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The Occurrence of Microplastics in Sediment Cores from Two Mangrove Areas in Southern Thailand

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Abstract: Mangroves are areas that connect the land and sea, and are important to the ecosystem. They are important places for food sources and the habitat of aquatic fauna in the tidal areas. However, the existence of plastic debris poses a risk to the aquatic environment. This study aimed to investigate the accumulation of microplastics (MPs) in sediment cores from two mangrove areas. The first mangrove area is in the outer section of the Songkhla lagoon (SK), while the second is in the coastal area of Pattani province (PN). Sediment core sampling was performed from SK = 8 stations and PN = 5 stations. Surface enrichment of MP was observed, especially in sediments of 0–4 cm. MPs were found throughout the depth in both areas, while fewer MPs were found in deeper sediment core layers ($p < 0.05$) at some stations inside the mangrove zone. Simple linear regression of the observed MPs and distance in the horizontal were found to be significant at SK within the mangrove zone with $r^2 = 0.79$ ($p < 0.05$). MP fibers were the most commonly found MP type in both areas and were less than 1 mm. Blue and black MPs were the most abundant colors found in both areas. The six polymer types reported in this study comprised polyethylene, rayon, rubber, styrene, Poly (vinyl acetate), and paint. The findings of the present study suggest that long-term monitoring of marine debris along coastlines is necessary to help improve national policies and measures related to marine plastic debris.

Keywords: microplastic; mangrove; sediment; wetland; polymer; FTIR

1. Introduction

Over recent decades, plastic pollution has become a global environmental concern due to increased plastic production and consumption. Global plastic production has increased exponentially from 0.35 million tons in the 1950s [1] to 359 million tons in 2018 [2]. When plastic is released into the ocean, plastic debris will break down continuously through physical, chemical, and biological processes [3,4], which results in the formation of hazardous secondary MPs in the sea. MPs are fragments of any plastic particles less than 5 mm in size [5]. They can be categorized based on their shape, size, color, and raw material. They are generally found in different shapes such as film, fragments, pellets, and fibers [6], which easily disperse into the environment. They are difficult to degrade and pose a long-term threat to marine ecosystems. Plastic contamination in the ocean is a global concern due to its negative effects on marine health and biota. MPs are easily ingestible by marine animals such as zooplankton [7], fish [8], and mollusk [9] due to their small-sized particles, which affect the health of marine biota [10]. Additionally, previous studies indicate that MPs can adsorb persistent organic pollutants (e.g., polycyclic aromatic hydrocarbons, polychlorinated biphenyls, and DDT) and heavy metals (e.g., cadmium, mercury, and chromium), which could be transferred to higher trophic levels [11–13].

Previous reports show that only 1% of plastic entering the marine environment remains as floating debris on the water surface [14]. Most MPs sink to deeper layers of the water column [15] and accumulate in sediments [16]. Mangrove forests have been identified as a major sink of marine plastic pollution [17,18], which can effectively trap MPs through their root systems and sediment [19]. Numerous investigations concerning MP pollution in sediments along Thailand's coastal areas have been conducted, yet few existing studies on MP pollution in mangrove sediment have been conducted. Importantly, mangrove forests are essential food sources and economic resources for coastal fisheries and people in Thailand. Moreover, MP accumulation in mangrove forest areas may influence aquatic animals and people who consume aquatic animals contaminated with MPs.

A mangrove forest is a group of trees and shrubs that are commonly found in coastal areas. A mangrove is a connective place between the land and sea and is important to the ecosystem, especially to the aquatic population. Mangroves are an important food source for aquatic fauna in tidal areas. In addition, the elongated root system makes it possible to trap sediment and pollutants such as trace metals. Mangroves are important carbon reservoirs [20] and regulators of nutrients and pollutants [21]. They provide food, medicine, and fuel; protect coastal zones [22]; and are home to various animal species [23]. Nonetheless, mangroves face threats from deforestation and land use changes [24], as well as erosion [25], farming [26], pollution [27], and climate change [28]. Monitoring the trends of various pollutants within core samples can be used to indicate the degree of human activities in mangroves. Monitoring vegetation cover can further determine whether mangrove areas face deterioration in terms of the reduction of mangrove forest areas. There have been numerous reports on MP ingestion in marine organisms [29]. Some studies of MPs in mangrove sediment have been conducted in Southeast Asia and East Asia, including in Vietnam [30], Indonesia [31], Singapore [32], Malaysia [33], and China [34]. A few studies have emerged in Thailand recently that describe MP ingestion and MP abundance in marine organisms such as sessile invertebrates (oyster, striped barnacle, and periwinkle) collected from eastern Thailand coastal areas [35], fish samples caught in the southern Gulf of Thailand coastal area and from fishery markets [36], and shrimp and fish samples from Songkhla Lagoon, southern Thailand [37]. Yet, few studies of MPs in beach sediment in coastal areas [38–40] have been performed until now, while few reports exist considering MPs in mangrove sediment.

