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Elucidating the distribution and characteristics of microplastics in water column of the northwestern South China Sea with a large-volume *in situ* filtration technology (plankton pump)

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Microplastic pollution has emerged as an undeniable marine environmental issue. While a distribution map of microplastics in the upper ocean has been established, the patterns of microplastics within the water column remain unclear. In this study, a large-volume *in situ* filtration device with filtration efficiency of 30 m^3/h was employed to investigate microplastics in the deep waters of the South China Sea. The abundance of microplastics ranged from 0.2 to 1.5 items per cubic meter (n/m^3), with an average of 0.56 ± 0.40 n/m^3. Microplastics are primarily fragments (72.58%) and fibers (20.97%), with the predominant polymer types being polypropylene (PP) and polyethylene terephthalate (PET). The average size of microplastics is 0.91 ± 0.97 mm, with no statistically significant differences observed across different water layers from 50 to 1000 meter (m). Non-metric Multidimensional Scaling (NMDS) analysis indicated that microplastics in the water column primarily originated from surface waters in the studied region. The occurrence of microplastics in the marine water column is a complex environmental process, influenced by a range of oceanographic mechanisms, including biological, chemical, and physical interactions. Our results provided reliable baseline data on microplastics in the water column of the South China Sea, contributing a better understanding to the vertical transport and fate of microplastics in this region.

KEYWORDS

microplastics, South China Sea, source, distribution, vertical transport

1 Introduction

Plastics are one of the most significant synthetic materials of the Anthropocene, having markedly enhanced the quality of human life (Geyer et al., 2017). However, inadequate end-of-life management has led to a substantial volume of plastic products becoming solid waste, resulting in severe environmental pollution (Rajmohan et al., 2019). The physical, chemical, and biological factors in the environment continuously alter the morphological characteristics and quantity of plastics (Barnes et al., 2009; Lambert et al., 2014). Throughout these processes, the size of plastic debris diminishes while their abundance exponentially increases. Plastic debris with a maximum dimension of less than 5 millimeters (mm) are classified as microplastics (Andrady, 2011). Due to their small size, microplastics can easily translocate across various environmental compartments, leading to their widespread distribution in terrestrial, marine, and atmospheric environments (Auta et al., 2017; Evangeliou et al., 2020; Gasperi et al., 2018; Xu et al., 2020). Consequently, microplastic pollution has emerged as a global environmental concern.

Oceans, covering approximately 70% of the Earth's surface, acts as a primary sink for both plastic waste and microplastics originating from land-based and ocean-based sources (Harris et al., 2021; Mai et al., 2020). Due to their lower density than seawater, the majority of microplastics remain suspended in the surface waters, where they are dispersed across global oceans through oceanic currents, including even the most remote open ocean and polar regions, while the rest will undergo vertical movement driven by various forces (Cózar et al., 2014; Lusher et al., 2015; van Sebille et al., 2015). These pollutants are particularly concentrated in hotspot areas such as river mouths, coastal waters, and gyre systems (Harris et al., 2021; Lebreton et al., 2018). However, due to technical and financial constraints, most studies have predominantly focused on the more accessible upper ocean layers, characterizing the horizontal distribution and transport of microplastics (Cózar et al., 2017; Li et al., 2021; Lusher et al., 2015).

Surface trawls, including manta, neuston and bongo trawls, are prevalently employed for collecting microplastics in the surface waters (0 to 0.5 m) (Mai et al., 2018). So far, microplastics surveys have been conducted across nearly all the world's oceans, including the Indian Ocean, the Pacific Ocean, the Atlantic Ocean, the Southern Ocean, and the Arctic Ocean (Chen et al., 2021; Isobe et al., 2017; Kanhai et al., 2017; Li et al., 2021; Liu et al., 2021; Lusher et al., 2015; Zhang et al., 2020b). These studies generally use nets with mesh sizes ranging from 50 to 3000 μm, with 330 μm being the most common (Isobe et al., 2015; Li et al., 2021; Stock et al., 2019).

Microplastics in surface waters can descend into deeper layers of the water column under the influence of vertical forces, such as vertical currents, biofouling, and biological transport (Kooi et al., 2017; Long et al., 2015). As such, the water column is considered a key sink for microplastics that have been lost from surface waters. The ocean water column is typically divided into several zones: epipelagic (< 200 m), mesopelagic (200-1000 m), bathypelagic (1000-4000 m), abyssopelagic (4000-6000 m), and hadopelagic (> 6000 m), each characterized by distinct physical conditions (Webb et al., 2010). To study microplastics in the water column, researchers have employed a variety of sampling devices, including CTD (conductivity, temperature, depth) water sampling Rosette, Multi-nets, vertical trawl, modified submersible pump and ROV (remotely operated vehicle) (Bao et al., 2022; Choy et al., 2019; Courtene-Jones et al., 2017; Li et al., 2020). Among those, sampling methods that allow for large volumes are particularly useful for obtaining more accurate data on microplastic abundance and vertical transport (Li et al., 2020; Liu et al., 2019).

Microplastics have become an integral component of marine debris, entering the detrital food web and potentially posing ecological risks to deep-sea organisms (Courtene-Jones et al., 2017). For instance, microplastic fibers have been identified within deep-sea organisms, such as *Crinoidea*, *Ophiuroidea*, and *Gammaridea*, which inhabit depths exceeding 4000 m in the western Pacific Ocean (Zhang et al., 2020a). These microplastics can cause mechanical damage to digestive systems, induce stress and immune responses, and hinder their growth of marine organisms (Wright et al., 2013). Additionally, microplastics can also adsorb heavy metals, persistent organic pollutants, and pathogens, leading to complex pollution that poses an even greater threat to the fragile deep-sea ecosystems (Carbery et al., 2018; Guzzetti et al., 2018). Therefore, understanding the vertical distribution and transport pathways of microplastics in the water column is crucial for predicting future pollution trends and assessing the ecological risks to deep-sea ecosystems.

