies in *Kepulauan* Seribu have reported the presence of microplastics in seawater, sediments, and marine organisms in this region, highlighting the extent of plastic pollution in urban tropical marine environments (Cordova et al., 2021; Hastuti et al., 2019; Rahmawati et al., 2023).

However, studies examining the spatial distribution and organ-specific accumulation of microplastics in benthic organisms, particularly sea cucumbers, remain limited. Understanding organ-specific accumulation is important to identify exposure pathways and evaluate the ecological risks associated with microplastic contamination. This study aims to investigate the spatial and organ-specific accumulation of microplastics in sea cucumbers collected from urban tropical islands in Indonesia, specifically *Pulau* Tidung Kecil and Pari in the *Kepulauan* Seribu. This study provides baseline data on microplastic contamination in benthic organisms and contributes to a better understanding of the distribution, exposure pathways, and ecological implications of microplastics in urbanised tropical marine ecosystems.

METHODOLOGY

Study area and species sampling

This study was conducted between April and September 2024 in the *Kepulauan* Seribu, Jakarta, Indonesia. Sampling was carried out at two urban tropical islands, *Pulau* Tidung Kecil and Pari, which are located in the northern coastal waters of Jakarta and are exposed to substantial anthropogenic pressures, including tourism, fisheries, and urban runoff. Three sampling stations were established at each island, at *Pulau* Tidung Kecil, the stations were located at coordinates: station 1 (5°47′59.9″ S; 106°31′17.2″ E), station 2 (5°48′01.1″ S; 106°31′22.7″ E), and station 3 (5°48′02.5″ S; 106°31′28.9″ E). At *Pulau* Pari, stations were located at: station 1 (5°51′50.8″ S; 106°36′36.7″ E), station 2 (5°51′45.8″ S; 106°36′47.1″ E), and station 3 (5°51′39.2″ S; 106°36′56.5″ E). The distance between stations was approximately 200 m to represent spatial variation within each island. Samples preparation and microscopic observation were conducted at the Zoology Laboratory, Faculty of Mathematics and Natural Sciences, Universitas Negeri

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Jakarta. We use FTIR from Integrated Laboratory and Research Center (ILRC), Universitas Indonesia.

