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Research Paper

Mangrove leaves: An undeniably important sink of MPs from tidal water and air

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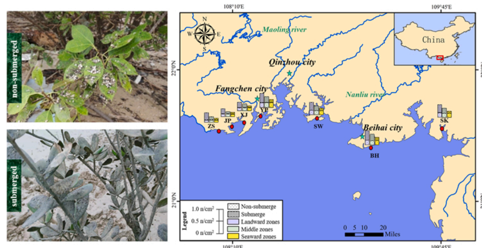
HIGHLIGHTS

- The abundance and characteristics of MPs on mangrove leaves are firstly reported.
- Air deposition is the dominant pathway for MPs on non-submerged mangrove leaves.
- Significant differences are obtained for MPs on submerged and non-submerged leaves.
- Contribution of tidal water to MPs on submerged mangrove leaves cannot be ignored.

GRAPHICAL ABSTRACT



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ABSTRACT

Capturing microplastics (MPs) were one of the important characteristics for terrestrial plant. Whereas, role of mangrove leaves in capturing MPs from tidal water and air were still largely unexplored. Here, we detected the spatial distribution of MPs at both submerged (0.10-0.49 n/cm^2) and non-submerged mangrove leaves (0.09-0.24 n/cm^2) in the Beibu Gulf. Abundance of MPs on submerged mangrove leaves was significantly higher than that on non-submerged mangrove leaves in landward and middle zone ($^*p < 0.05$). Almost no difference existed in the abundances of MPs detected on leaves of different mangrove species. Abundance of MPs on submerged mangrove leaves increased following the sequences of seaward zone (0.11 n/cm^2) < middle zone (0.21 n/cm^2) < landward zone (0.36 n/cm^2). PE MPs with uncoloured/fiber characteristics dominated the MPs both on the non-submerged and submerged mangrove leaves. Furthermore, contribution of tidal water was significantly greater than that of atmospheric deposition on MPs retention on submerged mangrove leaves. Results of this work highlight the importance of tidal water and air in the spatial distribution of MPs at mangrove leaves, and the globally MPs gross reserves at mangrove leaves cannot be ignored in evaluating the MPs sink in mangrove wetland.

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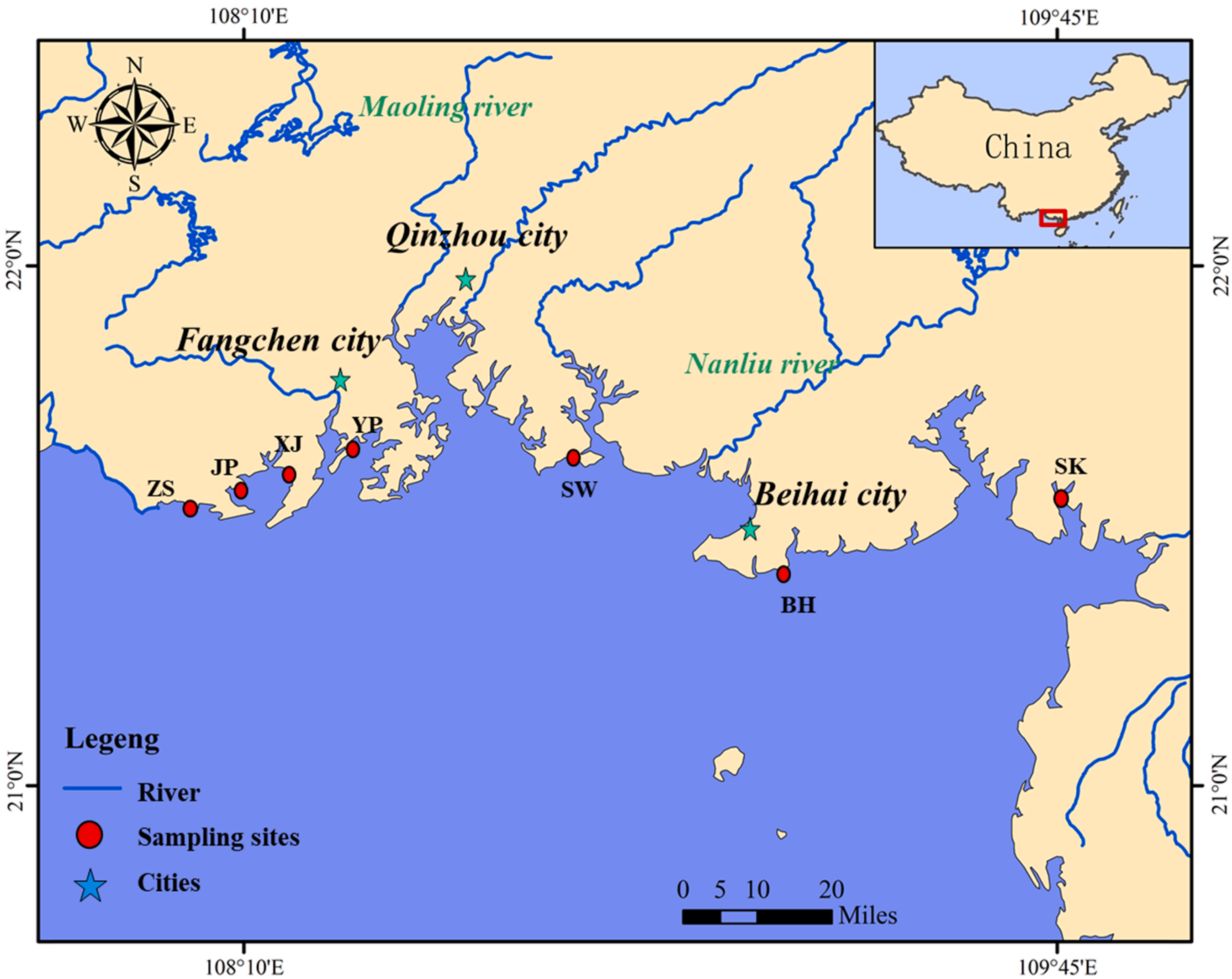

Fig. 1. Geographic location and sampling sites. The suffixes of ZS, JP, XJ, YP, BH, SW and SK denote Zhu Shan, Jiang Ping, Xin Ji, Yuzhou Ping, Bei Hai, Sanniang Wan and Shan Kou respectively.

