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Revealing Microplastic Contamination in Mangrove Sediments from Setiu Wetlands, Malaysia

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Abstract: *Mangrove ecosystems are vital for biodiversity conservation and coastal protection, serving as significant sinks for microplastics by trapping debris from both land and marine sources. This study investigates microplastic contamination in the mangrove sediments of Setiu Wetlands, Terengganu, a biodiversity hotspot with a unique landscape. Results revealed a concerning abundance of 2292 microplastic particles/kg of dry-weight sediment, with a high proportion of small-sized microplastics (< 1 mm). Areas influenced by aquacultural activities displayed the highest abundance, highlighting the connection between human activities and contamination levels. Over 80% of the microplastics were fibers, primarily transparent and black, with surface analysis revealing signs of environmental degradation, including cracks and pits. These surface modifications may facilitate biofilm growth and metal binding, potentially increasing their toxicity. Polypropylene was the most common polymer detected, linking contamination to the breakdown of packaging materials, fishing nets, and ropes. A significant inverse correlation was found between sediment pH and microplastic abundance, while no relationship was observed with organic matter content. These findings highlight the alarming presence of microplastics in mangrove ecosystems, stressing the need for urgent action in waste management, plastic reduction, and further investigation into the ecological consequences of this pervasive threat.*

Keywords: *microplastics; mangrove sediment; Rhizophora; Setiu Wetlands; South China Sea*

■ INTRODUCTION

Microplastics (MPs) are defined as small synthetic polymer particles, generally measuring less than 5 mm in diameter. They are classified into two categories: primary MPs, which are produced at their small size for specific applications such as microbeads in personal care products and synthetic fibers, and secondary MPs, which are formed through the degradation of larger plastic materials into smaller fragments, films, and fibers [1-2]. MPs can originate from both land-based and marine-based sources, including urban runoff, wastewater treatment effluents, the degradation of discarded plastic items (bags and bottles), industrial discharges, marine activities (i.e., fishing), and improper management of plastic waste [3]. Due to their diverse origins, MPs exhibit significant variations in shape, color, size, and polymer type, reflecting their complex environmental behaviors. MPs have been found to contaminate multiple ecosystems globally, including marine, freshwater, terrestrial, and atmospheric environments. MPs are widely distributed as emerging contaminants and have been detected in oceans, rivers, and soils [4], and even in remote locations such as the Arctic and deep-sea sediments [5]. Their persistence in the environment and their ability to disperse over long distances through water currents, wind, and other mechanisms further amplify their widespread occurrence [3]. This situation poses significant risks to ecosystems and human health. Research shows that organisms can easily ingest MPs due to their smaller sizes and appealing colors, leading to physical injuries, altered metabolic processes, and bioaccumulation in the food chain [6]. This bioaccumulation facilitates the spread of MPs across different habitats, impacting a wide range of species from lower to higher trophic levels, including humans, and potentially causing toxic effects [7]. Additionally, MPs contain various chemicals and additives that contribute to their inherent toxicity through leaching and enable them to act as carriers for pollutants, transporting harmful substances into biological tissues and organs [3]. This further heightens the risk of exposure to hazardous chemicals for both aquatic organisms and humans.

Mangrove forests, known for supporting diverse marine life, serve as crucial nurseries and feeding grounds [8]. They act as natural filters and biodiversity hotspots, playing a key role in sustaining ecosystem health. However, these forests are increasingly threatened by plastic waste, which constitutes up to 70% of marine pollution in coastal areas worldwide [9]. Due to their unique physical characteristics and proximity to coastal regions, mangroves are particularly susceptible to MPs accumulation [2]. The complex root structures and dense vegetation of mangroves act as physical barriers, reducing water flow velocity and creating calmer hydrodynamic conditions with low turbulence and wave action [10-11]. These conditions minimize the resuspension of MPs into water columns, promoting their deposition in sediments [10-12]. Additionally, interactions between MPs and sediment particles can lead to the formation of aggregates [13], which increase the sinking rate of these particles, making them more likely to settle in the sediment [14]. This process is further amplified by the high productivity and biomass of mangroves, which contribute organic matter in the sediment, creating an environment conducive to the deposition of MPs [2,11]. Tidal forces exacerbate this accumulation, as water currents driven by spring or astronomical tides transport sediments and various debris, including MPs, from coastal regions into mangrove areas [15]. Furthermore, human activities such as coastal development, tourism, and fishing significantly increase the influx of MPs into mangrove areas. Regions with higher human population densities and proximity to urban centers often show elevated concentrations of MPs in their mangrove sediments [16-17]. This combination of natural and anthropogenic factors allows mangroves to act as effective sinks for MPs [14,18-19]. As a result, MPs accumulate in mangrove sediments, potentially disrupting biodiversity and interfering with essential ecological processes. The presence of MPs in sediments can alter their physicochemical properties, nutrient availability, and microbial communities, which are critical for the health and functionality of mangrove ecosystems [20]. Additionally, MPs pose direct threats to mangrove-associated fauna [18,21]. For instance, Abd Rahim et al. [22] highlighted that commercially important mangrove crab species ingest MPs, mistaking them for natural prey or being attracted by their visual appeal, which poses significant health risks to local communities dependent on these species for food. Although global research on MPs in mangrove ecosystems is expanding [21], studies focusing on Malaysian mangroves remain limited. This research gap provides an opportunity to investigate the unique regional characteristics and potential impacts of MPs in these ecosystems, given that Malaysia accounts for approximately 4.3% of the world's total mangrove area [8], and is one of the Southeast Asian countries most affected by microplastic contamination [23].