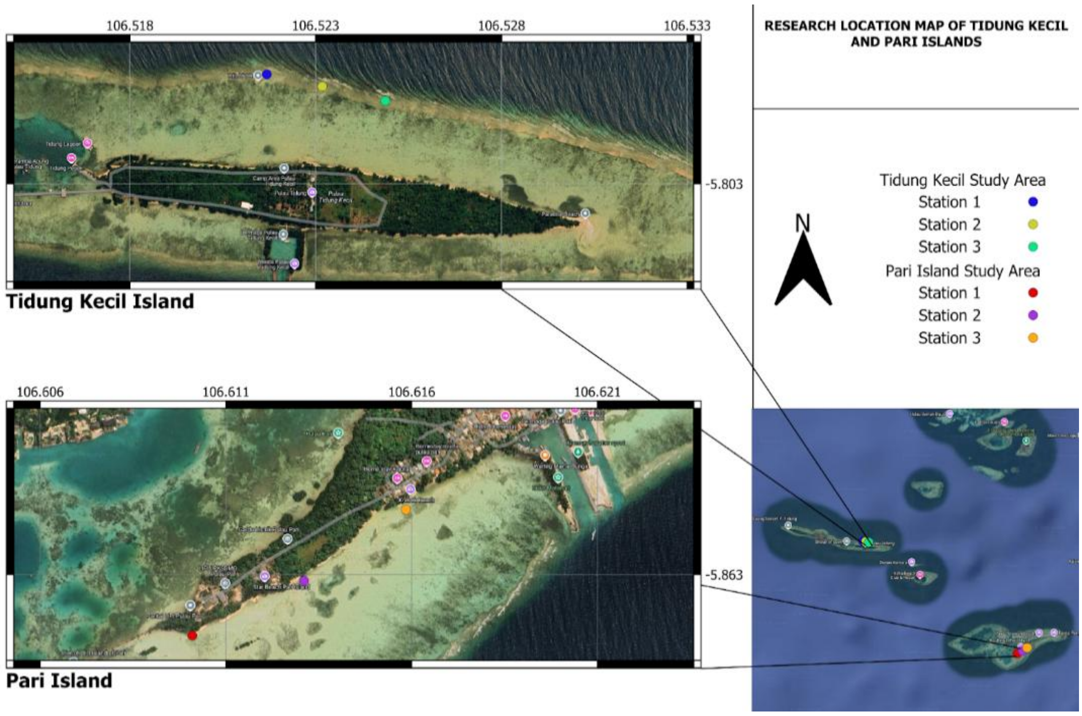

FIGURE 1. Sampling coordinates

Sample collection

Sea cucumber specimens were collected manually from shallow coastal areas at each sampling station during low tide. A total of 28 individuals of *Holothuria atra* (Jaeger, 1833) were collected across both islands. This species was selected due to its abundance and its ecological role as a benthic deposit feeder. Following collection, specimens were rinsed with distilled water to remove external debris and immediately preserved in 70% ethanol to prevent degradation prior to laboratory analysis.

Microplastic extraction from sea cucumber tissues

Microplastic extraction was adapted from Husin et al. (2021) with modifications, focusing on three anatomical compartments: tentacles (1 g), skin (10 g), and digestive tract (10 g). The tentacle subsample was limited to 1 g due to its relatively lower biomass compared to the skin and digestive tract. Each tissue sample was placed in a clean glass beaker and digested using 150 mL of 30% hydrogen peroxide (H_2O_2) to remove organic material without degrading plastic particles. Samples were incubated at 65 °C for 24 h in an incubator to ensure complete digestion of biological tissues. Following digestion, density separation was conducted by adding 50 mL of 20% sodium chloride (NaCl) solution to each sample. The mixture was allowed to settle for 24 h to facilitate the flotation of microplastic particles. The supernatant was then filtered using cellulose filter paper with a pore size of 20–25 µm. The filters were stored in clean, covered Petri dishes before microscopic analysis.

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Visual identification and quantification of microplastics

Microplastic particles retained on filter papers were examined using a stereo microscope (Fischer) with 40x magnification. Each filter paper was carefully examined to identify and quantify microplastic particles based on visual characteristics. Microplastics were classified into three categories using their morphology: fibres, fragments, and pellets (Lusher et al., 2020). Particles were counted manually and recorded for each tissue type and sediment sample (Maheswaran et al., 2022). Only particles with clear plastic characteristics, such as uniform colour, absence of cellular structures, and homogeneous texture, were included in the analysis (Horton et al., 2017).

Polymer identification using FTIR spectroscopy

Polymer composition of selected microplastic particles was analysed using Fourier Transform Infrared Spectroscopy (FTIR) with a Thermo Scientific Nicolet iS5 FTIR + NIR Spectrometer at the Integrated Laboratory and Research Center (ILRC), Universitas Indonesia. Microplastic particles were carefully transferred from filter papers onto the FTIR sample holder using sterile forceps. Spectral measurements were conducted within a wavelength range of 1900–2200 cm^{-1}. Obtained spectra were compared with reference spectra from the instrument's polymer library to identify polymer types. Only matches with high spectral similarity (>70%) were considered valid polymer identifications.

Quality control and contamination prevention

To minimise contamination, all glassware and equipment were rinsed with distilled water prior to use. Laboratory procedures were conducted in a clean environment, and samples were covered whenever possible. Cotton laboratory coats and non-plastic equipment were used to reduce airborne contamination. Procedural blanks were included to ensure that contamination during laboratory processing was negligible.