1. Introduction

The continuous increase in plastic production has exacerbated concerns about plastic waste around the world that is estimated to reach an accumulative 12 billion tons in landfills and the natural environment by 2050 (Andrady, 2011; Geyer et al., 2017). Owing to its durability, the most remarkable property in the entire material field, plastic waste accumulates and persists in ecosystems worldwide (Wright et al., 2020). Eventually, the plastic waste will lose its mechanical integrity and break into small pieces, via biotic and abiotic degradation pathways (e.g. photooxidation, abrasion) (Wright et al., 2020). The particles decomposed from human-manufactured plastics are defined as microplastics (MPs) of which diameter/size is less than 5 mm (Thompson et al., 2004; Machado et al., 2018). It is noteworthy that the presence of MPs poses threat to the environment and organisms in the ecosystem. 1) MPs are mistaken as foods easily and then ingested by organisms due to their small size. Once MPs are mistakenly taken up by organisms, it could lead to a series of adverse health effects, such as reduction of feeding activity, reproductive growth rate and weight, etc. (Lusher et al., 2017; Trestrail et al., 2020). 2) Due to their high surface area and non-polar property, MPs can act as transportation vectors of organic pollutants and heavy metals that are ubiquitous in the environment (Alimi et al., 2018; Besseling et al., 2013; McCormick et al., 2014). 3) MPs inevitably affect plant physiological growth, including phenotype, photosynthetic activities and oxidative stress (Rillig et al., 2019; Pignattelli et al., 2020; Bhattacharya et al., 2010; Gao et al., 2019; Gao et al., 2021).

As a barrier to land-based inorganic/organic pollutants delivery to the sea, mangrove wetland is considered to be an important repository of MPs (Paduani, 2021; Nor and Obbard, 2014; Martin et al., 2019; Li et al., 2018; Zhou et al., 2020). It further reported that the strong adsorption and fixation capabilities of MPs in mangrove forest can be ascribed to the dense and developed roots of mangrove plants which grow in clay-rich sediments with high organic matter (Liu et al., 2021). Given the luxuriant emerged root system and leaves of mangrove plant, it could form a natural filter which is capable of effectively retaining the plastic debris from both land-based and sea-based source (Lee et al., 2013; Dekiff et al., 2014; Mathalon and Hill, 2014; Yu et al., 2016; Deng et al., 2021). Liu et al. (2020) estimated that 0.13 trillion MPs retained on plant leaves in 11 countries, suggesting that the leaves of terrestrial plants were not only the intermediary in the migration process, but also an important sink of MPs. Although the depositions become more and more important input pathways for MPs enter into mangrove forest, the role of mangrove leaves, rather than root, in the above MPs retention processes were still largely unknown till now. Particularly, different from the terrestrial plant, the potential sources of MPs in mangrove leaf were complicated, including air and tidal water (ebb and flow). Lacking

