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Distribution pattern and influencing factors for the microplastics in continental shelf, slope, and deep-sea surface sediments from the South China Sea☆

Yongcheng Ding[a,b], Xinqing Zou[a,b,c,*], Hongyu Chen[a,b], Feng Yuan[a,b], Qihang Liao[a,b], Ziyue Feng[a,b], Qinya Fan[a,b], Ying Wang[a,b], Guanghe Fu[a,b,c], Wenwen Yu[d]

[a] *School of Geography and Ocean Science, Nanjing University, Nanjing, 210023, China*
[b] *Ministry of Education Key Laboratory for Coastal and Island Development, Nanjing University, Nanjing, 210023, China*
[c] *Collaborative Innovation Center of South China Sea Studies, Nanjing University, Nanjing, 210023, China*
[d] *Marine Fisheries Research Institute of Jiangsu Province, Nantong, 226007, China*

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A B S T R A C T

Marine microplastic pollution has become a major global concern in recent years and the fate of microplastics in the ocean is a hot issue of research. We investigated microplastic pollution in surface sediments in the northern South China Sea to explore its distribution characteristics and influencing factors across the continental shelf, continental slope, and deep-sea environments. It was found that the microplastic abundance of surface sediments was 130.56 ± 40.48 items/kg. The average abundance of microplastics in all three topographic areas gradually decreased with increasing distance offshore. However, the differences in microplastic diversity indices between the three areas were not significant and were higher than those in other seas of the world, indicating that the waters of the northern South China Sea are rich in microplastics from complex sources, with more pollution input channels. In the continental shelf, fibrous and low density microplastics accounted for the largest amount, with a low degree of microplastic aging, and were mostly transported by suspended-load. These microplastics were mainly influenced by human activities. In the deep sea, microplastics with higher density were the most abundant and the number of fibrous microplastics was fewer, while the average size was larger, mainly influenced by the bottom currents. These microplastics underwent long-term bedload transport. In the continental slope, the main factors affecting the distribution of microplastics were more complex. In addition to pollution by human activities, the slope also receives microplastic materials carried by bottom currents; therefore, the composition of microplastics in the slope combines those characteristics of microplastics in both the continental shelf and deep-sea areas. The findings of this study indicate that the South China Sea is affected by complex pollution sources under the dual effects of human activities and natural conditions; in particular, the pollution situation in the deep-sea area needs extensive attention.

1. Introduction

Approximately 6.3 billion tons of plastic waste were globally generated between 1950 and 2015, with 79% having been either discarded or buried (Geyer et al., 2017). Meanwhile, the rate of accumulation of plastic waste in oceans is rapidly increasing (Bergmann et al., 2017). Once disposed, plastic waste is gradually broken up by physical and chemical activities to form microplastics: debris under 5 mm in diameter (Thompson et al., 2004). Microplastics are widely distributed in various environmental media, and different types microplastics have been detected in water bodies, the atmosphere, and seabed sediments (Ding et al., 2021; Liu et al., 2021; Zhong and Peng, 2021; Zuo et al., 2020). Microplastics are mostly resistant to aging and degradation (Cui et al., 2021) and may persist in environmental media for hundreds of years (Cozar et al., 2014). Therefore, microplastic pollution has become a major global environmental issue alongside climate change, ozone depletion, and ocean acidification (Galloway and Lewis, 2016).

Microplastics settle and remain buried in the seafloor for long

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* Corresponding author. School of Geography and Ocean Science, Nanjing University, Nanjing, 210023, China.
E-mail address: zouxq@nju.edu.cn (X. Zou).

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periods when subjected to gravity or bioturbation, or when attached to microorganisms and organic matter (Patti et al., 2020). The total amount of microplastics on the global seafloor may be as much as approximately 14 million tons which is over 35 times the total estimated amount of microplastics in seawater (Barrett et al., 2020). Therefore, marine sediments may be the ultimate carrier for microplastic sinks in sedimentary environments in shallow nearshore, deep-sea, and submarine canyons (Van Cauwenberghe et al., 2015). Microplastics in sediments have become considered as the "technological fossils" of the Anthropocene (Patti et al., 2020; Zalasiewicz et al., 2016), as many researchers have reported on the fate of microplastics in seafloor sediments worldwide. For example, Qi et al. (2022) found that microplastic abundance in sediments decreased from the nearshore to the open ocean based on 26 surface sediment samples collected from deep-sea basins in the East Indian Ocean, while the microplastic spatial distribution was influenced by land-based inputs, riverine inputs, and human activities. Ling et al. (2017) found that hydrological conditions and sediment matrix properties played an important role in the deposition and retention of microplastics in marine sediments from 42 coastal and estuarine sites in southeastern Australia. Cunningham et al. (2020) concluded that microplastics had a similar dispersion behavior to low-density sediments from studying 30 deep-sea sediment cores from Antarctica and the Southern Ocean. Zhong and Peng et al. (2020) used a manned submersible to identify plastic litter accumulation in a submarine canyon in the northwestern South China Sea, demonstrating that the dispersal of deep-sea litter could be initially controlled by gravity currents, while turbidity currents may transfer plastic litter to deeper seafloors.

The South China Sea is the largest marginal sea in Southeast Asia and is at high risk of microplastic contamination due to intense human activity. Several studies have hypothesized that it may be a microplastic "reservoir" based on its content in the water (Cai et al., 2018; Woodall et al., 2014). However, there is still a lack of research on the end-media sediments that absorb microplastics in the South China Sea. In this study, we analyzed 32 surface sediment sampling sites in the northern South China Sea to (1) investigate the distribution characteristics of microplastics in different topographic areas in the northern South China Sea; (2) identify the main factors influencing the distribution of microplastics in that region; and (3) determine the complexity of microplastic assemblages in that region using a microplastic diversity index.

2. Materials and methods

2.1. Study area

The northern South China Sea was studied from 109° E to 122° E and 16° N to 22.5° N, covering part of the continental shelf, continental slope, and deep-sea areas (Fig. 1). The seafloor topography is high in the west and low in the east. The Xisha, Zhongsha, and Dongsha islands are distributed in the southwestern, southern, and northeastern ends of the study area, respectively, with complex sources of material and variable seafloor topography (Peng et al., 2018). The Shenhu area (Fig. 2b), situated between the Xisha Trough and the Dongsha Trough, is the transition zone between the land slope and the deep-sea basin (Yang et al., 2020). Based on water depth, we classified longshore areas shallower than 200 m as continental shelf, areas between 200 and 3000 m as continental slope, and areas deeper than 3000 m as deep-sea. Please see Table S1 for details on sampling stations.