This study aimed to investigate the accumulation of MPs in sediment cores in mangrove forests. The study area included Songkhla Lagoon and the coastal area of Pattani province, one of the important mangrove areas in Thailand. The results of this study offer valuable data to develop a conservation policy for mangrove areas in Thailand and other Southeast Asian countries.

2. Materials and Methods

2.1. Study Area

Sample collection was conducted in two locations with mangrove forests (Figure 1). The first mangrove area is at the outer section of Songkhla Lagoon (SK), Thailand (Figure 1), which is situated in southern Thailand and is connected to the Gulf of Thailand through a narrow strait. The outer section of Songkhla Lake receives pollutants from human activities via drainage from the Songkhla urban area [41]. The lagoon faces problems of environmental degradation due to urban expansion and industrialization. Sources of pollutants to the lake system include municipal waste from the cities of Hat Yai and Songkhla, industrial wastes mainly related to the rubber industry, seafood-processing industry, mining activities, and pollution from boats in Songkhla harbor [42]. The dominant mangrove species in the SK area is *Sonneratia caseolaris*. The second mangrove area is in the coastal area of Pattani province, adjacent to Pattani Bay (PN), Thailand (Figure 1). PN is a mangrove plantation area in new muddy flats that faces the open sea of the Gulf of Thailand. The main species is *Rhizophora apiculata*.

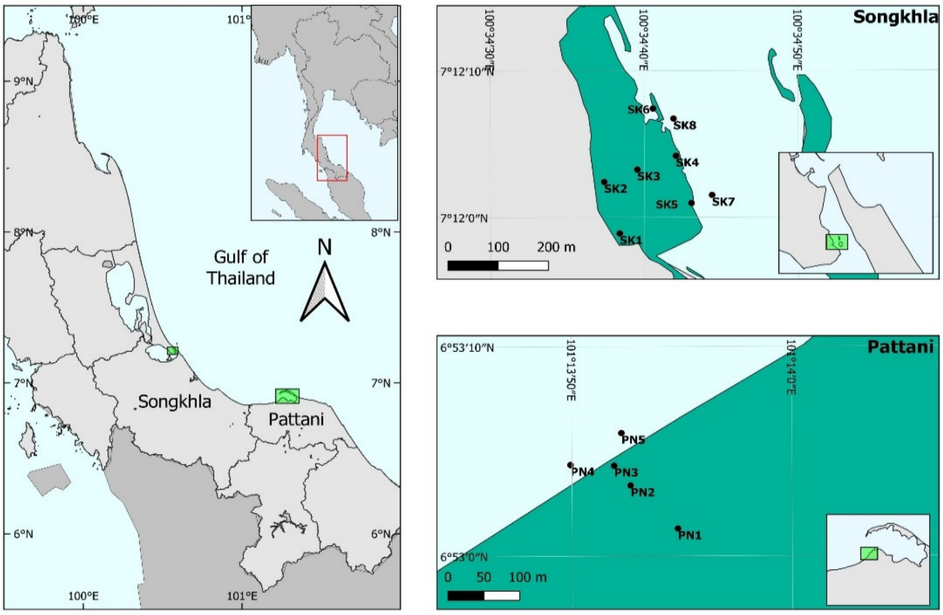


Figure 1. Study area of the two mangrove sites (in green) in Songkhla (SK) and Pattani (PN) provinces, southern Thailand.

2.2. Sediment Sampling

Sediment cores were collected from 13 stations (Figure 1). Eight stations (six inside and two outside the mangrove forest) were sampled in the SK area, while five stations (three inside and two outside the mangrove forest) were sampled in the PN area. The survey was conducted between March and April 2021. Sediment cores were collected by hand pushing using Plexiglas tubes (5 cm diameter and 50 cm length). The collected samples were transported immediately to the laboratory for further sub-sampling.

2.3. Sediment Preparation and Extraction

2.3.1. Experimental Control

To avoid microplastic contamination, distilled water and saturated NaCl were filtered before being used in the experiment. During the separation procedure, extensive measures were applied to avoid any contamination while handling and processing the samples. Cotton lab coats and polymer-free grove were worn to ensure minimal contamination during the experiment [43]. All equipment was rinsed with filtered distilled water before use. Furthermore, all sample processing was performed in a clean fume chamber. Blank was carried out by filtering the distilled water from an 8 cm petri dish filled with distilled water and placed next to the working zone with no observed MP.