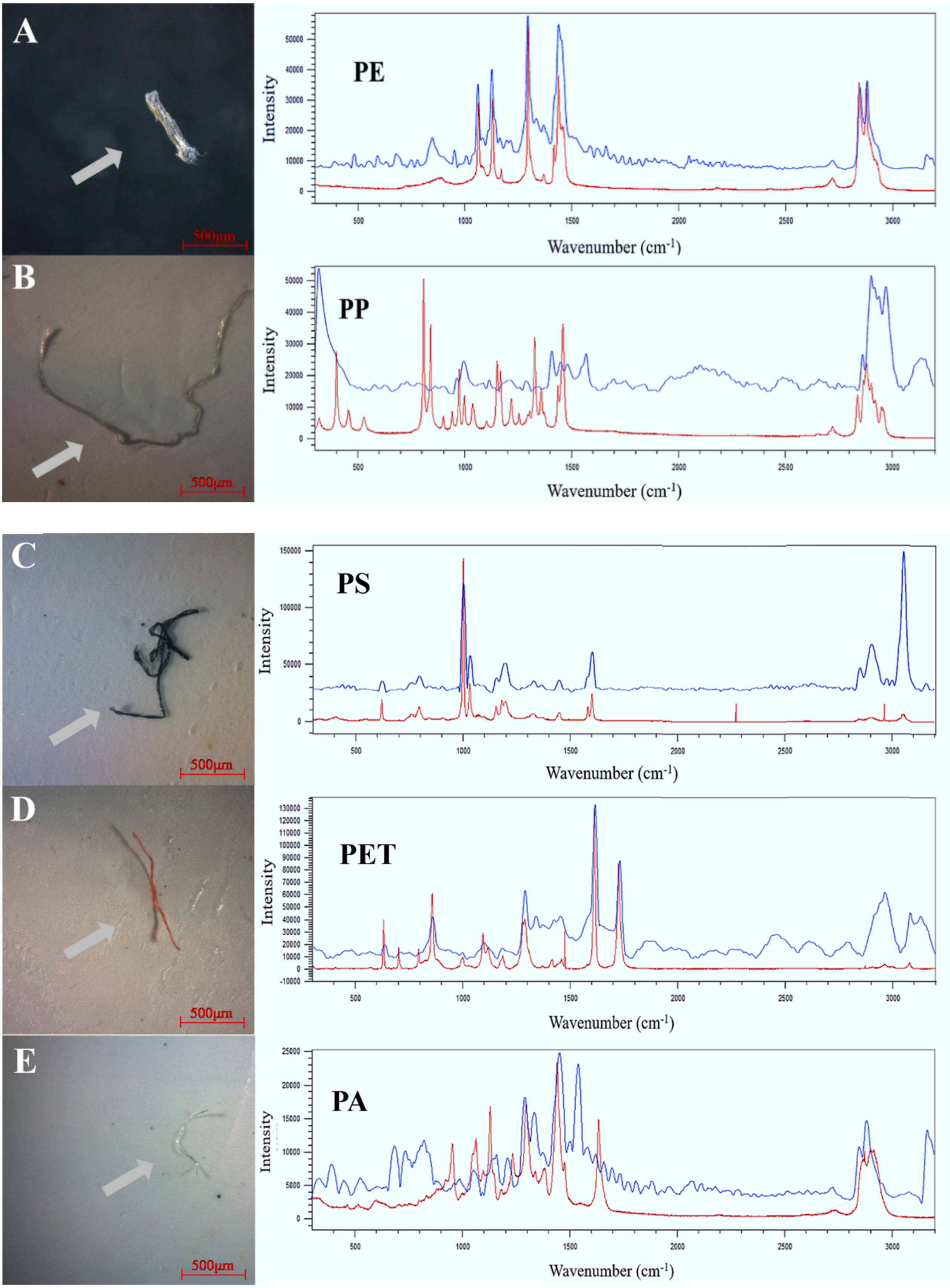

Fig. 2. Subsample of the extracted MPs on non-submerged and submerged mangrove leaves including their corresponding micro-Raman spectra. The blue spectra represent the measured MPs particles and the red spectra are the reference spectra from the Bruker spectra library.

of related studies, thus, impede our comprehensive understanding of the MPs retention mechanism for mangrove.

The Beibu Gulf in the northwest of the South China Sea was selected as the target area due to its largest area and the most abundant species of mangroves in China (Zhang et al., 2010; Yang et al., 2018). The main objectives of the present study were to (i) evaluate the abundance and characteristics of MPs retained on the mangrove leaves (submerged parts and non-submerged parts) collected from the Beibu Gulf, (ii) assess the contribution of the tide and atmosphere to the MPs retained on the mangrove leaves, and (iii) identify the potential sources of MPs adhering to mangrove leaves.

2. Material and methods

2.1. Study area

From July to August 2020, mangrove leaves, tidal waters and air samples were collected from 6 sites located on Beibu Gulf, Guangxi province, China. The research region has two main characteristics as following. First, it has a macrotidal environment with regular diurnal tides are dominant, and the overall trend of tidal change is significantly similar in every month (He et al., 2007; Long et al., 2022). Second, it covered six inflowing rivers and three coastal cities. The sampling sites are shown in Fig. 1 (21°61′–21°91′N, 108°47′–108°80′E) and the exact location of each site was recorded using portable GPS device. According to the different land use of coastlines and intensity of human activities, they are specifically classified into three categories: Zhu Shan (ZS), Jiang Ping (JP) and Xin Ji (XJ) were the village sites, and Yuzhou Ping (YP) and Bei Hai (BH) were the urban sites. The Sanniang Wan (SW) and Shan Kou (SK) sites were in tourist areas (national mangrove reserves).

For MPs in mangrove wetland, they mainly originate from anthropogenic activities. Besides, coastline land use play a relatively important role of in MPs dispersion and frequency in surface seawater along coastal areas, and MPs from land activities of the surrounding population could also be retained in the landward areas of the mangroves.

2.2. Sampling data collection

The collection of mangrove leaves in the sample sites were performed following our previous report (Zhang et al., 2020). Three replicate regions were established in the landward (inside), middle (the midpoint of the line between the landward site and the seaward site) and seaward (outside) zones of the mangrove forests. In ZS, YP, JP and XJ, *Aegiceras corniculatum, Vicennia mariana* and *Bruguiera gymnoihiza* are dominant species, while *Aegiceras corniculatum, Vicennia mariana* and *Rhizophora stylosa* were dominant in SK and BK. Furthermore, non-submerged mangrove leaves were from unflooded parts at high tide, and submerged mangrove leaves were from exposed parts at low tide. Three types of mangrove species were dominant for all sampling sites, and thus, at least 30 leaves were collected on each high and low tide part to ensure that the sample number of submerged or non-submerged leaves was more than 10. During sampling, the intact leaves were cut at the petiole with scissors and immediately were stored in the aluminum foil bag. The labeled aluminum foil bags were temporarily stored in refrigerator (4 °C). Finally, the leaves were temporarily stored in aluminum foil until laboratory analysis.

The tidal water samples were collected based on the method recorded in our previous study (Li et al., 2020). Briefly, 50 L tidal water sample was also collected at the same position of both the landward ($n = 3$), middle ($n = 3$) and seaward ($n = 3$) zones using steel water sampler. Then a 50 μm steel sieve was used to filter the surface water, and the residue on the steel sieve was washed into a 1 L blue cap bottle with Milli-Q water. The above operations were repeated for three times. All tools were washed with Milli-Q water before sampling. To avoid cross contamination, the sampling device was washed with Milli-Q water three times between respective samples for each operation. Water samples were then transferred into glass bottles and sent to the laboratory for subsequent experiment.

