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Unlocking accurate microplastic data: Advanced pump systems for diverse aquatic environments

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ABSTRACT

Microplastics (MiPs) pose a significant environmental threat due to their persistence and potential toxicity to biota that interact with or ingest them. Accurate assessment of MiP concentrations in aquatic systems is critical for understanding their distribution and impacts. This study develops the MiPCS Pump (Microplastic Collector System), an innovative pump-based sampling system integrating 80 μm mesh plankton nets. The system was tested against traditional net-based methods (manta and Apstein nets) in the Red River Delta and Cat Ba Archipelago, Vietnam. This innovative design features a suction basket excluding large particles (>5 mm), a mixing chamber and 5-way splitter for uniform distribution, and precise flow control (via flow metering) to five phytoplankton nets, ensuring accurate and simultaneous multi-sample collection. This advanced system provided more consistent and precise results, sampling a broader spectrum of MiP sizes, and enabling sampling across a variety of water depths and environmental conditions. Quantitatively, MiPCS Pump yielded significantly higher MiP concentrations (2.95–7.80 mg m^{-3} and 16.25–114.58 particles m^{-3}) compared to the net methods (1.59–3.27 mg m^{-3} and 0.78–26.62 particles m^{-3}). Although nets are effective for larger surface MiPs (mesoplastics) there is a lack of understanding of MiP catchability in nets, whereas the MiPCS Pump offers precise volume measurement, adaptability to various depths, and captures a broader size range, making it a more comprehensive method for assessing MiP pollution. This MiPCS Pump system is crucial for ensuring accurate and comparable data for global MiP monitoring and the development of effective plastic waste management policies.

1. Introduction

The escalating production and consumption of plastics have led to a global environmental crisis. Annual plastic production surpassed 400 million tons in 2022 (UNEP, 2023) and by 2050 this is estimated to reach approximately 600 million tons (Mikulec et al., 2023). Each year, an estimated 8–10 million metric tons of plastics end up in the ocean (Fava, 2022). Among the various forms of plastic pollution, microplastics (MiPs) – plastic particles smaller than 5 mm – are particularly pervasive (Razeghi et al., 2021). These particles originate from both intentional production and the degradation of larger plastics.

Due to their widespread presence and environmental persistence, MiPs have been detected in diverse aquatic ecosystems, from freshwater bodies to the open ocean. They pose significant risks to marine organisms and, indirectly, to humans who consume seafood (Hermabessiere et al., 2017; Wright and Kelly, 2017). MiPs can be ingested by various organisms, leading to physical harm, reproductive disorders, and compromised immune function (Monique et al., 2022). Research has shown that MiPs enter the food chain through marine birds (Amélineau et al., 2016), shellfish (Cho et al., 2019), fish (Alberghini et al., 2023),

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zooplankton (Malinowski et al., 2023), and coral (Soares et al., 2023). These particles not only harm marine life but also bioaccumulate, posing potential health risks to humans. Moreover, MiPs can act as carriers for persistent organic pollutants (POPs), trace metals, and pathogens, exacerbating their toxic effects. They have been linked to health issues such as cancer, fertility problems, and disruptions in hormonal, metabolic, and neurological functions due to endocrine-disrupting chemicals (EDCs) (UNEP, 2023). Consequently, MiPs present risks not only to individual organisms but also to entire ecosystems and human populations (Rochman et al., 2015).

Addressing this global issue requires accurate and comparable data on MiP distribution and abundance. Over the past decade, a variety of sampling techniques have been introduced and refined to meet the growing demand for precise field-based data on the prevalence of MiPs in the environment (Prata et al., 2019; Razeghi et al., 2021; Xia et al., 2024). These methods range from simple manual collection techniques, such as plankton nets (Dris et al., 2015) and sediment cores (Hanvey et al., 2017), to more sophisticated automated samplers and advanced filtration systems (Yuan et al., 2022). In water sampling for MiPs, the methods commonly used are nets, grabs, or pumps (Razeghi et al., 2021). However, sampling MiPs in dynamic aquatic environments is challenging. These include the vast surface area, constant water movement, and complex interactions between physical, chemical, and biological processes (Kvale et al., 2020; Montoto-Martínez et al., 2022). These factors complicate the development of standardised methodologies and hinder effective pollution assessments (Table S1). Traditional sampling tools, such as manta trawls and Apstein nets, are limited by their inability to capture smaller MiPs (<300 μm) and inconsistencies in volume measurements caused by net clogging and backflow resulting from net clogging (Hamidian et al., 2021; Razeghi et al., 2021).