Setiu Wetlands, the largest natural wetland on Peninsular Malaysia's East Coast, covers three river basins and forms a continuous 14 km lagoon. This dynamic landscape includes 9 interlinked ecosystems, where mangrove forests are vital for maintaining biodiversity [24]. Among the mangrove species, *Rhizophora apiculata* is the dominant mangrove species [25], making the surrounding sediments key areas for studying microplastic contamination. The wetland is integral to local livelihoods, particularly fisheries-related activities, and is recognized as a State Park that attracts ecotourism [22]. Activities such as boat tours, bird watching, and mangrove exploration significantly contribute to the local economy. However, Setiu Wetlands face growing threats from anthropogenic activities, including plastic pollution, habitat degradation, and hydrodynamic changes caused by altered river flows and land-use practices [22,26]. Given the critical role of mangrove ecosystems in supporting biodiversity and sustaining local communities, this research aims to quantify and characterize MPs in the mangrove sediments of *R. apiculata* in Setiu Wetlands, Terengganu. A comprehensive study of microplastic contamination in these areas is essential to inform the development of targeted conservation strategies, which are necessary to mitigate the adverse impacts on this fragile and invaluable natural resource while safeguarding the livelihoods dependent on it.

■ EXPERIMENTAL SECTION

The methodology of this study utilized a modified standardized approach following the guidelines from the National Oceanic and Atmospheric Administration [27] and the Intergovernmental Oceanographic Commission of the Western Pacific (IOC-WESTPAC) [28].

Materials

This study utilized zinc chloride ($ZnCl_2$, Sigma Aldrich), 35% hydrogen peroxide (H_2O_2), and filtered deionized water (18.2 MΩ).

Instrumentation

In this study, the observed MPs were physically sorted using a stereomicroscope (Carl-Zeiss Stemi 508, China) paired with a digital camera (Axiocam 208 color) and measurement software (Zen 3.3, Zen Lite). Surface analysis of the MPs was conducted using a scanning electron microscope with energy-dispersive X-ray spectroscopy (SEM-EDS, TESCAN with Bruker Quantax Compact Flash 600 mini) to assess surface roughness, morphological variations, and elemental attachment on their surfaces. Polymer identification of the MPs was performed using attenuated total reflectance-Fourier transform infrared spectroscopy (ATR-FTIR, ThermoFisher Scientific, USA). Sediment pH was measured using a Professional Benchtop pH meter (BP3001 Trans Instrument, Singapore), and soil organic matter (SOM) was determined through loss of ignition method using a muffle furnace (Carbolite ELF 11/6, UK).

Procedure

Sample collection and preparation

Eighteen surface sediment samples were collected from 3 stations (ST01-ST03; Fig. 1), with each station containing 2 individuals of *R. apiculata* spaced approximately 1 m apart (labeled as A and B, see Fig. 2). At each station, three replicate sediment samples were collected from each mangrove plant using a Ponar grab with dimensions of 229 × 229 mm and a 2 kg volume capacity. The bulk sampling method was applied, ensuring that the entire sample obtained with the Ponar grab was preserved without any reduction during the sampling process [29]. The samples were transferred into clean stainless-steel containers, covered with aluminium foil, labeled, and stored in an ice chest for transport to the laboratory at Universiti Malaysia Terengganu. All sampling tools were thoroughly pre-washed on-site with filtered deionized water before moving to the next station to prevent cross-contamination. Once in the laboratory, the samples were dried in an oven at 60 °C for up to 72 h, or until completely dry, to ensure all moisture was eliminated. The dried sediments were then carefully ground using a mortar and pestle. The samples were then sieved twice using 1 and 5 mm mesh to ensure a consistent and uniform particle size distribution for subsequent analysis [28].

Microplastics extraction

The sediment sample (< 1 mm) underwent MPs extraction through density separation using $ZnCl_2$ with a density of 1.7 g/cm^3 [29]. For extraction, 200 g of sediment was mixed with 250 mL of saturated $ZnCl_2$ in a 500 mL borosilicate glass bottle, which was sealed with a screw cap. The mixture was gently shaken until the sediments were thoroughly soaked and left to sit overnight, allowing the MPs to float on the surface. The supernatant was then filtered through a 0.3 mm stainless steel sieve, which was rinsed three times to ensure no sample loss. Next, 100 mL of the collected supernatant was placed in a glass beaker and digested with 25 mL of 35% H_2O_2 on a hot plate set at 60 °C, stirring at 180 rpm for approximately 6 h to completely remove organic matter. If the solution remained turbid, 25 mL of H_2O_2