The air samples were collected following the method by Cai et al. (2017). Atmospheric fallout was taken continuously from each zone of the mangrove forest using wide mouthed glass bottle (5 L) and fixed supports. Wide mouthed glass bottles are stabilized and lifted by fixing brackets so as not to be flooded by tidal water. It also makes sure that no mangrove leaf above the glass bottle place. The samples will be transferred in time after each rain to prevent sample spillage and loss. Air samples were collected from seven sites from August to September 2020. Ultimately, all the samples were carefully transported to the laboratory at the 4 °C until processing.

2.3. The pretreatment, quantification and identification of MPs in leaves and water samples

2.3.1. Pretreatment

Based on the method reported previously (Liu et al., 2020), the separation of MPs from leaf samples was performed as follows. The leaf samples were removed from the bags with tweezers and weighed, then placed in a 500 mL glass beaker in the laboratory. Subsequently, upper surface of the leaves was thoroughly flushed with filtrated Milli-Q water. Besides, the aluminum foil sample bags were washed. All of the water in the beakers was then filtrated with 1.2 μm GF/C glass microfiber filter membranes (Whatman, UK), and the filters were transferred to a covered glass Petri dish. These Petri dishes were placed in a desiccator for complete drying before further analysis.

The extraction of MPs in water samples was performed following our previously reported methods (Li et al., 2020). Briefly, the water samples were firstly subjected to a visual screening and the relatively large MPs were picked out and stored on filter membranes in glass Petri dishes. After that, the water samples were passed through 1.2 μm GF/C glass microfiber filter membranes (Whatman, UK) and the residues tripped on the membranes were transferred to a 1000 mL beaker. Finally, to minimize organic matter interference in the whole analysis process, 200 mL of hydrogen peroxide (30%) was added to the beakers, and adequate reaction time with the samples was allowed (approximately 24 h). The digestion process was carried out at 25 °C and the supernatant was filtered through 1.2 μm GF/C glass microfiber filter membranes directly after complete digestion. Similarly, the filter membranes were placed in covered glass Petri dishes for analysis.

2.3.2. Quantification and identification

As previously reported (Zhang et al., 2017; Di and Wang, 2018), the characteristics (color, size and shape) of the plastic were significantly different from the particulate matter in field. Based on this feature, all particles that retained on the filter membrane after the pretreatment were further detected and counted under the stereomicroscope (Stemi 508, Germany) at 3–4× magnification with the charge-coupled device and LED light. The suspected MPs account for 70–85% of total particles due to the large sample differences. Then, all selected particles were identified using a micro-Raman spectrometer (Renishaw inVia, UK). The parameters of micro-Raman spectrometer were as follows: excitation laser wavelength and energy were 532 nm and 15 mW (5%) respectively; emission wavenumber were collected from 300 to 3200 cm^{-1} (Fig. 2); and exposure time was 2.0 s. Six different micro-zones on the particles were selected and scanned (Jiao et al., 2021). Finally, the sample spectra were compared with a database from Renishaw Polymer database to verify the polymers types.

2.4. Statistical analysis

Analysis of the data was performed with SPSS 22.0 software (SPSS Inc., Chicago, IL, USA). All diagrams were drawn by Origin 9.0 software (OriginLab, U SA). After the normal distribution and homogeneity of variance were measured, the analysis of variance (ANOVA) was used to