Data analysis techniques

The collected data were analyzed descriptively, with microplastics categorised according to their morphology, organ distribution, and sampling sites, while abundance was calculated using a specific mathematical formula (Idris et al., 2025):

$$Abundance\ (particles\ g^{-1}) = \frac{Number\ of\ particles}{Dry\ weight\ of\ the\ \ organ\ (gram)}$$

Microplastic abundance data were analysed using a *Generalised Linear Model* (GLM) with a Gamma distribution and log link function because the data were continuous, non-normally distributed, and exhibited heterogeneity of variance. Statistical analyses were conducted using jamovi version 2.7(The jamovi project, 2025; Gallucci, 2019). Island, body part, and microplastic type were included as fixed effects in the model, while station was incorporated as an explanatory factor (Gallucci, 2019). Differences among factors were assessed using omnibus chi-square tests, while pairwise comparisons between groups were evaluated using Tukey post hoc tests with adjusted *p*-values to minimise Type I error. Parameter estimation and statistical model evaluation were performed using statistical modelling packages within the jamovi version 2.7.

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RESULTS AND DISCUSSION

Microplastics were detected in all examined body parts of sea cucumbers collected from *Pulau* Tidung Kecil and Pari, including the tentacles, skin, and digestive tract. Three microplastic types were identified, pellets, fibres, and fragments (**FIGURE 2**), with marked differences in abundance among body parts and islands.

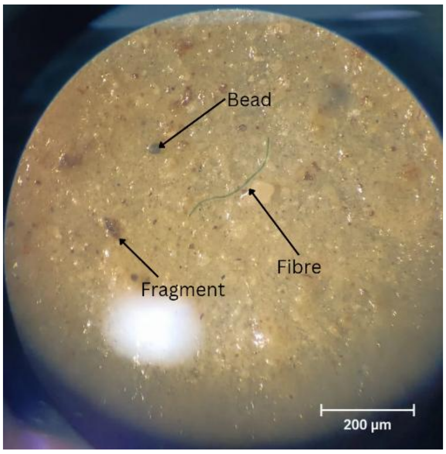

FIGURE 2. View of microplastics using a Fischer stereo microscope

Fragment microplastics are visually characterised by irregular, angular, and heterogeneous shapes with rough or fractured surfaces resulting from the breakdown of larger plastic debris through environmental weathering processes such as ultraviolet exposure, mechanical abrasion, and hydrolysis (Andrady, 2011). Their colours vary widely, including transparent, white, black, blue, red, and brown, depending on the original plastic material and environmental exposure (Cole et al., 2011). In contrast, fibre microplastics exhibit elongated, thread-like, or filamentous structures resembling synthetic hairs or strands, often displaying flexible and thin morphologies with smooth surfaces (Dris et al., 2016). Fibres are commonly observed in blue, black, red, transparent, or purple colours and are frequently associated with textile materials, fishing ropes, and synthetic nets (Gago et al., 2018). Beads or pellets are visually distinguished by their rounded, spherical, or oval morphology with relatively smooth and uniform surfaces due to their primary industrial manufacture (Fendall & Sewell, 2009). These particles are generally smaller and more morphologically homogeneous than fragments and are commonly transparent, white, or brightly coloured depending on their industrial or cosmetic application (Rochman et al., 2013).

Microplastic type fragment showed the highest abundance overall in sea cucumber from *Pulau* Tidung Kecil, particularly within the digestive tract, with a mean abundance of 53.833 ± 3.319, followed by the skin (30.983 ± 1.716) and tentacles (19.417 ± 4.900). Fibre particles were also abundant, especially in the tentacles (10.767 ± 5.645) and digestive tract (10.983 ± 0.126). In contrast, pellet abundance remained consistently low across all body parts, ranging from 1.167 ± 0.082 in the skin to 2.200 ± 0.140 in the digestive tract. Similarly, sea cucumbers collected from *Pulau* Pari exhibited a predominance of fibres and fragments. Fibre abundance was highest in the tentacles (16.533 ± 3.029), followed by the digestive tract and skin, both recording mean values of

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15.183, although with different variability patterns. Fragment particles were also abundant, particularly in the digestive tract (25.967 ± 0.572) and tentacles (8.800 ± 4.109). Pellet abundance at *Pulau* Pari was markedly lower than other microplastic types and approached zero in several observations.

