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Characteristics and potential human health risks of microplastics for commercial shrimp *Litopenaeus vannamei* from South Yellow Sea Mudflat

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ABSTRACT

Microplastics (MPs) ingestion through shrimp consumption pose potential health risks to humans. This study examined characteristics and risks of MPs in *Litopenaeus vannamei* collected from South Yellow Sea mudflat. MPs abundance in total soft tissues, pure soft tissues, midgut and hindgut ranged from 5.9 to 8.32, 1.77 to 2.50, 4.13 to 5.82 items/individual, and 0.36 to 0.51, 0.11 to 0.15, 61 to 83.2 items/g. The predominant shape, size, color, and polymer types were fiber, 0.001–0.25 mm, blue, and polypropylene (PP), with corresponding percentages were 42.31%–55.45%, 40.51%–60.22%, 24.71%–36.96%, and 34.11%–42.23%. MPs abundance in shrimps from marine estuaries was significantly higher than in pure mudflat. Annual dietary intake (ADI) and estimated dietary intake (EDI) of MPs from pure soft tissues declined substantially. Polymer risk index (PRI) of total soft tissues was significantly higher than that of pure soft tissues, indicating a considerable reduction in potential human health risks when midgut and hindgut are excluded from consumption. This study provides first characterization and risks of MPs for *Litopenaeus vannamei* from South Yellow Sea mudflat, potential health risks from consuming total or pure soft tissues of shrimp were comprehensively assessed to improve understanding of MP exposure pathways and plan strategies.

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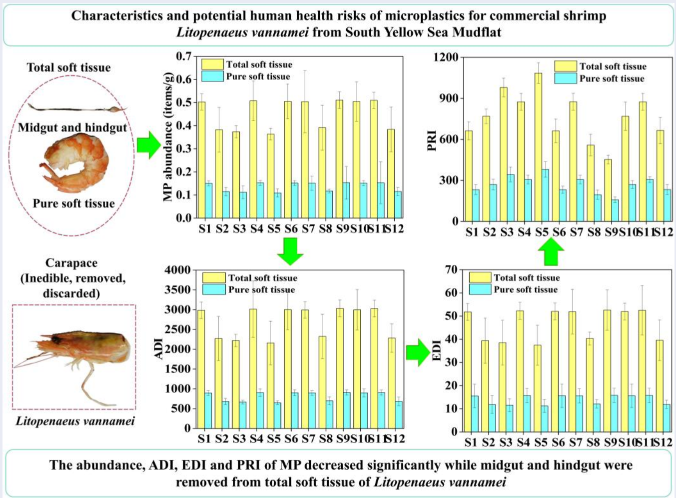
GRAPHICAL ABSTRACT



1. Introduction

Microplastics (MPs), defined as synthetic polymer particles $\leq$ 5 mm in size, have gained significant global attention recently (Aslam et al. 2023; Mbachu et al. 2023; Enyoh and Wang 2024; Fagiano et al. 2024). Primary MPs (deliberately produced) and secondary MPs (generated through fragmentation of macroplastic waste) predominantly arise from human-driven processes, including the washing of synthetic fabrics, mechanical erosion of vehicle tires, surface water runoff, atmospheric deposition, effluent discharge, deterioration of agrochemical films, groundwater, sediment, salt, etc. (Davidson et al. 2022; Khant and Kim 2022; Suteja et al. 2025), and, in particular, the widespread introduction of personal protective equipment (PPE) in recent years (Lee and Kim 2022; Sills and Adyel 2020; Wenclawiak et al. 2025). These MP particles disperse into multiple environmental matrices. Next, MP undergo complex multi-media environmental transports, involving dynamic cycling across aquatic (advection, turbulent diffusion, and settling/resuspension), atmospheric (long-range advection, and dry/wet deposition), and terrestrial (leaching and erosion) compartments, facilitated by biological vectors and cross-interface exchanges, and leading to pervasive global dispersion (Enyoh and Wang 2024; Hoang 2024; Zhang et al. 2024). Thus, these plastics have been detected across aquatic, atmospheric, and terrestrial environments, with particularly frequent reports in surface and marine waters (Maghsodian et al. 2022; Hoang 2024; la Cecilia et al. 2024). The abundance of MPs in aquatic environments is expected to rise due to the continued release of plastic waste and its degradation (Cui et al. 2023; Shen et al. 2023; Zhang et al. 2024). Therefore, the extensive dispersion of MPs is anticipated to impose detrimental impacts on various aquatic organisms.

These plastics are readily ingested by aquatic organisms, including shellfish, fish, shrimp, and crabs, due to their size similarity to natural prey items of marine species

(Huang et al. 2024; Khoshmanesh et al. 2023; Tran et al. 2024). Such ingestion may result in physical damage, including inflammation, metabolic disruption, potentially fatal responses, and toxic effects from chemical additives and adsorbed contaminants on MPs (Nan et al. 2020; Ogunola et al. 2022). Moreover, due to their hydrophobic nature, MPs can adsorb other environmental pollutants, such as persistent organic pollutants, heavy metals, and pathogens, thus acting as vectors for disseminating these hazardous substances (Pisani et al. 2022). This vector effect has significant scientific interest in characterizing MPs within aquatic species. In previous studies, MP was found in aquatic organisms such as fish, squid, scallops, lobster, crabs, shrimp, and mussels, etc., which are usually consumed by humans as delicious food (Seta et al. 2023; Timilsina et al. 2023). Considering MP from aquatic organisms may be transferred to humans via the food chain, their widespread occurrence has raised significant concerns regarding both ecological integrity and public health.