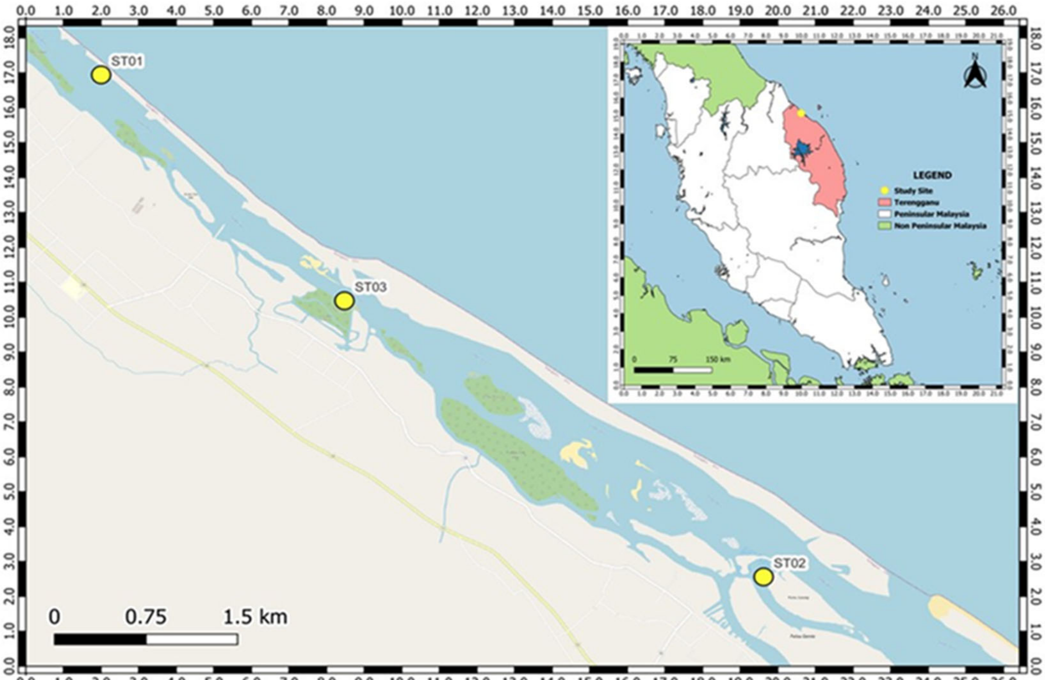

Fig 1. Map of sampling locations in Setiu Wetlands, Terengganu

was added until clarity was achieved. The mixture was then filtered through 1.2 μm glass microfiber filter paper (Whatman®) using a vacuum pump. The beaker containing the residue was rinsed three times with filtered deionized water to prevent sample loss. Finally, the filter paper containing the MPs was placed in a covered petri dish and dried in a glass desiccator until further analysis.

Physical and chemical characterization

The MPs observed on the dried filter paper were visually sorted under a stereomicroscope with a 7:1 zoom ratio and a magnification range of 0.8–5.6×. The MPs were categorized into five distinct shapes: fibers, fragments, films, pellets, and foams. Additionally, 10 colors were identified: transparent, black, blue, red, yellow, orange, brown, purple, white, and green. The longest dimension of each microplastic was measured and recorded, including its shape, maximum length, and color, using a Zeiss Camera Axiocam 208 color paired with ZEN Microscopy Software (Blue Edition). The MPs were further classified by size into 4 categories: type I (< 0.3 mm), type II (0.3–0.5 mm), type III (0.5–1.0 mm), and type IV (1.0–5.0 mm). To assess heat response, the MPs underwent the hot needle test, following the method described by Ibrahim et al. [26]. If the particles melted and curled upon contact with the heated needle, they were confirmed as plastics. The MPs were then collected using sterile stainless-steel forceps and stored in 10 mL glass vials containing approximately 2 mL of filtered deionized water. The abundance of MPs in each sample was calculated and expressed as the number of MP items per 0.2 kg of dry-weight sediment (items/kg d.w.) based on their shapes, colors, and sizes.

Approximately 20% of the representative samples were analyzed using SEM to examine the surface roughness and morphology of observed MPs. The samples were mounted on aluminum stubs and coated with a thin layer of gold before SEM analysis. Metals and minerals on the MP surfaces were identified using SEM-EDS, with a 15 kV voltage, 1.5 nA beam intensity, and a 15.7 mm working distance. For polymer identification, 20% of representative samples were analyzed using FTIR-ATR, equipped with a diamond crystal on a single reflection plate. The analysis was performed at a speed of 5 kHz, with a resolution of 4 cm^{-1}, scanning from 4000 to 450 cm^{-1} at 64 scans per sample rate. Spectra from polyethylene, polystyrene, and polypropylene were used for comparison, with unidentified spectra cross-referenced to a polymer library [30].

Sediment properties – pH and soil organic matter

The sediment pH was measured with a calibrated pH meter using a sediment-to-water ratio of 1:2.5. The SOM was determined using the loss on ignition method, where it was heated in a muffle furnace at 450 °C for 4 h [31].