TABLE 1. Microplastic abundance comparison

Location	Body part	Types of microplastics	Average number of particles			Total	SD
			Station 1	Station 2	Station 3		
Tidung Kecil	Tentacles	Pellet	2.8	1.75	1.5	2.017	0.563
		Fibre	6,8	18.75	6.75	10.767	5.645
		Fragment	17	15	26.25	19.417	4.900
	Skin	Pellet	0	0.175	0.175	1.167	0.082
		Fibre	0.3	0.875	0.325	5.000	0.265
		Fragment	5.52	2.025	1.75	30.983	1.716
	Digestive tract	Pellet	0.06	0,2	0.4	2.200	0.140
		Fibre	1.22	1.15	0.925	10.983	0.126
		Fragment	1.9	9.85	4.4	53.833	3.319
Pari	Tentacles	Pellet	0	0	1	0.333	0.471
		Fibre	18.6	18.75	12.25	16.533	3.029
		Fragment	11.4	3	12	8.800	4.109
	Skin	Pellet	0.06	0	0	0.200	0.028
		Fibre	1.58	1.725	1.25	15.183	0.199
		Fragment	1.68	0.4	1.3	11.267	0.537
	Digestive tract	Pellet	0.2	0.1	0.05	1.167	0.062
		Fibre	2.18	1.275	1.1	15.183	0.473
		Fragment	2.64	3.275	1.875	25.967	0.572

This spatial variation may be influenced by differences in environmental conditions, anthropogenic pressure, and proximity to pollution sources. *Pulau* Tidung Kecil is located closer to urban centres and receives higher inputs of plastic waste transported through ocean currents and river discharge from Jakarta Bay (Cordova et al., 2019). Hydrodynamic factors such as currents, wave action, and tidal processes can influence the distribution and accumulation of microplastics in marine sediments, which serve as the primary exposure pathway for benthic organisms such as sea cucumbers (Kane et al., 2020). Sea cucumbers are widely recognised as bioindicators of sediment contamination due to their deposit-feeding behaviour and continuous interaction with sediments (Fang et al., 2018). Therefore, the higher microplastic abundance observed in *Pulau* Tidung Kecil indicates greater environmental contamination in this area. The variation in contamination levels was also reflected in the composition of microplastic types detected across sampling sites (Cordova et al., 2019; Efadeswarni, 2019).

The dominance of fragments is commonly associated with the degradation of larger plastic debris through physical and chemical weathering processes, including ultraviolet radiation, mechanical abrasion, and hydrolysis (Muhsin & Zaid, 2026). Similar findings have been reported in Indonesian coastal ecosystems, where fragment and fibre

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microplastics are the dominant forms due to urban runoff, tourism activities, and domestic waste discharge (Cordova et al., 2019; Efadeswarni, 2019). The higher microplastic abundance in *Pulau* Tidung Kecil may be attributed to its proximity to urban pollution sources and hydrodynamic conditions that facilitate the accumulation of microplastics. Ocean currents, tidal movements, and sediment characteristics play an important role in the transport and accumulation of microplastics in coastal ecosystems (Kane et al., 2020). These findings indicate that urban tropical islands are particularly vulnerable to microplastic pollution. Differences in microplastic composition were accompanied by distinct accumulation patterns among sea cucumber body parts (Fang et al., 2018).

The higher abundance in tentacles is likely related to their function as primary feeding structures in deposit-feeding sea cucumbers. Tentacles directly interact with sediment particles, increasing the probability of microplastic attachment and ingestion (Fang et al., 2018; Sulardiono et al., 2023). Sea cucumbers ingest large amounts of sediment during feeding, which exposes them to microplastics present in benthic substrates (Wright et al., 2017). The digestive tract also exhibited relatively high microplastic abundance, indicating ingestion and internal accumulation. Microplastics ingested through feeding can accumulate within the digestive system due to their resistance to digestion and degradation (de Sá et al., 2018). This internal accumulation may affect feeding efficiency, nutrient absorption, and physiological processes (Vo & Pham, 2021). The skin exhibited the lowest abundance. This suggests that external tissues are less exposed compared to feeding and digestive organs. Microplastics detected in the skin may result from passive adherence rather than ingestion (Sulardiono et al., 2023). Fragment-type microplastics were dominant in all organs, consistent with previous studies showing that fragmented plastics are more readily ingested due to their irregular shapes and resemblance to natural sediment particles (Li et al., 2018).