2.2. Sample collection

Samples were collected in October 2019 by the "SHIYAN 1" scientific research vessel of the South China Sea Institute of Oceanology, Chinese Academy of Sciences, and in September 2020 by the "XIANGYANG

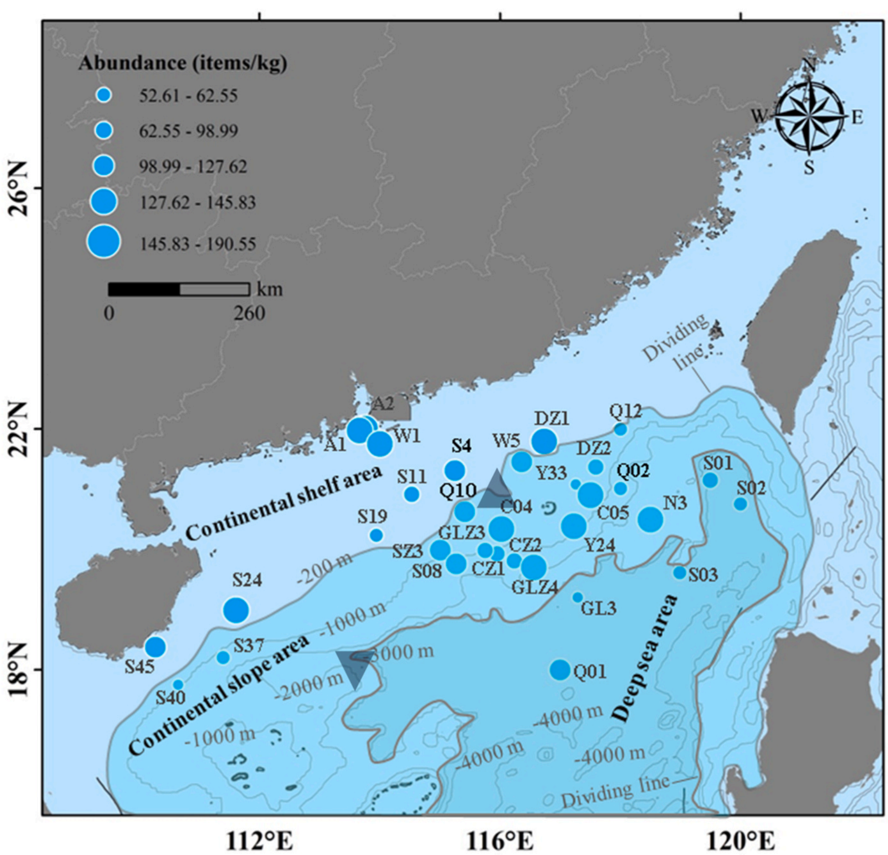

Fig. 1. Sampling stations in the northern South China Sea. The triangle and the inverted triangle represent the Dongsha and the Xisha troughs, respectively.

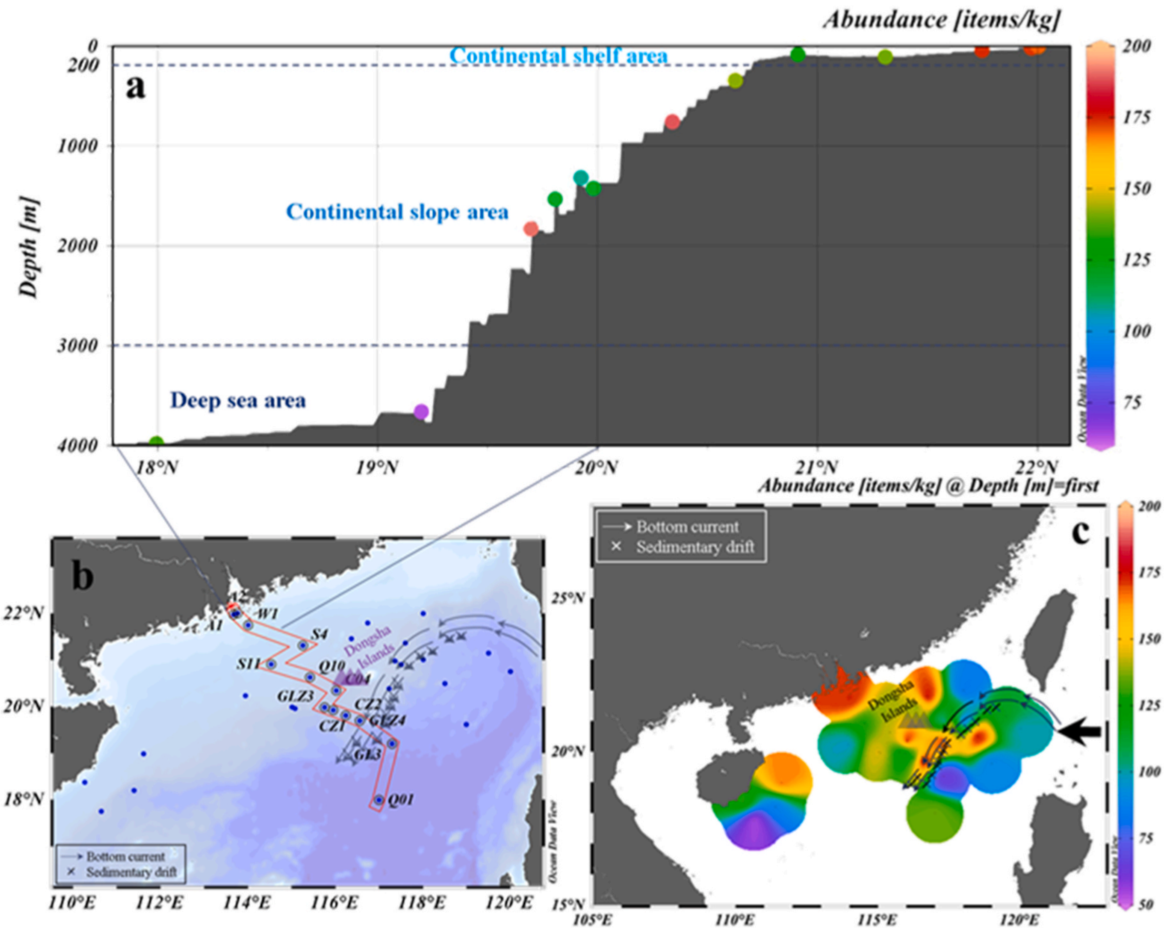

Fig. 2. (a) Microplastic abundance in cross-sectional view. (b) Sampling stations. (c) Microplastic abundance in surface sediments of the northern South China Sea.

HONG 18" research vessel of the First Institute of Oceanography, Ministry of Natural Resources of China. Sediments from 32 stations were collected using an onboard box sampler, from which approximately 500 g of surface sediment (0–5 cm) was collected in clean aluminum boxes using a stainless-steel spatula, stored at 4 °C for one month, then transported to the laboratory for processing.

2.3. Sampling method

Microplastics were extracted as follows. Each sediment sample of 50–100 g wet weight was dried in an oven (DHG-9203 A, Shanghai, China) for 12 h at 100 °C until a constant weight was achieved. The moisture content was calculated by the weight difference. The dried samples were homogenized with a mortar and pestle and transferred to a clean 2 L glass beaker, followed by the addition of 100 mL sodium hexametaphosphate (51 g/L) as a dispersant, before being stirred for 2–5 min and then dried at 65 °C (Wu et al., 2021). A saturated solution of potassium iodide (1.66 g/cm^3) was added to the dry sediment, placed on a magnetic stirrer (Wiggen Hauser, Straubenhardt, Germany) for 30 min, and left to stand to allow separation of the solid–liquid layer, followed by filtering the supernatant through a nylon filter membrane (Millipore, Massachusetts, U.S.A.) using a 47 mm glass sand core filter (Kaishide, Yancheng, China). The material retained on the membrane was transferred to 300 mL of 30% hydrogen peroxide solution for digestion. After covering the mouth of the beaker with aluminum foil and waiting for approximately 48 h, the reaction in the beaker stopped, the solution was clarified, and the digestion process was considered complete. Finally, the solution was filtered using a new nylon membrane, and then the membrane and retentate on the membrane were transferred to a transparent filter cartridge (Ximeng, Shanghai, China) with a diameter of 47 mm for storage.