Shrimp are particularly vulnerable to MP contamination due to their benthic scavenging habits and complex gastrointestinal structures, which facilitate the accumulation of ingested particles (Yin et al. 2022; Zhang et al. 2023). As a widely consumed protein source, shrimp can ingest MPs directly from the environment or indirectly through contaminated prey such as zooplankton. MPs have been detected in multiple shrimp species, including *Crangon crangon*, *Penaeus semisulcatus*, *Penaeus monodon,* and *Metapenaeus monocerous* (Abbasi et al. 2018; Yoon et al. 2022; dos Anjos Guimarães et al. 2023). However, very few studies have addressed MP contamination in the commercially significant shrimp species *Litopenaeus vannamei*, which is widely consumed in China. Ingested MPs have been shown to affect shrimp physiology, impair growth and reproduction, and accumulate in the digestive tract, potentially altering cellular processes. Moreover, as most commercially harvested and farmed shrimp are consumed by humans, accumulated MPs may be transferred to the human body through trophic transfer within the food chain (Ogunola et al. 2022). There have been studies reporting that MP posed potential health risks to human by evaluating estimated dietary intake (EDI) of shrimp with MP (Choong et al. 2021; Pisani et al. 2022; Mercy and Alam 2024), however, different MP polymers have different hazard scores and toxic effects to biota (Lithner et al. 2011), polymer risk indices should be more appropriate for assessing potential human health risk of MP. In short, shrimp, which serve as both commercially harvested species and prey for higher trophic organisms, play a pivotal role in the trophic transfer of MPs across different ecological levels (Fernández Severini et al. 2020; Jaafar et al. 2021). However, comprehensive data on MP characteristics in shrimp and their potential health role remain insufficient and poorly understood.

South Yellow Sea Mudflat, which is located in the coastal region of Lixiahe Plain in Jiangsu Province, is an important breeding base for commercial shrimp *Litopenaeus vannamei* in China (Tang et al. 2022). Lixiahe Plain, a low-lying alluvial plain of the Huaihe River characterized by an extensive network of waterways, receives pollutant-laden runoff from various rivers that ultimately discharge into the South Yellow Sea Mudflat. Previous studies have confirmed the presence of MPs in both the water and sediment of this coastal region (Guo et al. 2024). Moreover, MPs can be ingested and bioaccumulated in *Litopenaeus vannamei*, a commercially significant aquaculture species widely cultivated in the South Yellow Sea Mudflat. These shrimp, valued for their high nutritional protein content, are a common dietary component for humans (Fagiano et al. 2024). Therefore, MPs may be transferred and accumulated in the human body through trophic pathways, potentially posing health risks via shrimp consumption (Wu et al. 2020). However, the specific characteristics and associated health risks of MPs in *L. vannamei* from this region remain poorly understood.

In this study, the characteristics and potential risks of MP from commercial shrimp *Litopenaeus vannamei* along the South Yellow Sea Mudflat were identified and assessed. First, the abundance, size, shape, color, and polymer of MP from shrimps from twelve sampling sites along the South Yellow Sea Mudflat were identified. Second, the potential health risks associated with MP exposure through the consumption of different shrimp tissues were systematically evaluated based on dietary intake and polymer risk indices. This study presents the first investigation into the MP characteristics and associated human health risks in *Litopenaeus vannamei* from the South Yellow Sea Mudflat, providing significant understanding for MP management in shrimp. Furthermore, possible human health risks from consuming total or pure soft tissues of shrimp were comprehensively assessed to improve understanding of MP exposure pathways and plan strategies for reducing associated health risks.

2. Methods and materials

2.1. Sampling and treatment

Commercial shrimp (*Litopenaeus vannamei*) were purchased from shrimp culture ponds along the South Yellow Sea Mudflat (Figure S1). Approximately 10 individual shrimp ($n = 10$) were collected from each sampling site for analysis. These shrimps were then dissected, and the carapace was removed. Pure soft tissue, midgut, and hindgut were separated from the total soft abdominal tissue of each shrimp. Wet weights of the total soft tissue, pure soft tissue, midgut, and hindgut were recorded. Sampling sites were categorized based on their proximity to marine estuaries: sites S1, S4, S6, S7, S9, S10, and S11, which were adjacent to river estuaries, were classified as Group I, while sites S2, S3, S5, S8, and S12, which were located on pure mudflat areas further from the estuaries, were classified as Group II.