2.3.2. Microplastic Extraction from Sediment

Sediment cores were sectioned every 2 cm through the depth and then oven dried at about 50 °C. Due to the agglutination of organic matter, it was necessary for it to be removed from the sediment before analysis [44]. For the typically muddy sediments observed in tidal flats and mangrove forests, MPs were frequently covered or partly covered by clays and organic matter, so a procedure to clean the samples using deionized water was utilized in this study. About 30–50 g of dry sediment was placed in a beaker (1 L). Then, 100 mL of deionized water was added to the sediment, which was stirred vigorously for 5 min using a magnetic stirrer for the purpose of cleaning and separating MPs from the sediment. Thereafter, 400 mL of saturated NaCl (1.2 g/cm^2) was added based on the method of Chinfak et al., 2021 [45] and Wang et al., 2020 [46], with some minor changes. The NaCl method has been widely used to separate microplastics from sediments [45–47]. A rod was used to mix, after which the mixture was left for 24 h to allow the sediment to settle. Then, 250 mL supernatant was filtered through a glass microfiber GF/B (Whatman, pore size 1 μm) using a vacuum system. Another 250 mL of NaCl was added to the original sample beaker, and the same density separation and filtration was repeated twice for each sediment sample with a new filter paper. Thereafter, all filter paper was oven dried at 50 °C.

2.3.3. Microplastic Identification

To identify the MPs in the filter paper under a stereomicroscope, visual identification was based on the morphological and physical characteristics of plastic particles. A stereo zoom microscope camera with an attachment (Olympus SZ61, lenses 110AL2X-2 with Canon EOS 600D) was used in this method. As the filters were completely dry, there was no bias in the light reflection from the microscope. The criteria to accept the particles as plastic before being verified by the FTIR spectrophotometer involved the hot needle test [48], which was applied for suspected cases where the researchers were unable to distinguish between plastic and organic matter. In the presence of a hot needle, plastic pieces will melt or curl. We also applied the Hidalgo-Ruz et al. (2012) [49] rules to assist in identifying most MPs that were encountered in this analysis. Rule 1: No cellular or organic structures visible. Rule 2: Fibers should be equally thick throughout their entire length. Rule 3: Particles should exhibit homogenous color throughout the item. We recorded the shape, color, and size of each item.

To ensure an uncontaminated reading by FTIR, the selected MP samples were not covered or were partly covered by clays and organic matter (observed under a stereomicroscope). The MPs were analyzed to identify polymer types using a micro Fourier Transform Infrared(μFTIR) spectrometer, Frontier model coupled with a Spotlight 200i FTIR microscope (PerkinElmer Inc., Waltham, MA, USA). The wavelength used was 4000–600 cm^{-1} with an attenuated total reflection (ATR) mode using a scanned rate of 16 and resolution of 4 cm^{-1}. To minimize the error from the background during the identification process, the peak of CO_2 and H_2O was removed from the value. The obtained polymer type was compared with the library, called the Polymer Introductory Library, and 70% matching was accepted.

2.4. Data Analysis

Data analysis of MP abundance, size, color, and shape were performed using MS Excel 2007 (Office Professional Plus 2019) software. A correlation test was performed to find the relationship between the number of MPs found in the sediment and the depth. A significance level of 0.05 was considered for all of the analyses.

3. Results and Discussion

3.1. Vertical Accumulation of MPs

A total of 13 sediment cores were obtained from both areas at various depths, between 18–42 cm for SK and 18–38 cm for PN (Table 1). The range of MPs found in SK was from 71–108 items and 71–155 items for PN. The range of MPs inside the zone for SK and PN were 71–108 items and 71–84 items, respectively. Vertical profiles of the amount of MPs found in the sediment core are given in Figures 2 and 3. Most MPs showed only slight vertical variations, with some exceptions. Surface enrichment of MPs was observed, especially in sediments of 0–4 cm in both areas. Differences were observed between the sediments from inside and outside the mangrove areas. At some stations, the correlation between MP and depth was significant ($p < 0.05$) in terms of the decrease with depth (SK02, SK05, SK07, and PN03). Generally, a decreasing trend in depth was observed at SK, except for at SK08, which is located outside the mangrove area and resulted in amounts of MPs similar to all depths. The MPs detected at every layer of the sediment samples varied between station and depth. The amount of MPs inside the mangrove area was higher on average in both areas, potentially because mangrove roots could trap marine debris and MPs during high tide. MPs entered during high tide and then attached to the roots or bushes at low tide, then MPs sank onto the surface sediment and mixed into the deeper layers by biological and physical processes in the mangrove. Sediments from the inside zone of SK had a greater abundance of MPs in the mangrove sediment, which could be because of the location of SK in the shelter of the lagoon and near the community, while the PN is far from the community and faces the open sea (GoT). SK provided a lagoon-mouth mangrove forest. However, the selected mangrove forest was dominated by a shore parallel tidal current. When high tide floods into a forest, debris and MPs suspended in water also reach inside the mangrove. While a mangrove forest can reduce the current energy, the suspended MPs settle and become trapped in the sediment. The vertical profiles at PN varied among stations and only PN03 showed a significant ($p < 0.05$) decrease in MPs with depth.

Table 1. Position and sediment sampling information.