The South China Sea, the largest semi-enclosed marginal sea in the western Pacific, is an area of particular concern. Surrounded by continents, peninsulas, and islands, and receiving large rivers like the Pearl River and Mekong River, the South China Sea is a hotspot for microplastic contamination (Cai et al., 2018; Zhu et al., 2019b). These rivers were recognized as the leading contributors to the influx of riverine plastics and microplastics into the ocean, with the region also being a significant fishing ground and shipping corridor, where abandoned fishing gear and maritime waste further contribute to plastic pollution (Lebreton et al., 2017; Wang et al., 2019). Extensive studies have already been conducted on the distribution of microplastics in the surface waters of the South China Sea, including areas such as the Pearl River Estuary, Xisha Islands, Zhongsha Islands, and Nansha Islands (Cai et al., 2018). For example, Tan et al. (2020) reported an average microplastic abundance of 0.056 ± 0.034 n/m^3 around remote coral reefs of Nansha Island, with polypropylene (PP) and polyethylene (PE) being the predominant types. Additionally, microplastic pollution has penetrated into the benthic sediment environment (Huang et al., 2023; Peng et al., 2019). Microplastics were also detected in zooplankton groups, seabirds and deep-sea fish, posing potential ecological risks to the biota (Sun et al., 2017; Zhu et al., 2019a, 2019b).

Vertical transport is an important mechanism for microplastics to travel from surface waters to the seabed. Cai et al. (2018) detected microplastics in the water column (0-200m) using a bongo trawl, with an average abundance of 0.045 ± 0.093 n/m^3. Similarly, Wang et al. (2022) investigated the distribution of microplastic fibers in water column off southeast China. However, the information about microplastic pollution in deeper water columns of the South China Sea is still relatively limited, which impedes our understanding of their vertical transport. To address the above knowledge gaps, we conducted a sampling campaign to investigate microplastics in water column (50-1000 m) of the northwestern South China Sea using a large-volume *in situ* filtration device at specific layers for the first time. Our goals were to 1) provide baseline data on the abundance and characteristics of microplastics; 2) elucidate the potential relationship between microplastic distribution and environmental factors; and 3) evaluate and synthesize sampling methods and transport mechanisms of microplastics in the water column.

2 Materials and methods

2.1 Study area

A total of 11 samples of microplastics in water column were collected onboard the R.V. SHI YAN 3 at three stations in the northwestern South China Sea from July 25 to August 15, 2020. This sampling campaign was part of a scientific expedition supported by the National Natural Science Foundation of China (Figure 1). The sampling stations were positioned along the same longitude (115°E), with an average water depth of 1,515 m. Three layers of samples were collected at station W1 (50, 200, 500 m) and W2 (50, 200, 1000 m), while samples were taken from five depths at station W3 (50, 200, 500, 800 and 1000m). Stations W2 and W3 are located near the Zhongsha Atoll in the central South China Sea. Detailed information on the sampling stations was shown in Supplementary Table S1 of Supplementary Material.

2.2 Sample collection

In this study, microplastics from specific water layers were collected using a large-volume *in situ* filtration device, namely plankton pump (KC Denmark, Figure 2). The device is powered by an external battery (24 V, 10 A/h), and offers a filtration capacity of 30 m^3/h. To ensure the stability and proper orientation of the instrument within the water column, a counterweight flow guide is mounted opposite the battery. This guide plate is fitted with an annular zinc block to mitigate the corrosion of metal structure by seawater. Seawater was drawn into a nylon filtration mesh with size of 60 μm by the rotation of propeller, with the filtered water passing through the net and residual material collecting in a bottom tube. A 60 μm filter size has been widely used in similar studies, providing consistency with existing literatures (Li et al., 2020; Liu et al., 2019). Sampling delay time was adjusted based on deployment depth and speed to filter 10 m^3 of water at each target layer. After filtration, the device was retrieved to the deck using an electric winch, where the filtration net and other parts were thoroughly rinsed with filtered water. The bottom collection bag was then removed, and the residual material was washed into sample bottles with Milli-Q

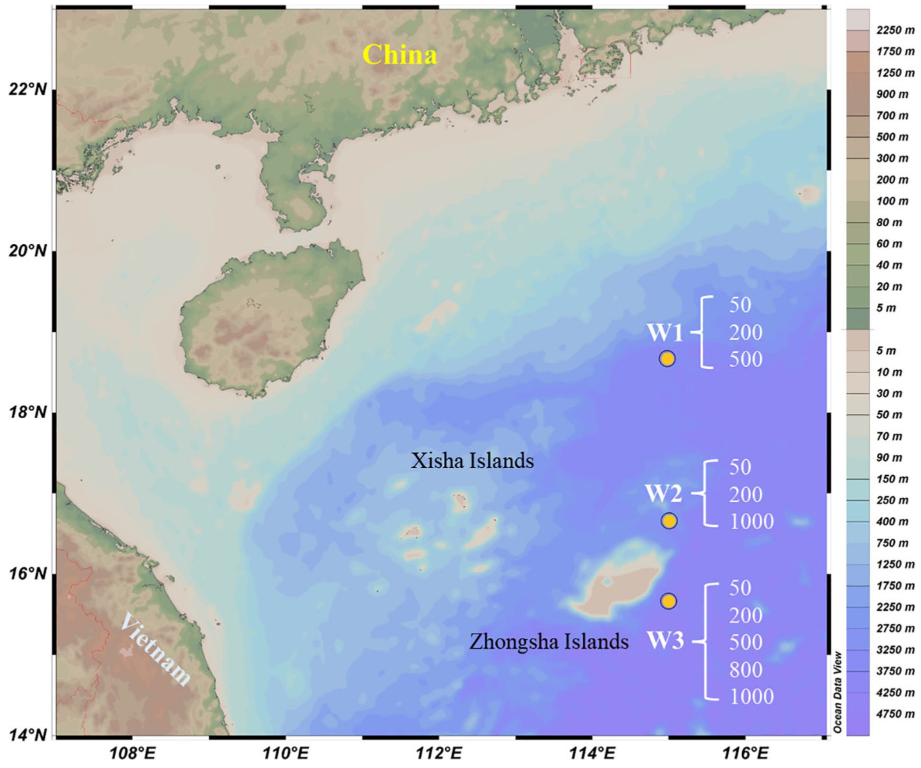

FIGURE 1
Sampling stations for microplastics in water column of the northwestern South China Sea.