2.2. MP extraction, observation, and identification for shrimps

The soft tissues of shrimps were digested using 10% potassium hydroxide solution, and the digestion solution was filtered using a filter membrane of glass fiber (Whatman, GF/B, 1.0 μm) for MP extraction. The MP on glass microfiber membrane was dried in an oven (50 °C for 24 h) and was observed using a stereomicroscope (Nikon, Tokyo, Japan). The MP polymer was identified through Fourier-transform infrared spectroscopy (FTIR). Given that approximately 50.00% of detected MPs are typically selected for FTIR analysis in previous studies (Ory et al. 2017; Ding et al. 2019; Lam et al. 2023), a total of 613 MP items (approximately 70.00% of the detected MP; the sizes of most MP items were concentrated on 0.001–0.25 mm) from shrimps across twelve sampling sites were analyzed using FTIR in this study. The detailed procedures for MP extraction, observation, and polymer identification were listed in the supporting information (Lam et al. 2023; Ory et al. 2017; Ding et al. 2019, 2020). The units of MP abundance were items/individual and items/g, respectively. The shapes of MP were categorized as fiber, foam, fragment, granule, film, and pellet according to the key geometric form parameters, including aspect ratio, roundness, regularity index, etc., while aspect ratio of fiber ≥ 3, $1 <$ aspect ratio of fragment < 3, and roundness of fragment < 0.7, $0.9 <$ aspect ratio of granule < 1.1 and roundness of granule > 0.85, porosity of film $< 5\%$ and thickness/length < 0.01, porosity of foam $> 60\%$, sphericity of pellet > 0.95 and surface roughness $< 0.5\,\mu$m, respectively (GESAMP 2019). MP sizes were classified into the following ranges: 0.001–0.25 mm, 0.25–0.5 mm, 0.5–1 mm, 1–2 mm, 2–3 mm, and 3–5 mm according to key parameters including maximum length, maximum diameter, maximum ferret diameter, minimum ferret diameter, etc. The colors of detected MP were recorded as white, orange, black, red, blue, green, transparent, and yellow.

2.3. MP risk assessment for human health

Potential human health risks of MP were evaluated by annual dietary intake (ADI), EDI, and polymer risk index (PRI) (Lam et al. 2023), and ADI, EDI, and PRI of MP were calculated as follows:

$$\mathrm{ADI} = \mathrm{MPA} \times \mathrm{ASC}$$
$$\mathrm{EDI} = \mathrm{ADI}/\mathrm{AAW}$$
$$\mathrm{PRI} = \sum (\mathrm{P_n} \times \mathrm{S_n})$$

Here, ADI is expressed in items/capita/year. MPA represents MP abundance (items/kg) in shrimp, and ASC denotes the annual shrimp consumption of 5.94 kg/capita/year according to data from the Food and Agriculture Organization (FAO , 2023). EDI (items/kg/year) is calculated by dividing ADI by the average adult weight (AAW), which is considered to be 57.7 kg/capita (Lam et al. 2023). In the PRI equation, Pn represents the polymer percentage of MP detected in shrimp, and Sn indicates the hazard score for each polymer type (Lithner et al. 2011), while MP polymers with hazard scores, including polypropylene (PP, hazard score: 1), polyethylene (PE, hazard score: 11), polystyrene (PS, hazard score: 30), polyethylene terephthalate (PET, hazard score: 4), and polyvinyl chloride (PVC, hazard score: 10551), polyacrylonitrile (PAN, hazard score: 11521), polymethyl methacrylate (PMMA, hazard score: 1021), polyacrylic acid (PAA, hazard score: 230), and polyamide (PA, hazard score: 47) as shown in Table 1, were considered and adopted for calculating PRI. All PRI values and potential human health risk levels are listed in Table S1.

2.4. Quality assurance and control

All experimental procedures were conducted in a dust-free, sealed laboratory with constant pressure and temperature to prevent airborne MP contamination during sample pretreatment. Control experiments were performed: a wet filter membrane was placed on the laboratory bench to monitor airborne MP contamination during sample handling; particles on the control membranes were examined using a stereomicroscope and FTIR. No MPs were detected on these membranes. Furthermore, blank tests using the

Table 1. Detailed information for MP polymers identified in shrimp *Litopenaeus vannamei* from South Yellow sea Mudflat.

	Polymer	Abbreviation	Monomer	Score (Lithner et al. 2011)
1	Polyethylene	PE	Ethylene	11
2	Polypropylene	PP	Propylene	1
3	Polystyrene	PS	Styrene	30
4	Polyethylene terephthalate	PET	Ethanediol	4
5	Polyvinyl chloride	PVC	Vinyl chloride	10551
6	Polyacrylonitrile	PAN	Acrylonitrile	11521
7	Polymethyl methacrylate	PMMA	Methyl methacrylate	1021
8	Polyacrylic acid	PAA	Acrylic acid	230
9	Polyamide	PA	Adipic acid	47
10	Chlorinated polyethylene	CPE	Ethylene	–
11	Polyvinylidene fluoride	PVDF	Vinylidene fluoride	–
12	Rayon	–	–	–

same digestion protocol (excluding shrimp tissues) were performed to examine procedural contamination, with no MP detected. Therefore, blank correction was not required in this study. All shrimp samples were stored in aluminum foil bags to reduce external MP exposure. Laboratory tools (glassware, tweezers, and scalpels) were wrapped in aluminum foil (Su et al. 2020), and all solutions were filtered using a glass micro-fiber membrane (Whatman, GF/B, 1.0 μm). Laboratory personnel wore cotton lab coats, nitrile gloves, and protective masks throughout the experimental procedures.

2.5. Statistical analysis

All measurements were performed in triplicate, and the results were averaged. Standard deviations (SDs) were calculated to assess the variability within each sample. The differences in MP abundance among total soft tissue, pure soft tissue, midgut, and hindgut of shrimps were analyzed by the Kruskal-Wallis and Dunn tests. Mann–Whitney tests were applied to evaluate differences in MP abundance between shrimp samples from Group I and Group II; differences in ADI and EDI values between total and pure soft tissues; ADI and EDI values between groups; and PRI values between total and pure soft tissues. All Kruskal–Wallis, Dunn, and Mann–Whitney tests were performed using IBM SPSS Statistics.