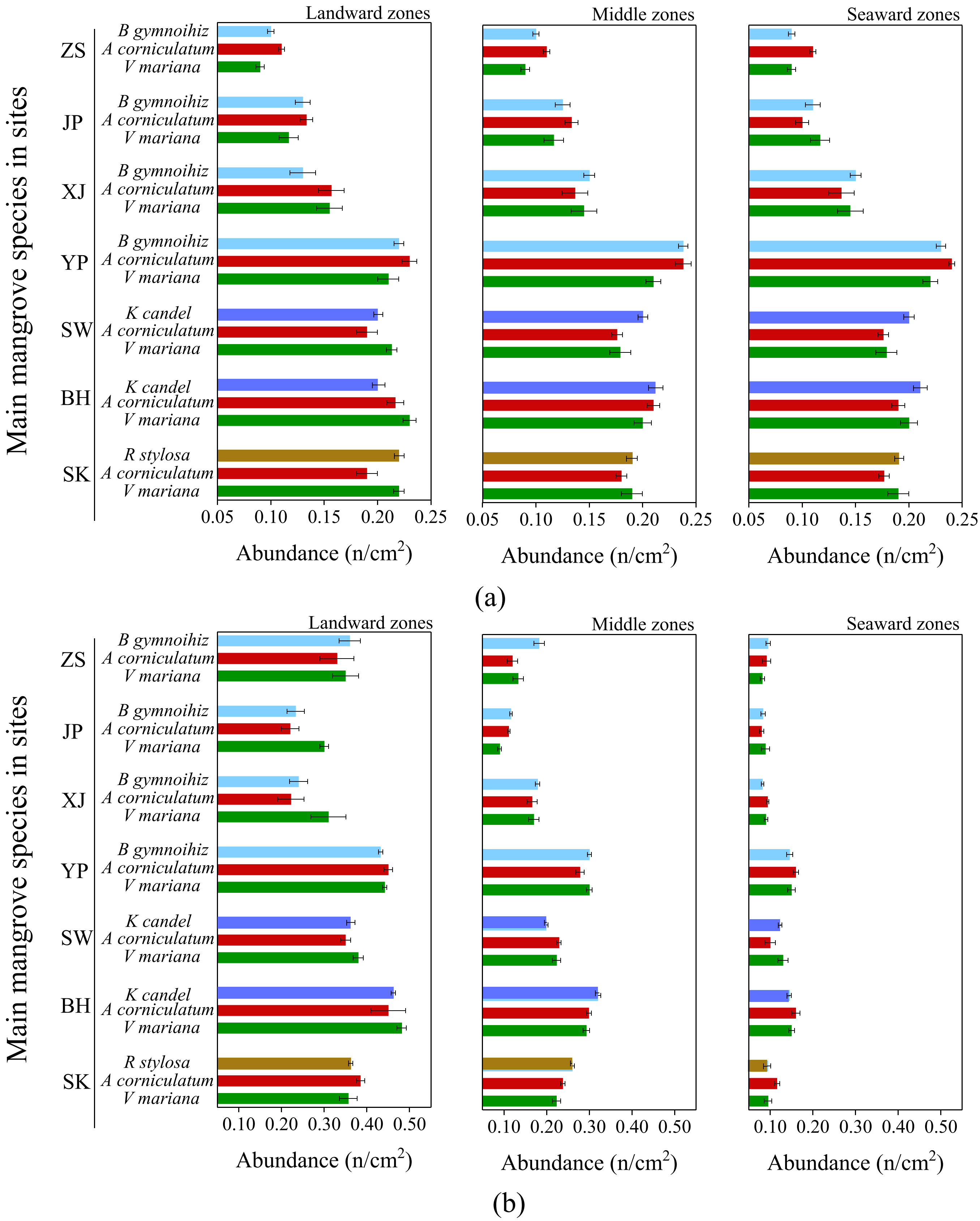

Fig. 3. Abundance of MPs on non-submerged (a) and submerged (b) mangrove leaves of different mangrove species, including *Aegiceras corniculatum, Vicennia mariana*, *Bruguiera gymnoihiza* and *Rhizophora stylosa*, from landward, middle and seaward zones at all sample sites. The suffixes of ZS, JP, XJ, YP, BH, SW and SK denote Zhu Shan, Jiang Ping, Xin Ji, Yuzhou Ping, Bei Hai, Sanniang Wan and Shan Kou respectively.

compare abundance differences of MPs on the leaves of different mangrove species and in different areas. Linear regression was used to measure the correlation between MPs on leaves and MPs in air and tidal water. In all cases, $p < 0.05$ was recognized as statistically significant. Leaf area was calculated by Image J software (version 1.51j8).

2.5. QA/QC

To minimize potential pollution, the methods in the present study followed the previously recorded methods (Li et al., 2019). Firstly, the metal containers or samplers were used and latex gloves were worn to avoid sample contamination during the entire sampling process. Secondly, non-plastic products were used throughout the experiment and washed with Milli-Q water, while aluminum foil should cover the open container and then put the container into the fume hood at the time of no experiment. Thirdly, for sample processing and analysis (Milli-Q water, 30% H_2O_2, and potassium formate), the solvents used in the samples were filtered through GF/C glass microfiber filter (Whatman, UK) prior to use. The beakers were filled with a potassium formate aqueous solution with a density of 1.5 g/cm^3. The residues and potassium formate aqueous solution were mixed well, and then MPs were separated by the density difference after settling for 12 h. The above separation process was repeated three times. In addition, the results of laboratory analysis were adjusted through blank tests and no MPs were found in the blank samples.

3. Results and discussion

3.1. Abundance of MPs on mangrove leaves on the Beibu Gulf

Considering the fact that some leaves of mangroves are flooded by intermittent tidal water, MPs on non-submerged and submerged mangrove leaves were identified and counted respectively. Fig. 3 displayed the abundance of MPs on non-submerged (a) and submerged (b) mangrove leaves of various mangrove species at all sample sites. The results showed the abundances of MPs on non-submerged mangrove leaves ranged from 0.09 n/cm^2 to 0.24 n/cm^2, much lower than the corresponding submerged fractions (0.10–0.49 n/cm^2). Additionally, no obvious differences were obtained between MPs in non-submerged mangrove leaves from Beibu Gulf and terrestrial plant leaves (0.07–0.19 n/cm^2) from Shanghai city ($F_{(1, 12)} = 1.27$, $p > 0.05$).

Spatially, for non-submerged mangrove leaves, the highest MPs content was exhibited in YP and BH where located in the bustling urban area of Fangcheng City (mean = 0.23 n/cm^2 and 0.21 n/cm^2 respectively), while the minimum MPs abundance appeared in the remote suburbs of Dongxing city (XJ: mean = 0.15 n/cm^2, JP: mean = 0.12 n/cm^2, ZS: mean = 0.10 n/cm^2). Surprisingly, the MPs abundance on non-submerged mangrove leaves in national mangrove reserves with less human activities has reached to 0.19 n/cm^2, as in both SK and SW sites. Such results indicated that the development degree of surrounding sites may not be the dominant factors for the spatial distribution of MPs in mangrove wetland of Beibu Gulf. However, no significant difference was observed among the abundances of MPs on non-submerged mangrove leaves in different mangrove species ($F_{(4, 16)} = 0.588$, $p > 0.05$), indicating the atmospheric deposition of MPs was irrelevant factor to tmangrove species.