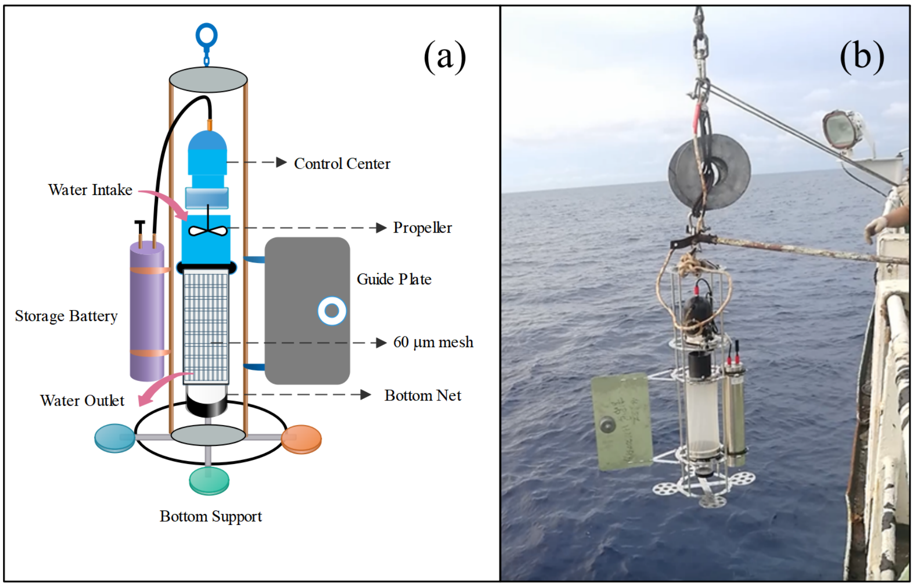

FIGURE 2
Schematic diagram **(a)** and field operation **(b)** of the sampling device.

water, followed by storage at low-temperature (4°C) until laboratory analysis. Additionally, environmental variables at each station were measured by a shipborne SeaBird Electronics SBE911 plus conductivity temperature depth (CTD), which were applied to analyze the potential relationship between microplastic distribution in water column and environmental factors.

2.3 Laboratory analysis

The isolation and identification of microplastics were performed following the methodology outlined by Li et al. (2022). Organic matter in the samples was digested using a 30% H_2O_2 solution with the pH range of 4.5 to 5.5 to facilitate the separation of microplastics. Microplastics were subsequently transferred onto glass fiber filter membranes (GF/A Whatman, 1.6 μm pore size, 47 mm diameter) using a vacuum filtration system, followed by natural drying in sterile petri dishes. All filter membranes were meticulously examined under a stereomicroscope (Leica M165 FC, Germany), equipped with a high-resolution camera for capturing images of suspected microplastics. The polymer composition of microplastics were then confirmed using a Micro Fourier Transform Infrared Spectrometer (μ-FTIR) (Thermo Nicolet iN10, USA). In transmission mode, the detector spectral range was 675-4000 cm^{-1}, with 32 scans co-added to target substances on the diamond crystals, achieving a resolution of 4 cm^{-1}. The polymer type was confidently identified if the quality index of the spectrum, compared to common polymer reference libraries, exceeded 70%. To minimize external contamination, stringent preventative measures were implemented. For instance, the entire laboratory analysis was conducted in an enclosed ultra-clean laboratory. All instruments and reagents underwent rigorous decontamination procedures, such as high-temperature treatment or thorough rinsing, to eliminate any potential microplastic contamination. Additionally, laboratory personnel were strictly prohibited from wearing any clothing made of plastic materials.

2.4 Statistical analysis and data visualization

Statistical analysis was performed using the SPSS (version 19.0). Data are reported as mean ± standard deviation (SD). One-way ANOVA was used to evaluate significant differences in the size of microplastics among different water layers and sampling stations. NMDS analysis based on Bray-Curtis distance was employed to assess the similarity and homogeneity of microplastic compositions among different stations and water layers. To explore potential relationships between microplastic abundance and the physicochemical properties of seawater, a Mantel test was performed. Pearson correlation analysis was used to calculate the raw correlation between two distance matrices, with values ranging from -1 to 1. A value of -1 indicates a negative correlation, 0 represents no correlation, and 1 denotes a positive correlation. One of the matrices undergoes random permutation of its rows and columns to preserve symmetry, and the correlation coefficient between the permuted matrices was recalculated. This permutation procedure was repeated 9,999 times. The original observed correlation coefficient was then compared with the distribution of correlation coefficients generated by the permutations, with a *p*-value less than 0.05 indicating statistical significance. Before conducting one-way ANOVA and Pearson correlation analysis, the data were tested for normality. All the diagrams were produced by software ODV (version 5.1.7), Origin (version 2024), Rstudio (2021) and Edraw Max (version 13.0.1).

3 Results

3.1 Vertical distribution of microplastics in water column

In the northwestern South China Sea, the abundance of microplastics in the water column decreases with increasing depth, as shown in the Figure 3. Pearson correlation analysis indicated a significant negative correlation between microplastic abundance and water depth (r = -0.74, $R^2 = 0.49$, $p < 0.01$). Overall, the range of microplastics abundance was from 0.2 to 1.5 n/m^3, with an average of 0.56 ± 0.40 n/m^3. Specifically, the average microplastic abundance at the water layer of 50 m is 1.00 ± 0.43 n/m^3, with the highest value (1.5 n/m^3) occurred at station W1 (Figures 3a, d). The abundance of microplastics at the layer of 200 m ranged from 0.4 to 0.9 n/m^3, with and average value was 0.63 ± 0.25 n/m^3 (Figure 3c). The average abundance of microplastics in deep water of 500 and 1000 m was 0.3 and 0.2 n/m^3, respectively. The abundance of microplastics showed a noticeable synchrony with water temperature, while exhibiting an opposite trend with salinity (Figure 3d). The halocline in the South China Sea was located at a depth of 200 m. The microplastic abundance, water temperature and salinity at each water layer of sampling stations was showed in Supplementary Table S1 of Supplementary Material.

3.2 Characteristics of microplastic community in water column

A total of 62 microplastics were identified from water column in the South China Sea. The microplastics predominantly comprised fragments (72.58%), fibers (20.97%), lines (3.22%), and films (3.23%) (Figure 4). Microplastic fragments were present in all water layers, while films and lines were only observed at the water layer of 50 m. Microplastics exhibited seven colors: transparent, green, blue, black, red, gray, and white. Transparent and green microplastics were the most dominant, accounting for 43.55% and 22.58%, respectively. Most fragment-type microplastics were transparent in color, accounting for approximately 53.3%. The primary colors of fiber-type microplastics were black and blue, each accounting for 46.15%. There was the most diverse color of microplastics in water layer of 200 m, with six different colors observed. A total of eight polymer types were identified, including polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polycarbonate (PC), polytetrafluoroethylene (PTFE), phenoxy resin (PR), alkyd resin (AR), and polymethyl methacrylate (PMMA). PET (22.58%) and PP (22.58%) were the most prevalent, followed by PE and AR. Microplastics composed of PET polymers predominantly exhibited the forms of fibers and fragments. Film-type microplastics were entirely transparent and