2.4. Microplastics observation and identification

The dried membranes were observed under a stereomicroscope (Leica Microsystems, Wetzlar, Germany). The total particle number and length were recorded and sorted according to the morphology and color of the microplastics. The composition of all suspected microplastic particles was identified using a Fourier transform infrared micro-spectroscopy (Thermo Nicolet iN10, Waltham, U.S.A.) with a spectral range of 675–4000 cm^{-1} using 32 scans at 4 cm^{-1} resolution. Samples with a match of >70% were considered plastics by comparison with a common spectral library (Mecozzi et al., 2016).

2.5. Microplastic diversity index

Considering that microplastic color and shape are more susceptible to physicochemical processes than microplastic type, we chose to use a modified microplastic diversity index (*MDI*) (Wang et al., 2019) based on Simpson's diversity index (Lou, 2006; Simpson, 1949) to analyze the complexity of microplastic assemblages in different areas using the following Equations (1) and (2):

$$q = n_i / N, \tag{1}$$

$$\mathrm{MDI} = 1 - \sum_{i}^{s} q_{2}, \tag{2}$$

where n_i is the number of individuals in the ith microplastic type, N is the total number of microplastics, S is the total number of microplastic types, and q is the proportion of different types of microplastics. The range of the *MDI* is between 0 and 1; values closer to zero reflect a lower plastic particle diversity (Li et al., 2020).

2.6. Carbonyl index

According to the detection of Fourier transform infrared microspectroscopy, most of the microplastic samples appeared to be aging. This was determined based on the formation of carbonyl groups (C═O), which is considered an effective indicator for evaluating the aging degree of polymers (Di Pippo et al., 2020). Several studies have used the carbonyl index (*CI*) to quantify the aging of plastics. The *CI* is the ratio of the carbonyl peak intensity to the reference peak intensity, with the reference peak position being consistent with the published literature (Di Pippo et al., 2020; Zhang et al., 2010). The *CI* was calculated using Equation (3):

$$CI = \text{peak intensity of the carbonyl peak /peak intensity of the reference peak} \quad (3)$$

2.7. Quality control and quality assurance

A clean pre-treatment environment ensures the reliability of microplastics data (Wesch et al., 2017). Strict experimental standards were applied during field sampling and indoor experiments. Nitrile gloves were worn during sampling while stainless steel spatulas and aluminum boxes were washed three times with Milli-Q water before use. For indoor experiments, benches and laboratory equipment were cleaned with Milli-Q water before use, glassware was covered with aluminum foil when not in use, and cotton laboratory coats, nitrile gloves, and masks were utilized. A clean blank film was placed near all samples during sample analysis to correct the environmental background.

2.8. Data analysis

The abundance of all microplastics was calculated as the number of particles per kg of dry sediment (items/kg dw). Graphs were plotted using Origin 2019b (Origin Lab Corporation, Northampton, MA), ArcGIS 10.1, and Ocean Data View 5.3.0, and the data were analyzed using Microsoft Excel 2019 and SPSS 18.0. One-way analysis of variance (one-way ANOVA) and Duncan's multiple comparisons were used to test for any differences. Tamhane's T2 multiple test was used instead of Duncan's test when the variances were unequal. Spearman's test was used to perform correlation tests. Non-metric multidimensional scaling (NMDS) was used to analyze between-group similarity for microplastic data within areas. All data were tested for normality using the Shapiro–Wilk test.

3. Results and discussion

3.1. Microplastic distribution and influencing factors

A total of 382 microplastics were identified from 32 surface sediment samples (Fig. 1), with abundances ranging from 52.61 to 190.55 items/kg (mean: 130.56 ± 40.48 items/kg; Fig. 2, Fig. S1, Table S1). The abundance of microplastics in the continental shelf, continental slope, and deep-sea areas were 151.16, 128.64, and 100.42 items/kg, respectively (Fig. 3a), with a significant difference in microplastic abundance between the shelf and deep-sea areas (one-way ANOVA, $p < 0.05$).

The average microplastic abundance in surface sediments of the northern South China Sea, which is the largest marginal sea in China, is larger than that of the Yellow Sea (42.80 items/kg) (Zhao et al., 2018) and East China Sea (121.00 items/kg) (Peng et al., 2017), and lower than that of the Bohai Sea (171.80 items/kg) (Zhao et al., 2018). There is extensive deposition of anthropogenically discharged plastic waste at the bottom of the Bohai Sea, mainly due to the closed environment resulting in weak hydrodynamic conditions and poor seawater circulation (Dai et al., 2018). Compared with other marine areas in the world, the average abundance in the northern South China Sea is at a moderate level (Table S2). The heterogeneous distribution of microplastics in different marine areas in the world indicates that they are affected by many different factors.

As shown in Fig. 2, the continental shelf areas with the higher average abundance are the most affected by human activities since they are close to the highly industrialized and densely populated Pearl River Delta (e.g. A1, A2, W1), which receives a large amount of factory wastewater discharge, ship discharge, and domestic waste (Ding, 2019). The positive correlation (Spearman's test, $p < 0.05$) between microplastic abundance and increasing offshore distance in the shelf also indicates that the shelf is strongly influenced by land-based sources (Fig. 3b). In addition, the shallow depth of seawater in the continental shelf area coupled with the gentle slope of the seafloor can be assumed to facilitate the accelerated deposition of many types of microplastics and land-based input (Jang et al., 2020) (Table S3). Sediment input from land is an important route for microplastics to enter the ocean (Harris, 2020). The high abundance of microplastics in the continental slope is