To address these limitations, this study aims to develop (1) and evaluate (2) a novel pump-integrated phytoplankton net system featuring an 80 μm mesh size applied, the MiPCS Pump (Microplastic Collector System). This system, designed with input from aquaculture and plankton sampling expertise, enhances precision, adaptability, and operational efficiency for MiP collection across various aquatic environments. A standardised and accurate MiP sampling technique is essential for ensuring data comparability and facilitating global assessments of MiP pollution. This information can inform the development of effective management strategies to mitigate the environmental and health impacts of MiPs.

2. Materials and methods

2.1. Sampling sites and strategy

Sampling sites were strategically selected (Fig. 1) in urban and aquaculture areas within the Red River Delta and Cat Ba Archipelago to evaluate the performance of two MiP sampling techniques (nets and MiPCS Pump) across a freshwater-to-marine salinity gradient. The sampling locations included RR1 (Lien Ha, Hanoi) in the mid-upstream region of the Red River before it enters the Day tributary and flows through Hanoi; RR2 (Ba Lat gate, Ninh Binh) in the estuarine zone of the Red river; and CB1'-CB3' (Cat Ba island), representing marine environments at a cage aquaculture farm (CB1') and sites located approximately 300 m (CB2') and 600 m (CB3') away from the cage aquaculture area in the Cat Ba Archipelago. To investigate the spatial distribution of MiPs in the water column, samples were collected at three depths: surface (0–50 cm), mid-depth (4–8 m), and near the bottom of the water bodies (2–3 m above the bottom). Water depth measurements were obtained using echo-sounding equipment (HONDEX PS-07, Japan).

2.1.1. Net sampling methods (using manta trawl and Apstein net)

Surface water samples were collected using a modified manta trawl method (Kovač Viršek et al., 2016; Silva et al., 2018) representing in Fig. S1. Briefly, the sampling device consisted of a manta trawl (Hydro-Bios 438,217, opening aluminium mouth of W × H = 300 × 150 mm) equipped with a neuston net (2000 mm long and a mesh size of 300 μm) and a detachable cod-end. The trawl was deployed horizontally at the water surface for 30 min at a vessel speed of 2–3 knots during the collection of a single sample. For mid-water and bottom samples, an Apstein phytoplankton net (Hydro-Bios, Germany) was used following the method described by Sambolino et al. (2022). The net was deployed at various depths for 30–45 min, and a flow meter was mounted to the net mouth to measure the filtered water volume (V), which was calculated using the following formula:

$$V = \pi \times \left(\frac{d}{2}\right)^2 \times v \times t \quad (1)$$

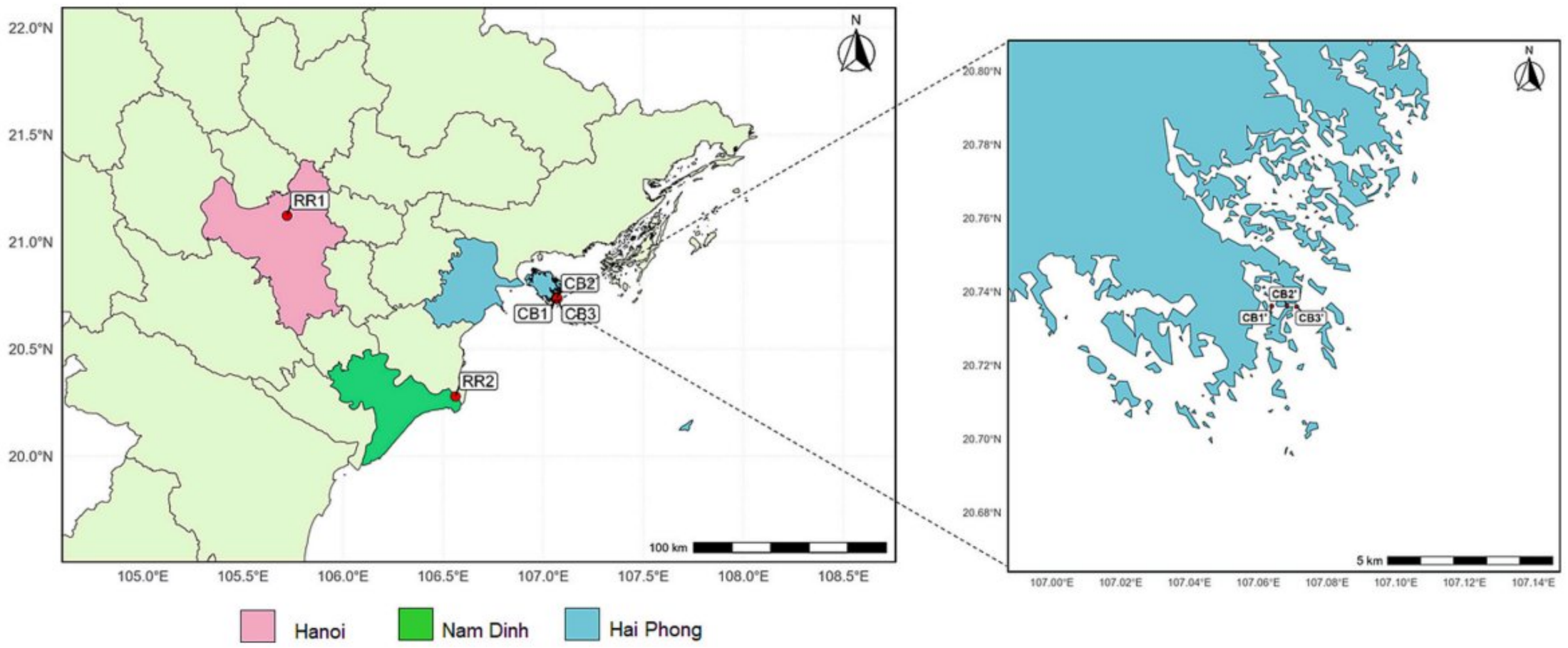

Fig. 1. Sampling locations within the Red River Delta and Cat Ba Archipelago. Left panel: RR1 (Lien Ha, Hanoi) in the mid-upstream Red River; RR2 (Ba Lat gate, Ninh Binh) in the estuarine zone; CB1'-CB3' (Cat Ba Island) in marine environments. Right panel: Detailed view of Cat Ba sites showing the cage aquaculture farm (CB1') and sampling locations at 300 m (CB2') and 600 m (CB3') from the aquaculture facility. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

where V is the volume of filtered water (m^3); "d" is the diameter of the plankton net opening (m); "v" is the flow velocity (m/s); and "t" is the towing time (s). If there was no water flow (e.g., slack tide), a boat was employed to tow the Apstein plankton net for approximately 30 min. The net was towed at a speed of 2–3 knots, about 25 m from the back of the boat to minimise turbulence. For the net sampling methods, all the material retained within the net's length was collected in the cod-end. Upon retrieval, the cod-end was detached and its contents were transferred into a 50 mL Falcon tube. The cod-end was rinsed twice with net-filtered water to collect remaining particles. The entire net and cod-end were then thoroughly washed with net-filtered water before redeployment.

2.1.2. Advanced in situ pump system with plankton nets (MiPCS Pump Method)

This study introduces an innovative in situ pump system integrated with plankton nets (hereafter referred to as the MiPCS Pump method) designed for collecting water samples from both the surface and various depths of the water column. In general, the MiPCS Pump system consisted of a stainless-steel suction basket cluster and a pump cluster including a mixing chamber and a water distribution system. As illustrated in Figs. 2&1S, the system comprises:

1. **Suction basket cluster** designed to accurately collect surface water while preventing the suction of large particles (> 5 mm), including a cylindrical tube (20 cm diameter) with one open end (mouth) connected to a 5 mm mesh-trash filter basket and one closed end. Two floats positioned near the basket's opening kept it suspended approximately 5 cm below the water surface.
2. **Self-priming centrifugal pump**: Powered the system, drawing water into the mixing chamber through a one-way valve connected to the suction pipe.
3. **Mixing chamber and distribution system**: A chamber connected to a 5-way hose splitter directed water into five sampling pipes, each equipped with a flow meter for precise volume control.
4. **Plankton nets**: the water is flowed through five nylon plankton nets (800 mm in length, 80 μm mesh size) for concentrating particles in stainless-steel cod-end assemblies.

