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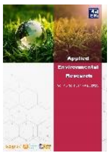

Research Article

Spatial Distribution and Potential Ecological Risk of Microplastics in Surface Sediments of the Inner Gulf of Thailand

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Abstract

The global surge in plastic usage during the COVID–19 pandemic raised concerns about increased microplastic (MP) contamination in aquatic environments. This study assessed the abundance, characteristics, and ecological risk of MPs in surface sediments of the inner Gulf of Thailand during the post–COVID–19 period (April 2021). The sediment samples were analyzed via density separation, stereomicroscopic examination, and polymer identification via micro–FTIR. The mean MP abundance was 196.07 ± 85.60 pieces kg^{-1}, with concentrations ranging from 73.08 to 351.19 pieces kg^{-1}. PTFE and PP were the dominant polymer types, comprising 50% and 32% of all the MPs, respectively. Fibers (34%) and fragments (24%) were the most common shapes, whereas transparent (42%) and white (32%) were the predominant colors. A significant inverse correlation was observed between MP abundance and seawater depth, as well as between the PTFE and PP fractions, suggesting that the deposition of MPs depends on the horizontal–vertical distance and the properties of the MPs. The pollution indices indicated moderate contamination ($C_f = 2.72 \pm 1.19$), moderate polymer–specific risk (PRI = 95.35±133.45), and low potential ecological risk ($E_r = 0.87 \pm 0.83$). Although MPs are present at moderate levels in sediments, the COVID–19 pandemic did not significantly increase MP contamination or ecological risk in the benthic environments of the inner Gulf. However, the potential impacts on the water column remain uncertain and warrant further investigation.

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Introduction

Microplastic (MP) contamination in coastal sediments has become an urgent environmental issue, underscoring the broader crisis of plastic pollution in marine ecosystems. Microplastics, defined as plastic particles smaller than 5 mm, originate from a variety of sources, including the degradation of larger plastic debris, microbeads in personal care products, and synthetic fibers released from textiles [1]. These particles are generally classified into two categories: primary MPs, which are manufactured at small sizes (e.g., plastic beads), and secondary MPs, which are produced through the fragmentation of larger plastic items under environmental stressors [2]. Microplastics are pervasive and persistent in the environment, entering coastal zones through riverine transport, surface runoff, and direct deposition from anthropogenic activities.

The environmental threat posed by MPs is largely due to their physicochemical properties—persistence, bioaccumulation potential, toxicity, physical impacts on biota, and ability to transport invasive species and chemical pollutants. For example, MPs have been found in the digestive systems of zooplankton, which serve as the base of the marine food web, leading to reduced feeding efficiency, physical blockage, and exposure to hazardous chemicals adsorbed onto the

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plastic surface [1]. Higher trophic state organisms, including fish, seabirds, and marine mammals, are similarly affected through trophic transfer and direct ingestion [3].

The sedimentation of MPs is influenced by their density and their interactions with biological and environmental materials. Low–density plastics can sink through aggregation with biofilms, microalgae, and biofouling organisms, increasing particle density and promoting deposition in aquatic sediments [4]. This process begins with microbial colonization of plastic surfaces (biofilm formation), followed by the attachment of algae and invertebrates, ultimately increasing particle mass and causing them to settle [5–6]. The sedimentation of MPs alters their environmental fate and increases their ecological impact, particularly in benthic habitats, where they can harm sediment–dwelling organisms and act as vectors for concentrated pollutants via sorbed toxins and microbial communities [7].

The inner Gulf of Thailand is a semi–enclosed bay, which is a critical region for marine biodiversity and economic activities. Major rivers such as the Mae Klong, Tha Chin, Chao Phraya, and Bang Pakong rivers flow into this area, delivering both freshwater and land–based pollutants. Previous studies have confirmed widespread MP contamination in the inner Gulf of Thailand across various environmental matrices, although the methods used for sampling and analysis differ. For example, MP concentrations were reported to be 4.0± 3.8 particles L^{-1} in the Chao Phraya River during tidal cycles [8] and 9.97 particles L^{-1} in surface waters of the inner Gulf of Thailand [9]. In biota, MPs were detected in the gastrointestinal tracts of 46.9% of the commercially important fish species sampled from the region [10]. Sediment studies reported a likely increasing trend of MPs over time, from 83–328 pieces kg^{-1} in 2004 [11], from 25–362.5 pieces kg^{-1} in 2011 [12], to 48.61–14,469.84 pieces kg^{-1} in 2018 [13].

The COVID–19 pandemic (late 2019–early 2021) intensified plastic consumption due to the widespread use of single–use plastic items, particularly personal protective equipment (PPE), such as disposable face masks. Mismanagement of these plastic wastes may have contributed significantly to MP pollution. Laboratory experiments have shown that disposable masks can release 525–1,038 MP particles in 30 days at 40 °C in tap water [14], and under mechanical stress, 1.3–4.4 × 103 particles per mask are released [15].

Given the sharp rise in plastic usage during the pandemic, we hypothesize that MP abundance in the sediment of the inner Gulf of Thailand increased during this period. Therefore, this study aims to investigate the abundance and characteristics of MPs in surface sediments of the inner Gulf of Thailand during the dry season of the second year of the COVID–19 pandemic (April 2021). This study also explored the spatial distribution and ecological risk associated with MP contamination in this important coastal region, contributing to an early post–COVID-19 baseline for plastic pollution in marine sediments.

Materials and methods

1) Sample collection and extraction

In April 2021, MP contamination in sediments was investigated at 13 sampling stations across the inner Gulf of Thailand via a Smith–McIntyre grab sampler (Figure 1). Surface sediments (0–2 cm) were collected via a clean wooden spoon and transferred into aluminum containers, which were immediately sealed with aluminum foil to prevent contamination. All the sediment samples were stored at ambient temperature until further analysis.

The extraction procedure was adapted from the method developed by the NOAA Marine Debris Program [16], with slight modifications. Initially, sediment samples were oven–dried at 60 °C and then weighed and disaggregated using a dispersion solution consisting of $Na_6P_6O_{18}$ and Na_2CO_3. Two–step separation was carried out using a saturated NaCl solution (density = 1.2 g cm^{-3}). In the first step, disaggregated sediments were mixed with filtered NaCl solution to allow plastic particles to float. The floated materials were then subjected to wet peroxide oxidation (WPO) using H_2O_2 and $FeSo_4$ in H_2SO_4 to eliminate the remaining organic matter. After oxidation, the particles were again floated in a NaCl solution to further purify the plastic particles.

The final supernatants were filtered through 12 µm Nuclepore Track–Etched membranes (Whatman, catalog no. 110616). The retained particles were examined under a stereomicroscope (Shodensha NSZ405J3, Japan). Only particles that remained intact under needle–touch testing (i.e., not soft or breakable) were classified as MPs. The identified MPs were further categorized by shape and color. The particle shapes were defined as follows: pellets: smooth, spherical or elliptical particles; fragments: irregular particles with cracked or broken surfaces; fibers: thin, thread–like or filamentous particles; films: thin, flat, membrane–like or sheet–like particles; and foams: spongy, porous particles. The colors were visually classified as red, green, blue, brown, black, white, or transparent. After identification, all the plastic particles were dried at room temperature and stored in a desiccator until further analysis. Throughout the extraction process, all containers and tools were either made of cleaned glassware or covered with aluminum foil to minimize plastic contamination. Additionally, three blank controls were prepared by rinsing all the equipment with deionized water and processing them in the same manner as the actual samples. Only one particle of 16-50 µm PE and one particle of 16-50 µm PP were identified in one of three blank controls.