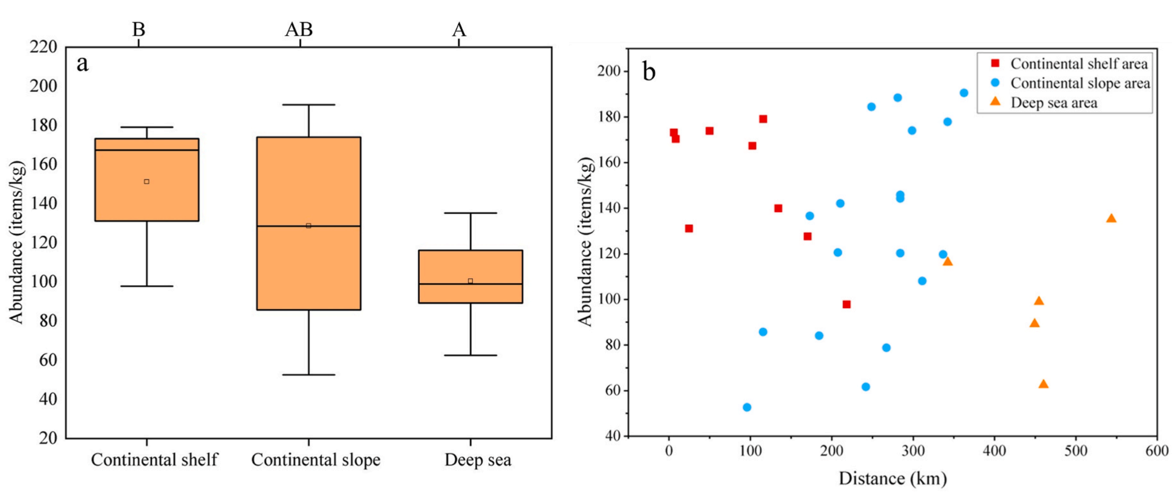

Fig. 3. (a) Microplastic abundance in three areas (the absence of the same capital letter between areas represents a significant difference), and (b) microplastic abundance in three areas versus shoreline distance.

mostly located in the Shenhu landslide area in the lower part of the slope fold (Fig. 2a). The abundant source of material from the Pearl River Delta facilitates the accumulation of benthic sand and deltaic deposits along the shelf edge of the Shenhu area. These sediments were mostly uncompacted or poorly compacted, which provides source material for landslides (Chen et al., 2012) and facilitates the accumulation of abundant land-derived microplastics. The transport of bottom currents also contributes to microplastic accumulation in this area; their movement is similar to that of surface currents (Kane et al., 2020). Models of microplastic transport suggest that some bottom currents have shear stresses close to or exceeding those required to carry fibers and debris, and indicate that previously deposited microplastics may be resuspended (Kane et al., 2020). Strong deep-water underflow activity exists throughout the study area (Luedmann et al., 2005; Shao et al., 2007) (Fig. 2b). The bottom currents transport sediment and microplastics along the northern slope of the South China Sea towards the southwest, and eventually enter into the sea's central basin. In this study, the areas with high microplastic abundance on the continental slope were mostly located along the movement path of the bottom currents (Fig. 2b); the northern part of the high-abundance area is close to the Dongsha Islands (Fig. 2a), and material from its southeastern slope is transported along its northeast-southwest slope. Similarly, studies have confirmed that strong, fast bottom currents recorded in deep-sea submarine canyons can allow microplastics to accumulate at the seafloor (Kane et al., 2020), as well as play an important role in the lateral transport of microplastics globally (Kane et al., 2020; Pohl et al., 2020). In recent years, multiple turbidity signals have been predicted and detected in the northern South China Sea, implying the influence of bottom currents on microplastic transport (Li et al., 2020; Zhang et al., 2018).

Deep-sea areas which are less affected by human activities were also found to have accumulated microplastics. Therefore, the factors affecting the distribution of microplastics in surface sediments of the seafloor is complex, with seafloor currents and seafloor topography serving as potentially important drivers of microplastic accumulation (Kane et al., 2020; Pohl et al., 2020).

3.2. Morphological characteristics of microplastics

Fragmented and fibrous plastics (37% and 32%, respectively) were the most abundant, with granular plastics (25%) also being plentiful (Fig. 4a). However, film (4%) and foam plastics (2%) accounted for only a small percentage of the total microplastics. Fragmented and granular microplastics are mainly derived from the decomposition of large industrial products and waste product degradation (Peng et al., 2020; Shim et al., 2018). Large quantities of these in the northern South China Sea is likely derived from industrial products in the southeastern coastal region such as Guangdong Province, which added the greatest industrial value to China in 2020 (Statistics Bureau of Guangdong Province, 2021). The plastic product production and output value of this region consistently ranked first in China (National Bureau of statistics of the People's Republic of China, 2021). Meanwhile, the well-developed fishery farming activities in the coastal areas of the South China Sea may be an important source of fibrous plastics since fishing nets, ropes, and other equipment placed in the water are highly susceptible to shedding fibers (Sun et al., 2018). Similarly, municipal wastewater discharged from washing clothes contains large amounts of fibrous material that collect in the estuary and flow into the sea (Xiong et al., 2019; Zhao et al., 2015). Relatively small amounts of film and foam-like plastics are likely to come from the cracking and shredding of plastic bags and cushions used in everyday life, as well as from agricultural production (Sun et al., 2018). In recent years, the Chinese government has implemented stringent "plastic bans" by regulating the use of everyday plastic products at the general population level, and the number of residents littering plastic film and foam in coastal areas of China has reduced accordingly.

In terms of color, white microplastics were the most abundant (47%), followed by black (26%), blue (10%), transparent (8%), yellow (5%), red (3%), and green (1%) (Fig. 4b). Blue microplastics are mostly derived from fishing gear (Possatto et al., 2011). Some of the microplastic colors may be similar to that of natural marine food in the ocean (Abayomi et al., 2017; Pan et al., 2019), leading to color-specific

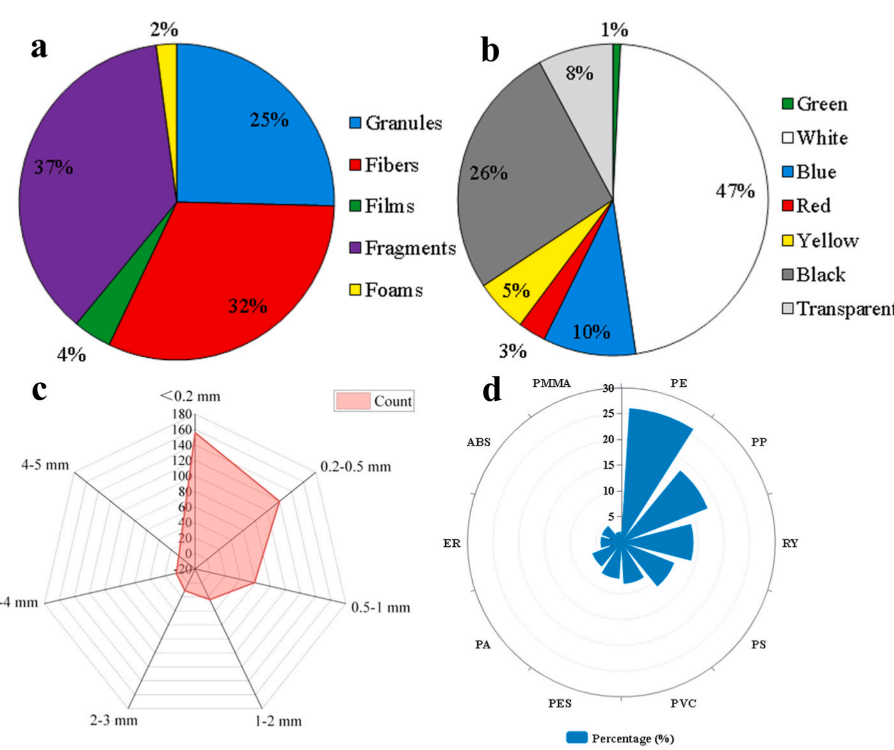

Fig. 4. Microplastic characteristics: (a) Shape, (b) color, (c) size, and (d) percentage of all types. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

ingestion by marine organisms (Yuan et al., 2021). The clear and white plastic fragments ingested by sea turtles often result in their death (Bugoni et al., 2001).