Effects of island location, body part, and microplastic type on microplastic accumulation in *Holothuria atra*

Statistical analysis using a GLM demonstrated that island location, body part, and microplastic type significantly affected microplastic abundance in sea cucumbers **TABLE 2**.

TABLE 2. Results of GLM tests for microplastic abundance in sea cucumbers

Factor	χ^2	df	p-value
Island	6.11	1	0.013
Body part	108.52	2	< 0.001
Types of microplastic	121.95	2	< 0.001

χ^2 = chi-square value; df = degrees of freedom; p-value = statistical significance level.

Among the analysed factors, microplastic type showed the strongest influence on microplastic abundance ($\chi^2 = 121.95$, $p < 0.001$), followed by body part ($\chi^2 = 108.52$, $p < 0.001$). Island location also exhibited a significant effect ($\chi^2 = 6.11$, $p = 0.013$), indicating spatial variation in microplastic contamination between *Pulau* Tidung Kecil and Pari. The significant effect of island location may be associated with differences in anthropogenic activities, hydrodynamic conditions, and proximity to pollution sources, which influence

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microplastic distribution and accumulation within coastal ecosystems (Cordova et al., 2019; Kane et al., 2020). To further identify the specific patterns of microplastic accumulation, pairwise comparisons among sea cucumber body parts were subsequently evaluated using Tukey post hoc analysis.

TABLE 3. Tukey post hoc comparisons among sea cucumber body parts

Comparison	Difference	p-value (Tukey)	Interpretation
Tentacles vs Skin	11.507	< 0.001	Highly significant
Tentacles vs Digestive tract	6.130	< 0.001	Highly significant
Skin vs Digestive tract	0.533	0.032	Significant

Difference = mean difference between body parts; p-value (Tukey) = adjusted significance value from Tukey post hoc test.

Post hoc Tukey analysis revealed significant differences in microplastic abundance among sea cucumber body parts **TABLE 3**. Tentacles exhibited significantly higher microplastic abundance than both the skin and digestive tract ($p < 0.001$), whereas the difference between the skin and digestive tract was also significant ($p = 0.032$). The elevated abundance detected in tentacles is likely related to their direct interaction with sediment particles during deposit-feeding activities, increasing the probability of microplastic attachment and ingestion (Fang et al., 2018). The digestive tract also showed substantial accumulation, indicating internal retention of ingested microplastics, while the skin exhibited comparatively lower contamination levels. In addition to organ-specific accumulation patterns, differences among microplastic types were also examined to better understand the dominant forms of contamination within sea cucumber tissues.

TABLE 4. Tukey post hoc comparisons among microplastic types

Comparison	Difference	p-value (Tukey)	Interpretation
Pellet vs fibre	0.0715	< 0.001	Highly significant
Pellet vs fragment	0.0455	< 0.001	Highly significant
Fibre vs fragment	0.6372	0.16	Not significant

Significant differences were also observed among microplastic types **TABLE 4**. Pellet microplastics differed significantly from both fibres and fragments ($p<0.001$), whereas no significant difference was detected between fibres and fragments ($p=0.160$). These findings indicate that fibres and fragments constituted the dominant microplastic forms accumulated in sea cucumber tissues. Fragment and fibre dominance has frequently been associated with the degradation of larger plastic debris, domestic wastewater discharge, fishing activities, and textile-derived contaminants in coastal ecosystems (Andrady, 2011; Gago et al., 2018). The absence of significant differences between fibres and fragments suggests that both microplastic types are similarly abundant and widely distributed within the studied marine environment.