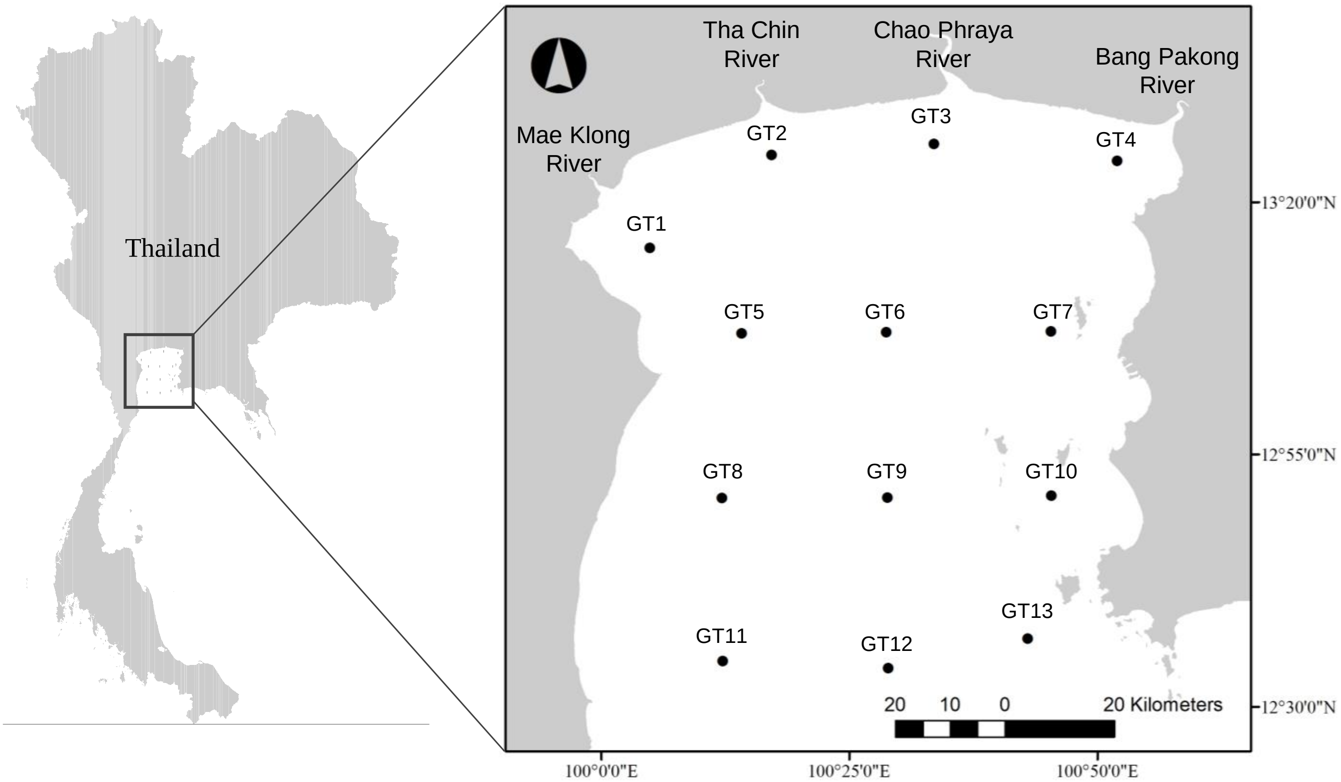

Figure 1 Map illustrating the 13 designated surface sediment sampling sites across the inner Gulf of Thailand.

2) Plastic identification

The chemical composition of the plastic particles was identified via Fourier transform infrared microscopy (micro–FTIR; LUMOS II, Bruker, Germany). A total of 253 particles representing 81.8% of the 309 plastic–like particles initially categorized under a stereomicroscope were selected for polymer identification. Each particle was placed on a potassium bromide (KBr) window and analyzed via transmission mode FTIR in the spectral range of 700–4,000 cm^{-1}, with a scan time of 48 scans per measurement. The resulting IR spectra were compared against reference libraries, including the Bruker ATR–FTIR Complete Library, BPAD Bruker ATR–Polymer Library, and B–KIMW Bruker ATR–IR Library for polymers, plastics, and additives. The particles were confirmed as MPs if their spectral similarity matched a reference spectrum with a confidence value greater than 60%. Additionally, the particle size was measured via the contrast function in the micro–FTIR imaging system. The particle sizes were categorized as 16–100, 100–300, or 300–5000 µm, according to Vibhatabandhu et al. [13]. All spectral analyses and data processing were performed via OPUS 8.5 SP1 software. On the basis of the spectral results, 90.5% of the analyzed particles were confirmed as plastic polymers, whereas the remaining nonplastic particles were identified as natural fibers, including wool.

3) Data analysis

The abundance of MPs in the sediment samples was expressed as the number of particles per kilogram of dry sediment weight (pieces kg^{-1}). To minimize the influence of potential contamination, the particle counts were normalized by subtracting the values obtained from procedural blank samples. The spatial distribution patterns of MPs across the study area were visualized via geostatistical analysis via ordinary kriging interpolation in ArcGIS®. The normality of the investigated data was tested via the Shapiro–Wilk test. To investigate the relationships of MP contamination, Spearman's rank correlation coefficient was used to analyze the correlations between water level, MP abundance, and MP characteristics due to the non-normal distribution of the data. Statistical significance was assessed at a 95% confidence interval. The ecological risk associated with MPs was further evaluated via a suite of indices, including the contamination factor (C_f), polymer risk index (PRI), and ecological risk factor (E_r), providing an integrated assessment of pollution levels and potential environmental impacts.

3.1) Contamination factor

The contamination factor (C_f), originally introduced by Hakanson [17], is defined as the ratio between the concentration of a contaminant in the surface sediment (C_S) and its corresponding baseline concentration in preindustrial or background sediment (C_0) and is expressed as shown in Eq.1:

$$C_{f,i}=C_S/C_0 \qquad \text{(Eq.1)}$$

Xu et al. [18] adapted the C_f for assessing MP pollution by using the minimum reported abundance of MPs from the literature as the background concentration (C_0). In the present study, a value of $C_0 = 72.7$ pieces kg^{-1} was used, which was based on the minimum abundance of MPs detected in the sediment profile at a depth of 25–30 cm from the surface in the inner Gulf of Thailand [13], which is assumed to be baseline conditions. The C_f values were categorized into four levels of contamination: low ($C_f < 1$), moderate ($1 \leq C_f < 3$), considerable ($3 \leq C_f < 6$), and very high ($C_f \geq 6$).

3.2) Polymer risk index

The present study used the PRI, which is a valuable tool for assessing the ecological risks associated with MP contamination in sediments by incorporating both the abundance and hazard potential of different plastic polymers. Unlike conventional methods that quantify MP particles solely on the basis of number or mass, this index evaluates risk on the basis of the specific chemical composition of polymers. Each type of plastic, such as polyvinyl chloride (PVC), polystyrene (PS), and PE, has different degrees of environmental hazard due to its monomer toxicity, associated chemical additives, and potential to leach harmful substances. The PRI is calculated by multiplying the proportion of each polymer in a sample by its corresponding hazard score and summing the results across all identified polymers (Eq. 2). This approach allows researchers to identify not only the quantity but also the toxicity–weighted risk of MP pollution.

$$\mathrm{PRI} = \sum \mathrm{S_n} \times (\mathrm{P_n}/\mathrm{C_s}) \qquad \text{(Eq.2)}$$

where S_n is the polymer hazard ranking score from Lithner et al. [19], which varies with the polymer structure and chemical composition. For example, PAs have a ranking score of PA6 ($S_n = 50$), PA6,6 ($S_n = 63$), and PA6,10 ($S_n = 47$). In this study, the highest value of $S_{n,i}$ was used if more than one score was provided. The value of PRI represents 4 risk levels: low (PRI<10), moderate (10 ≤ PRI < 100), high (100 ≤ PRI < 1,000), and very high (PRI ≥,1,000).

3.3) Ecological risk factors

The widely used ecological risk index model (E_r) developed by Hakanson [17] was applied to assess the potential ecological risk associated with MPs. In this context, the toxic response factor (T_r) for MPs, which reflects their potential to cause harm to aquatic organisms and ecosystems, was adapted on the basis of the conceptual framework proposed by Vibhatabandhu et al. [13] as shown in Eqs.3 to 4.

$$\mathrm{T_r} = \sum \log(\mathrm{S_n}) \times (\mathrm{P_n}/\mathrm{C_s}) \qquad \text{(Eq.3)}$$

$$\mathbf{E_r} = \mathbf{T_r} \times \mathbf{C_f} \qquad \text{(Eq.4)}$$

The E_r for MPs was classified according to Hakanson's framework [17], which has been adapted for MP contamination. The categories include low potential ecological risk ($E_r < 40$), moderate potential ecological risk ($40 \leq E_r < 80$), considerable potential ecological risk ($80 \leq E_r < 160$), high potential ecological risk ($160 \leq E_r < 320$), and very high potential ecological risk ($E_r \geq 320$). This classification provides a systematic approach for evaluating the ecological threat posed by MPs in aquatic environments.