In terms of microplastic particle size, the range for the entire study area was 50–4800 μm, with an average length of 534 μm. The particle size was concentrated below 500 μm (72%), with 41% below 200 μm (Figs. 4c), and 16%, 6%, and 6% of microplastics ranged between 500 and 1000, 1000–2,000, and 2000–5000 μm, respectively. Similar to results obtained in previous studies (Cozar et al., 2014; Zhang et al., 2020), the particle size of microplastics below 500 μm accounted for more than 50% of the total, suggesting that most of the smaller-sized microplastics enter the sediment from the water. One assumption is that smaller microplastics may sink to the seafloor through attachment to feces or marine snow (Galloway et al., 2017; Zhang et al., 2020). This is concerning since smaller microplastics may be more toxic to marine organisms (Kögel et al., 2020; Qi et al., 2022).

3.3. Polymer types and sources of microplastics in sediments

The main types of plastics found in surface sediments in the northern South China Sea were polystyrene (PS), polypropylene (PP), polyethylene (PE), polyester (PES), polyvinyl chloride (PVC), rayon (RY), polyamide (PA), epoxy resin (ER), acrylonitrile butadiene styrene (ABS), and polymethyl methacrylate (PMMA) (Fig. 4d). The southeast coast of China has a well-developed industrial trade, port, and shipping industry, indicating that it contributes to many types of microplastic pollution. The most abundant plastic type was PE (26%) which was identified in 91% of the stations, followed by PP (18%) (Fig. 5a). There was 14%, 11%, 8%, 7%, 6%, 4%, 4%, and 2% of RY, PS, PVC, PES, PA, ER, ABS, and PMMA, respectively, with PMMA identified at only four stations. PP and PE are currently the two most common plastic types (Mai et al., 2019), used to produce a variety of industrial and residential products (Liu, 2020). They have been found in relatively high abundance in the surface marine sediments from several Asian countries (Zhang et al., 2020). In addition, China has the highest production capacity for PP and PE globally; they are the two most common types used in China (China Plastic Processing Industry Association, 2021). The mass production and use of PP and PE as the main raw material for daily and industrial products inevitably generates a large amount of waste that is discharged into the sea. PA, PVC, and PS are mostly derived from farming devices such as ropes and foam floats. Prolonged immersion and wear-and-tear may also cause the proliferation of microplastics (Hinojosa and Thiel, 2009). Meanwhile, PES and RY are the main fiber types derived from textile products such as clothing, which easily shed and enter the sea through washing or by atmospheric deposition (Ding et al., 2021; Zhou et al., 2017). ER, ABS, and PMMA, which were identified in smaller quantities in this study, are mostly used in lubricants, preservatives, and other products of high-performance industries; presumably they are mainly sourced from vessels engaged in commercial marine activities (Ding, 2019).

3.4. Distribution patterns of microplastics in different topographic areas

Regarding the proportion of microplastic types across the three topographic areas (Fig. S2a), we found that the proportion of fibers showed a decreasing trend from the continental shelf to the deep sea. Fiber behavior in the ocean is completely different from that of debris and particles because they have a relatively large surface area and mass, resulting in a very low settlement velocity, as well as transportation in the form of suspended matter and easy discharge from the high-energy tidal environment on adjacent coasts or shelves (Harris, 2020).

The longer the aging of the microplastics in seawater, the higher the *CI* and the lighter the color (Rodríguez-Seijo and Pereira, 2016). We calculated the average *CI* of the five types of microplastics identified in the three areas (Fig. S2b). The proportion of these five types of microplastics exceeded 65% of the total, and their characteristic peaks and reference peaks were obvious. In this study, the PP, PE, PES, RY and PS carbonyl peaks were located at 1735.69, 1712.55, 1616.12, 1643.12, and 1670.12 cm^{-1}, respectively, and the reference peaks were located at 975.85, 721.28, 2969.97, 2900.54, and 2923.68 cm^{-1}, respectively. We found that the average *CI* of microplastics in the different areas ranked as follows: continental shelf < continental slope < deep sea. Meanwhile, the color of the microplastics in the deep-sea area was lighter and showed signs of discoloration, indicating that microplastics in the deep-sea area had been submitted to longer and more intense physicochemical processes by seawater.

Notably, the average particle size of microplastics in the three areas ranked as follows: deep sea (801 μm) > continental shelf (529 μm) > continental slope (477 μm), with significant differences between the deep-sea and continental shelf areas (one-way ANOVA, $p < 0.05$) and between the deep-sea and continental slope areas (one-way ANOVA, $p < 0.05$) (Fig. S3a). This indicates that large microplastic particles are more easily found in the deep sea. Combining the densities of the different types of microplastics (weighted average density of all microplastics in the study = 1.13 g/cm^3; Text S1), we found that the proportion of denser plastics (> 1.13 g/cm^3) (PVC, RY, ER, PMMA, and PES) in the deep-sea area was 51%, while on the continental shelf and slope, it was only 31% and 29%, respectively (Fig. S3b). This is consistent with Harris's (2020)

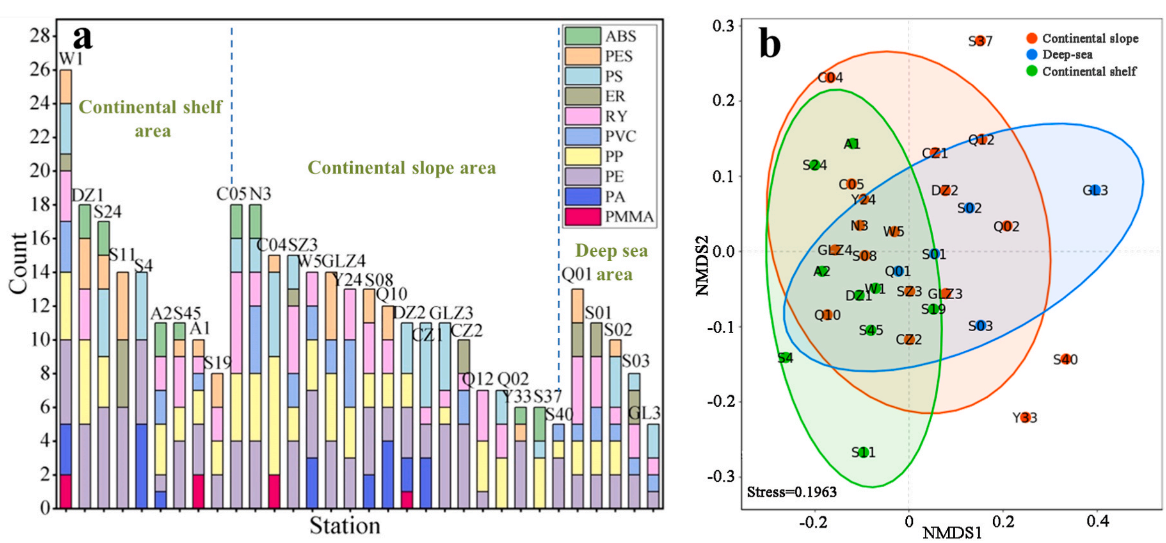

Fig. 5. (a) Different types of microplastics in each sampling station, and (b) NMDS of microplastics.

findings, which showed that, compared to those in offshore environments, many large-sized and high-density microplastics in deep-sea areas are transported in the bedload, enabling hydraulic sorting and deposition together with sediment particles.