Similar phenomenon was found in submerged mangrove leaves, the abundance of MPs ranged following Fangcheng city (BH: mean = 0.31 n/cm^2, YP: mean = 0.30 n/cm^2) > national mangrove reserves (SK: mean = 0.24 n/cm^2, SW: mean = 0.23 n/cm^2) > Dongxing city (ZS: mean = 0.19 n/cm^2, XJ: mean = 0.17 n/cm^2, JP: mean = 0.15 n/cm^2). Nevertheless, for the sampling sites in the high urbanization cities (Fangcheng and Dongxing city), the MPs abundances on submerged mangrove leaves were not in the same order with that of non-submerged mangrove leaves. The results demonstrated tidal water has a stronger positive effect on the retention of MPs on submerged mangrove leaves, and the human activities could produce different interference for MPs abundances on non-submerged and submerged mangrove leaves.

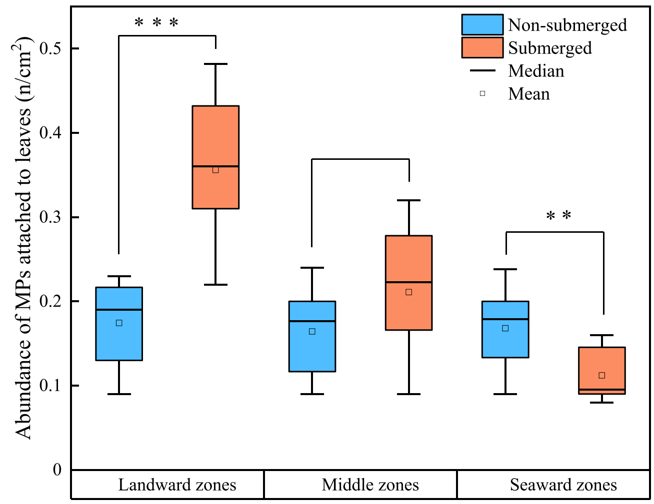

Fig. 4. Abundance of MPs adhered to the submerged leaves and non-submerged mangrove leaves at all sample sites. From left to right are the mangrove landward, middle and the seaward zones respectively (ANOVA test, *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$).

3.2. MPs on mangrove leaves from landward, middle ward and seaward zones

Owning to the huge gaps in MPs transportation pathways, one mangrove forest are divided into landward, middle ward and seaward zones based on their distance from land, as it in our previous reports (Zhang et al., 2020). Each zone contains the submerged and non-submerged mangrove leaves. As shown in Fig. 4, no significant differences of MPs attached to the non-submerged mangrove leaves were observed among landward, middle ward and seaward zones ($F_{(2, 18)} = 1.27$, $p > 0.05$), while significant gaps appeared when the objective is changed to the submerged mangrove leaves ($F_{(2,18)} = 1.27$, $p < 0.001$). The mean abundance of MPs in these three zones following the sequences of landward region (0.36 n/cm^2) > middle ward region (0.21 n/cm^2) > seaward region (0.11 n/cm^2).

From seaward to landward region, the tidal velocity exhibits continuous weakening trend (Fry and Aubrey, 1990). Besides, the time of submerged mangrove leaves undergo tidal water followed the order seaward region > middle ward region > landward region. In nearly all kinds of mangrove forests, currents with persistent and high-speed provide predicament to the deposition and attachment of suspended particulate matter, especially to the light density fraction like MPs, onto mangrove leaves (Furukawa et al., 1997; Schettini and de Miranda, 2010). As the MPs are transported to land, currents become progressively slower, allowing MPs to stick steadily to mangrove leaves, and making the landward mangrove leaves become an idea niche for MPs. Furthermore, high velocity flow can flush the MPs that have been already fixed on the leaves and continue to attenuate as the flow rate decreases, which is a possible explanation for the negative effect of tidal water on the occurrence of MPs in the seaward region. The above results highlight that tidal was an irreplaceable input pathway for MPs on submerged mangrove leaf, displaying positive and negative effects on MPs deposition in landward and seaward region, respectively.

3.3. Color, shape and type characteristics of MPs on mangrove leaves

Totally, the 11 characteristics of MPs on non-submerged and submerged mangrove leaves were obtained (Fig. 5). For non-submerged mangrove leaves, polyethene (PE) was the dominant type accounting