Station	Zone	Latitude N	Longitude	Sediment Depth (cm)
SK1	Inside	7.1996945	100.5773295	42
SK2	Inside	7.2006720	100.5770522	38
SK3	Inside	7.2009051	100.5776506	34
SK4	Inside	7.2011649	100.5783487	34
SK5	Inside	7.2002687	100.5786262	30
SK6	Inside	7.2020615	100.5779352	18
SK7	Outside	7.2004212	100.5789980	26
SK8	Outside	7.2018703	100.5783058	34
PN1	Inside	6.8836973	101.2318894	18
PN2	Inside	6.8842695	101.2312951	26
PN3	Inside	6.8845326	101.2310883	26
PN4	Outside	6.8845442	101.2305366	38
PN5	Outside	6.8849661	101.2311807	30

The cumulative MP abundance between the two study locations (at 10 cm depth) ranged from 106–413 and 108–180 items/kg dry weight, respectively. Table 2 presents a comparison of the data from this study with findings from other areas in the world. Fiber and fragments found were similar in other studies around the world. However, the concentrations of MPs from the present study were higher than those undertaken in Indonesia and Singapore [31,32], and lower than Iran, China, and Brazil [34,50–55]. Therefore, mangroves have the potential to act as sinks for MPs and other pollutants [17,18].

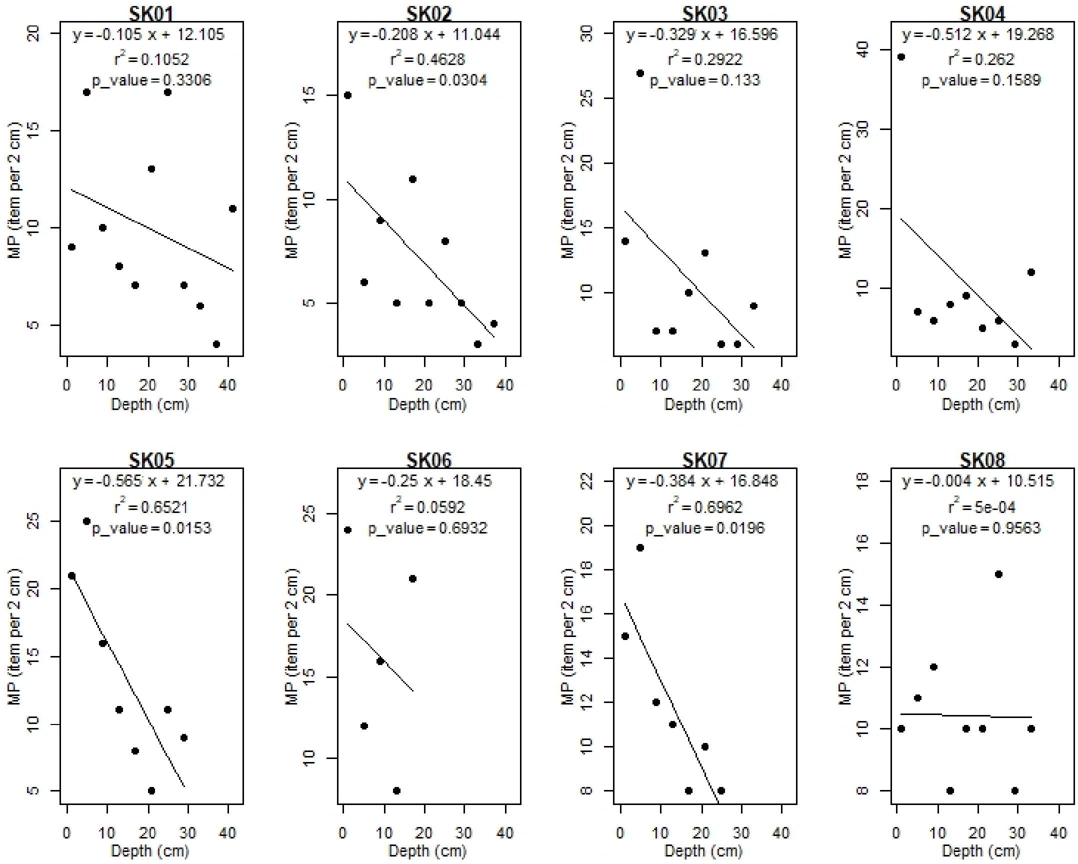


Figure 2. MP vertical distribution in the sediment core at the SK stations.