Generally, low-density, small-sized microplastics are mainly transported in continental shelf area in the form of suspended-load rather than bedload. On the other hand, microplastics with large particle size and high density are mainly transported in deep-sea areas in the form of bedload. They undergo a fragmentation and size reduction process until the plastic particles are sufficiently small such that they can no longer be transported as bedload, whereas the transport of microplastics as suspended-load is not affected by mechanical breakage. This explains the high aging degree of microplastics in deep-sea samples observed in this study.

3.5. Microplastic diversity in the northern south China sea

NMDS is a data analysis method that reduces a multidimensional object (sample or variable) to a low-dimensional space for localization, analysis, and categorization while retaining the original relationships between the objects (Fan et al., 2022). The microplastic type, color, shape, and particle size data from each station in the three areas were analyzed using NMDS and showed that the developed model is reasonable (stress < 0.2) (Data-S1; Fig. 5b). The sampling points between the three areas overlap across a large area and are not clearly separated; only a few individual points were farther away, indicating that the difference between groups is small and that the physicochemical characteristics of the microplastics is relatively similar across the three areas. The microplastic diversity indices were 0.85, 0.84, and 0.79 for the continental shelf, continental slope, and deep-sea areas, respectively. An overall value of 0.84 was obtained for the entire study area, which is higher than that in all other oceanic areas that met the calculation requirements (Table S2). This mainly includes the Eastern Indian Ocean (0.54) (Qi et al., 2022), Western Pacific Ocean (0.65) (Zhang et al., 2020), Mediterranean Coastal Zone (0.71) (Graca et al., 2017), Baltic Sea (0.66) (Tata et al., 2020), and Canadian Arctic Circle (0.56) (Adams et al., 2021). Overall, the microplastic diversity index in all three areas was high and did not significantly differ (one-way ANOVA, $p > 0.05$) (Table S4). This validates the NMDS results and indicates the richness and complexity of microplastic sources in the northern South China Sea. The transport of microplastics from the shallow (shelf-zone) to deep-water areas where there is almost no human activity implies that their final destination may be deep-sea sediments (Zhong and Peng, 2021). The transport of bottom currents can also explain the high microplastic diversity in the deep-sea area of this study.

Similar to the factors affecting the abundance of microplastics, the prominent microplastic diversity index in the northern South China Sea reflects the diversity of regional pollution input channels and high activities such as large coastal litter discharges, active bottom current movements, and intensive marine navigation, all of which are high-risk sources of plastic contamination.

4. Conclusions

The contamination of microplastics in surface sediments of the northern South China Sea and the main factors affecting microplastics distribution across different topographic areas were investigated. The average abundance of microplastics in surface sediments from the northern South China Sea was 130.56 ± 40.48 items/kg; the main shapes were fragmented (37%) and fibrous (32%); the most common color was white (47%); the most common type was PE (26%); and the microplastic particle size was mainly below 500 μm (72%), with 41% of this fraction being below 200 μm. The average abundance of microplastics in different areas ranked as follows: continental shelf > continental slope > deep sea, and the abundance of microplastics in the continental shelf area is significantly higher than that in the deep-sea area. The diversity indices of microplastics in the continental shelf, continental slope, and deep-sea areas do not significantly differ, but are higher than that of other marine areas in the world, indicating that microplastics in the northern South China Sea are of complex origin. This also suggests that the study area contains more channels for pollution input and has more frequent regional activities which contribute to a higher risk of contamination. The impact of human activities is the main factor affecting the microplastic abundance and diversity in the continental shelf area, with land-based emissions being the main source of pollution. The abundance is significantly and positively correlated with shoreline distance. Low-density (<1.13 g/cm^3) and fibrous microplastics account for a relatively large amount and have low microplastic aging, and tend to undergo transport in suspended-load materials. The deep-sea area is mainly influenced by the microplastic-carrying effect of bottom currents, with a higher proportion of high-density microplastics (>1.13 g/cm^3) and a higher degree of microplastic aging overall than in the continental shelf area, while the average particle size is larger and the amount of fibrous microplastics is lower. The continental slope area is affected by more complex factors, receiving pollutants from both land-based sources and underwater currents. The composition of microplastics combines the characteristics of continental shelf and deep-sea areas and the distribution is spatially heterogeneous. We suggest that the widespread distribution of microplastics in the northern South China Sea implies that seafloor sediments are the ultimate resting place of microplastics and that deep-sea areas potentially pool large amounts of microplastics. This requires greater attention from society and the government to control the source of the contamination by reducing land-based emissions to slow the increase in total microplastics in the ocean.

Author statement

Yongcheng Ding: Investigation, Data curation, Writing – original draft, Formal analysis. Xinqing Zou: Conceptualization, Supervision, Resources, Methodology. Hongyu Chen: Methodology, Visualization. Feng Yuan: Software. Qihang Liao: Software. Ziyue Feng: Visualization. Qinya Fan: Software. Chuchu Zhang: Investigation. Ying Wang: Methodology. Guanghe Fu: Resources. Wenwen Yu: Investigation.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2022.119824.

References

Abayomi, O.A., Range, P., Al-Ghouti, M.A., Obbard, J.P., Almeer, S.H., Ben-Hamadou, R., 2017. Microplastics in coastal environments of the Arabian Gulf. Mar. Pollut. Bull. 124 (1), 181–188.

Adams, J.K., Dean, B.Y., Athey, S.N., Jantunen, L.M., Bernstein, S., Stern, G., Diamond, M.L., Finkelstein, S.A., 2021. Anthropogenic particles (including microfibers and microplastics) in marine sediments of the Canadian Arctic. Sci. Total Environ. 784, 147155.

Barrett, J., Chase, Z., Zhang, J., Holl, M.M.B., Willis, K., Williams, A., Hardesty, B.D., Wilcox, C., 2020. Microplastic pollution in deep-sea sediments from the great Australian bight. Front. Mar. Sci. 7.

Bergmann, M., Wirzberger, V., Krumpen, T., Lorenz, C., Primpke, S., Tekman, M.B., Gerdts, G., 2017. High quantities of microplastic in Arctic deep-sea sediments from the HAUSGARTEN observatory. Environ. Sci. Technol. 51 (19), 11000–11010.

Bugoni, L., Krause, L., Petry, M.V., 2001. Marine. Debris and human impacts on sea turtles in southern Brazil. Mar. Pollut. Bull. 42 (12), 1330–1334.

Cai, M., He, H., Liu, M., Li, S., Tang, G., Wang, W., Huang, P., Wei, G., Lin, Y., Chen, B., Hu, J., Cen, Z., 2018. Lost but can't be neglected: huge quantities of small microplastics hide in the South China Sea. Sci. Total Environ. 633, 1206–1216.