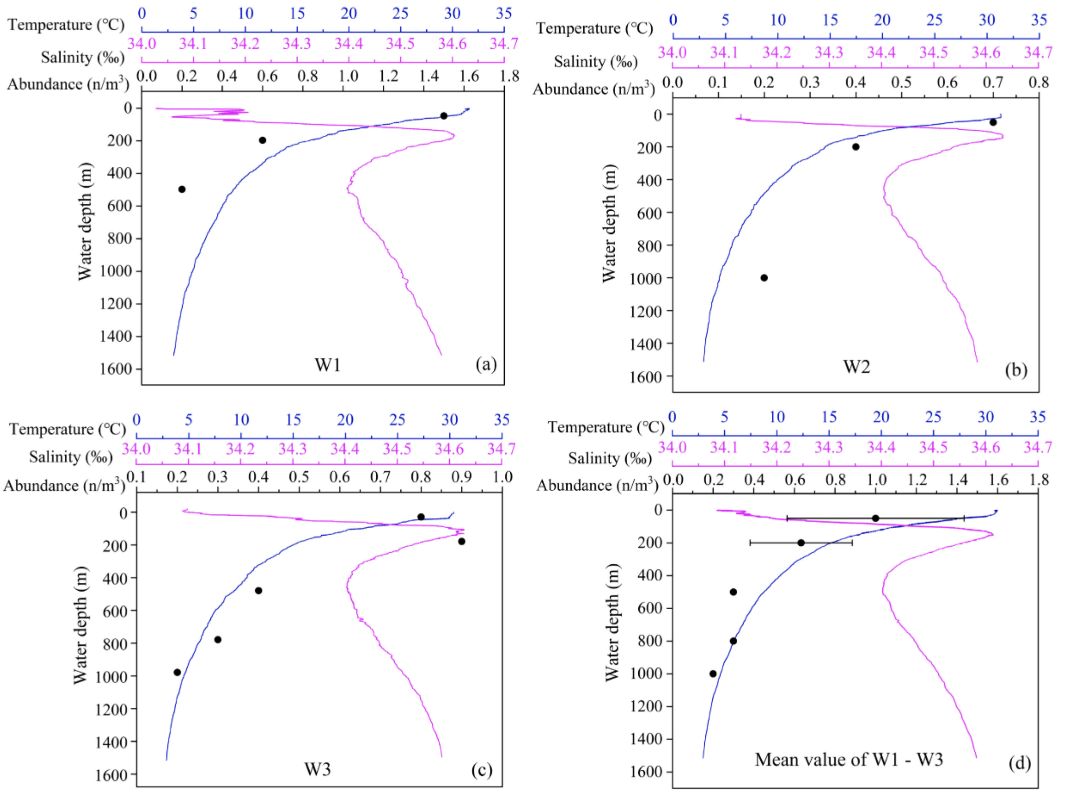

FIGURE 3
Microplastic abundance in the depth profile at sampling stations (**a**: W1, **b**: W2, and **c**: W3), and the average microplastic abundance across all sampling stations **(d)**. Temperature and salinity profiles are also indicated.

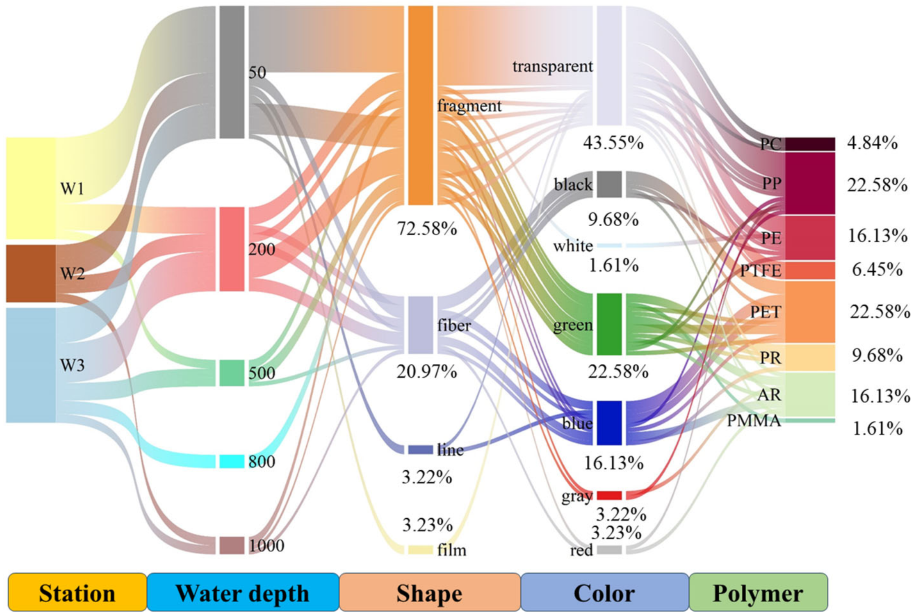

FIGURE 4
Shape, color and polymer type composition of microplastics in different water layers of three stations in the northwestern South China Sea.

composed of PE. PP, PE, AR, and PR were mainly found in water layers above 500 m, while PMMA was only present at 1000 m. The sole PMMA microplastic identified was a green fragment, standing out as the only specimen of this polymer in the sample. The detailed information about microplastic characteristics in each water layer of sampling stations was provide in Supplementary Table S2 of Supplementary Material.

3.3 Size distribution of microplastics

The size of microplastics in water column of the South China Sea ranged from 0.07 to 4.72 mm, with an average size of 0.91 ± 0.97 mm (Figure 5b). The one-way ANOVA results indicated that microplastic sizes do not differ significantly across various water layers ($F_{4,\ 57} = 0.193$, $p > 0.05$; Figure 5a). Overall, the average size of microplastics exhibited a trend of initially increasing before 500 m and then decreasing. The largest average size of microplastics was observed at the depth of 500 m (1.14 ± 1.46 mm). The lowest average size of microplastics was 0.58 ± 0.57 mm, locating at the depth of 1000 m. The largest microplastic size was recorded at a depth of 200 m of station W3, while the smallest was observed at 50 m at the same station. There was no significant difference in microplastic sizes among the three stations ($F_{2,\ 59} = 0.689$, $p > 0.05$). The frequency distribution chart showed that microplastics smaller than 1 mm accounted for more than 70% of the total (Figure 5c). Microplastics sized between 3-4 mm were not detected in the seawater samples.