The suction basket prevented large particles (>5 mm) from entering, while the pump (WB30XTl, Honda, Thailand; max flow rate 1100 L/min) maintained a consistent flow. PVC-coated steel wire reinforced hose connected the pump's inlet (Φ 50 mm) to the water suction pipe and the outlet (Φ 34 mm) connected to the mixing chamber. Water was then distributed from the mixing chamber through a multiple sampling pipe system (PVC tube, Φ 75 mm, length of 800 mm). The water distribution and flow tracking devices were mounted on a customizable metal shelf. Water distribution was regulated using a bypass valve to prevent flow fluctuations and air bubble formation.

Filtered water passed through the plankton nets suspended beneath the 05 outflow water pipes, and MiPs were concentrated in stainless-steel cod-end assemblies equipped with latex tubes. Following filtration, the cod-end was rinsed thoroughly with on-site filtered water after passing through an 80 μm mesh net. The concentrated MiPs were then transferred to a 50 mL sterile Falcon tube and stored at 4 °C in a refrigerated box until further analysis, following the same procedure used for the net-based methods.

To ensure accuracy, flow meters were calibrated after each sampling location. The entire net and cod-end assembly were meticulously cleaned with filtered water before starting a new sampling cycle. This integrated system enables the precise and simultaneous collection of multiple water samples at the same time, ensuring accurate and comparable data collection.

2.2. Microplastic separation and analysis

The method for separating MiPs from water samples was adapted and optimized from previously published protocols (Tagg et al., 2015; Al-Azzawi et al., 2020). In summary, samples were first filtered through an 80-μm stainless steel filter using a laboratory vacuum filtration pump (Rocker 300, Rocker Scientific, Taiwan). Residual silt was removed by thorough washing with reverse osmosis (RO) water. Next, retained materials were transferred to a 150 mL glass beaker using 20–30 mL of a 0.07 M $FeSO_4$ solution.

A Fenton reaction was employed to digest organic matter in the samples. Briefly, the H_2O_2 (30 %, Thermo Fisher, USA) solution was gradually added to the $FeSO_4$ solution until a ratio between $FeSO_4$:H_2O_2