3. Results

3.1. MP abundance from shrimp

Figures 1 and S2 illustrate that MP were detected in *Litopenaeus vannamei* from 12 sampling sites along the South Yellow Sea Mudflat. The MP abundance across the total soft tissues, pure soft tissues, midgut, and hindgut of the shrimps varied between 5.9 and 8.32, 1.77 and 2.50, 4.13 and 5.82 items/individual, and 0.36 and 0.51, 0.11, and 0.15 61 83.2 items/gram, respectively. These findings indicate a significantly higher MP abundance in the midgut and hindgut than in other tissue types. As shown in Tables S2 and S3, the p values of Kruskal–Wallis tests and Dunn tests were all lower than .01, which further confirmed the significant differences in MP abundance between the total soft tissue, pure soft tissue, midgut, and hindgut, emphasizing that the midgut and

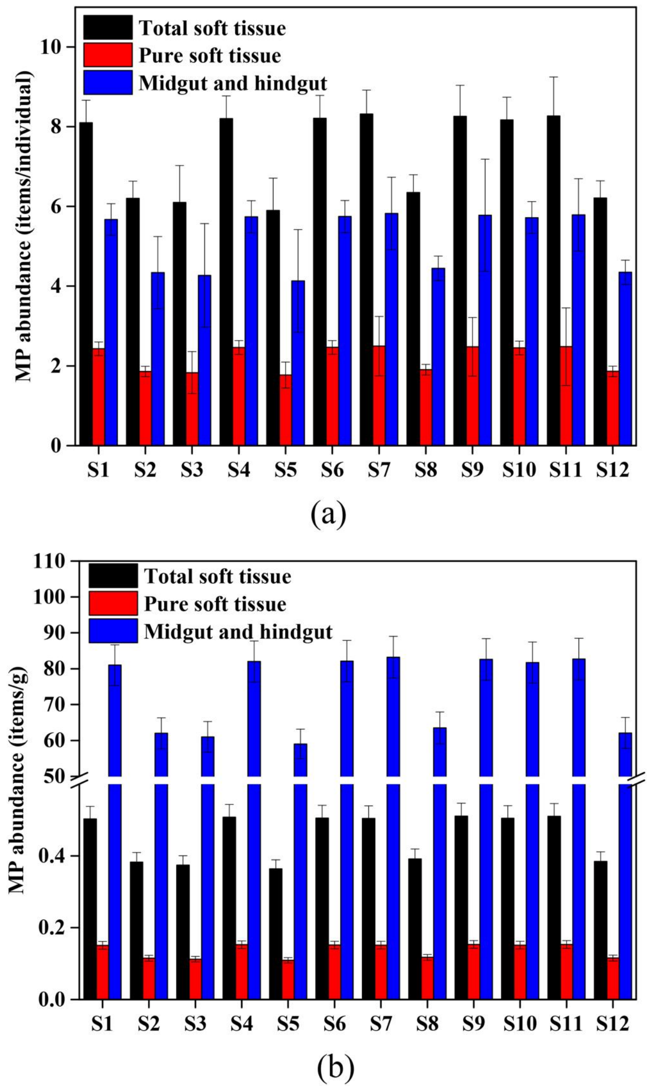


Figure 1. MP abundance for shrimp ($n = 10$ for each sampling site), (a) units: items/individual; (b) units: items/g.

hindgut contained higher MP levels than the total and pure soft tissues. The results also indicated that MP intake via consumption of different shrimp tissues varied significantly. MP intake from pure soft tissues, excluding the midgut and hindgut, was substantially lower than that of total soft tissues, including pure soft tissues, midgut, and hindgut.

Among the sampling sites, the MP abundance of different soft tissues for shrimps from Group I, including S1, S4, S6, S7, S9, S10, S11, seemed to be higher than that of Group II, including S2, S3, S5, S8, and S12 (Figure 1). The results were confirmed using Mann–Whitney tests to compare MP abundance between sampling Group I and Group II. The p values from the Mann–Whitney tests were below .01, as presented in Table S4.

3.2. MP characteristics in shrimps

Figure 2a shows that various MP shapes were identified in the shrimps, including fragments, fibers, films, granules, foams, and pellets. Among these, fibers represented the largest proportion, accounting for 42.31% to 55.45% of the identified MP shapes, followed by fragments (25.00%–30.95%), films (7.14%–15.71%), pellets (3.97%–11.69%), granules (0.95%–8.14%), and foams (0.95%–2.78%).

Figure 2b shows that the MP sizes were categorized as 0.001–0.25 mm, 0.25–0.5 mm, 0.5–1 mm, 1–2 mm, 2–3 mm, and 3–5 mm. The sizes of MP from shrimps among different sampling sites ranged from 0.0011 to 4.73 mm, while the average size of MP was 0.19 mm. As shown in Figure 2b, the maximum proportion of MP size was in the range of 0.001–0.25 mm (40.51%–60.22%), followed by size ranges of 0.25–0.5 mm (19.35%–32.91%), 0.5–1 mm (7.53%–13.92%), 1–2 mm (4.12%–8.64%), 2–3 mm (3.16%–6.17%), and 3–5 mm (0.88%–1.27%).