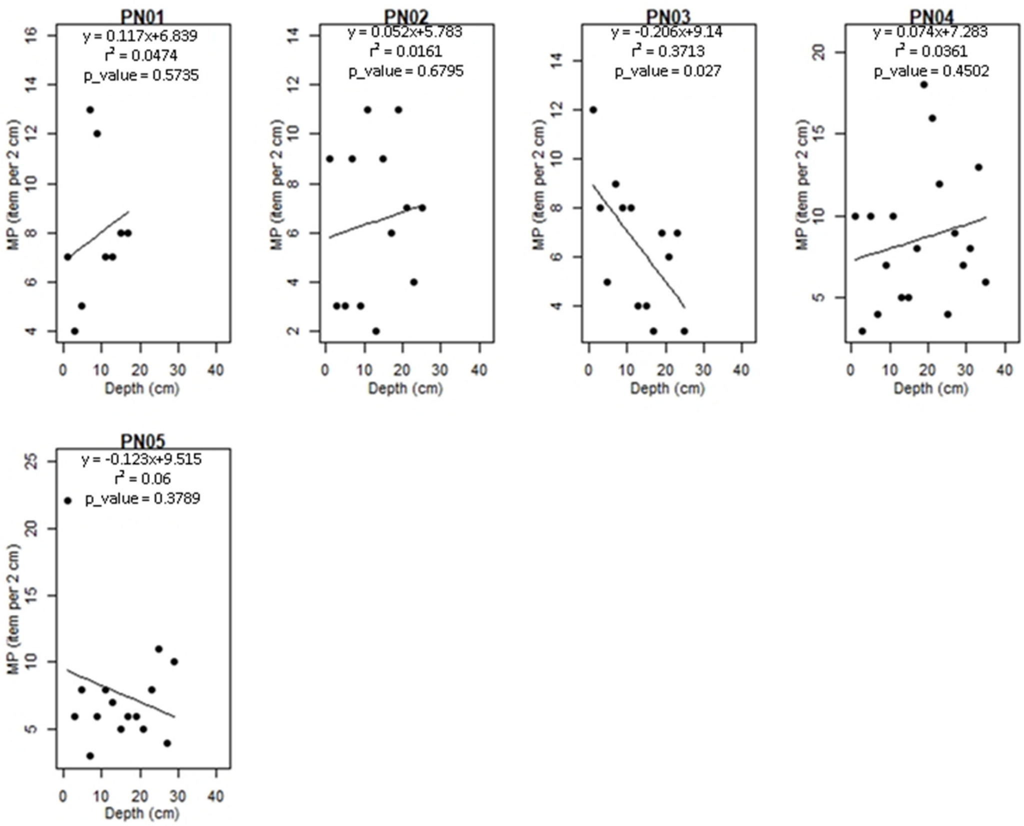


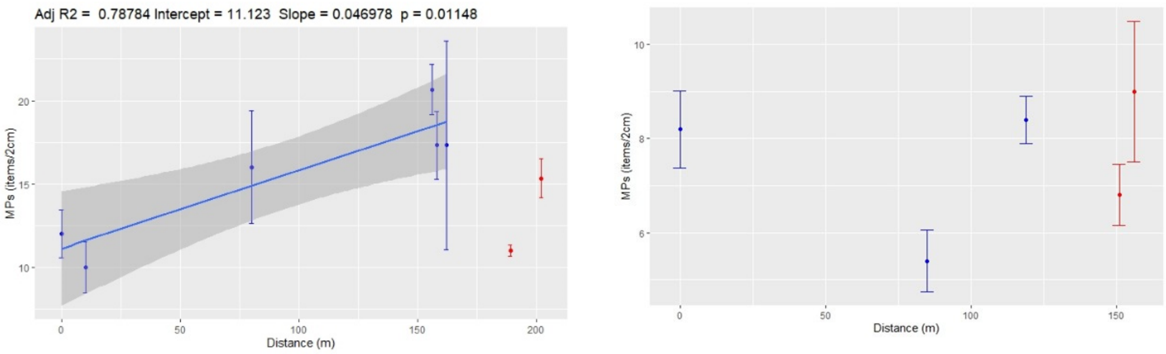
Figure 3. MP vertical distribution in sediment cores at PN stations.

Table 2. Abundance and distribution characteristics of microplastics in mangrove sediments.