FTIR analysis results

The FTIR spectral analysis revealed that microplastic composition across all samples was predominantly characterised by polyolefin-based polymers, particularly

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polyethylene (PE) and polypropylene (PP), as indicated by strong aliphatic C–H stretching and CH_2 bending vibrations. In addition to these dominant polymers, secondary contributions from polyethylene terephthalate (PET), polyester, and weak indications of polyamide were also detected through the presence of carbonyl (C=O), aromatic C=C, and C–O stretching bands. This compositional pattern suggests that the primary sources of microplastics are likely derived from common domestic and packaging materials, which are widely recognised as major contributors to marine plastic pollution (Hidalgo-Ruz et al., 2012; Rochman et al., 2013).

TABLE 5. FTIR spectral profiles and inferred polymer composition of microplastics detected in different organs of *Holothuria atra* collected from *Pulau* Pari and Tidung Kecil

Location	Organ	FTIR peaks (cm^{-1})	Functional group	Indicated polymer type	Exposure interpretation
Pari	Skin	3200–3400	O–H stretching	Oxidised polymers	Environmental weathering / moisture adsorption
		2920–2850	Aliphatic C–H stretching	PE, PP (Polyolefins)	Dominant microplastics
		1650–1550	C=O, amide	Oxidised polymers / polyester	Plastic degradation
		1450–1370	CH_2 bending	PE, PP	Polyolefin confirmation
		1240–1000	C–O stretching	Polyester	Advanced oxidation
	Tentacles	~3300	O–H stretching	Oxidised polymers	Environmental exposure
		2890–2850	C–H stretching	PE, PP	Direct exposure during feeding
		1630–1600	C=O / aromatic C=C	PET / aromatic polymers	Complex plastic indication
		1018–1030	C–O stretching	Polyester / polyamide	Mixed polymers
		870–850	Aromatic ring vibration	PET	Synthetic plastic presence
	Digestive Tract	2920–2850	C–H stretching	PE, PP	Dominant
		1455	CH_2 bending	PE, PP	High accumulation
		~850	Skeletal vibration	Polyolefins	Internal retention
Tidung Kecil	Skin	~3334	O–H stretching	Oxidised polymers	External exposure
		2921–2840	C–H stretching	PE, PP	Common microplastics
		~1650	C=O stretching	Polyester	Degradation
		1550–1450	Amide / N–H vibration	Organic interactions	Adsorption processes
	Tentacles	~3330	O–H stretching	Oxidised polymers	Exposure during feeding
		~2898	C–H stretching	PE, PP	Direct contact
		~1639	C=O stretching	Polyester	Complex polymers
		~1018	C–O stretching	Polyester / polyamide	Mixed composition
	Digestive Tract	~1413	CH_2 bending	PE, PP	Dominant
		~1032	C–O stretching	Polyester	Polymer variation
		~854	Skeletal vibration	Polyolefins	High accumulation

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Across both study locations, a consistent exposure pattern was observed based on FTIR peak intensity, following the order: digestive tract > tentacles > skin. This gradient indicates that the digestive tract serves as the primary pathway of microplastic uptake through ingestion, where particles accumulate and are retained for longer durations. The tentacles represent a transitional exposure zone associated with feeding activities and direct contact with contaminated particles, while the skin reflects secondary exposure through external adherence from surrounding seawater and sediment (Lusher et al., 2013; Wright et al., 2013). Such findings are consistent with previous studies highlighting ingestion as the dominant route of microplastic entry in benthic marine organisms.

The FTIR approach employed in this study should be interpreted as qualitative to semi-quantitative, as polymer identification was based primarily on spectral peak characteristics and relative peak intensity rather than standardised absorbance quantification. Consequently, inferential statistical analyses such as ANOVA or t-tests could not be directly applied to the FTIR spectra due to the absence of quantitative concentration data and standardised spectral calibration procedures (Jung et al., 2018; Primpke et al., 2020). Nevertheless, comparative spectral interpretation revealed consistent differences in peak intensity among organs, with the digestive tract exhibiting the strongest and most complex spectral signals. This pattern suggests a greater tendency for microplastic accumulation within digestive tissues and supports the hypothesis that ingestion represents the dominant pathway of microplastic uptake in benthic deposit-feeding organisms.