Figure 2c displays the eight identified colors of MP found in the shrimps in all twelve sampling sites, including orange, white, black, red, blue, transparent, green, and yellow. The proportion ranges for each color were as follows: blue (24.71%–36.96%), transparent (14.49%–36.54%), red (5.88%–24.62%), black (7.69%–18.13%), yellow (1.54%–

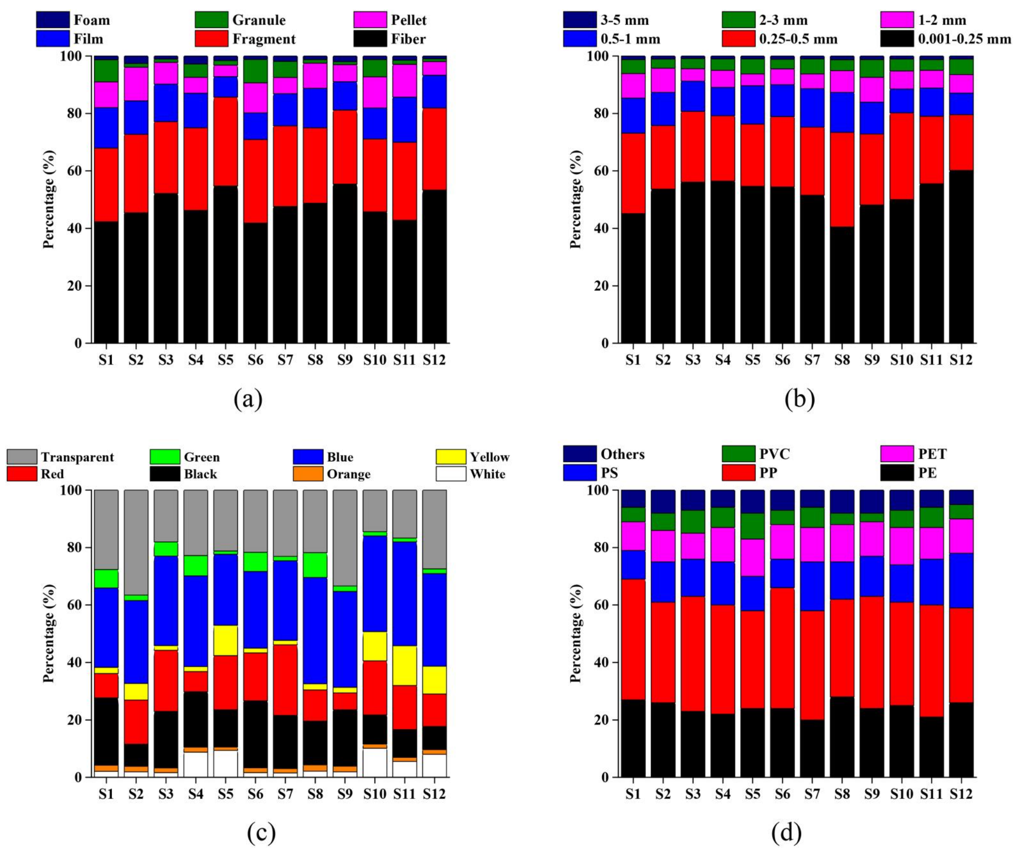


Figure 2. MP characteristics in total soft tissue of shrimp, (a) proportional distribution of MP shapes; (b) proportional distribution of MP sizes; (c) proportional distribution of MP colors; (d) proportional distribution of polymer composition.

13.89%), white (1.53%–10.14%), green (1.18%–8.70%), and orange (1.16%–2.17%). The results indicated that the predominant colors of MP in shrimps were blue, transparent, and red. This could be attributed to the specific color preferences shown by aquatic organisms. MP with shiny or transparent colors are more likely to be ingested unintentionally by these organisms, as they may resemble natural prey items more closely than MP of other colors (Yin et al. 2023, Zhang et al. 2023).

Given that approximately 50.00% of detected MPs are typically selected for FTIR analysis in previous studies (Ory et al. 2017; Ding et al. 2019; Lam et al. 2023), a total of 613 MP particles, representing about 70.00% of the total observed items, from shrimp collected from all sampling locations were examined for FTIR characterization. Among these, 566 particles were positively identified as plastic polymers, resulting in an accuracy of 92.33% using stereomicroscopy, which exceeds the established threshold of 90.00% (Ory et al. 2017). As shown in Figure 2d and Table 1, 12 distinct plastic polymers were identified in shrimps from the South Yellow Sea Mudflat. The major MP polymers were PP, PE, PS, PET, and PVC (Figure S3), while their proportions of polymers among the 12 sampling sites were 34.11%–42.23%, 20.89%–28.19%, 10.17%–19.37%, 9.26%–13.96%, and 3.26%–9.16%, respectively. The proportion of other MP polymers, including PAN, chlorinated polyethylene (CPE), PMMA, polyvinylidene fluoride (PVDF), PAA, rayon, and PA, ranged from 5.09% to 8.61% across the 12 sampling sites.

3.3. Potential human health risk for MP from shrimps

Shrimps are a popular food for humans due to their pleasant taste and high protein content, but they may also be a source of MP ingestion. The abdominal tissues (total soft tissues) of shrimps, after removal of the carapace, are the edible parts consumed. The midgut and hindgut are located within the total soft tissue. This study evaluated the potential risks of MP consumption from total and pure soft tissue (excluding the midgut and hindgut). As Figures 3 and 4 shown, the ADI, EDI, which indicated annual MP intake for an adult (items/capita/year) and estimated annual MP intake per kilogram (kg) of body weight (items/kg/year), respectively, for adults of MP by consuming total soft tissues of shrimps among twelve sampling sites were 2159.33–3034.29 items/capita/year and 37.42–52.59 items/kg/year, respectively, while ADI, EDI for adults of MP by consuming pure soft tissues of shrimps were in the range of 647.80–910.29 items/capita/year and 11.23–15.78 items/kg/year, respectively. These results suggested that ADI and EDI of MP by consuming the total soft tissues of shrimps were significantly higher than those of pure soft tissues of shrimps. However, the results of Mann–Whitney tests for ADI and EDI of MP between total soft tissue and pure soft tissue were < 0.01, as shown in Table S5. The Mann–Whitney test results for ADI and EDI of MP from shrimps between sampling sites in Group I and Group II, as shown in Table S6, yielded $p < .01$. This indicates that the ADI and EDI values for various soft tissues from shrimps in Group I, which included sites S1, S4, S6, S7, S9, S10, and S11, were significantly higher than those of Group II (comprising sites S2, S3, S5, S8, and S12). These findings align with the observed MP abundance in shrimps, as depicted in Figure 1.