Locations	Size (mm)	Abundance of MPs (Items/kg d.w)	Dominate Shape	Polymer Types	Color	Ref.
Singapore's coastline, Singapore	-	12.0 ± 8.0–62.7 ± 27.2	fiber (72.0%) films (23.3%)	PP, PVC, Nylon	transparent, blue and red	[32]
Muara Angke Wildlife Reserve, Indonesia	0.2–4.8	28.1 ± 10.3	foam (13.3%) fragment (10.1%)	PS (44.6%) PP (29.2%) PE (15.4%)	-	[31]
Persian Gulf, Iran	<5.0	1258 ± 291	fiber (83%) film (11%) fragment (6%)	PE, Nylon, PET	red, blue and transparent	[50]
Qinzhou Bay, China	0.16–5.0	15–12,852	fragment (94%) fiber (0.5%) sphere (5.2%)	PS (>98%), PP, PE	white (98%), transparent (1%), yellow, green, red, and blue (<1%)	[34]
Maowei Sea, China	<5.0	520 ± 8–2310 ± 29	fragment	PP (47.5–79.2%) PE (2.5–42.5%) PS (1.8–12.8%)	white (64.6%) transparent (20.3%)	[51]
Pearl River Estuary, China	<5.0	100–7900	fiber (70%) fragment (28–29%)	PP, PE, PET, PS copolymer, LDPE, Cellophane	green (28.3–47.6%) black (21.2–43.1%)	[52]
Jinjiang Estuary, China	0.03–5.0	980 ± 254.6–2340 ± 198	fiber (68.6%) film (15.3%) particle (12.4%) fragment (15.3%)	PET, PE, PP	transparent (47.7%), white (25.3%), blue (15.3%) red, black and yellow(11.7%)	[53]
Guangxi, Coastal South China Sea	<5.0	17.7 ± 8.1–611.8 ± 81.5	fiber (74.7%) fragment (14.9%) the pellet (1.8%) foam (4.2%)	PE, PP, PS Polyamide	blue (26.7%), black (22.3%) transparent (17.5%), purple (3.4%)	[54]
Southeast Brazil	<5.0	3080	filament (88.7%) fragment (11.3%)	-	blue (54%), transparent (21%) black (10%), red and green (6%), yellow and white (1%)	[55]
Thailand: Songkhla lagoon (SK) and Pattani (PN) coastal area	<5.0	108–180 (PN) 106–413 (SK)	fiber fragmentttani coastal areap organism. (n the inner lagoon. al rangeurnal tide with a low tidal range of 0.6 m atteh inlet	PE, rayon, rubber, styrene, paint, and poly (vinyl acetate)	white, yellow, pink, silver, purple, red, green, black, dark blue, light blue, and transparent	This work

3.2. Horizontal Accumulation of MPs

Figure 4a presents the number of MPs observed at 0–10 cm depth and the distance from the shore. The inner zone of SK (SK01 to SK06) tended to show an increase of MPs by distance from landside (SK01) to forest border (SK06: lagoon side). The simple linear regression of observed MP numbers by the distance of the inner zone resulted in r^2 = 0.79 with a p-value of 0.011 ($p < 0.05$). The reduction of MPs numbers at the landside can be explained by the mangrove forest topography. The inside most of the mangrove (landside: SK01 and SK02) forest trended to be at a higher elevation, leading to them expressing a shorter residence time for water. Meanwhile, in the inner zone closest to the mangrove border (lagoon side), the tidal current dropped immediately [56], which resulted in MPs sinking in this area. Moreover, the border of the forest and the highest residence time of the tide resulted in more suspended MPs in the lagoon water. However, the amount of MPs in our results in the PN area had no significant relation to distance (Figure 4b). This was likely because of the lower density and younger mangrove compared to SK, in which the forest was less able to trap MPs compared to SK. Another potential explanation is the topography. From our observations, there was no elevation difference between inside and outside the mangroves. In addition, a further potential reason is that PN is located next to the open sea. MPs are easily transported as suspended loads by the current, waves, tides, and coastal erosion process from other places to the deposit site, thus possessing a dynamic quantity of MPs present in the sediment according to their short residence time in the coastal sediment [57]. Furthermore, plastic debris was found in the study area, which was likely suspended or drifted with the high tide to the mangrove, and could become trapped into the mangrove roots and nearby sediment during low tide (Figure 5).



(**a**) (**b**)

Figure 4. Number of MPs by distance from the innermost points at SK station (**a**) and at PN station (**b**); error bars illustrate the standard error of the mean; blue colors indicate the inner zone; red colors indicate the outer zone. Note that this data correspond with the results from the upper 10 cm depth only.

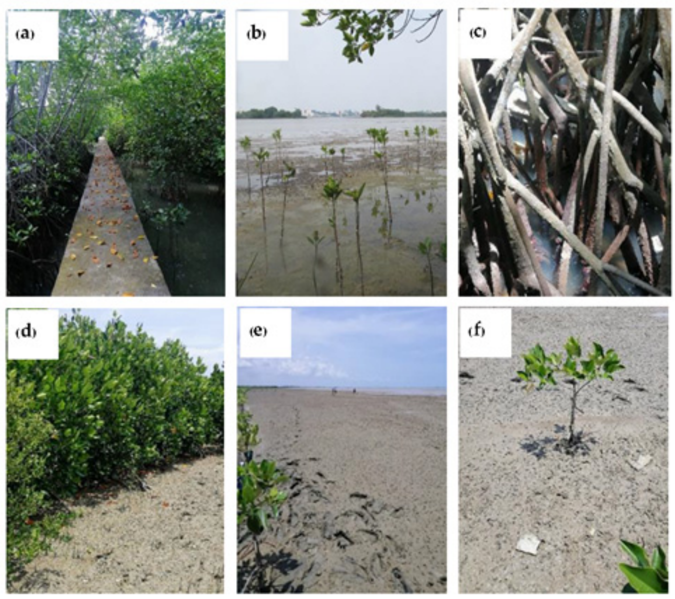


Figure 5. Mangrove area at SK (**a**) inner zone; (**b**) outside zone; (**c**) debris trapped in mangrove root; and at PN (**d**) inside zone, (**e**) outside zone, and (**f**) debris stand on the mudflat.