Contamination control

All equipment used (composed solely of metal, stainless steel, or glass) was rinsed with filtered deionized water both before and after use at each sampling station. Laboratory tools and glassware were pre-washed with filtered deionized water and 80% ethanol to reduce cross-contamination. Researchers wore clean cotton lab coats and latex gloves, avoiding any plastic materials. For quality control, blank filter papers were included during sampling and laboratory procedures to assess potential airborne MPs contamination that could lead to over-quantification of MPs.

Statistical analysis

Statistical analyses were performed using XLSTAT 2019. The Shapiro-Wilk test was applied to evaluate the normality of the dataset, ensuring the selection of appropriate statistical tests to prevent inaccuracies due to improper analysis methods [26]. To identify significant differences in total MP abundance across sampling stations, the Kruskal-Wallis test with Bonferroni correction ($p < 0.05$) was used. The Mann-Whitney test was then employed to compare MP abundance in sediments between the two mangrove species (A and B) across stations. Spearman's correlation coefficient was calculated to assess the relationship between MP abundance and sediment properties, specifically pH and SOM.

■ RESULTS AND DISCUSSION

MPs Abundance: Size, Color, and Shape

MPs were found at all sampling stations, with a total abundance of 2,292 items/kg d.w and a mean of 382 ± 161 items/kg d.w. Station 1 (ST01A and ST01B) exhibited the highest concentration of microplastics, followed by station 2 (ST02) and station 3 (ST03), as shown in Fig. 2.

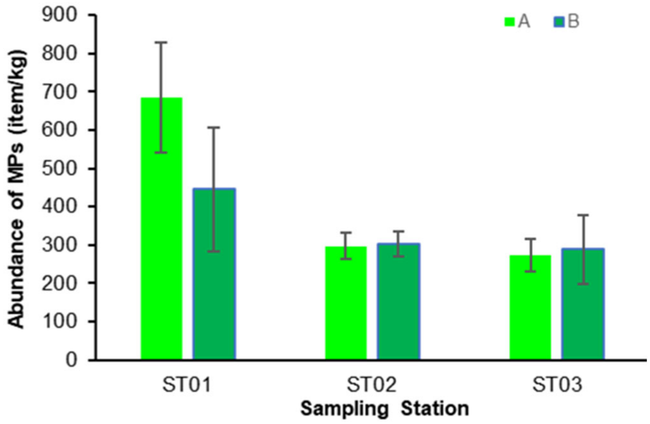

Fig 2. Total abundance of MPs in mangrove sediments of Setiu Wetlands

There was a significant difference between the sampling stations, as confirmed by statistical analysis using the Kruskal-Wallis test ($p < 0.05$). The elevated levels at ST01 may be attributed to nearby aquacultural activities that utilize plastic equipment such as nets, cages, and foam buoys, which can contribute to MPs generation through degradation and accumulation in mangrove sediments over time [32]. The geomorphology at station 1 also contributed to the scattered flow and currents, which may explain the distribution of the MPs in the surrounding areas.

In contrast, ST02 and ST03 showed lower MPs accumulation, likely due to their locations being affected by seawater intrusion and the proximity of the nearby jetty. Additionally, both stations experienced relatively less local human activity, resulting in potentially lower inputs of plastic waste. Seawater intrusion can change sediment dynamics and hydrology, which may reduce MP accumulation by increasing sediment transport and dilution, thereby affecting the retention capacity of mangrove sediments [33]. Furthermore, disturbances in the jetty area could have caused the resuspension of MPs from the sediment into the water column, further decreasing their abundance in the sediments. Although sediment samples were collected from two different mangrove plants at each station, no significant difference ($p > 0.05$) was found in MPs abundance between A and B across the sampling locations.

In this study, MPs with small size (< 1 mm) were more prevalent than large-sized MPs (1–5 mm), comprising 58 to 66% of the observed MPs at each sampling station (Fig. 3). Among these, type III MPs (0.5–1.0 mm) were the most prevalent at all stations. This suggests that secondary MPs generation is particularly conducive in mangrove sediments. The unique structural features of mangrove ecosystems, such as their complex root systems and sediment dynamics, may enhance the trapping and retention of smaller MPs [13]. It is important to note that low-density MPs are more likely to be resuspended into the water column, which may explain the relatively lower proportion of smaller MPs (types I and II) observed in the mangrove sediment [34]. However, the density of MPs is not solely dependent on particle size. The distribution of both large and small MPs in mangrove sediments may also be influenced by factors such as interactions with suspended soils, metal attachments, natural colloids, and associations with organic or inorganic materials [2], warranting further investigation.