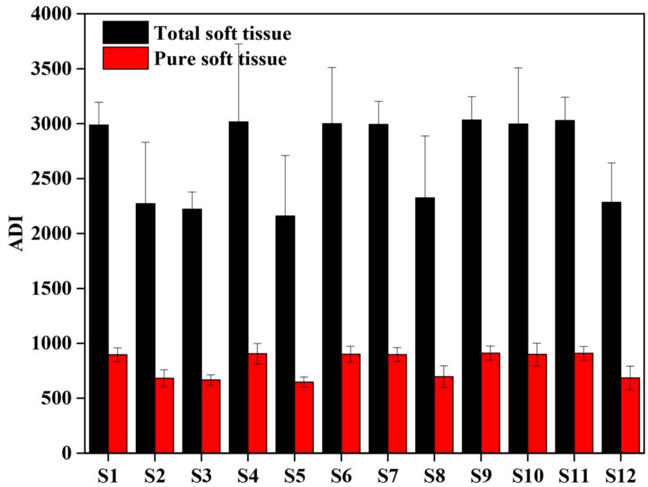


Figure 3. The average ADI of MP from soft tissues of shrimp.

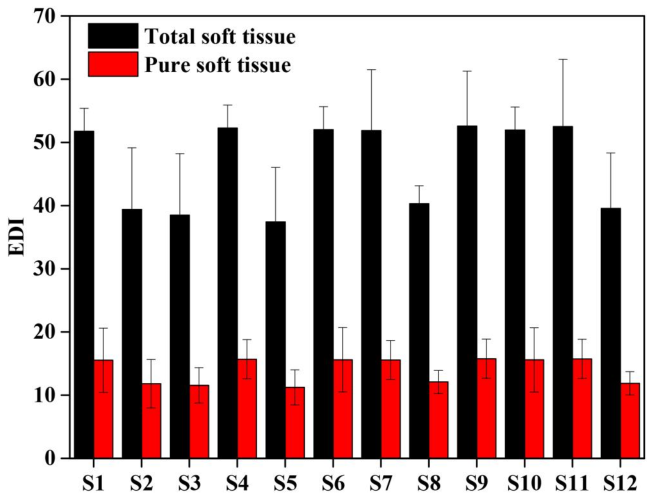


Figure 4. The average EDI of MP from soft tissues of shrimp.

In this study, the sampling sites of Group II were located in pure mudflat areas, whereas the sampling sites of Group I were primarily associated with the marine estuaries of rivers. This suggests that the abundance and characteristics of MP in shrimps were significantly influenced by the surrounding environmental factors (Fagiano et al. 2024; Portillo De Arbeloa and Marzadri 2024). As shown in Figure 5, the average PRI, which was calculated based on content and chemical toxicity of MP polymers (Lam et al. 2023), of MP from total soft tissues of shrimps for 12 sampling sites was 452.43–1084.88, while the average PRI of MP from pure soft tissues of shrimps for twelve sampling sites was 158.35–379.71. Based on the PRI levels (Table S1), the MP PRI for the total soft tissue of shrimp from sampling site S5 (PRI: 1084.88, Figure 5) was classified under hazard level IV. In comparison, the MP PRI for total and pure soft tissue from the remaining sampling sites was classified under hazard level III. The PRI for total soft tissues of shrimps was significantly higher than that for pure soft tissues, as confirmed

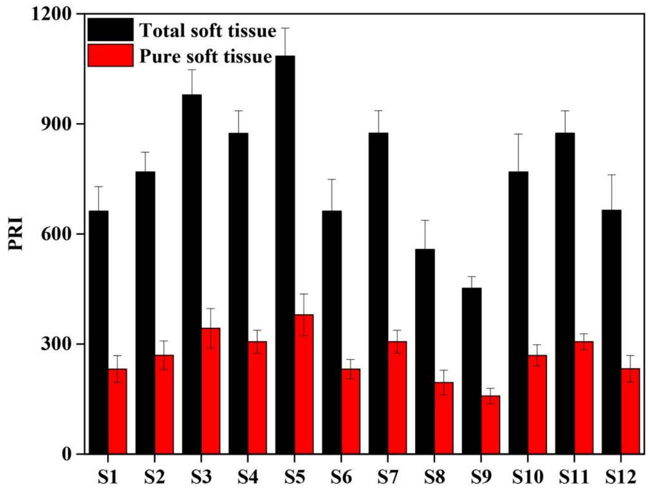


Figure 5. The average PRI of MP from soft tissues of shrimp.

by the results of the Mann–Whitney tests, which showed $p < .01$ for the PRI comparisons between total soft tissues and pure soft tissues of shrimps (Table S7). These results indicated that the potential human health risk for MP from shrimp could decrease significantly when the midgut and hindgut were removed from the total soft tissues of shrimps.