Results and discussion

1) Spatial distribution of MP contamination

The spatial distribution of MP contamination in surface sediments of the inner Gulf of Thailand shows a distinct geographical trend closely aligned with the proximity to major river mouths and the intensity of coastal activities. On the basis of the data from 13 sampling stations (GT1 to GT13), the total concentration of MPs ranged from 73.1 to 351.2 pieces kg^{-1} (average 196.07 ± 85.60 kg^{-1}), reflecting substantial spatial variability (Figure 2). The highest MP concentrations were recorded at GT4 (351.2 pieces kg^{-1}), GT3 (307.1 pieces kg^{-1}), GT2 (280.9 pieces kg^{-1}), and GT1 (251.1 pieces kg^{-1}), which are located in the lower estuary of the Bang Pakong, Chao Phraya, Tha Chin and Mae Klong Rivers, respectively. These rivers are significant conduits for land-based plastic waste originating from densely populated urban, agricultural and particularly industrial zones, underscoring their role as major sources of MP pollution. In contrast, stations located in southern GT13 (73.1 pieces kg^{-1}) and offshore GT7 (105.3 pieces kg^{-1}) exhibited significantly lower MP concentrations, suggesting a reduced influence from direct riverine input and possibly more effective sediment dilution or dispersion by oceanographic processes. The central Gulf area, represented by stations GT6, GT9, and GT12, displayed moderate contamination levels ranging from approximately 131.3 to 206.7 pieces kg^{-1}, which indicated intermediate contamination. The spatial gradient visualized in the interpolated map supports these findings, clearly indicating greater MP accumulation in the northern region near the estuarine outlets and tapering toward the southern and south-eastern zones. This pattern highlights the influences of riverine transport [8], sediment deposition dynamics [20], and coastal anthropogenic pressures on the distribution of MPs in marine sediments.

Compared with those in the other areas, the abundance of MPs in this study was moderate (Table 1). Notably, the separation technique, sampling equipment, detectable size of MPs, and quantification methods used differ. Like in this study, the abundance of MPs in most previous studies was visually quantified under a microscope, and plastic-like particles were randomly sampled for chemical identification. By this quantification, the abundance of MPs strongly depended on observation under a microscope, and plastic confirmation was affected by the number of particles sampled during chemical identification. However, in our study, several particles were sampled for analysis, as 253 of 309 particles were identified as plastics. The abundance of MPs in sediment tended to fluctuate due to the sampling time and study site.

In our study area, the abundance of MPs tended to increase compared with earlier surveys conducted in 2004 [11] and 2011 [12]. However, the detected levels remain lower than those recorded in 2018 [13], in the Chao Phraya lower estuary [20], and in coastal mangroves in the eastern gulf [21].

The discrepancy between this study and the investigation in 2018 may be attributed to the spatial scope and positioning of the sampling stations. In the 2018 study, stations were located predominantly within estuarine zones and in closer proximity to the shoreline, areas more directly influenced by riverine discharge and land–based plastic inputs, which can result in greater MP accumulation in sediments. The sampling stations in the mangroves of the eastern gulf [21] and the Chao Phraya River lower estuary [20] also presented high abundances of MPs at the same characteristics as the sampling locations, which are near the shoreline or in the river estuary. Furthermore, the statistical analysis in the present study revealed a strong and significant inverse correlation between MP abundance and seawater depth ($r_s = -0.758$, $p = 0.003$), indicating that MP concentrations decrease as depth increases (Table 2).

Previous studies revealed that the aggregation of MPs in the matrix of marine snow [31], as well as the flocculation of MPs with sediment and suspended solids [32], enable the settling of MPs. In the water column, the model simulations revealed that biofouling on the surface of the MPs caused the particles to settle, and the deformation of the MPs also moved the particles upward again [6]. A sedimentation trap experiment in a river estuary revealed that a high fraction of low-density plastics settle in the bottom water, but this fraction was lower in the surface sediment, suggesting that some MP particles may be suspended in the water column [20].

The inverse relationship between MPs in sediment and the depth of seawater suggests that MP aggregation in the water column may be more likely to settle in shallow estuaries or areas near coastal lines. However, MPs may remain suspended in the water column for extended periods, particularly in deeper offshore areas, before eventually settling into bottom sediments. In other words, hydrodynamic conditions, such as water column mixing and particle buoyancy, play important roles in the vertical transport and deposition of MPs, thereby influencing their spatial distribution in marine sediments.

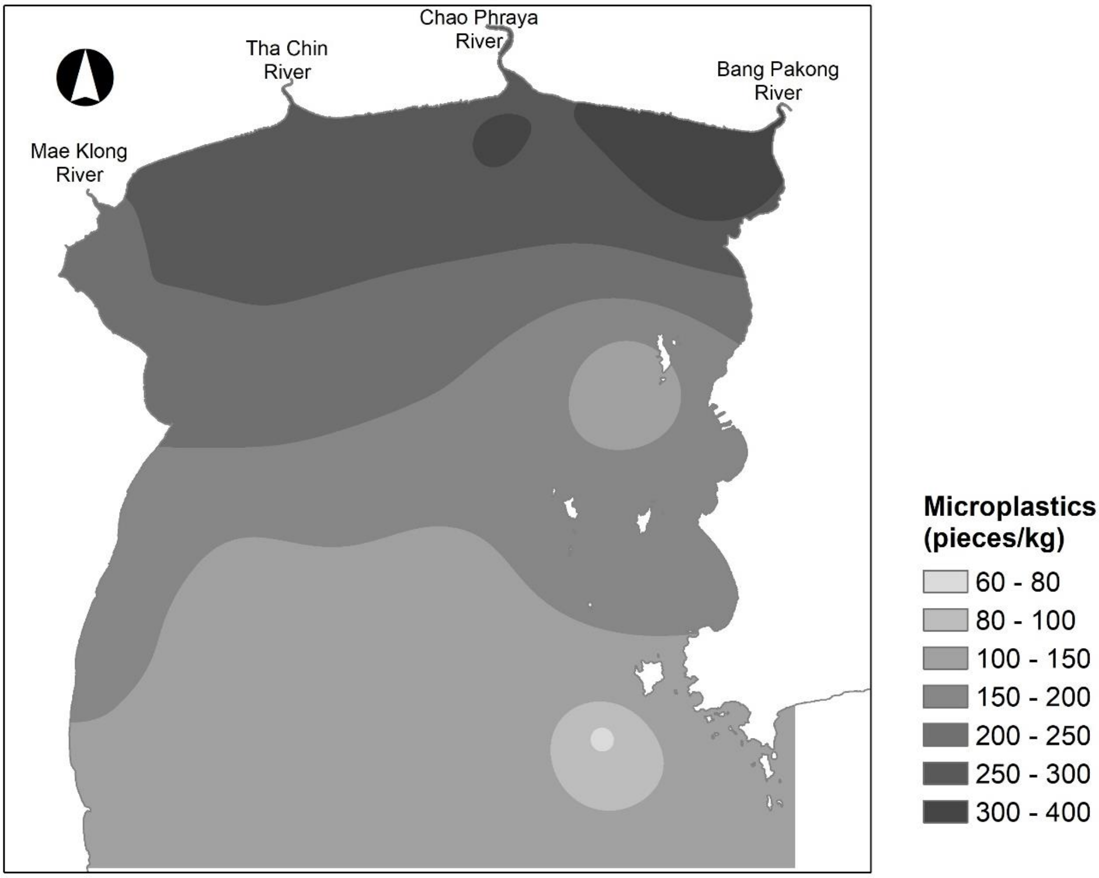

Figure 2 Spatial distribution patterns of MP contamination in surface sediments across the inner Gulf of Thailand.