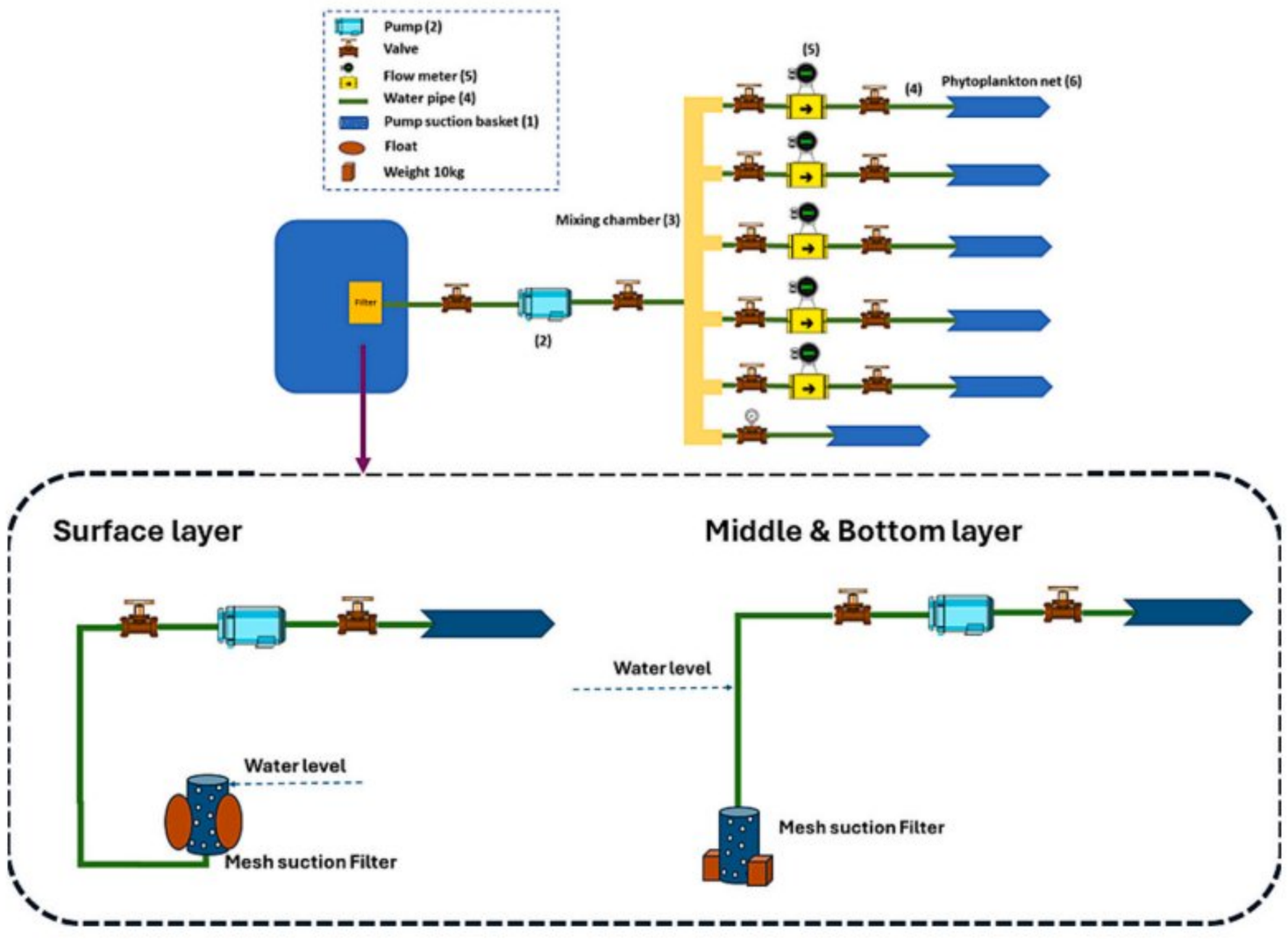

Fig. 2. Schematic diagram of the MiPCS Pump system. The dotted box illustrates the dual-depth sampling configuration using a single pump with two inlet lines positioned at different water depths (surface 0–50 cm and deeper layers 4–8 m or near-bottom).

of 1:2 (*v*/v) was achieved. After 20 min reaction, additional H_2O_2 was slowly added until the solution became clear and yellow-free to confirm no more organic matter. The solution was neutralized with concentrated H_2SO_4 (Thermo Fisher, USA) and filtered through a 80 μm metal filter and rinsing with distilled water to remove excess iron and acid.

For samples containing sand or sediment, a density separation process using saturated calcium chloride ($CaCl_2$, Thermo Fisher, USA), with a density of 1.48 g/cm^3 at 40–45 °C was conducted to isolate MiPs. The collected supernatant was filtered through an 80 μm stainless-steel filter to collect MiPs. Collected particles were analyzed under a stereo microscope (Euromex SB.1903, Italy) equipped with a camera (Euromex DC.10000-Pro, Italy) and identified based on colour and shape (Sambolino et al., 2022). MiPs were dried at 70 °C in a drying oven for two days until a constant mass was achieved, confirmed using an analytical balance with a precision of ±0.01 mg.

2.3. Contamination control and quality assurance

To minimise the introduction of MiP contaminants during the analytical process, lab coats (made of polyester-cotton blend) were worn throughout all procedures. The glassware was washed with distilled water, then dried, and stored in aluminium foil, and all sample processing was conducted in dedicated clean workspaces with minimal air movement. Airborne contamination was monitored using blank controls (clean petri dishes placed in the work area during sample processing), which were analyzed identically to samples. Blanks showed an average of 2.3 (±1.7) fibres of various colour (transparent, black and others), indicating low-level background contamination, which was subsequently subtracted from experimental results to ensure data accuracy and reliability.

2.4. Data analysis

Results are presented as mean values of the different replicates ± standard error (SE). The statistical analysis was conducted using Origin 2024 and R Studio (RStudio, Inc) software. The data was examined for homogeneity of variance, with the variables being divided by shape (fragment, fibres) and colour. The analysis of variance (ANOVA) was employed to identify variations in MiP concentrations in water among different sampling sites. When significant differences ($p < 0.05$) were detected, a *t*-test was conducted to compare groups, such as differences between sampling methods.