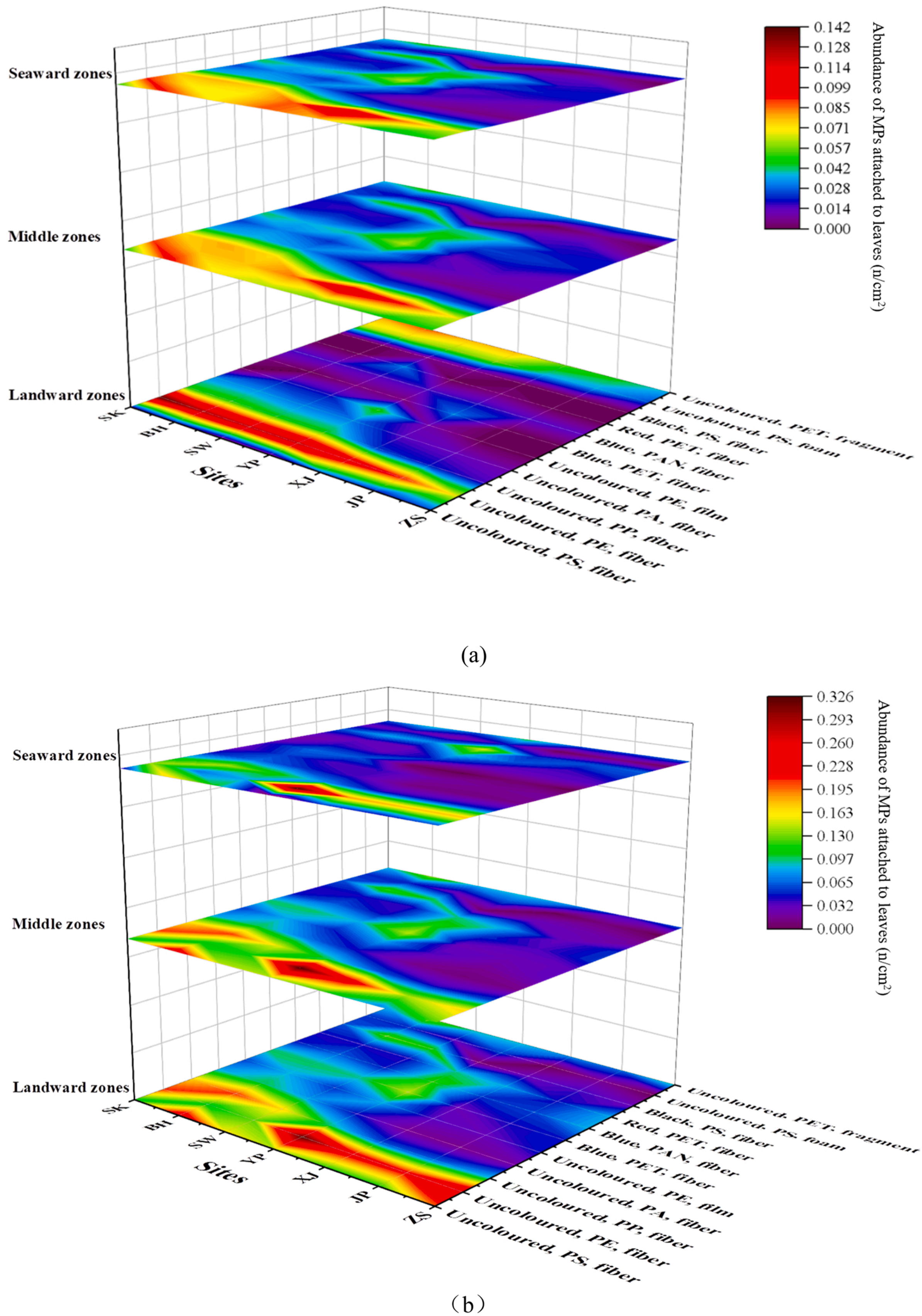

Fig. 5. Abundance of MPs with different characteristics (X-axis) on non-submerged (a) and submerged (b) mangrove leaves from landward, middle and seaward zones (Z-axis) at all sample sites (Y-axis). The suffixes of ZS, JP, XJ, YP, BH, SW and SK denote Zhu Shan, Jiang Ping, Xin Ji, Yuzhou Ping, Bei Hai, Sanniang Wan and Shan Kou respectively.

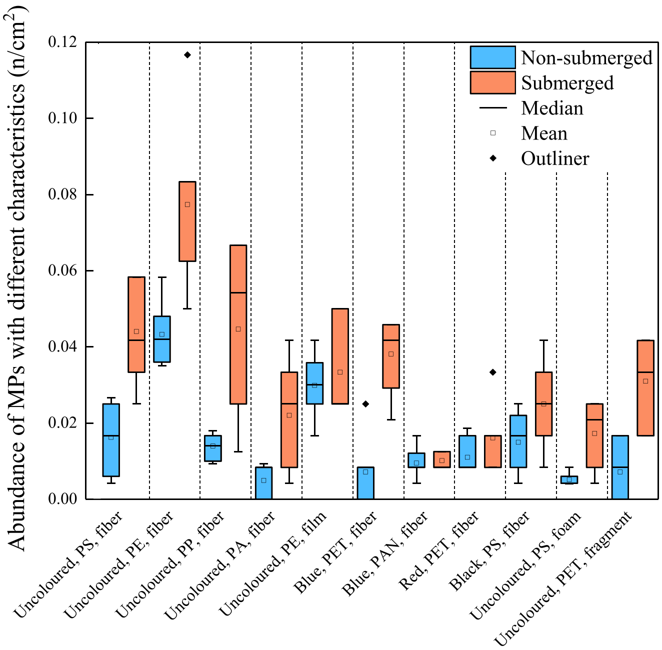

Fig. 6. Abundance of MPs with eleven characteristics on submerged and non-submerge mangrove leaves from landward, middle and seaward zones at all sample sites.

for no less than 33% of total MPs, while polyamide (PA) displayed the lowest proportion (less than 5%). That is in consistent with the commonly used plastic at the surrounding of Beibu Gulf (Zhao et al., 2015). For shape, size and color characteristics of MPs, the proportion of fiber morphology (71–79%), < 1 mm (71–82%) and uncolored (67–73%) dominated on the non-submerged mangrove leaves (Fig. S2). Similar results were obtained for the type, shape and color of MPs on submerged mangrove leaves. However, the size characteristic was the exception, i.e. the proportion of < 1 mm MPs on non-submerged mangrove leaves significantly higher than submerged mangrove leaves, largely due to relative small size MPs in the dominant source of non-submerged mangrove leaves (air).

In detail, the highest and lowest MPs detected on non-submerged mangrove leaves were the PE MPs with the characteristics of uncolored and fiber (0.03–0.08 n/cm^2) and polyacrylonitrile (PAN) MPs with blue and fiber (0.01 n/cm^2) respectively (Fig. 6). PE-based plastic products, instead of PAN, are widely used in fisheries and mariculture that are adjacent to mangrove forest. Ultraviolet radiation and mechanical stress of waves greatly accelerate the broken of PE plastic into small fragments, making it easily transported via air and deposition to non-submerged mangrove leaves.