4 Discussion

4.1 Sources and transport mechanisms of microplastics

PET and PP were identified as the predominant polymers of microplastics in the water column of the South China Sea. PET, the primary constituent of polyester fibers, is widely used in textiles and clothing, entering into oceans through sewage and surface runoff (Cesa et al., 2017). The density of PET (1.35-1.40 g/cm^3) is higher than that of seawater (1.025 g/cm^3), which typically causes it to sink to the lower water column and accumulate in seabed sediments (Zhang et al., 2020a). Similarly, PTFE (2.13-2.33 g/cm^3) and PMMA (1.18 g/cm^3), which also have higher densities than seawater, were detected in this study, consistent with findings from the eastern Indian Ocean and western Pacific Ocean (Li et al., 2020). In contrast, PP and PE are predominantly used in packaging materials and lines, ropes and nets for fisheries (Wang et al., 2019). Due to their lower densities, PP and PE are widely dispersed in the surface waters of the ocean (Li et al., 2021; Zhang et al., 2020b).

NMDS analysis was used to assess the similarity in microplastic composition among the three sampling stations. The stress value of the NMDS plot was 0.0856, which is considered acceptable, as a stress value below 0.1 suggests that the two-dimensional projection accurately reflects the relationships among the samples (Figure 6a). There were significant differences in the microplastic community (abundance, shape, color and polymer) among the three stations.

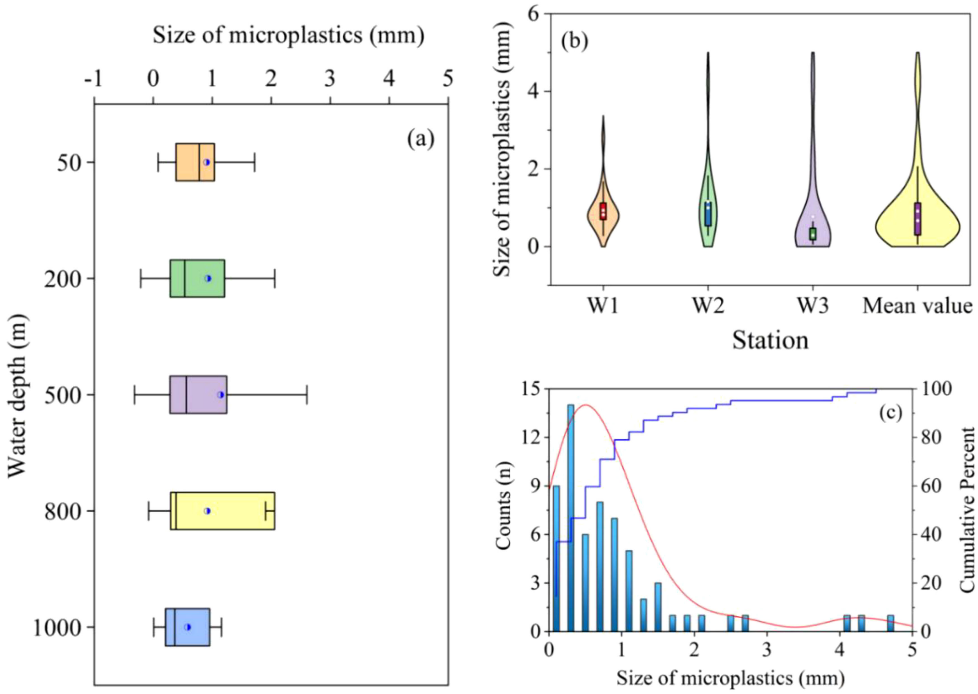

FIGURE 5
Size of microplastics among the different depths **(a)**, stations **(b)** and frequency distribution **(c)** in water column of the northwestern South China Sea.

Microplastics collected from station W1 and W2 showed substantial variation, while station W3 exhibited an intermediate pattern, possibly influenced by different ecological environments. The relative clustering of samples from station W2 indicated a more uniform ecological environment within this station, whereas the dispersion of station W1 samples suggested greater diversity in its community structure. The microplastic community in the photic zone (< 200 m) was relatively stable, while the aphotic zone exhibited greater diversity (> 200 m) (Supplementary Figure S1 of Supplementary Material). The partial overlap between the two zones suggested that microplastics from the upper ocean layers could be a critical source of microplastics in the deeper water. Kane et al. (2020) used numerical simulations to integrate microplastic pollution data with oceanographic information, showing that the transport and accumulation of seabed plastics in the Tyrrhenian Sea were controlled by bottom-layer temperature and salinity circulation. Deep-sea gravity flows not only transport nutrients like dissolved oxygen and organic carbon but also play a crucial role in the vertical transport of microplastics, as well as their erosion and accumulation on the seabed. Submarine canyons, unique topographical features on the continental slope that connect shallow seas with deep-sea plains, serve as important conduits for turbidity currents, which possess substantial capacity for transporting and depositing dense water masses and sediments (Canals et al., 2006).

Understanding the mechanisms of vertical transport of microplastics in the water column is essential for gaining insights into the environmental fate of marine microplastics. The density difference between microplastics and seawater plays a primary role in determining their buoyancy in the ocean. Consequently, the vertical transport of microplastics is influenced by factors that alter either the density of the microplastics or the properties of the seawater. The results of Mantel test showed that the abundance of microplastics in water column of the South China Sea was significantly negatively correlated with depth, salinity, and density, and significantly positively correlated with conductivity and dissolved oxygen (Figure 6b). These physicochemical properties of seawater are important factors in marine primary productivity and oceanic dynamic processes. Temperature and salinity, for instance, influence the density of seawater and drive ocean circulation patterns across different depths, which is known as thermohaline circulation (Schmidt et al., 2004). Wind-driven turbulent mixing is a key force behind the vertical transport of microplastics in surface water and is also influenced by heat flux (Brunner et al., 2015). According to an idealized diurnal heating model, daytime increases in sea surface temperature can inhibit the sinking of microplastics, while nighttime cooling can enhance their sedimentation flux (Kukulka et al., 2016). This dynamic interplay of factors suggests that the behavior of microplastics in the ocean is intricately linked to the physicochemical characteristics of seawater and oceanic circulation patterns.