Table 1 A comparative analysis of MPs in surface sediment of the inner Gulf of Thailand and different study areas

Study area	Sampling year	Sample collection	Density separation	Study size (mm)	Abundance (pieces kg^{-1})	Main polymer
Iceland, Iceland shelf [22]	2011	Multi-cores, 0-1 cm	N/A	0.25-5.0	350	ABS, PVC, PE
China, Pearl River Estuary [23]	2015	Stainless steel shovel, 0-5 cm	NaCl	0.05-5.0	851	PPPE copolymer
Indonesia, Banten Bay [24]	2016	Smith-McIntyre, 0-10 cm	NaCl	<0.1-5.0	267	Cellophane
The northern Bering and Chukchi Seas [25]	2017	Box corer, 0-5 cm	KI	0.1-5.0	22.8	PP, PET, Rayon
Brazil, Guanabara Bay [26]	2017	Van Veen grab, 0-5 cm	NaCl	0.015-5.0	528	PE, PA
The Antarctic coastal [27]	2021	SCUBA divers, Van Veen grab, top layer	NaCl	0.1-5.0	180	PEST, PA
Argentina, the Río de la Plata estuary [28]	2021	Stainless steel tools, superficial, 50 cm, and 100 cm	NaCl	<5.0	547.83	PP, PET
China, Zhelin Bay [29]	2021	Peterson grab, 500 g	$ZnCl_2$	0.02-5.0	2,054.17	Rayon, PP, PS, PE
Chao Phraya River upper estuary [30]	N/A	Van Veen grab, 500 g	NaI	0.05-5.0	91	PP, PE, PS
Chao Phraya River lower estuary [20]	2021	Gravity core, 0-2 cm	NaCl	0.016-5.0	2,634	Epoxy, EVA, PE
Thailand, coastal mangroves in the eastern of the Gulf of Thailand [21]	2022	Clean shovel, 0-5 cm	NaCl	<0.1-5.0	2,213.33	PP, PE
Thailand, the Gulf of Thailand	2004 [11]	Gravity core, 0-2 cm	NaI	0.315-5.0	206.75	PE
	2011 [12]	Box sampler, 0-5 cm	NaCl	0.02-5.0	150.4	Rayon, PES, acrylic, epoxy
	2018 [13]	Smith-McIntyre grab, 0-5 cm	NaCl	0.016-5.0	1,381.91	PP
	2021 (Present study)	Smith-McIntyre grab, 0-1 cm	NaCl	0.016-5.0	196.07	PP, PTFE

Additionally, the COVID–19 pandemic has markedly intensified MP contamination in aquatic environments, driven primarily by increased production, use, and improper disposal of single–use plastic items such as PPE. Among these, disposable face masks, gloves, and face shields have become significant sources of secondary MPs through degradation in terrestrial and aquatic systems [33–34].

A national–scale study in China reported a notable increase in MP concentrations in 77.27% of monitored watersheds for water media and 47.62% for sediment media during the pandemic period, linking this surge to PPE–related waste [35]. The dramatic escalation in the use of single–use plastics due to public health protocols, including lockdowns and mandatory masking, has resulted in an estimated global consumption of more than 129 billion face masks and 65 billion gloves per month during the pandemic [36]. Improperly managed waste from these products, particularly in regions with insufficient solid waste infrastructure, has contributed significantly to the increased input of plastics into freshwater and marine ecosystems [37]. Field studies across Asia and Europe have reported the detection of mask–derived microfibers and polymer fragments in both surface water and sediments, further corroborating the contribution of COVID–19-related debris to MP pollution [38]. Moreover, recent findings suggest that face masks, which are primarily composed of PP and polyester, are capable of releasing thousands of microfibers per day under environmental exposure conditions such as UV radiation and mechanical abrasion, accelerating the formation of MPs in natural settings [39].

Table 2 Spearman’s rank correlation coefficient of the relationships between water depth and each categorized MPs

	Depth (m)	MPs (pieces/kg)	PP (%)	PE (%)	PS (%)	PTFE (%)	PA (%)	16-100 µm (%)	100-300 µm (%)	300-5,000 µm (%)	Red (%)	Blue (%)	Green (%)	Brown (%)	Black (%)	White (%)	Transparent (%)	Pellet (%)	Fragment (%)	Fiber (%)	Film (%)
MPs	-0.758**																				
PP (%)	-0.615*	0.533																			
PE (%)	0.260	-0.084	0.066																		
PS (%)	-0.024	0.167	0.149	-0.148																	
PTFE (%)	0.203	-0.368	-0.747**	-0.393	-0.412																
PA (%)	0.392	-0.132	-0.081	0.456	0.024	-0.175															
16-100 µm (%)	0.038	-0.192	-0.264	-0.173	-0.329	0.363	-0.301														
100-300 µm (%)	0.104	-0.027	0.060	0.142	0.364	-0.198	0.348	-0.940**													
300-5,000 µm (%)	-0.329	0.329	0.517	0.071	-0.168	-0.450	0.302	-0.201	0.027												
Red (%)	-0.342	0.416	0.154	-0.028	-0.277	0.121	0.264	-0.389	0.255	0.361											
Blue (%)	0.081	-0.442	-0.251	-0.325	0.065	0.495	-0.436	-0.135	0.269	-0.497	-0.256										
Green (%)	-0.515	0.620*	0.017	-0.115	-0.370	0.096	-0.324	0.079	-0.288	0.235	0.491	-0.324									
Brown (%)	-0.148	0.323	0.117	-0.207	0.100	0.017	-0.478	0.192	-0.301	0.129	-0.146	0.016	0.195								
Black (%)	-0.165	0.214	-0.319	0.029	0.233	0.143	-0.160	-0.066	0.077	-0.329	0.007	0.135	0.306	-0.240							
White (%)	-0.791**	0.434	0.736**	-0.214	-0.185	-0.313	-0.439	-0.181	0.038	0.322	0.248	0.081	0.332	-0.045	-0.143						
Transparent (%)	0.698**	-0.604*	-0.258	0.338	-0.125	-0.049	0.752**	0.121	0.016	0.013	-0.208	-0.269	-0.559*	-0.552	-0.330	-0.500					
Pellet (%)	0.368	-0.604*	-0.593*	-0.142	-0.514	0.676*	0.085	0.082	0.049	-0.268	0.315	0.304	0.035	-0.529	0.049	-0.148	0.297				
Fragment (%)	0.292	-0.173	-0.440	0.271	0.490	0.140	0.140	-0.165	0.349	-0.470	-0.054	0.114	-0.315	-0.029	0.393	-0.558*	-0.003	0.041			
Fiber (%)	-0.088	0.412	0.258	0.471	0.167	-0.275	0.326	-0.011	-0.110	0.141	-0.020	-0.263	-0.035	0.362	-0.033	-0.225	-0.011	-0.648*	0.058		
Film (%)	-0.159	0.275	0.527	-0.121	0.167	-0.538	0.200	-0.330	0.209	0.738**	-0.094	-0.213	-0.105	0.256	-0.341	0.236	0.033	-0.555*	-0.492	0.209	
Foam (%)	-0.132	-0.071	-0.434	-0.399	-0.006	0.505	-0.551	0.346	-0.341	-0.416	-0.215	0.495	0.358	0.025	0.610*	-0.027	-0.396	0.247	-0.050	-0.198	-0.379

Remark: ** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

Although some regions experienced temporary reductions in MP input due to lower industrial activity or tourism, these declines were generally outweighed by the increase in pandemic–associated plastic waste. This highlights a trend toward long–term accumulation of MPs in the environment if current disposal practices remain unregulated. This investigation revealed a moderate abundance of MPs in the sediment after COVID–19. The amount of MPs accumulated in the sediment did not increase from that before the pandemic. Only contamination in sediment could not clearly indicate that the number of MPs increased in our study area; meanwhile, the raised MPs could be suspended in the water.