The color of MPs in mangrove sediments can vary depending on the types of plastic polymers, the age and weathering of the items, and the presence of additives or pollutants that influence coloration [17]. Fig. 4(a–f) depicts the distribution of colors among the various shapes of MPs identified in this study. The observed MPs were identified in 7 colors, including transparent, black, red, blue, green, white, and pink, as shown in Fig. 5. Transparent (34–57%) and black (34–48%) MPs were the most prevalent in the sediment samples. Transparent MPs are often linked to packaging materials, such as bags and bottles [35], while black MPs may originate from tire wear particles, nets, or ropes [36]. As plastic materials degrade due to environmental exposure, they break down into smaller particles that can accumulate in mangrove sediments. This degradation often results in color distortion of the plastics [37]. Similarly, research

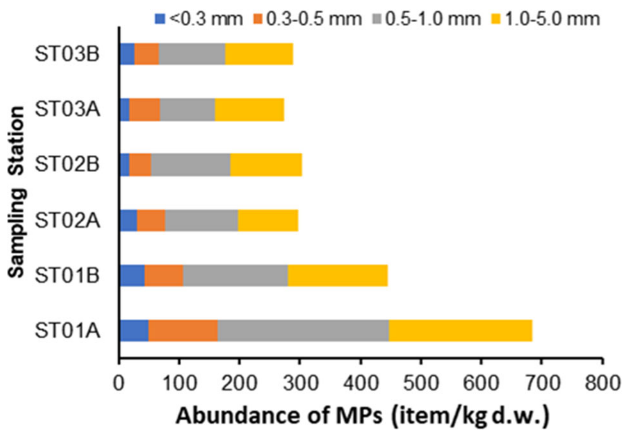

Fig 3. Size distribution of MPs in mangrove sediments of Setiu Wetlands

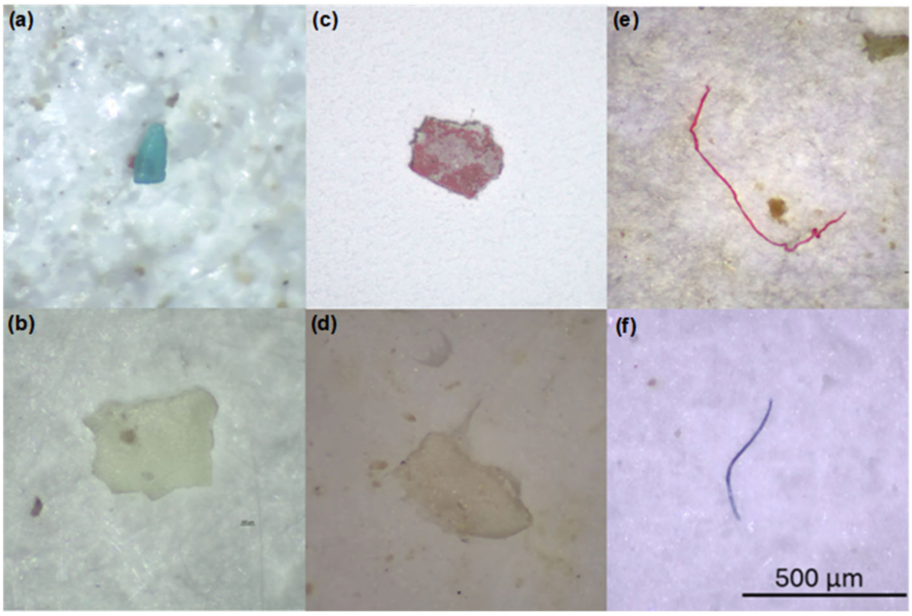

Fig 4. The image of identified MPs: (a) blue fragment, (b) red fragment, (c) and (d) transparent films, (e) blue fiber, and (f) red fiber

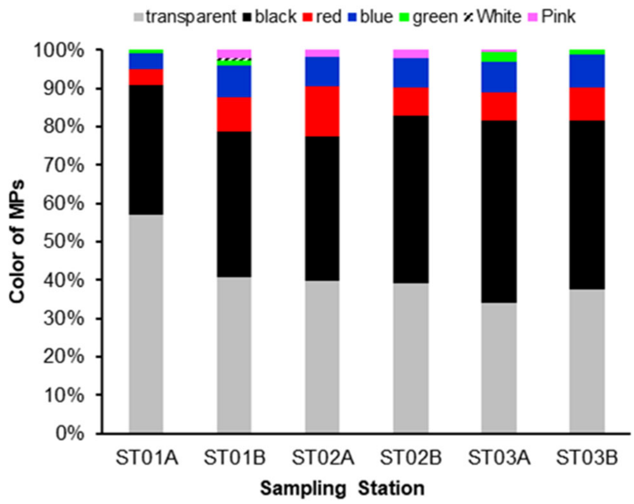

Fig 5. The color distribution of MPs in the mangrove sediments of Setiu Wetlands

by Ibrahim et al. [38-39] in Setiu Wetlands found that black and transparent MPs were the most frequently observed colors in the biota, specifically in wild and cage-cultured Asian sea bass (*Lates calcarifer)* and wild bivalve (*Scapharca cornea)*. This finding suggests that MPs found in both sediment and biota within the study area likely originate from common sources. Our findings are consistent with a study conducted in the coastal mangroves of Singapore [40] but differ from those reported in other Southeast Asian countries (Table 1), indicating variations in the sources of MPs pollution.