For the submerged mangrove leaves, the PE, polystyrene (PS) and polypropylene (PP) with uncolored and fiber characteristics dominated the MPs characteristics. Similarly to MPs characteristics on non-submerged mangrove leaves, PE MPs with uncolored/fiber characteristics and PAN MPs with blue/fiber characteristics exhibited the highest and lowest proportions of MPs respectively. Notably, the two least MPs, PAN MPs with blue/fiber characteristics and polyethylene terephthalate (PET) MPs with red/fiber characteristics, on submerged mangrove leaves showed no significant difference from non-submerged mangrove leaves. High density of PET and PAN were considered as the dominant reasons induced this interesting phenomenon. High density MPs deposited with flocs are difficult to flocculate and showed loose relationships with current velocity at the flood. That is, PAN and PET MPs were more easily retained in mangrove sediment, rather than submerged mangrove leaves, due to the limited resuspension capability. Additionally, in comparison to other MPs, additive of PET and PAN MPs promote the attachment of MPs and cellulose components of plant cells due to electrostatic force, as reported by Bhattacharya et al. (2010) and their adsorption is enhanced due to the roughness of plant cellulose surface.

3.4. Source of MPs on mangrove leaves

Abundances and characteristics of MPs in air and tidal water were detected to analysis the potential sources of MPs on non-submerged and submerged mangrove leaves (Table S1). Significant linear relationships were observed between the MPs with various characteristics in air and on non-submerge leaves (Spearman correlation coefficients $^*p < 0.05$), except for the MPs with characteristics of uncolored, PS and foam. The results suggested air was the primary source and pathway for MPs on non-submerge mangrove leaves from landward to seaward region in Beibu Gulf. The only exception was mainly due to the MPs with foam characteristic, in comparisons to other MPs, displayed much less adhesive forces to both epicuticular wax layer and clay mineral at mangrove leaves (Liu et al., 2006), making less foam MPs deposited on non-submerged mangrove leaf.

Regarding to the submerged mangrove leaves, a significantly positive linear relationship was obtained between the total abundance of MPs in the exposed environmental matrixes (tidal water and air) and on submerged mangrove leaves (Spearman correlation coefficients $^*p < 0.05$). Further analysis demonstrated that there existed significant correlations between MPs with different characteristics in tidal water and on submerged mangrove leaves, while the results for MPs in air were almost completely opposite with p values higher than 0.05 (Table S2 and S3). It implied the role of tidal water was superior to that of air in the sources of MPs on submerged mangrove leaves. Additionally, the disappearances of MPs with foam characteristics in submerged mangrove leaves are exceptional, which were largely due to the relative high level of MPs in tidal water masked the abundance and characteristics fluctuation degree of MPs. Extreme weather, such as typhoon, crush the common used plastic in aquaculture to MPs, and these MPs are transported to the mangrove leaves via air pathway, leading to the experimental outliers of MPs on non-submerge mangrove leaves (Wang et al., 2019; Chen et al., 2021). Whereas the effects of extreme weather were partly attenuated by tidal water, providing a relatively stable environmental conditions for the retention of MPs on submerge mangrove leaves (Deng et al., 2021; Zamprogno et al., 2021).

Thirty-five percent of the mangroves worldwide have disappeared due to increasing pollution and human destruction, and the amount of mangroves continues to decline by 1–2% a year (Hamilton and Casey, 2016; Kovacs et al., 2015). According to the latest data of global mangrove area measurement (8849 ha) (Zhang et al., 2021), the mean value of MPs at non-submerged (0.169 n/cm^2) and submerged mangrove leaves (0.226 n/cm^2) in this survey, and the mangrove leaf area index (LOI) of 1.81, it was estimated that approximately 2.58×10^{11}-3.46×10^{11} MPs were present on mangrove leaves of Guangxi provinces. It implied that mangrove leaves played a nondeductible role in MPs retention in mangrove wetland. For comprehensive understanding of the process and mechanism of mangrove plants in capturing of MPs, the individual contribution of mangrove leaves and roots need to be further investigated.

4. Conclusion

Abundances of MPs on non-submerged (0.09–0.24 n/cm^2) and submerged (0.10–0.49 n/cm^2) mangrove leaves on Beibu Gulf were firstly detected in this study, revealing that mangrove leaves were indispensable potential sink for coastal MPs. The MPs abundances on non-submerged mangrove leaves were dominated by their contents in air, while the tidal water exhibited a significant positive effect on the MPs abundances on submerged mangrove leaves. For the spatial distribution of MPs, the urbanization and human activities were not critical factors. Indeed, continuous and high-speed tidal water was the dominant factor responsible for the MPs abundances on submerged mangrove leaves, following the order landward region > middle region > seaward region.

CRediT authorship contribution statement

We have made substantial contributions to the conception or design of the work, as well as the acquisition, analysis, or interpretation of experimental results for this study; We have drafted the work or revised it critically for important intellectual content; We have approved the final version to be published; We agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

All persons who have made substantial contributions to the present study have been reported in the manuscript and have given their written permission to be named.

Haifeng Sun: Conceptualization, Supervision, Project administration. **Ruilong Li:** Investigation, Writing – review & editing. **Chaoxian Wei:** Data curation, Writing – original draft. **Meng Jiao:** Methodology. **Yijin Wang:** Editing.

Declaration of Competing Interest

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 paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jhazmat.2021.128138.

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