2) Characteristics of MPs

The composition and physicochemical characteristics of MPs in the surface sediments of the inner Gulf of Thailand revealed a predominance of polytetrafluoroethylene (PTFE), accounting for 50% of the total MPs identified (Figure 3a). Within this group, 33% of the PTFE particles were in the 16–100 µm size range, and an additional 17% were in the 100–300 µm range. Other detected polymers included PP (32%), PE (9%), PS (6%), and PA (3%), indicating that the diverse origins of plastic pollution are likely related to domestic, industrial, and commercial sources. Overall, the majority of the MPs observed were less than 300 µm in size: 59.95% were 16–100 µm in size, and 37.28% were 100–300 µm in size. Larger MPs in the 300–5,000 µm range represented only a minor fraction (2.37%), with PP contributing 1.95% and PTFE contributing only 0.43% to this size class.

In terms of morphological classification (Figure 3b), fibers were the most prevalent shape, comprising 34% of the total MPs, followed by fragments (24%), pellets (19%), foams (13%), and films (10%). Color distribution analysis revealed that transparent MPs dominated (42%), followed by white (32%), black (15%), and brown (8%) MPs, reflecting a combination of aged plastic debris and recently introduced materials. The shape and appearance of MPs may also provide clues regarding their origin. Fibers, the most dominant MP shape identified in this study (34%), are widely recognized as a common form of MP pollution in marine environments. Previous studies have attributed fibrous MPs primarily to the degradation of synthetic textiles, fishing gear, and packaging materials [40–43]. These fibers are often released into aquatic systems through domestic wastewater effluents, abrasion of clothing during washing, and the breakdown of plastic ropes and nets in marine activities. The prevalence of these fibers in estuarine sediments reflects both their widespread usage and their high dispersal potential because of their light weight and flexible structure.

Notably, PTFE (density 2.17 g cm^{-3}) was detected as the main polymer type in the sediment, although NaCl solution (density 1.2 g cm^{-3}) was used in the extraction process. The experiments presented the capillary force, lyophobicity, and surface tension of water, in addition to the buoyancy force, which enabled 1.63–4.77 mm-PTFE sphere particles to be suspended on the surface of the water [44]. The observation of PTFE in the samples extracted by the NaCl solution indicated not only that the density of the solution can float lower-density plastic particles but also that the surface tension of the solution and the hydrophobicity of the plastics can, although the plastics, such as PTFE, have a higher density than the solution does.

However, PTFE has been detected in a few studies. While PTFE has been detected in surface water, halocline water, and intermediate water of the East Indian Ocean [45], the Arctic deep-see sediment also contains PTFE >500 µm [46]. In our study area, PTFE was detected in the surface water of the inner Gulf of Thailand [9, 47], the water column during the 24-hour tidal cycle in the lower Chao Phraya River estuary [8], the sandy beach sediment [48], and the surface sediment of the inner Gulf of Thailand (this study).

The plastic identification of those studies revealed that the observation of PTFE depended on the number of plastic particles and the particle sampling during chemical identification. Accordingly, PTFE was detected when more than 3900 particles were sampled [47], and all the extracted particles in the samples [8, 45–46, 48] were identified. All-particle identification, however, cannot find PTFE when an Al_2O_3 filter is used in the analysis [13, 20, 46]. While industrial products, as anti-abrasive or protective layers, are considered sources of PTFE in seawater [45], PTFE is selected for a wide range of applications, such as bushings and seals in compressor hydraulic applications, automotive applications, pipe liners, high-temperature wire and cable insulation, nonstick home cookware, and fabric coated with aqueous dispersion [49].

Distribution maps of the plastic composition (Figure 4) reveal a high tendency to detect each type of plastic particle: PTFE in the northern estuary and eastern part, PP in the eastern and western estuaries and center of the gulf, PE in the southwestern part and eastern estuary, PS in the northwestern estuaries and hot spots in the eastern and northern parts, and PA in the southwestern part. Correlation analysis revealed significant relationships between MP characteristics and water depth (Table 2). Strong negative correlations were found between the PP fraction and water level (r_s = –0.615, p = 0.025), white color and water depth (r_s = –0.791, p = 0.001), and between the PP and PTFE fractions (r_s = –0.747, p = 0.003). Additionally, a significantly positive relationship was also observed between PP and white color (r_s = 0.736, p = 0.004). The sedimentation of PP may occur at lower water levels, and its behavior may contrast with that of PTFE.

As white or transparent MPs refer to new plastic [50], the inverse relationships of PPs and white-colored MPs with water depth, in addition to the positive relationships between PPs and white-colored MPs, indicate that new PPs likely accumulated in areas of estuaries where the depth was shallow and/or where the location was near land-based river runoff sources. The vertical transport of low-density plastics (<1.0 g cm^{-3}), PP, PE, and PS in sediment was experimentally regulated by heteroaggregation with the matrix of marine snow [31]. Compared with freshwater, the flocculation of sediment and suspended solids in estuaries enables the settling of PE-MPs at 5–21 times greater velocities in saltwater water [32]. The simulated model revealed that the oscillation of PE and PP in the water column was regulated by density according to biofouling formation and disaggregation [6]. A sediment trap experiment revealed that high fractions of PP and PE at the bottom settled to the bottom water within 24 hours, but these fractions were lower in the surface sediment [20]. In addition, the resuspension of plastic particles during a tidal current can also be investigated in a river estuary [8]. This vertical movement of PP in shallow water is less dynamic because the short settling distance results in rapid accumulation of PP aggregates in the sediment. The low-density plastics (PP, PE, and PS) in deeper water may form aggregates, oscillate in the vertical water column, be horizontally transported, and settle to the sediment; as a result, these plastics may be dispersed and accumulate widely in the sediment.

In contrast, the distribution map of the PA fraction, the positive relationship between PA and transparent MPs ($r_s = 0.752$, $p = 0.003$), and that between transparent MPs and water depth ($r_s = 0.698$, $p = 0.008$) suggest that the other groups of new fragmented plastics did not accumulate in the shallow area of the river estuary. The high-density plastic PA (1.1 g cm^{-3}) has fewer interactions with the environment and settles faster to sediment near marine-based sources.