3. Results

3.1. Assessment of microplastic concentration and distribution

The highest concentrations of MiPs were observed in riverine (RR: mid-upstream and RR2: estuarine), with lower levels observed in marine and marine aquaculture sites (Fig. 3A&B). The MiPCS Pump method consistently yielded higher MiP concentrations than the net method, especially in deeper water layers; MiP concentrations in water measured by the MiPCS Pump method ranged from 2.95 to 7.80 mg/m^3, whereas the net method reported values between 0.08 and 2.45 mg/m^3 (Fig. 3A). Similar trends were observed for particle abundance (items/m^3), with surface layers showing higher concentrations than deeper layers using both sampling methods (Fig. 3B). The MiPCS Pump method consistently detected higher MiP concentrations than the net method across all sampling locations, primarily due to its ability to capture smaller particles (80–5000 μm) compared to the net method's effective range (330–5000 μm). This expanded size range represents a fundamental methodological capability difference, as passive net-based methods cannot achieve mesh sizes finer than ~330 μm in field conditions due to rapid clogging and backflow phenomena that compromise filtration efficiency and volume measurement accuracy.

Marine samples generally exhibited lower MiP concentrations than

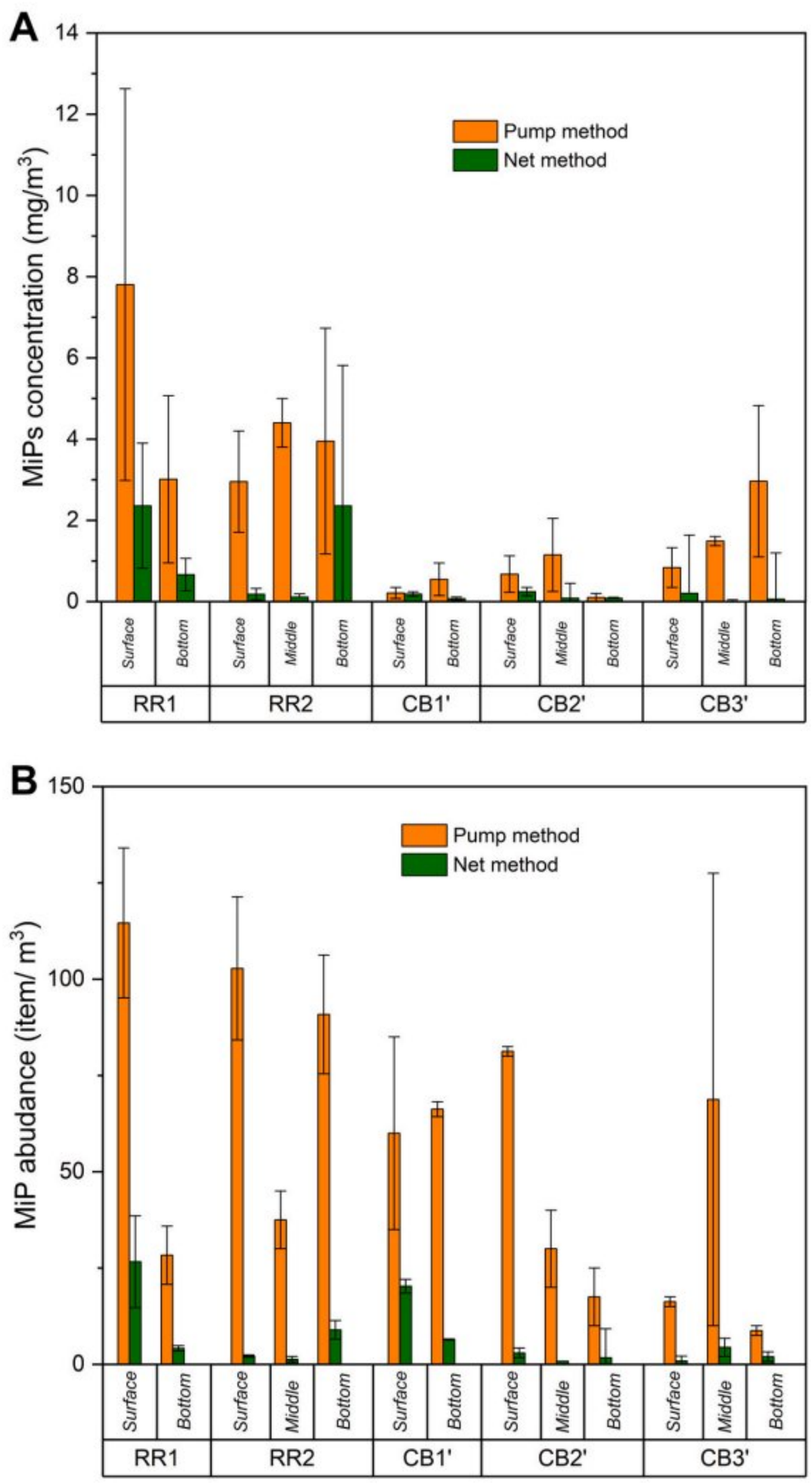

Fig. 3. Microplastic concentrations (**A**) and abundance (**B**) at all sampling locations within the Red River Delta region and Cat Ba Island collected by both sampling methods (pump and net). Concentrations in (**A**) are represented as weight of microplastics, whereas abundance in (**B**) as number of microplastic item. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

riverine samples for both methods. Between methods, the MiPCS Pump approach detected significantly higher MiP concentrations in surface water (CB1': 0.21 ± 0.11 mg/m^3; CB2': 0.68 ± 0.45 mg/m^3; CB3': 0.78 ± 0.49 mg/m^3) compared to the net method (CB1': 0.19 ± 0.11 mg/m^3; CB2': 0.25 ± 0.11 mg/m^3; and CB3': 0.21 ± 0.12 mg/m^3). The MiPCS Pump method also reported 1.5 to 2 times higher MiP concentrations in middle and bottom layers compared to the surface layer, except in the upstream region of the Red River (RR1). In contrast, the net method predominantly captured MiPs from surface layers, where concentrations were 4 to 60 times higher than those in deeper layers, except at the estuarine site (RR2). This exception may be attributed to strong currents facilitating mixing between bottom and adjacent water layers.