Furthermore, the highest PRI of MP from shrimps corresponded to sampling site S5 (1084.88 for total soft tissue, 379.71 for pure soft tissue), while the lowest PRI of MP from shrimps corresponded to sampling site S9 (452.43 for total soft tissue and 158.35 for pure soft tissue), suggesting an obvious difference in the PRI of MP for shrimps among different sampling sites.

4. Discussion

4.1. MP abundance

Previous studies have also reported a higher abundance of MPs in the gastrointestinal tracts than in the pure soft muscle tissues of *Decapod crustaceans* (Daniel et al. 2020b; Jaafar et al. 2021). Many studies have specifically focused on the characteristics of MPs and the potential risks associated with total soft muscle tissues of *D. crustaceans*, as the gastrointestinal tracts are often removed when consuming these organisms (D'Costa 2022; Ogunola et al. 2022; Sathish et al. 2020). However, the midgut and hindgut, which are located within the abdominal muscle tissues of shrimps, may not be efficiently or promptly removed. The relatively higher MP abundance in the midgut and hindgut of shrimps could pose a potentially higher health risk to humans when consuming these crustaceans.

MPs are typically ingested and initially accumulate in the gastrointestinal tracts of shrimps. Over time, some MPs may be assimilated into the muscular tissues, while the majority of the MPs in the gastrointestinal tracts are likely to be removed from the shrimp's body via the midgut and hindgut (Yin et al. 2022; Zhang et al. 2023). Therefore, the dietary intake and potential risks of MP in shrimp soft tissues containing midgut and hindgut are significantly higher than those in soft tissues from which the midgut and hindgut have been removed. Previous studies have shown that the characteristics of MP in different tissues of organisms can be affected by species, size, and feeding habits, with filter-feeding organisms typically showing higher MP abundance than predatory organisms (Khoshmanesh et al. 2023; Ogunola et al. 2022). Moreover, MP tends to accumulate in the gastrointestinal tracts of aquatic organisms initially, and some MPs may later be assimilated into other soft tissues (Daniel et al. 2020a; Jaafar et al. 2021). This aligns with the findings of this study, where significantly higher MP abundance was observed in the midgut and hindgut compared to the pure soft tissues of shrimps.

Riverine systems are heavily shaped by surrounding ecological and anthropogenic influences, resulting in the widespread occurrence of MPs throughout freshwater networks. As river water is commonly used to supply aquaculture ponds near coastal estuaries, it is crucial to determine MP concentrations within shrimp cultivation environments. Therefore, the MP levels in estuarine environments may indirectly shape the MP characteristics of cultured *D. crustaceans*. Considering that MP pollution along the South Yellow Sea Mudflat has been largely attributed to anthropogenic activities (Tang et al. 2022; Cai et al. 2023), and that MP profiles in aquatic organisms are readily affected by environmental contamination levels (Maghsodian et al. 2022; Liu et al. 2024), the MPs detected in shrimps may serve as indicators of MP pollution in the aquaculture water environment.

4.2. MP characteristics

Previous studies have provided substantial evidence confirming that fibrous MPs are the most frequently detected shape in various aquatic species (Teng et al. 2019; Yin et al. 2022). Three primary factors may explain the predominance of fibrous MPs observed in this study. First, one contributing factor is the substantial input of fibrous plastic debris derived from textile manufacturing, clothing disposal, and fishing-related activities within the river systems of Jiangsu Province, which borders the South Yellow Sea. This influx has likely led to elevated fibrous MPs concentrations in neighboring aquaculture environments (Cai et al. 2023; Tang et al. 2022). Thus, the elevated presence of fibrous MPs in the aquaculture environment was similar in the shrimp samples, where fibers emerged as the predominant MP morphology. Second, fibrous MPs were usually smaller than other-shaped MPs; smaller fibrous MPs were more likely to be ingested by shrimps (Mercy and Alam 2024). Thirdly, fibrous MPs are generally more difficult for aquatic organisms to excrete due to their tendency to entangle and accumulate within the gastrointestinal tract (Joyce et al. 2022; Nan et al. 2020; Wu et al. 2020). These findings suggest that the metabolic processing of MPs varies according to shape, thus influencing the relative abundance of different MP morphologies in aquatic organisms. Moreover, previous studies have reported that MPs of smaller size (minor-MP, $\leq$1 mm) are more likely to be ingested, as their sizes closely resemble natural food particles, whereas the ingestion of larger MPs is comparatively limited (Pisani et al. 2022; Tang et al. 2022; Yin et al. 2022). Moreover, biofouling on the surface of MPs can significantly increase their chances of ingestion by shrimps, as such particles may be mistakenly recognized as natural food sources (Fabra et al. 2021). Biofouling tends to develop more rapidly on MPs of smaller size due to their relatively larger specific surface area compared to larger particles (Amaral-Zettler et al. 2021). This phenomenon enhances the probability of ingestion of smaller-sized MPs ($\leq$1 mm) by aquatic organisms. Although the detection of nanoscale MPs may have been limited by the methodological sensitivity employed in this study, the findings demonstrated that lower-size fraction MPs were more frequently identified in shrimp specimens and constituted a significant proportion of the total MP load, indicating a predominance of minor-sized MPs within the analyzed tissues. Despite detecting various MP colors within shrimp samples, blue particles were the predominant type in this study. This prevalence may be due to the resemblance of blue coloration to the natural appearance of prey items typically targeted by aquatic crustaceans (Ory et al. 2017; Nan et al. 2020), which might explain the major blue MPs identified in shrimps in this study. PE, which was commonly associated with fishing gear, and PET, which was frequently used in textiles, were among the dominant polymer types identified, suggesting contributions from both aquaculture and land-based anthropogenic activities (Teng et al. 2019).