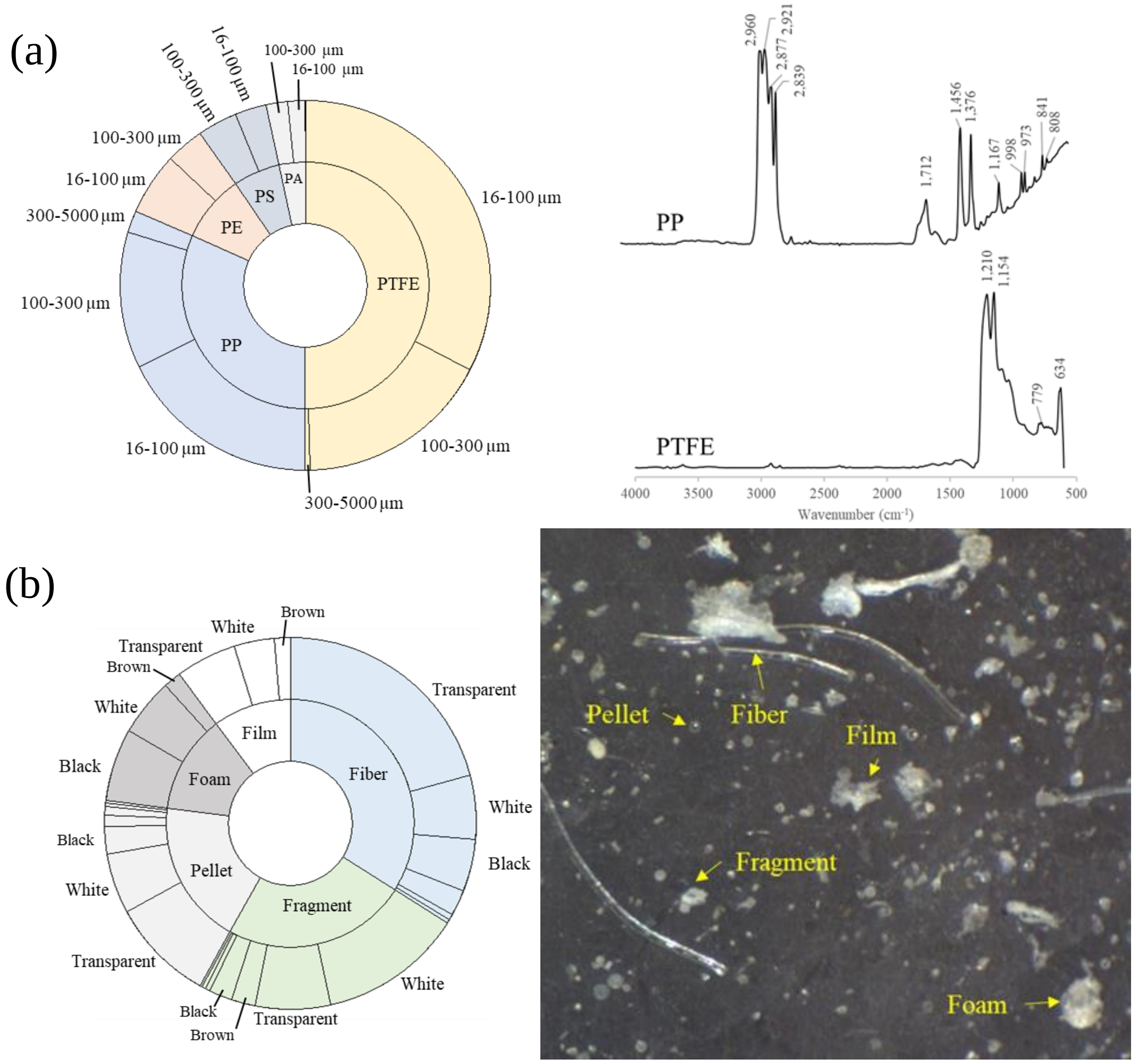

Figure 3 Characteristics of MP detected in surface sediments of the inner Gulf of Thailand including (a) composition of plastic polymer types with associated size classes and (b) composition of MP shapes and colors.

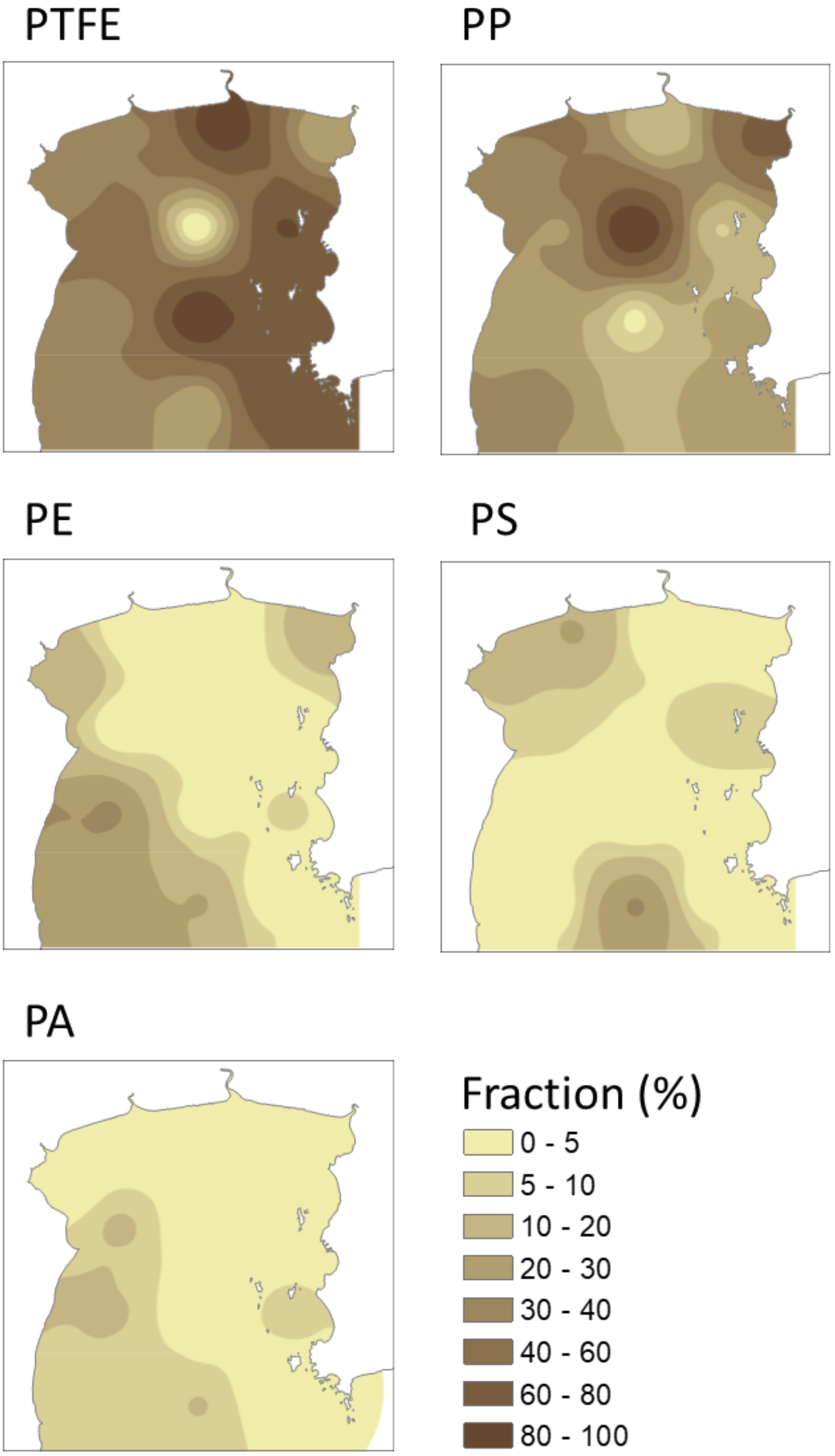

Figure 4 Spatial distribution (%) of polypropylene (PP), polytetrafluoroethylene (PTFE), polyethylene (PE), polystyrene (PS), and polyamide (PA) fractions in surface sediments of the inner Gulf of Thailand.

PTFE (2.1 g cm^{-3}), which can float on water because of its hydrophobicity, capillary force and surface tension [44], may increase its surface wettability and affect plastic settling via aggregation and biofouling. According to the inverse relationship, the behavior of the aggregation and sedimentation of MPs may differ between PP and PTFE. The aggregate formation of floated PP may increase the density of the particles, resulting in their settling to the seabed, although suspension in the water column is also possible because of the buoyancy force and biofouling disaggregation. While the settling of PTFE may be related to its surface wettability, aggregation may enhance the wettability and particle size of PTFE. As a result, the PTFE-aggregate particles, which have a relatively high wettability, may rapidly settle because of their high density. However, the vertical transport and sedimentation of MPs according to polymer type are still unclear, especially in environmental field investigations. Our findings present different sedimentation patterns of MPs on the basis of their plastic polymer–specific properties.

3) Ecological risk assessment

Microplastics are ubiquitously present in the surface sediments of the inner Gulf of Thailand, with contamination levels indicating an overall moderate pollution status. The average C_f for the MPs was 2.72±1.19 (range 1.01–4.86), which falls into the "moderate to considerable" contamination category [51]. In practical terms, C_f values above 1 indicate that the MP concentrations exceed baseline levels; indeed, several northern estuarine sites C_f had values between 3.34 and 4.86, reflecting considerable MP contamination (Figure 5a). The average PRI in the inner Gulf sediments was 95.35 ±133.45, with values ranging from near zero (0.11) to 389.86 at certain sites. High-risk levels of the polymer (PRI=100–1,000) were observed in northwestern estuaries, the middle of the eastern coast, and the southern part of the gulf (Figure 5b). Despite the moderate to high MP loads and polymer risk, the E_r for MPs in inner Gulf sediments is generally low. The mean E_r was 0.87 ± 0.83 (range 0.00–2.56), indicating a low potential eco–risk level, which tended to be higher in the northwestern estuaries and southern part of the Gulf (Figure 5c). The risk factors for MPs include two main components: the abundance of contaminated MPs and the chemical composition

Spatially, MP contamination in the inner Gulf was heterogeneous, with the highest sedimentary MP abundances (and C_f values) observed in the upper Gulf, especially in the northwestern estuaries (Figure 5a). These areas receive substantial urban and riverine runoff from the Bangkok metropolitan region and the Bang Pakong communities, which likely deliver large quantities of plastic debris. These northern estuaries, which are fed by major rivers (e.g., Bang Pakong and Chao Phraya), appear to act as MP accumulation zones. Estuarine environments are known to facilitate the deposition of suspended particles via flocculation [52] and sedimentation processes [20]. Moreover, the inner Gulf's semi–enclosed nature and low hydrodynamic energy likely promote the retention of MPs in sediments, concentrating pollution near river mouths [13]. In contrast, some central and eastern coastal sites presented lower C_f values (below 3), indicating only moderate contamination. Notably, even the least contaminated sites had $C_f > 1$, underscoring that MPs are pervasive throughout the inner Gulf sedimentary environment.