Chen, S., Sun, Y., Wu, S., 2012. Sea bottom landslide in the shenhu area on the north margin of south China sea and triggering mechanisms. Mar. Geol. Front. 28 (6), 40–45.

China Plastic Processing Industry Association (CPPIA), 2021. China Plastics Industry Yearbook 2021. Chemical Industry Press, Beijing, China.

Cozar, A., Echevarria, F., Gonzalez-Gordillo, J.I., Irigoien, X., Ubeda, B., Hernandez-Leon, S., Palma, A.T., Navarro, S., Garcia-de-Lomas, J., Ruiz, A., Fernandez-de-Puelles, M.L., Duarte, C.M., 2014. Plastic debris in the open ocean. Proc. Natl. Acad. Sci. U. S. A. 111 (28), 10239–10244.

Cui, Y., Chen, Y., Liu, X., Dong, S., Wu, B., 2021. Computational Redesign of a PETase for Plastic Biodegradation under Ambient Condition by the GRAPE Strategy. ACS Catal. 11, 1340-1350.

Cunningham, E.M., Ehlers, S.M., Dick, J.T.A., Sigwart, J.D., Linse, K., Dick, J.J., Kiriakoulakis, K., 2020. High abundances of microplastic pollution in deep-sea sediments: evidence from Antarctica and the southern ocean. Environ. Sci. Technol. 54 (21), 13661–13671.

Dai, Z., Zhang, H., Zhou, Q., Tian, Y., Chen, T., Tu, C., Fu, C., Luo, Y., 2018. Occurrence of microplastics in the water column and sediment in an inland sea affected by intensive anthropogenic activities. Environ. Pollut. 242, 1557–1565.

Ding, Y., 2019. Microplastics in the Surface Seawater of the Northeastern South China Sea and Western Pacific: Occurrence Characteristics and Management Approaches. Master Thesis. Xiamen University, Xiamen. China.

Ding, Y., Zou, X., Wang, C., Feng, Z., Wang, Y., Fan, Q., Chen, H., 2021. The abundance and characteristics of atmospheric microplastic deposition in the northwestern South China Sea in the fall. Atmos. Environ. 118389.

Di Pippo, F., Venezia, C., Sighicelli, M., Pietrelli, L., Di Vito, S., Nuglio, S., Rossetti, S., 2020. Microplastic-associated biofilms in lentic Italian ecosystems. Water Res. 187, 116429.

Fan, Y., Zheng, J., Deng, L., Rao, W., Zhang, Q., Liu, T., Qian, X., 2022. Spatiotemporal dynamics of microplastics in an urban river network area. Water Res. 212, 118116.

Galloway, T., Cole, M., Lewis, C., 2017. Interactions of microplastic debris throughout the marine ecosystem. Nat. Ecol. Evolut. 1, 116.

Galloway, T.S., Lewis, C.N., 2016. Marine. Microplastics spell big problems for future generations. Proc. Natl. Acad. Sci. USA 113 (9), 2331–2333.

Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv. 3 (7), e1700782.

Graca, B., Szewc, K., Zakrzewska, D., Dołęga, A., Szczerbowska-Boruchowska, M., 2017. Sources and fate of microplastics in marine and beach sediments of the Southern Baltic Sea—a preliminary study. Environ. Sci. Pollut. Res. 24 (8), 7650–7661.

Harris, P.T., 2020. The fate of microplastic in marine sedimentary environments: a review and synthesis. Mar. Pollut. Bull. 158, 111398.

Hinojosa, I.A., Thiel, M., 2009. Floating marine debris in fjords, gulfs and channels of southern Chile. Mar. Pollut. Bull. 58 (3), 341–350.

Jang, M., Shim, W.J., Cho, Y., Han, G.M., Song, Y.K., Hong, S.H., 2020. A close relationship between microplastic contamination and coastal area use pattern. Water Res. 171, 115400.

Kane, I.A., Clare, M.A., Miramontes, E., Wogelius, R., Rothwell, J.J., Garreau, P., Pohl, F., 2020. Seafloor microplastic hotspots controlled by deep-sea circulation. Science 368 (6495), 1140–1145.

Kögel, T., Bjorøy, Ø., Toto, B., Bienfait, A.M., Sanden, M., 2020. Micro- and nanoplastic toxicity on aquatic life: determining factors. Sci. Total Environ. 709, 136050.

Ling, S.D., Sinclair, M., Levi, C.J., Reeves, S.E., Edgar, G.J., 2017. Ubiquity of microplastics in coastal seafloor sediments. Mar. Pollut. Bull. 121 (1–2), 104–110.

Li, S., Li, W., Alves, T.M., Wang, J., Feng, Y., Sun, J., Li, J., Wu, S., 2020. Large-scale scours formed by supercritical turbidity currents along the full length of a submarine canyon, northeast South China Sea. Mar. Geol. 424, 106158.

Liu, G., 2020. China is the world's largest producer of plastic products, plastic pollution control calls for whole process management. Environ. life 2020 (7), 26–33.

Liu, M., Ding, Y., Huang, P., Zheng, H., Wang, W., Ke, H., Chen, F., Liu, L., Cai, M., 2021. Microplastics in the western Pacific and south China sea: spatial variations reveal the impact of Kuroshio intrusion. Environ. Pollut. 288, 117745.

Lou, J., 2006. Entropy and diversity. Oikos 113, 363e375.

Luedmann, T., Wong, H., Berglar, K., 2005. Upward flow of north Pacific deep water in the northern South China sea as deduced from the occurrence of drift sediments. Geophys. Res. Lett. 32, L05614.

Mai, L., You, S., He, H., Bao, L., Liu, L., Zeng, E.Y., 2019. Riverine microplastic pollution in the Pearl River delta, China: are modeled estimates accurate? Environ. Sci. Technol. 53 (20), 11810–11817.

Mecozzi, M., Pietroletti, M., Monakhova, Y.B., 2016. FTIR spectroscopy supported by statistical techniques for the structural characterization of plastic debris in the marine environment: application to monitoring studies. Mar. Pollut. Bull. 106 (1–2), 155–161.

National Bureau of statistics of the People's Republic of China (NBSPRC), 2021. China Statistical Yearbook 2021. China Statistics Press, Beijing, China.

Pan, Z., Guo, H., Chen, H., Wang, S., Sun, X., Zou, Q., Zhang, Y., Lin, H., Cai, S., Huang, J., 2019. Microplastics in the northwestern Pacific: abundance, distribution, and characteristics. Sci. Total Environ. 650, 1913–1922.

Patti, T.B., Fobert, E.K., Reeves, S.E., Burke Da Silva, K., 2020. Spatial distribution of microplastics around an inhabited coral island in the Maldives, Indian Ocean. Sci. Total Environ. 748, 141263.

Peng, C., Wang, P., Zhou, X., Yang, L., 2018. Bathymetry inversion based on gravity-geologic method in south China sea. Hydrogr. Surv. Charting 38 (2), 8–11.

Peng, G., Zhu, B., Yang, D., Su, L., Shi, H., Li, D., 2017. Microplastics in sediments of the Changjiang estuary, China. Environ. Pollut. 225, 283e290.