Moreover, there was no statistically significant correlation between microplastic characterization (i.e. color, shape and polymer type) and water depth, indicating that the intrinsic properties of microplastics along cannot determine their buoyancy or floating behavior in the ocean. This is further

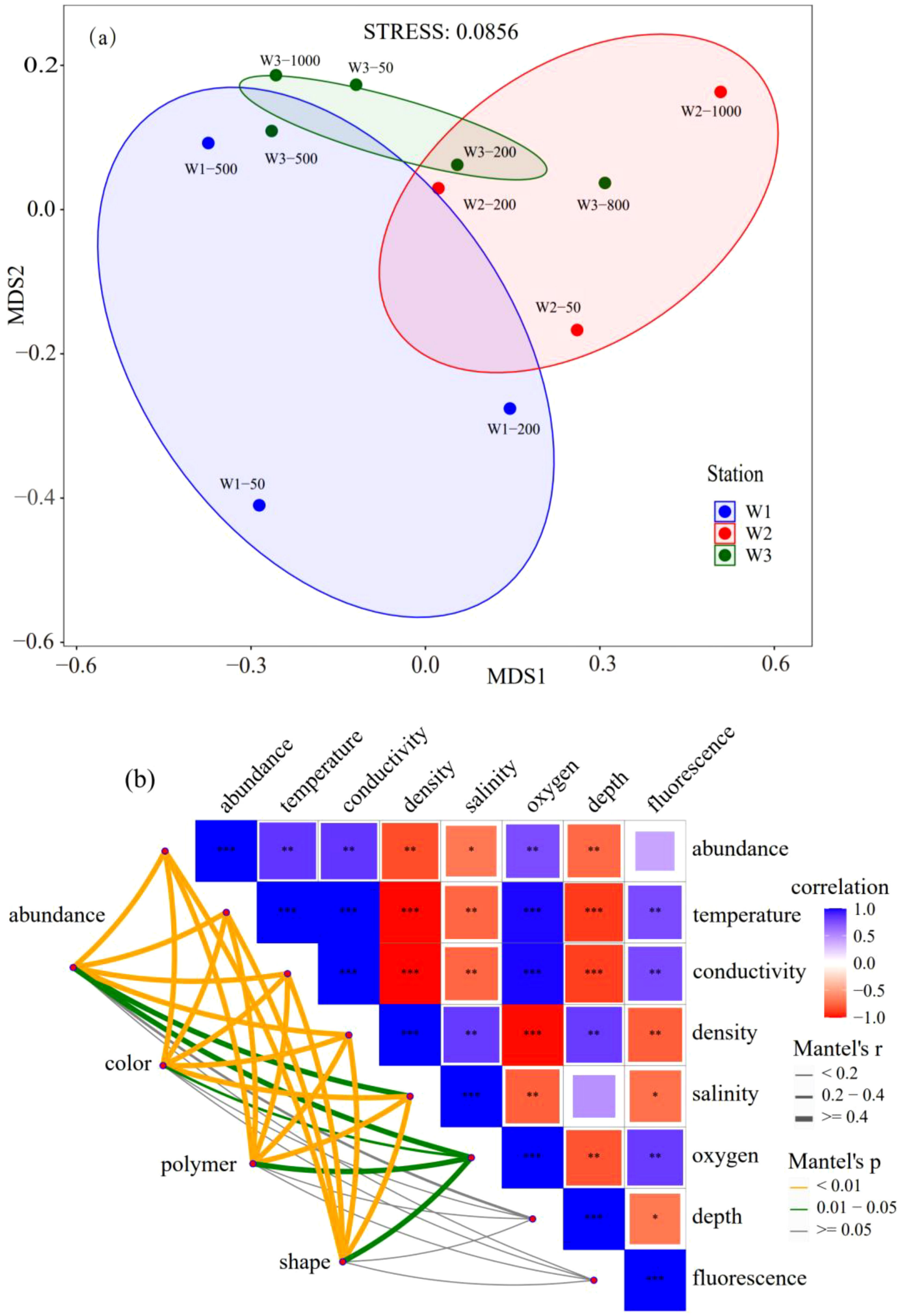

FIGURE 6
Non-metric multidimensional scaling analysis (NMDS) of microplastics among three stations in water column **(a)** and Mantel test for microplastic abundance and characteristics and environmental factors **(b)** in the South China Sea. Note: Each point on the plot corresponds to a specific sample, with labels such as W1-50 indicating the station (W1) and the sampling water depth (50 m). The points are colored based on their station of origin: blue for W1, red for W2, and green for W3. ***indicates a highly significant correlation ($p < 0.001$), ** denotes moderate significance ($p < 0.01$), and * signifies statistical significance ($p < 0.05$).

corroborated by the presence of PP and PE particles, which have lower densities than seawater, in deep water (1000 m). In fact, biological processes are believed to play a critical role in regulating the vertical transport of marine microplastics (Porter et al., 2018; Zhao et al., 2018). The formation of "Plastisphere" on the surface of microplastics, along with the attachment of inorganic materials, can significantly alter the density, weight and surface characterizations of these particles. These modifications can effectively change their buoyancy, allowing microplastics to either remain suspended in the water column or sink to deeper depths (Zettler et al., 2013; Oberbeckmann et al., 2015; Zhao et al., 2018).

The biological pump is a major component of the marine food web, serving as a key food supply chain for organisms at lower trophic levels (Wieczorek et al., 2019). Laboratory studies have shown that microplastics can be ingested by copepods and transferred up the food chain to higher trophic levels (Setälä et al., 2014). Microplastics can also be transported vertically through biological aggregation, particle flocculation, and marine snow (Katija et al., 2017; Porter et al., 2018). Zhao et al. (2018) found that over 70% of marine snow contained microplastics, confirming its role as a significant carrier of microplastics in vertical transport. Furthermore, marine organisms, such as plankton and fish, ingest microplastics present in the surface waters (Desforges et al., 2015; Zhang et al., 2019). Through their vertical migration and subsequent fecal deposition, these organisms facilitate the translocation of microplastics into deeper strata of the water column (Law, 2017). Hence, the vertical transport of microplastics in the marine water column is a complex environmental process, influenced by a combination of oceanographic mechanisms, including biological, chemical, and physical interactions. These multifaceted processes underscore the challenges in predicting the behavior and fate of microplastics in marine ecosystems, highlighting the importance of considering a range of factors in studying their transport and impact.

4.2 Comparison with other global regions

A ubiquitous presence of microplastics has been reported in the water column across global oceans (Table 1). Our results showed that microplastics were present throughout the water column (50-1000 m) in the northwestern South China Sea. The abundance of microplastics in this study was found to be lower than in the eastern Indian Ocean but higher than in Western Pacific Warm Pool (Li et al., 2020; Zong et al., 2024). The South China Sea is a relatively semi-enclosed marginal sea, characterized by limited water exchange rates (Shu et al., 2018). It is significantly influenced by substantial riverine inputs and numerous coastal anthropogenic discharges, making it particularly vulnerable to human activities (Chau et al., 2023; Chen et al., 2021).