The spatial pattern with northern estuaries as contamination hotspots is consistent with the inner Gulf acting as a sink for land–based plastics. The inner Gulf of Thailand sediments averaged 1,381.79 MP pieces kg^{-1} in a recent survey [13], and peaks in the Tha Chin River estuary were reported, mirroring our finding that river outflows drive localized MP accumulation. These patterns align with global observations that sheltered coastal zones near population centers tend to accumulate higher MP concentrations. Similar C_f ranges have been reported in other coastal regions with human influence; for example, urban estuarine sediments in South Asia often have C_f in the range of 1–5 (moderate–contamination) [53], which is comparable to our observations. Importantly, however, high MP abundance alone does not directly equate to high ecological risk, as discussed below.

The relationships among the C_f, PRI, and E_r are presented in Table 3. A weak nonsignificant relationship of C_f with PRI and E_r was observed. The significant relationships between E_r –PRI (r_s = 0.817, p = 0.001), E_r –the fraction of PS (r_s = 0.670, p = 0.012), and PRI–the fraction of PS (r_s = 0.920, p = 0.000) indicated that the eco–risk of MPs was more likely to be regulated by plastic type than by abundance. For example, no eco–risk factor for MPs (E_r =0.00) was possible when the toxic response factor was zero (T_r=0) because only PP (polymer hazard ranking score, S_n=1) and PTFE (not classified in hazard categories of chemical substances, S_n =0) were detected in the sediment samples, whereas the risk increased when the composition of PS (S_n =1,628) was observed.

To better gauge the role of polymer composition in eco-risk evaluation, we applied a PRI, which incorporates both MP abundance and the hazard potential of the polymer types present [51]. The average PRI in the inner Gulf sediments was 95.35±133.45, with values ranging from near zero (0.11) to 389.86 at certain sites. This range corresponds to low to moderate risk on the polymer–specific risk scale [13]. Most locations fell below PRI 150 (indicative of low risk), and the overall mean PRI (~95) suggests that, on balance, the inner Gulf has moderate polymer hazard loading. However, several hotspot areas presented markedly elevated polymer risk. Notably, the northwestern estuaries, the mid–eastern coastline, and parts of the southern inner Gulf all presented PRI values in the 100–1,000 range (Figure 5b). These PRI levels reach Category III (hazardous) territories [13, 51], denoting considerable to high polymer–specific risk. In these areas, although the MP counts were not the highest, the types of presented plastics are of greater concern. For example, one of the northwestern estuarine sites had a PRI approaching 389.86, substantially higher than the Gulf average, which is a clear indication that certain polymers impart greater ecological risk potential than other regions.

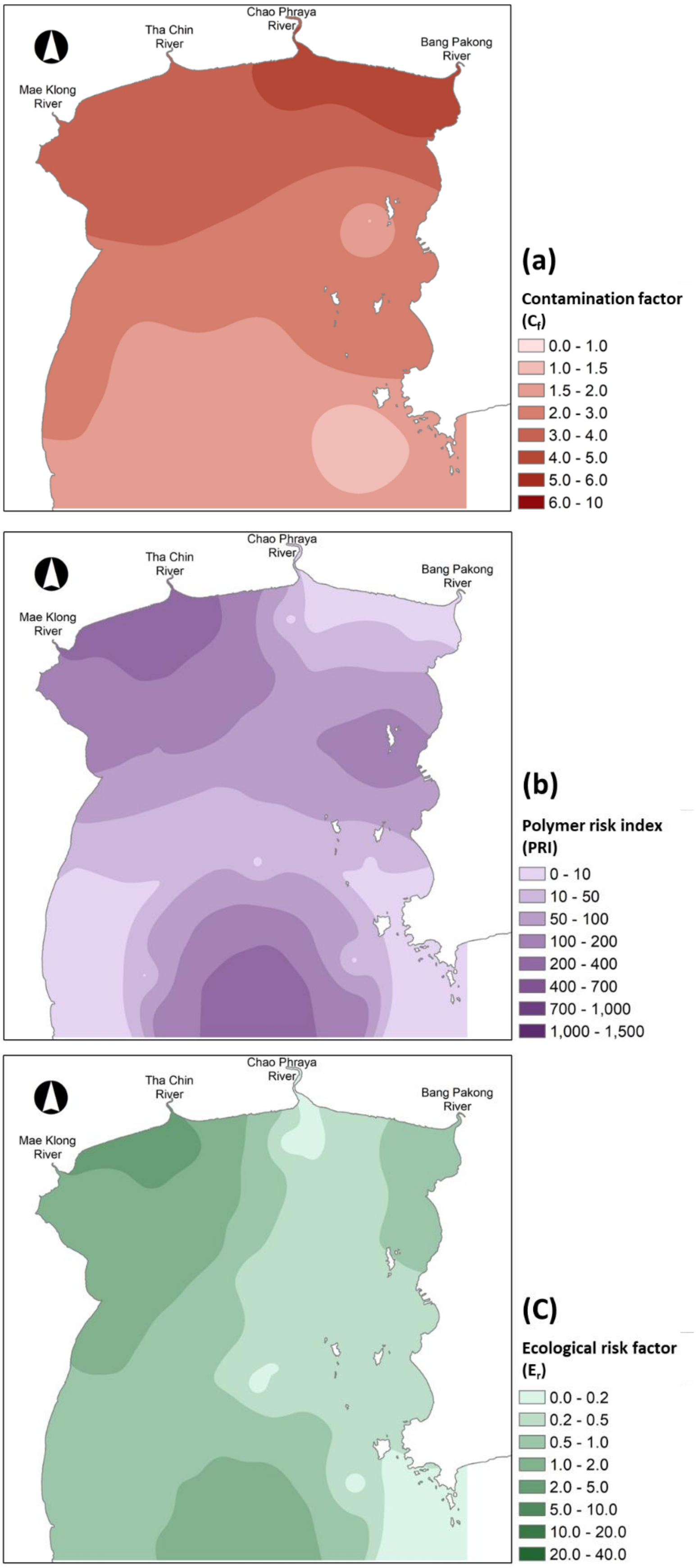

Figure 5 Assessment of MP pollution in surface sediments of the inner Gulf of Thailand, represented by: (a) contamination factor, (b) polymer risk index, and (c) ecological risk factor.

Table 3 Spearman's rank correlation coefficient of the relationships between index of eco-risk and each categorized MPs

Correlations	Contamination factor (C_f)	Polymer risk index (PRI)	Toxic response factor (T_r)	Eco-risk factor (E_r)
Total MPs	1.000**	0.088	0.140	0.360
PP (%)	0.533	0.258	0.239	0.410
PE (%)	-0.084	0.133	0.454	0.402
PS (%)	0.167	0.920**	0.718**	0.670*
PTFE (%)	-0.368	-0.549	-0.523	-0.594*
PA (%)	-0.132	0.254	0.486	0.423
16-100 um (%)	-0.192	-0.429	-0.454	-0.487
100-300 um (%)	-0.027	0.467	0.470	0.421
300-5000 um (%)	0.329	-0.034	0.007	0.175
Red (%)	0.416	-0.282	-0.134	-0.027
Blue (%)	-0.442	0.000	-0.083	-0.140
Green (%)	0.620*	-0.524	-0.442	-0.284
Brown (%)	0.323	0.056	-0.119	-0.004
Black (%)	0.214	0.005	0.121	0.171
White (%)	0.434	-0.192	-0.228	-0.085
Transparent (%)	-0.604*	0.066	0.168	0.003
Pellet (%)	-0.604*	-0.577*	-0.528	-0.660*
Fragment (%)	-0.173	0.465	0.466	0.300
Fiber (%)	0.412	0.346	0.591*	0.696**
Film (%)	0.275	0.275	0.179	0.338
Foam (%)	-0.071	-0.269	-0.289	-0.267
C_f		0.088	0.140	0.360
PRI			0.889**	0.817**
T_r				0.950**