In terms of shape, fibers were the most prevalent, accounting for over 80% of the total MPs observed, followed by fragments, films, and foams, with rare occurrences of pellets (Fig. 6). Our findings are consistent with earlier research conducted on estuarine sediments in Setiu Wetlands [26] and other studies in Southeast Asia on mangrove sediments [16,40,43-45], which similarly

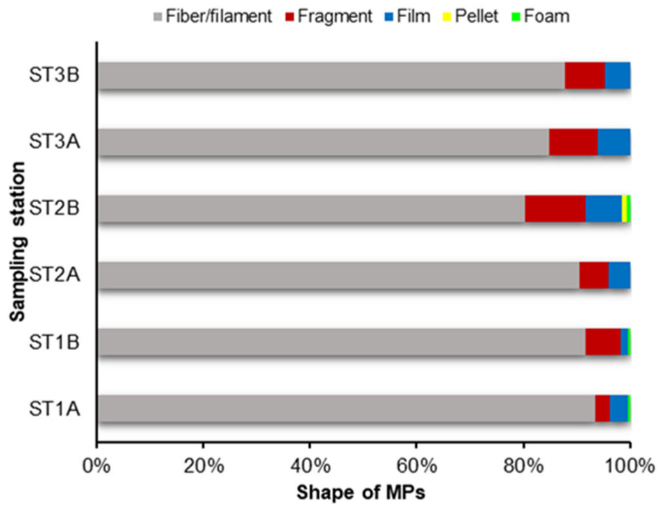

Fig 6. Shape distribution of MPs in mangrove sediments of Setiu Wetlands

Table 1. The abundance of MPs in selected mangrove sediments in southeast Asia

Location	Range of MPs abundance (item/kg d.w.)	Size range (mm)	Major shape	Major color	Major polymer*	Ref.
Butuan Bay, Philippines	40.00–71.10	NA	Fiber	Blue	PP	[16]
Coastal mangroves, Singapore	12.00–62.70	0.02–5.00	Fiber	Transparent	PE and PP	[40]
Semanta Mangrove, Kapar, Malaysia	65.00–117.00	NA	Fragment	NA	PS	[41]
Jakarta, Indonesia	69.86–78.52	0.20–5.00	Fragment	NA	PE and PP	[42]
Surabaya, Indonesia	103.17–103.00					[42]
Cilacap, Indonesia	10.51–9.62					[42]
Berau, Indonesia	19.69–16.78					[42]
Kuala Gula, Perak, Malaysia	25.00–130.00	<0.50–>1.00	Fiber	Blue	NA	[43]
The eastern coast of Thailand	700.00–5750.00	<1.00–5.00	Fiber	Blue	PP	[44]
Lach Huyen Port, Hai Phong city, Vietnam	0.00–3150.00	0.30–5.00	Fiber	White and yellow	NA	[45]
Setiu Wetlands, Terengganu, Malaysia	185.00–800.00	<0.30–5.00	Fiber	Transparent and black	PP	This study

*Note: NA-not available; PP-polypropylene, PE-polyethylene, PS-polystyrene reported microfibers as the dominant form of MPs. Despite methodological variations across studies, the consistent prevalence of fibers underscores their secondary origin, likely stemming from degraded plastic debris that has persisted and accumulated within mangrove ecosystems.

Fibers, often originating from synthetic fabrics like nylon and polyester used in clothing and consumer products, are released into the environment through wastewater generated during laundry [2]. They can also originate from the degradation of synthetic materials, such as fishing nets and ropes [46]. Once introduced into mangrove habitats, these fibers gradually accumulate in the sediments. This transport process allows fibers to disperse widely before settling in mangrove sediments, where their persistence results in elevated concentrations over time [17].

Compared to previous studies, the abundance of MPs in sediments from this study was higher than that reported in the Philippines [16], Singapore [40], Indonesia [42], and other areas in Malaysia [41,43], but lower than findings from Thailand [44] and Vietnam [45] (Table 1). The variation in MP abundance across these geographic areas is largely influenced by the level of human activities near the study sites. Locations with higher MP levels consistently correlate with increased anthropogenic activity. This highlights the critical role that human actions play in contributing to the presence of MPs in different environmental settings [42,44-45]. Since Setiu Wetlands is a semi-enclosed system and a protected area due to lagoon morphology, its ecosystem is highly sensitive to environmental changes and human activities [22,26]. The restricted exchange with external waters means that pollutants or changes in water quality can persist longer and have more profound effects on the mangrove ecosystem. Therefore, implementing a long-term monitoring program is crucial to safeguard the health and stability of this ecosystem.