3.3. Microplastic Identification

There were 13 colors found in the sediment from SK, consisting of brown, white, yellow, pink silver, purple, red, green, black, dark blue, light blue, transparent, and others (Figure 6a). Black and blue were the most commonly found in SK. At PN, 11 colors were found, including white, yellow, pink, silver, purple, red, green, black, dark blue, light blue, and transparent (Figure 6b). Blue was the most common at PN. The dominant size in both areas was less than 1 mm (Figure 7). Sizes from 1–5 mm were more commonly found inside the mangrove area at SK. Fiber was the most abundant in the area (Figure 8), and was more commonly found outside the mangrove area. An example MPs found in this study is shown in Figure 9. MPs from SK are probably associated with human activity and fishing in the lagoon, while the MP source at PN could be from fishing nets in the coastal area. From the FTIR investigation, the six types of polymers found in this study were polyethylene, rayon, rubber, styrene, Poly (vinyl acetate), and paint. Polyethylene or PE is a common thermoplastic that is widely used in many applications such as food packaging and containers [58]. In polymer context and composition, PE is mainly used for HDPE ropes and the fabrication of fishing nets. This type of rope is used extensively in fishing activities and the docking of ships in marine-related industries [59]. Rayon is a cellulose fiber generated from natural sources of cellulose and synthetic cellulose fibers. Generally, rayon fiber is used to produce artificial silk and other textiles. Paint can come from fragments off fishing boats in the lagoon and coastal areas. Surprisingly, in this study, very common pollutants such as polyvinyl chloride (PVC) and acrylic were not observed, even in areas closest to sources of urban pollution. These results are similar to previous studies, which reported no PVC in marine organisms in southern Thailand [29,37], although they were found on beaches on the eastern coast of Thailand and the Andaman sea [38,57].

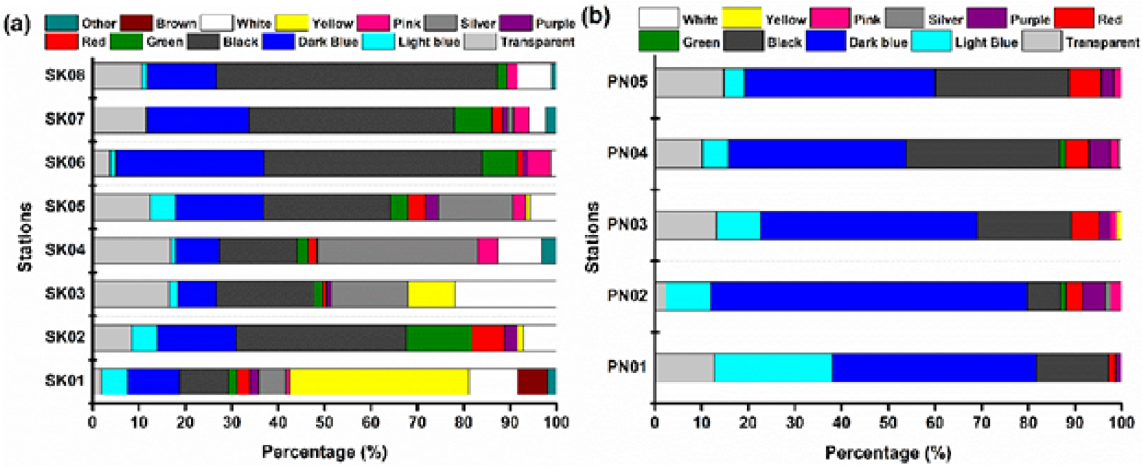


Figure 6. MP colors found in (**a**) SK and (**b**) PN stations.

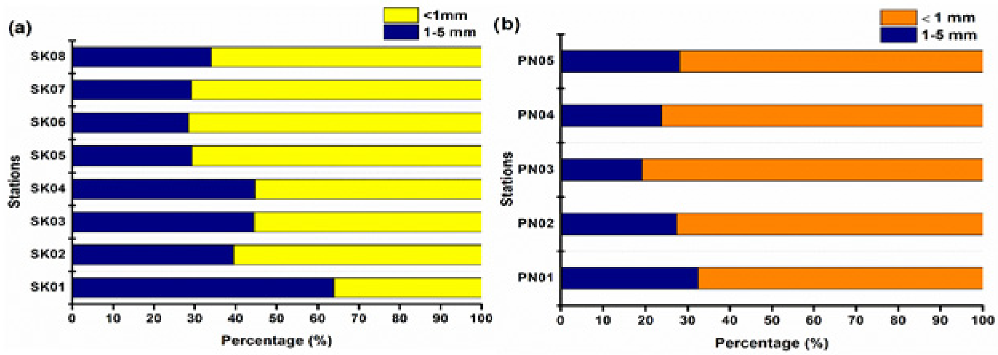


Figure 7. MP sizes found in (**a**) SK and (**b**) PN stations.