Remark: **. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

Consequently, the spatial pattern of the E_r reflects the distribution of PRI more than it mirrors the raw MP abundance. As a Spearman rank correlation analysis revealed that E_r was strongly positively correlated with PRI ($r_s = 0.817$, $p = 0.001$), we found that E_r was highest in the northwestern estuaries and southern gulf, corresponding to the zones with elevated PRI. In contrast, if abundance alone was driving risk, one would expect a closer correspondence between E_r and C_f; however, those correlations were weaker (data presented in Table 3), reinforcing that it is the type of plastic, more than the quantity, that governs E_r in this system. In support of this, we observed a significant correlation between E_r and the PS fraction in the MP assemblage at each site ($r_s = 0.670$, $p = 0.012$). Similarly, PRI was even more strongly correlated with the PS fraction ($r_s = 0.920$, $p < 0.001$). Together, these statistical relationships demonstrate that sites with higher proportions of PS tend to exhibit disproportionately higher risk indices. In other words, the polymer composition rather than the sheer MP count is the key regulator of ecological risk in inner gulf sediments.

This finding is in agreement with the emerging consensus in the literature; recent studies have noted that polymer type often poses a greater risk than MP abundance alone. For example, a risk assessment in South African coastal waters similarly revealed that the chemical nature of MPs (i.e., polymer identity) is more consequential for ecological risk than the particle concentration [13]. Our results empirically reinforce this principle in a Southeast Asian context.

The influence of polymer type is best exemplified by the role of PS in our study. PS was not the most abundant polymer across all samples, yet where it occurred at higher fractions, the hazard indices spiked. PS is known to be more chemically hazardous than many other common polymers owing to its toxic monomer (styrene) and associated additives. It ranks among the top polymer types of environmental concern, as global hazard assessments have shown; for example, styrene plastics (along with PVC and certain polyurethanes) are ranked with high hazard scores in terms of their potential ecotoxicological impact [13]. In contrast, PP is the dominant polymer in many of our samples, is generally considered to have low toxicity and is often found to pose minimal chemical risk [13, 53]. Compared with polymers such as PS or PVC, PP and other polyolefins (such as PE) tend to sorb fewer toxic substances and leach fewer toxic monomers [13].

This disparity is reflected in our risk calculations: sediment sites composed mainly of PP (and similarly inert polymers such as PTFE) yielded negligible E_r values. These sites, despite containing MPs, likely present little chemical threat to benthic organisms beyond physical interference or ingestion risk. PTFE, in particular, is an inert fluoropolymer whose presence in the environment has not been associated with acute toxicological effects; hence, it is excluded from hazard rankings [19]. Our data underscore that an abundance of low–hazard polymers can dilute the overall risk, whereas even a modest amount of high–hazard polymers can substantially increase the risk index.

This numerical index E_r is adapted from Håkanson's approach (originally developed for heavy metals) to account for the toxicity of plastic polymers [13]. An E_r value less than 40 is considered low risk in conventional assessments, and our values are two orders of magnitude lower, highlighting that most sites pose minimal ecological risk from MPs when considering polymer toxicity. In fact, at one extreme end of our observations, E_r was essentially zero at sites where only PP and PTFE were detected. This result is unsurprising given that PTFE is a chemically inert polymer not classified into standard hazard categories, and PP is among the least hazardous plastic types [13, 53]. In the absence of any polymer with a known toxicological hazard (i.e., when the "toxic response factor" T_r for all present polymers = 0), the ecological risk factor by definition decreases to zero. Thus, the presence of MPs alone does not guarantee ecological risk, and the polymer composition is crucial.

An ecological risk assessment for the contamination of MPs in surface sediment of the inner Gulf of Thailand in 2021 (this study) revealed a low potential ecological risk level (E_r = 0.87±0.83, range 0.00–2.56); however, moderate contamination (C_f = 2.72±1.19, range 1.01–4.86) with a moderate risk of plastic polymers (PRI = 95.35±133.45, range 0.11–389.86) was found. As the sampling was conducted after COVID-19, the eco-risk was re-evaluated to determine the effects of the pandemic on sediment contamination, polymer composition, and the eco-risk factors associated with MPs. The sedimental risk assessment, which included the contamination of MPs and heavy metals, revealed low potential ecological risk in 2018, with high variation in the risk index of MPs: C_f = 0.67–167.47, PRI = 3.00–731.56, and E_r = 0.33–70.22 [13]. Since the beginning of the COVID-19 pandemic in 2021, contamination and eco-risk levels in the sediment have not significantly increased since 2018. However, contamination in the water was not included in this evaluation. Affected by plastic product utilization without management during the pandemic, higher contamination and eco-risk might have occurred in the water, which could be transported to other areas where ocean water circulation is associated.

Overall, the inner Gulf of Thailand can be characterized as being moderately contaminated with MPs but with localized high–risk polymer hotspots. This pattern suggests that while general plastic pollution control (reducing total inputs) is important, special attention should be given to the types of plastics entering this marine system. Management efforts may need to prioritize sources of high–hazard polymers, such as PS foam waste, which was evidently linked to elevated risk in our study. Our results contribute to a growing body of evidence that polymer–specific risk assessment is essential for understanding and mitigating the ecological impacts of MP pollution [13, 19]. By interpreting MP contamination in light of polymer composition, we obtain a more nuanced picture of environmental risk: the benthic ecology of the inner Gulf of Thailand currently faces a low overall risk from MPs, but this risk could escalate if the polymer profile shifts toward more toxic materials. In conclusion, comprehensive MP pollution management in a region should not only aim to reduce the quantity of plastics released but also consider the quality (i.e., polymer type) of plastics, as the latter can disproportionately influence ecological outcomes.

Conclusions

This study investigated the abundance, physicochemical characteristics, and ecological risk of MPs in surface sediments of the inner Gulf of Thailand via field sampling conducted in April 2021, following the COVID–19 pandemic. The results revealed the widespread presence of MPs, with an average concentration of 196.07±85.60 pieces kg^{-1}, ranging from 73.08 to 351.19 pieces kg^{-1}. Higher MP abundances were consistently recorded in estuarine zones, particularly near river mouths, where hydrodynamic conditions and anthropogenic activities converge to increase MP accumulation. A significant inverse relationship between MP abundance and seawater depth (r_s = –0.758, $p < 0.05$) suggested that shallower regions near estuaries act as key depositional zones.

In terms of polymer composition, PTFE was the most prevalent polymer, comprising 50% of all identified particles, followed by PP at 30%. The inverse correlations between PP abundance and both seawater depth (r_s = –0.615, $p < 0.05$) and the PTFE proportion (r_s = –0.747, $p < 0.01$) indicate that polymer–specific density plays a critical role in MP transport and deposition processes. Lighter polymers such as PP are more likely to remain suspended or mobile within the water column, whereas denser materials such as PTFE tend to settle more efficiently to sediment.

Assessment of the pollution status revealed that the C_f of the MPs was moderate, with an average value of 2.72±1.19, whereas the PRI, reflecting the hazard potential of the identified polymers, was 95.35±133.45, also indicating moderate risk. Both indices were notably higher in estuarine zones, further confirming these areas as pollution hotspots. Despite this, E_r, which integrates both abundance and polymer hazard profiles, remained low across all the sites (range 0.00–2.56). While the MPs that were moderately present in the sediment and estuarine zones presented elevated contamination and polymer risk, the ecological risk to benthic organisms was minimal at the current levels. These findings suggest that the sedimentation of MPs is a complex, time–dependent process influenced not only by input sources and local hydrodynamics but also by polymer–specific properties such as density and biofouling potential. The presence of MPs with low ecological risk in deeper sediments also implies long–term persistence and potential resuspension under dynamic conditions. Therefore, continued monitoring is recommended to track shifts in MP composition and concentration, especially in light of changing plastic usage patterns and hydrological variability in the postpandemic context.

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