Peng, L., Fu, D., Qi, H., Lan, C., Yu, H., Ge, C., 2020. Micro- and nano-plastics in marine environment: source, distribution and threats — a review. Sci. Total Environ. 698, 134254.

Pohl, F., Eggenhuisen, J.T., Kane, I.A., Clare, M.A., 2020. Transport and burial of microplastics in deep-marine sediments by turbidity currents. Environ. Sci. Technol. 54 (7), 4180–4189.

Possatto, F.E., Barletta, M., Costa, M.F., Ivar Do Sul, J.A., Dantas, D.V., 2011. Plastic debris ingestion by marine catfish: an unexpected fisheries impact. Mar. Pollut. Bull. 62 (5), 1098–1102.

Qi, H., Li, H., Meng, X., Peng, Li, Zheng, H., Wang, L., Wang, W., Chen, K., Zhang, J., Zhang, H., Cai, M., 2022. Fate of microplastics in deep-sea sediments and its influencing factors: evidence from the Eastern Indian Ocean. Sci. Total Environ. 828, 154266.

Rodríguez-Seijo, A., Pereira, R., 2016. Chapter 3: morphological and physical characterization of microplastics [C]. Rocha-Santos T, Duarte A C. Compr. Anal. Chem. 75, 49–65. Netherlands: Elsevier.

Shao, L., Li, X., Geng, J., Pang, X., Lei, Y., Qiao, P., Wang, L., Wang, H., 2007. Deep water bottom current deposition in the northern South China Sea. Sci. China Earth Sci. 50 (7), 1060–1066.

Shim, W., Hong, S., Eo, S., 2018. Marine. microplastics: abundance, distribution, and composition. In: Zeng, E. (Ed.), Microplastic Contamination in Aquatic Environments. Elsevier, Amsterdam, pp. 1–26.

Simpson, E., 1949. The measurement of diversity. Nature 163, 688.

Statistics Bureau of Guangdong Province (SBGP), 2021. Guangdong Statistical Yearbook 2021. China Statistics Press, Beijing, China.

Sun, X., Liang, J., Zhu, M., Zhao, Y., Zhang, B., 2018. Microplastics in seawater and zooplankton from the Yellow Sea. Environ. Pollut. 242, 585–595.

Tata, T., Belabed, B.E., Bououdina, M., Bellucci, S., 2020. Occurrence and characterization of surface sediment microplastics and litter from North African coasts of Mediterranean Sea: preliminary research and first evidence. Sci. Total Environ. 713, 136664.

Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W., McGonigle, D., Russell, A.E., 2004. Lost at sea: where is all the plastic? Science 304 (5672), 838.

Van Cauwenberghe, L., Devriese, L., Galgani, F., Robbens, J., Janssen, C.R., 2015. Microplastics in sediments: a review of techniques, occurrence and effects. Mar. Environ. Res. 111, 5–17.

Wang, T., Zou, X., Li, B., Yao, Y., Zang, Z., Li, Y., Yu, W., Wang, W., 2019. Preliminary study of the source apportionment and diversity of microplastics: taking floating microplastics in the South China Sea as an example. Environ. Pollut. 245, 965–974.

Wesch, C., Elert, A., Wörner, M., Braun, U., Klein, R., Paulus, M., 2017. Assuring quality in microplastic monitoring: about the value of clean-air devices as essentials for verified data. Sci. Rep. 7, 5424.

Wu, Q., Liu, S., Chen, P., Liu, M., Cheng, S., Ke, H., Huang, P., Ding, Y., Cai, M., 2021. Microplastics in seawater and two sides of the Taiwan Strait: reflection of the social-economic development. Mar. Pollut. Bull. 169, 112588.

Woodall, L.C., Sanchezvidal, A., Canals, M., Paterson, G.L.J., Coppock, R., Sleight, V., Calafat, A., Rogers, A.D., Narayanaswamy, B.E., Thompson, R.C., 2014. The deep sea is a major sink for microplastic debris. R. Soc. Open Sci. 1 (4), 140317.

Xiong, K., Zhao, X., Zhou, Q., Fu, C., Tu, C., Li, L., Luo, Y., 2019. The pollution characteristics of microplastics in the water and sediments of Sanggou bay in the Yellow Sea. Mar. Environ. Sci. 38 (2), 8–11.

Yang, J., Yao, P., Zhang, X., 2020. The distribution and controlling factors of the concentration and structure of dissolved inorganic nutrients in the Shenhu Area, northern South China Sea. Hai Yang Xue Bao 42 (10), 132–143.

Yuan, F., Ding, Y., Wang, Y., Yu, W., Zou, X., Chen, H., Fu, G., Ding, D., Tang, J., Tang, X., Zhang, Z., Li, S., Li, D., 2021. Microplastic pollution in Larimichthys polyactis in the coastal area of Jiangsu, China. Mar. Pollut. Bull. 173, 113050.

Zalasiewicz, J., Waters, C.N., Ivar Do Sul, J.A., Corcoran, P.L., Barnosky, A.D., Cearreta, A., Edgeworth, M., Gałuszka, A., Jeandel, C., Leinfelder, R., McNeill, J.R., Steffen, W., Summerhayes, C., Wagreich, M., Williams, M., Wolfe, A.P., Yonan, Y., 2016. The geological cycle of plastics and their use as a stratigraphic indicator of the Anthropocene. Anthropocene 13, 4–17.

Zhang, D., Liu, X., Huang, W., Li, J., Wang, C., Zhang, D., Zhang, C., 2020. Microplastic pollution in deep-sea sediments and organisms of the Western Pacific Ocean. Environ. Pollut. 259, 113948.

Zhang, J., Li, W., Song, Y., Chen, D., 2010. The IR characterization of PEN/PET blend fibers. Hi-Tech Fiber & Appl. 35 (6), 30–34+50.

Zhang, Y., Liu, Z., Zhao, Y., Colin, C., Zhang, X., Wang, M., Zhao, S., Kneller, B., 2018. Long-term in situ observations on typhoon-triggered turbidity currents in the deep sea. Geology (Boulder) 46 (8), 675–678.

Zhao, J., Ran, W., Teng, J., Liu, Y., Liu, H., Yin, X., Cao, R., Wang, Q., 2018. Microplastic pollution in sediments from the Bohai Sea and the Yellow Sea, China. Sci. Total Environ. 640 (641), 637e645.

Zhao, S., Zhu, L., Li, D., 2015. Microplastic in three urban estuaries, China. Environ. Pollut. 206, 597–604.

Zhong, G., Peng, X., 2021. Transport and Accumulation of Plastic Litter in Submarinecanyons—The Role of Gravity Flows. Geology.

Zhou, Q., Tian, C., Luo, Y., 2017. Various forms and deposition fluxes of microplastics identified in the coastal urban atmosphere. Chin. Sci. Bull. 62 (33), 3902–3910.

Zuo, L., Sun, Y., Li, H., Hu, Y., Lin, L., Peng, J., Xu, X., 2020. Microplastics in mangrove sediments of the Pearl River Estuary, South China: correlation with halogenated flame retardants' levels. Sci. Total Environ. 725, 138344.