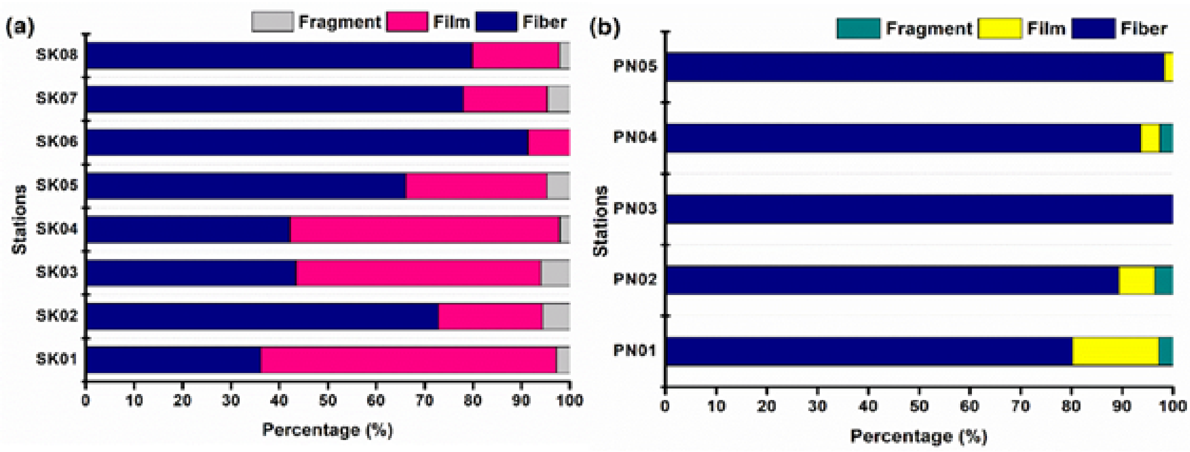


Figure 8. MP types found in (**a**) SK and (**b**) PN stations.

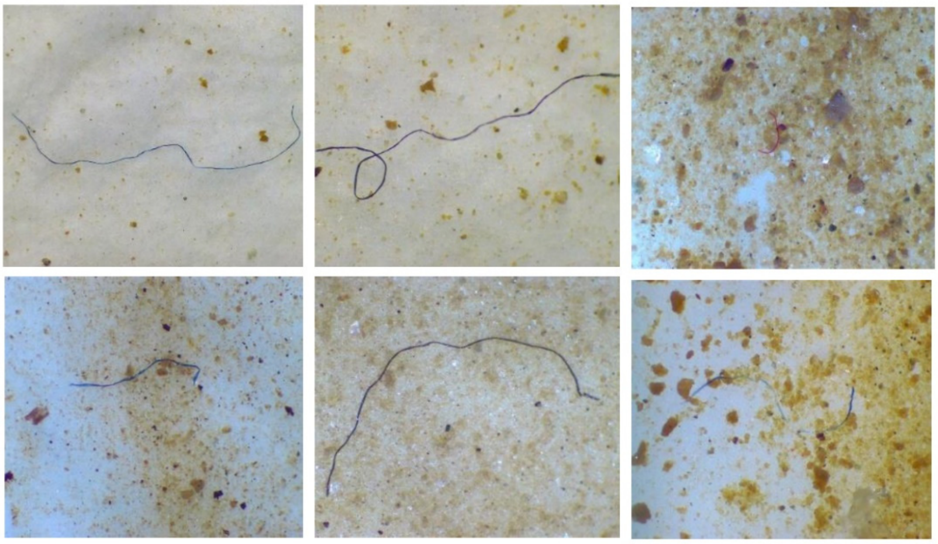


Figure 9. Examples of fibers found in SK and PN mangrove areas.

4. Conclusions

This study was the first to report on the presence of MPs in mangrove sediment cores from two mangrove areas in southern Thailand. From the study, we found that the accumulation of MPs in mangrove areas in both SK and PN varied according to core depth. This research was undertaken in a single season, so the authors recommend further research to be conducted covering all seasons. In addition, a comparison of the results with the age of sediment would be meaningful. Mangroves are an important wetland currently contaminated with MPs, which can be harmful to benthic fauna and marine organisms. Sediments in coastal and lagoon ecosystems play an important role as a major source for feeding benthic organisms, but they can also accumulate many toxic substances. Anthropogenic pressures can also lead to increased chemical and microbiological pollution of lagoons and coastal areas. Therefore, long-term monitoring of marine debris along coastlines, including apparently pristine and environmentally protected areas, is necessary to help improve national policies and measures related to marine plastic debris.

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Conflicts of Interest: The authors declare no conflict of interest.

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