The findings of this study indicated that MP detected in shrimps from the South Yellow Sea Mudflat showed a wide range of polymer types, shapes, sizes, and colors, reflecting the complexity of their sources and environmental pathways. The diverse characteristics of MP observed, such as fibrous and fragmented shapes, varied colors, and multiple polymer compositions, highlight the heterogeneous and multifaceted nature of plastic pollution in this region. Moreover, the predominance of irregularly shaped and sized MPs suggests that many particles resulted from the progressive fragmentation and environmental degradation of larger plastic debris, rather than originating as primary MPs (Sait et al. 2021). These findings highlight the complex and multifaceted nature of MP pollution in aquaculture environments and emphasize the necessity of evaluating MP contamination based on physicochemical attributes to better understand their environmental fate and ecological risks (Lam et al. 2023).

4.3. Potential human health risk for MP

In this study, both the ADI and EDI of MP from the pure soft tissue of shrimp were significantly reduced after removing the midgut and hindgut from the total soft tissue. This reduction was attributed to the substantially higher MP abundance found in the midgut and hindgut compared to that in the surrounding muscular tissue (Figure 1), aligning with previous reports that showed a higher concentration of MP in the gastrointestinal tracts of aquatic organisms than in other soft tissues (Abbasi et al. 2018; Daniel et al. 2020a). Several studies have confirmed that the ADI, EDI, and associated health risks related to crustacean consumption are significantly lower when gastrointestinal tracts are thoroughly removed, as opposed to the consumption of whole intact crustaceans (Jaafar et al. 2021; Ogunola et al. 2022). These findings highlight that the extent of gastrointestinal tract removal significantly influences MP intake and the associated health risks from crustacean consumption (D'Costa 2022; Ogunola et al. 2022).

The highest ADI and EDI values for MP from shrimp consumption were recorded at sampling site S9, while the lowest values were observed at sampling site S5, as shown in

Figures 3 and 4. These results highlight the importance of comprehensively evaluating the potential human health risks associated with MP in shrimp, considering both MP intake and polymer composition. The hazard score for PVC was significantly higher than that of other MP polymers (Lithner et al. 2011), and the higher PRI of MP at sampling site S5 was primarily due to the higher proportion of PVC, as demonstrated in Figure 2d. The PRI evaluation in this study may overestimate the potential human health risks of MP from shrimp because the PRI evaluates the risks of plastics based on the potential toxicity of the polymer (Lithner et al. 2011), which differs from the risks posed by MP. Moreover, the bioavailability of polymers and plastics varies; for instance, an organism may ingest a 1 mg plastic particle and excrete it without experiencing any harmful effects. However, organisms ingesting a smaller amount of polymers can cause more effects because polymers are more bioavailable and can reach the target site to cause the impact. Therefore, the polymer hazard and MP metabolism in biota might be considered simultaneously to evaluate the future MP health risk. As highlighted in the above studies, recent studies have predominantly focused on the total soft tissues of shrimps (Daniel et al. 2020b; Timilsina et al. 2023). This study comprehensively assesses MP characteristics and PRI in both total and pure soft tissues of shrimps. These findings contribute key dietary reference data for consumers and improve our understanding of potential human exposure to MP through shrimp consumption. Absolutely, traceability of MP, including potential pollution sources and patterns of MP distribution in the study area, would be helpful for enhancing the scientific rigor and interpretability of MP characteristics, which will be studied in the future.

5. Conclusion

This study evaluated the characteristics and potential human health risks of MP in commercial shrimp (*Litopenaeus vannamei*) from the South Yellow Sea Mudflat. MP were detected in all 12 sampling sites, with significantly higher abundance in the midgut and hindgut (4.13–5.82 items/individual; 61–83.2 items/g) compared to pure soft tissues (1.77–2.50 items/individual; 0.11–0.15 items/g). Shrimp from Group I sites (marine estuaries) showed higher MP abundance than those from Group II (mudflat areas). The predominant MP traits included fiber shape, small size (0.001–0.25 mm), blue color, and polymers, such as PP, PE, PS, PET, and PVC. Furthermore, ADI and EDI values were significantly higher for total soft tissues than pure soft tissues, and for Group I than Group II, consistent with observed MP abundance. Similarly, PRI values were also higher in total soft tissues, indicating a reduced potential health risk when the midgut and hindgut were removed. Overall, this study provides novel insights into MP characteristics and associated health risks in *L. vannamei* from this region, offering useful references for dietary safety and MP pollution control in aquaculture. In the future, integrated management strategies, including source control (optimized feed formulation, reduced plastic gear use), enhanced water treatment (implementing multi-stage particle-retention filters and biofilters in recirculating systems), and rigorous monitoring protocols to assess exposure levels and ecological impacts, is necessary for effective mitigation of MP in aquaculture systems.

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Author contributions

Qingyuan Guo: Conceptualization, Methodology. Jiaxuan Luan: Data curation, Visualization. Kai Yang: Project administration. Qingqin Meng: Validation. Xiaomei Shen: Software, Methodology. Mingzhe Cai: Methodology. Xuan Li: Software. Feng Liang: Data curation. Bairen Yang: Investigation. Tianming Chen: Resources, Software. Cheng Ding: Funding acquisition. Min Xu: Software.

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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Data availability statement

All data and materials are available upon request (376271668@qq.com).

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