Characteristics of MPs: Surface Analysis and Polymer Identification

Fig. 7(a) and 7(b) illustrate a black microfiber characterized by grooves and surface fractures, which are indicative of mechanical and oxidative weathering processes [26]. Fig. 7(c) and 7(d) depict a red MP fragment exhibiting a pit hole and clear evidence of biofouling, highlighting the propensity of organic materials to adhere to microplastic surfaces [23]. Fig. 7(e) and 7(f) show a transparent MP filament with a biofilm and diatom attached at one end, suggesting prolonged exposure to the environmental condition. These surface morphologies indicate that the MPs in the mangrove environment have undergone weathering [17] and microbial colonization over time [7]. In turn, this increases the specific surface area of MPs, enhancing their capacity to adsorb toxic elements [3,47]. The SEM-EDS results confirmed the presence of Cu, Fe, Ti, Ca, Zn, Al, and Ni on the MPs' surfaces, indicating their ability to bind with metals. This finding suggests that MPs can serve as vectors for inorganic pollutants in the environment [3], posing increased risks of harmful impacts on aquatic organisms through bioaccumulation and biomagnification [3,6-7]. These effects are particularly concerning in the Setiu Wetlands mangroves.

FTIR analysis revealed that the observed microplastics were composed of polypropylene (PP) polymer. The FTIR spectrum of a black fiber from ST01 (Fig. 8) displayed characteristic absorption bands of PP, with prominent peaks at 2921 cm^{-1} (C–H stretching) and 1447 cm^{-1} (CH_2 bending) [30]. The presence of these characteristic bands confirms the detection of PP in the analyzed MPs sample. Additionally, the presence of carbonyl (C=O) peak at 1634 cm^{-1} was recorded, attributed to the weathering polymer [48], and corresponding to the SEM images. Despite its low density, the deposition of PP into mangrove sediments can be explained by the formation of biofilms on the weathered surfaces of MPs, as shown in Fig. 7. The development of these biofilms increases the weight of PP, facilitating its settling in the sediment rather than remaining suspended in the water column [16]. The unique environmental conditions of mangrove ecosystems, characterized by dense root structures and high organic matter content [11], further promote the accumulation of PP. PP is one of the most extensively produced polymers, widely used in various applications such as plastic wraps and bags, ropes, non-woven fabrics, air filters, diapers, and fishing nets [18]. These