Regrading microplastic characteristics, fragment- and fiber-shaped microplastics were found to be the most prevalent types, consistent with findings from other regions. The primary sources of fibrous microplastics in the ocean are the aging and washing of textiles, which enter the marine environment through wastewater systems and atmospheric transport (Chan et al., 2024; Wang et al., 2021). Previous have demonstrated that fibers are the dominant microplastic shape in the Pearl River and offshore water of the north South China Sea (Lin et al., 2018; Wang et al., 2022). The shape and surface structure of microplastics influence the formation of biofilms. A previous study has shown that fibrous microplastics are more prone to biofouling compared to spherical microplastics (Chubarenko et al., 2016). Interestingly, microplastic fibers were found in deep water (1000 m) in this study. Microplastic sizes decreased significantly as the sampling depth increased in the Baltic Sea, West Pacific and East Indian Ocean (Li et al., 2020; Zobkov et al., 2019). Smaller microplastics are more likely to overcome the barrier of the thermohaline layer and penetrate into deeper water layers.

In contrast to our study, Kanhai et al. (2018) did not observe a significant correlation between microplastic abundance and the physicochemical properties of water, including temperature, salinity, and density in the Arctic Central Basin. Vertical thermohaline circulation driven by temperature and salinity gradient might act as a sink buffer for microplastics in the Baltic Sea (Zobkov et al., 2019). Additionally, a positive correlation between the size of microplastics and particulate organic carbon were found in the HAUSGARTEN water column, associated with biological processes (Tekman et al., 2020). The inconsistent results suggest that the environmental factors influencing microplastic distribution may vary significantly across regions, such as ocean currents and sources. For example, near-bottom currents can resuspend microplastics from sediments into the water column, increasing turbidity. A positive correlation between microplastic abundance and turbidity has been observed in the near-bottom waters of the Baltic Sea (Zhou et al., 2021).

The inconsistency in sampling methodologies is a significant barrier for comparing microplastic data across studies. Variations in sampling tools, mesh sizes, and sampling volumes contribute to this challenge (Figure 7). Submersible pump filtration systems, for example, allow for precise and quantitative collection of microplastic samples from specific depths, such as those used by Cai et al. (2018) to collect small-sized microplastics (44-330 μm) in the South China Sea. Similarly, shipboard underway water systems provide an opportunistic method for continuous sampling at specific depths, a technique successfully employed in studies in the Atlantic, Pacific, Indian, and Arctic Oceans (Desforges et al., 2014; Enders et al., 2015; Kanhai et al., 2018; Li et al., 2022). Vertical plankton trawls have also been employed for microplastic sampling, with studies such as those by Cai et al. (2018) and Gorokhova (2015) focusing on the water column in the South China Sea and the Baltic Sea, respectively. However, vertical trawls are limited to collecting microplastics from a set depth to the surface due to the nature of vertical towing. Additionally, multi-net plankton trawls have enabled more targeted sampling of specific water layers (Kooi et al., 2016; Marcel et al., 2018). Reisser et al. (2015) utilized a novel 12-layer multi-net to study microplastics in the upper 5 m of the North Atlantic gyre, finding that microplastic abundance decreases exponentially with depth. This method provides data highly comparable to those obtained from surface trawls and is of significant importance for studying the vertical transport of microplastics in the upper ocean. Moreover, CTD water sampling systems, consisting primarily of a CTD monitoring system and rosette water samplers (e.g., Niskin bottles), allow for water sampling at any depth and time. Dai et al. (2018) used a CTD water sampler to study the vertical distribution of microplastics in the water column (0-30 m) of the Bohai Sea, finding an average abundance of 2.2 n/L. Peng et al. (2018) employed the same method to quantify microplastic pollution in the water column of the Mariana Trench (2500-11000 m), demonstrating that the hadal and ultra-abyssal zones might serve as significant reservoirs for microplastics. Additionally, sampling methods that combine *in situ* filtration systems with CTD water samplers or Remote Operated

TABLE 1 Global comparisons of content and distribution of microplastics in water column.

Study areas	Methods	Depth (m)	Abundance (n/m^3)	Dominant Shape	Dominant Color	Dominant Polymer	Size (μm)	Reference
North Atlantic Ocean	CTD	7-2227	70.8	fiber	blue	PES	400-8300	Courtene-Jones et al., 2017
Arctic Central Basin	CTD	8-4369	0-375	fiber, fragment	blue, transparent	PES, blends	1000-5000 (most)	Kanhai et al., 2018
Southern Mariana Trench	CTD	2500-11000	2.06-13.51 n/L	fiber, rod-like	blue, red	PET, PA	1000-3000	Peng et al., 2018
Monterey Bay	ROV-pump	5-1000	2.9-15	–	–	PET, PA	100-5000	Choy et al., 2019
South China Sea	CTD	1-40	0.2-45.2 n/L	fiber, fragment	red, black, blue	rayon, PET	7-4856	Ding et al., 2019
Gulf of Lions	WP2 plankton net	0-100	0.23 ± 0.20	–	light, dark	PET, PA	240-4930	Lefebvre et al., 2019
Baltic Sea	submersible pump	0.5-91	32.2 ± 50.4	fiber	–	PET	<1000 (most)	Zobkov et al., 2019
East Indian Ocean	plankton pump	50-1000	0.88 ± 0.52	fragment, fiber	–	PTFE, PET	38-6630	Li et al., 2020
West Pacific Ocean		2-4000	1.29 ± 0.83			PET, PMMA	30.1-4559.7	
HAUSGARTEN observatory	large-volume pump	1-5350	95 ± 85	–	–	PA	≤25 (most)	Tekman et al., 2020
Baltic Sea	CTD	1-437	5.8 ± 5.0 n/L	fiber, fragment	black. blue	rayon, PET	27.3-5000	Zhou et al., 2021
Arctic Ocean	Vertical trawl	0-200	0.15 ± 0.03	–	–	alkyd, PU	200.1-4694.1	Bao et al., 2022
North South China Sea	CTD	0-300	0.13 ± 0.19	fiber	blue, black	PET, PP	96.2-1983.2	Wang et al., 2022
Indonesian Throughflow	CTD	5-2450	1.06 ± 0.65	fiber, fragment	–	PVEMA, PES	1000-2000 (most)	Manullang et al., 2024
Southern Black Sea	Plankton net	2-30	1.74-21.07 (average)	fiber	blue	PET, PE	1000-2000 (most)	Öztekin et al., 2024
Yangtze River Estuary East China Sea	CTD	1-67.6	1.26-220.14 n/L	fiber	colored	PES, rayon	20-5000	Ge et al., 2024
Western Pacific Warm Pool	plankton pump	0.5-1000	0.37 ± 0.27	fiber, fragment	green, red	PET, PP	125-4971	Zong et al., 2024
	CTD	5-5300	115.12 ± 64.13	fiber, fragment	red	PET, PE	85.4-3364.1	
East China Sea offshore	CTD	0-178	0-55.59 n/L	fiber	transparent, black	PES, PE	20-5000	Li et al., 2025
San Pedro Bay, USA	Net sampling	0-352	0.03-8.71	fiber	black	PE, PP	< 2500 (most)	Singh et al., 2025
South China Sea	plankton pump	50-1000	0.56 ± 0.40	fragment, fiber	transparent, green	PET, PP	70-4720	this study