In contrast, no substantial differences in polymer composition were identified between *Pulau* Pari and Tidung Kecil, as both locations displayed highly comparable FTIR functional group profiles dominated by aliphatic C–H, CH_2 bending, and C–O stretching vibrations associated with polyolefin and polyester polymers. The predominance of polyethylene (PE) and polypropylene (PP) observed in this study is consistent with numerous marine microplastic investigations worldwide, where these polymers are frequently reported as the dominant constituents due to their extensive use in packaging materials, fisheries-related products, and domestic waste (Rochman et al., 2013; Barboza et al., 2018; Frias & Nash, 2019).

Overall, the FTIR-based semi-quantitative comparison demonstrated a consistent organ-specific distribution pattern, reinforcing the ecological significance of ingestion-mediated exposure pathways in *Holothuria atra*. The similarity in polymer composition between both islands further suggests that coastal plastic contamination in the *Kepulauan* Seribu may originate from comparable anthropogenic sources, particularly urban runoff, tourism activities, and marine debris transport. These findings contribute to the growing body of evidence indicating the widespread occurrence of polyolefin-dominated microplastic pollution in tropical marine ecosystems and its potential implications for benthic organism health and sediment-associated ecological processes.

Overall, the three FTIR graphs collectively demonstrate that microplastic exposure in Pari and Tidung Sea cucumbers occurs through both external adherence (skin) and internal ingestion (tentacles and digestive tract) (Iwalaye et al., 2020; Shukhairi et al., 2024). The dominant presence of aliphatic C–H stretching, CH_2 bending, carbonyl, and C–O functional groups strongly indicate polyolefin- and polyester-based microplastics, which are among the most prevalent polymers in marine debris worldwide (Hidalgo-Ruz et al., 2012; Rochman et al., 2013). These findings are consistent with global reports indicating that sea cucumbers are widely exposed to microplastics via multiple pathways,

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with potential ecological and toxicological implications (Cocci et al., 2025; Shukhairi et al., 2024). The spectral similarities between species suggest that both ecological niche and feeding behavior contribute to microplastic uptake patterns, particularly in sediment-associated marine environments.

CONCLUSIONS

This study confirmed the widespread presence of microplastics in *Holothuria atra* from *Pulau* Tidung Kecil and Pari, with contamination detected across all organs. Fragments and fibres dominated, while pellets were less abundant. The digestive tract showed the highest accumulation, indicating ingestion as the main uptake pathway in deposit-feeding sea cucumbers. GLM analysis revealed that island location, body part, and microplastic type significantly influenced microplastic abundance, reflecting environmental and anthropogenic factors. FTIR analysis identified polyethylene (PE) and polypropylene (PP) as the predominant polymers, pointing to domestic waste and fisheries as major sources of contamination in the *Kepulauan* Seribu. These findings show the vulnerability of *Holothuria atra* to microplastic exposure and suggest its potential role in monitoring sediment-associated pollution, while highlighting the urgent need for improved plastic waste management and ongoing ecosystem surveillance.

AUTHOR CONTRIBUTIONS

H.I.: project conception; R.D.M., M.N.A.G., S.D.T.S., K.G.L., A.D.A.S., S.M.F.S., U.S., R.Y.: methodology, sampling, preparation samples, original manuscript draft; R.D.M, M.N.A.G., S.D.T.S.: manuscript review and editing; A.D.S.: FTIR data analyses.

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CONFLICTS OF INTEREST STATEMENT

There are no conflicts to declare.

ETHICAL COMPLIANCE

This study was conducted in accordance with ethical guidelines. Sea cucumber specimens were collected under appropriate permissions and handled responsibly to minimise ecological impact. All procedures were carried out with respect for animal welfare.

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