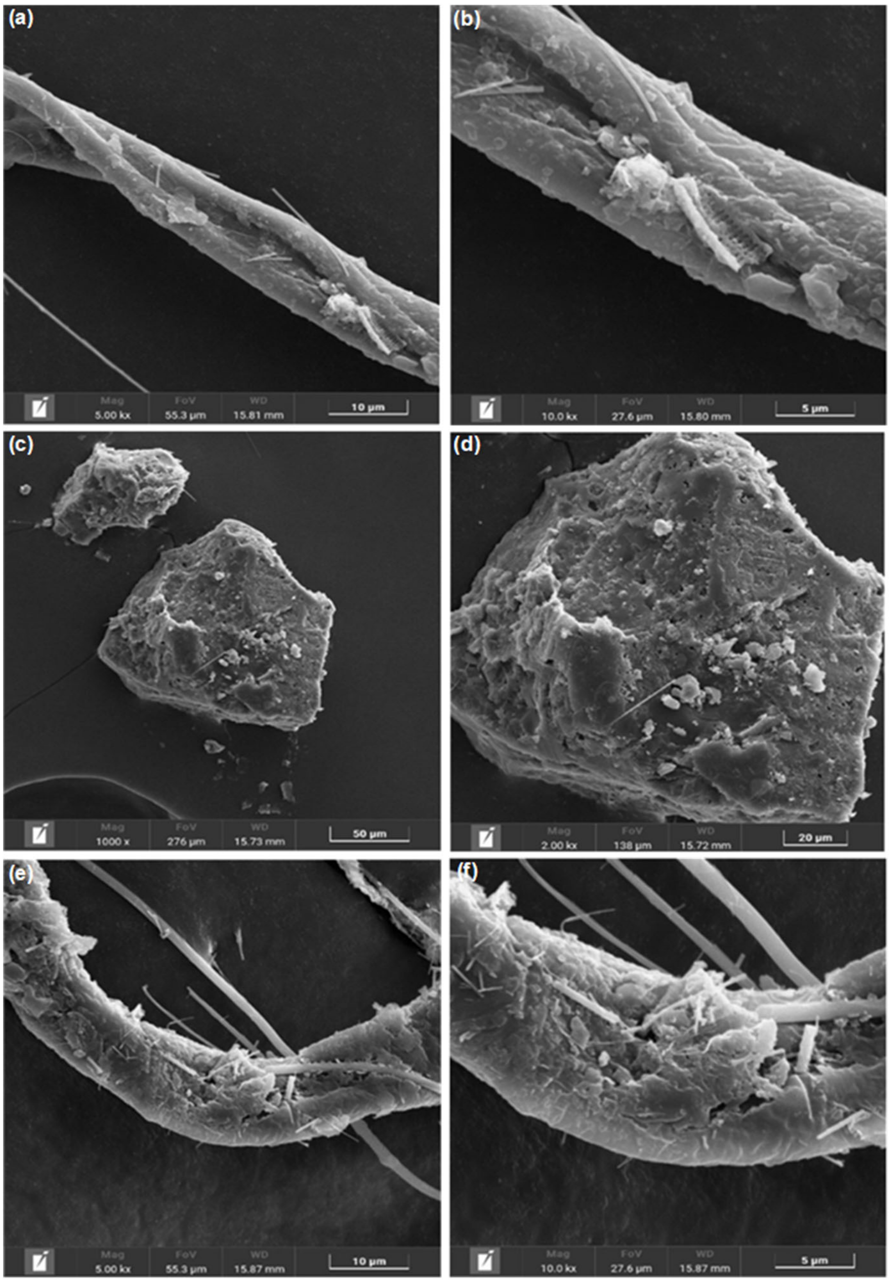

Fig 7. The SEM images of weathered MPs: (a) fiber and (b) enlarged view of fiber a; (c) fragment and (d) enlarged view of fragment c; (e) filament and (f) enlarged view of filament e

items are commonly found in the mangrove and estuarine areas, where they may originate from human anthropogenic activities in nearby regions, land-based sources, or be transported by seawater intrusion [22,26]. The inefficient waste management could lead to the accumulation of these pollutants in mangrove areas, which are essential for coastal protection (i.e., storm wave attack) and biodiversity (i.e., for fish migration or breeding) [3,14]. The mangroves inadvertently act as filters, trapping plastics and other debris, which highlights the critical need for improved waste management and reduction of plastic use, especially products that easily end up in aquatic environments. This is further supported by Raheman et al. [49], who found that the roots of Rhizophora mangroves aid in soil formation by trapping sediment and depositing debris.

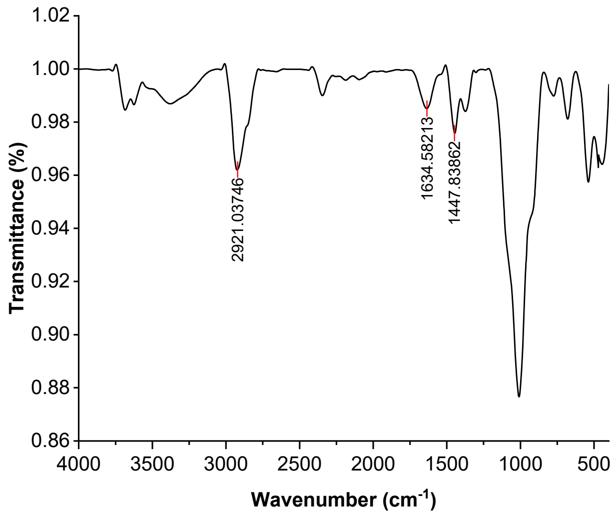

Fig 8. ATR-FTIR spectra showing polypropylene (PP) MP from mangrove sediment

The Impact of Sediment Properties on MP Abundance

The average sediment pH was 5.29 ± 0.29, indicating slightly acidic conditions. The lower pH observed may be due to the timing of the sampling, which took place during low tide. This allowed for the accumulation of acids from decomposing organic matter and anthropogenic inputs, such as waste from nearby aquaculture activities [9]. On the other hand, the mean value of SOM for mangrove sediments was 6.73 ± 3.43%. A significant negative correlation was found between sediment pH and MP abundance ($r = -0.75$, $p < 0.05$) based on Sperman correlation analysis. Lower pH levels may alter the surface charge of both MPs and sediment particles, enhancing MPs adsorption [3-4]. Additionally, acidic conditions can affect microbial activity, potentially reducing MPs degradation rates and increasing their persistence [34]. However, no correlation was observed between SOM and MPs abundance.

■ CONCLUSION

The function of Rhizophora mangroves is not only to protect from storm wave attacks but also to trap the sediment, including any kind of debris. Therefore, this study reports significant MP contamination in the sediments of Rhizophora mangroves at Setiu Wetlands, with levels exceeding those found in other regions of Malaysia. The highest abundance of MPs was likely linked to aquaculture activities that use plastic equipment, which breaks down into MPs of various sizes, colors, and shapes. The degradation process enhances biofilm development and metal adsorption on MPs. The presence of PP MPs raises concerns about potential risks to aquatic life through bioaccumulation and biomagnification. Regular monitoring, especially near fish farms, and regulations to reduce plastic use in aquaculture are essential to address these issues. Since MPs can transport pollutants, further research on sediment characteristics and mitigation strategies is critical to safeguard ecosystem health and biodiversity.

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■ CONFLICT OF INTEREST

The authors declare no conflicts of interest concerning the publication of this paper.

■ AUTHOR CONTRIBUTIONS

Nur Syafiqah Mohd Maulana conducted field sampling and drafted the original manuscript. Muhammad Shiddiq Zulkifli performed field sampling and laboratory work. Aina Arifah Khalid handled field sampling and microplastic extraction. Maisarah Jaafar conceptualized the study, conducted field sampling, and wrote and revised the manuscript. Rohani Shahrudin conducted field sampling and revised the manuscript. Sabiqah Tuan Anuar conducted field sampling and revised the manuscript. Effi Helmy Ariffin is responsible for statistical data analysis, funding acquisition, and revising the manuscript. All authors have approved the final version of the manuscript.

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