PET, polyethylene terephthalate; PP, polypropylene; PE, polyethylene; PA, polyamide; PES, polyester; PTFE, polytetrafluoroethylene; PMMA, polymethyl methacrylate; PU, polyurethan; PVEMA, polymethyl vinyl ether-co-maleic acid.

Vehicles (ROVs) have been applied in Monterey Bay and the Arctic (Choy et al., 2019; Tekman et al., 2020).

However, due to limitations in sampling time and cost, a single water layer typically yields only a few hundred liters of water during an oceanographic expedition. In most studies, smaller volumes of water samples are often directly filtered onto membranes, minimizing the loss of microplastic fibers and reducing external contamination, making it more effective for studying small-sized microplastics. However, the smaller sample volumes may introduce greater variability and potential biases in the results. In general, small-volume sampling methods, such as those using CTD, yield significantly higher microplastic abundance than large-volume sampling methods like plankton pumps and exhibit greater variability (Table 1). Besides, large-volume sampling methods

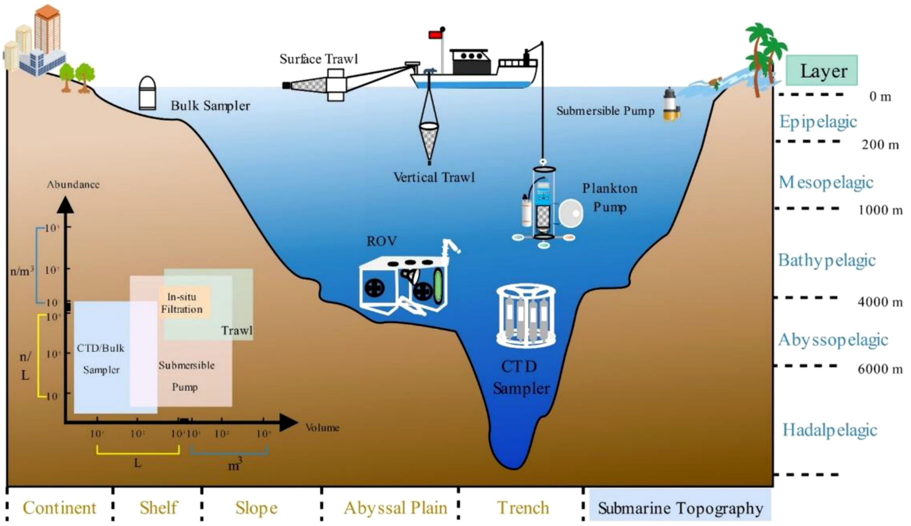

FIGURE 7
Summary chart of sampling methods for microplastic pollution in aquatic environment.

capture a broader variety of microplastics, reduce the loss of low-abundance types, and provide more accurate quantification. Liu et al. (2019) conducted the first field test of large-volume *in situ* filtration technique in the East China Sea using a plankton pump, validating its impact on improving microplastic quantification accuracy, particularly in deep water. The large-volume *in situ* filtration technology has been used to collect microplastics from the 4000 m layer of the Western Pacific, showing that microplastic abundance was at least 1–2 orders of magnitude lower than those from small-volume samples (Li et al., 2020). Though large-volume sampling methods are recommended for accurate and stable data, they also come with certain limitations, such as requiring more ship time for deployment, retrieval, and sample collection (Liu et al., 2020).

The mesh size of the sampling tools plays a critical role in determining the quantification of microplastic abundance and the composition of microplastics in the samples (Bai et al., 2022). Dris et al. (2015) compared the effectiveness of surface trawls with 80 µm and 330 µm mesh sizes, finding that the 80 µm mesh collected microplastics at a rate approximately 30 times higher than the 330 µm mesh, with fibers being the predominant type. Selecting the appropriate mesh size requires balancing the risk of clogging with the desired microplastic size range. Smaller mesh sizes improve the capture of finer particles but increase the likelihood of clogging, which can impede the filtration. Therefore, optimizing mesh size is crucial for achieving both efficiency in sample processing and comprehensive representation of the microplastic population under study.

5 Conclusions

In this study, we investigated the abundance and distribution of microplastics in water column of the South China Sea utilizing a large-volume *in situ* filtration device, namely plankton pump. Microplastics were detected at various water layers, with their abundance exhibiting a significant negative correlation with water depth. Notably, Microplastics with a density lower than seawater, such as PP, have infiltrated the deep water (800 m), indicating their potential to travel long distances through the water column. The NMDS analysis revealed a high degree of similarity between microplastic communities in the photic zone and the aphotic zone, suggesting that microplastics in the water column are primarily derived from surface waters. The vertical transport of marine microplastics from the surface water to deep water is driven by various oceanographic and biogeochemical processes. The findings from this study underscore the importance and promising advantages of *in situ* large-volume sampling methods, such as the plankton pump, for investigating microplastics in the deep-sea water column. By providing foundational data on microplastics pollution in deep waters of the northwestern South China Sea, this study contributes to the knowledge necessary for guiding efforts to mitigate microplastic contamination in this critical marine environment. Looking ahead, future research should focus on establishing standardized methodologies for microplastics pollution in water column, including concerning the smaller microplastics (< 60 µm), which have not been widely addressed. Furthermore, interdisciplinary collaboration involving *in situ* field observations, laboratory simulations, physical modelling, and biogeochemical studies is strongly encouraged to better assess the vertical transport mechanisms, fate of microplastics in the water column, as well as their impacts on the marine ecosystem and the biogeochemical cycling.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

CL: Data curation, Funding acquisition, Investigation, Writing – original draft. LZ: Conceptualization, Funding acquisition, Methodology, Writing – review & editing. XW: Visualization, Writing – review & editing. DL: Resources, Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2025.1556592/full#supplementary-material

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