A comparison of MiP concentrations across different aquatic environments (riverine, aquaculture farm, and marine) highlighted

significant differences between the MiPCS Pump and net methods ($p < 0.05$; Fig. S3). Specifically, the mean MiP concentrations for MiPCS Pump method were 4.08 ± 0.50 mg/m^3 in riverine sites, 0.38 ± 0.26 mg/m^3 in aquaculture farms, and 0.96 ± 0.21 mg/m^3 in marine locations; In contrast, the net method recorded mean concentrations of 0.35 ± 0.07, 0.13 ± 0.06 and 0.17 ± 0.05 mg/m^3, respectively. Both methods revealed the same concentration pattern: riverine (RR1 and RR2) > ocean (CB2') > marine cage aquaculture (CB3'). This trend may be driven by factors such as proximity to pollution sources, transport of MiPs via river flow, human activities in aquaculture, and variations in hydrodynamic conditions (Xia et al., 2025; Cai et al., 2021).

Among environmental factors, salinity, turbidity, and TDS emerged as significant factors influencing MiP distribution, especially for the net method. For the net method, negative Spearman correlation coefficients were observed between MiP concentrations and salinity ($R = -0.55$), turbidity ($R = -0.50$), and TDS ($R = -0.52$) ($p < 0.05$; Table S2). In contrast, for the MiPCS Pump method a highly significant negative correlation was found only between salinity and MiP concentrations ($R = -0.73$, $p < 0.001$), suggesting that sediment and plastic particles may have distinct sources or transport dynamics.

3.2. Enhanced morphological resolution

MiPs collected by MiPCS Pump and net methods were classified into two morphological categories: fibres and fragments (Fig. 4A & B). Fibres dominated the MiP composition in both sampling methods, representing 48–95 % of the total MPs, with an average of 87 ± 2.6 %. The MiPCS Pump method consistently captured a broader range of MiP sizes and morphologies, with fibres comprising 87 % of particles across all sampling sites (Fig. 4A). In contrast, the net method yielded a lower proportion of fibres (76 ± 3.3 %) and correspondingly higher proportion of fragments (23.9 ± 3.3 %), particularly at site CB2', where fragments constituted 52.5 ± 8.7 % of MiPs collected (Fig. 4B). These morphological disparities can be attributed to differences in mesh size between the two methods: 80 μm for the MiPCS system versus 330 μm for the conventional net method, resulting in distinct capture efficiencies for fibres and fragments.

Black, blue, brown, and transparent MiPs were the most frequently observed colours in both methods (Figs. S4). These accounted for a high proportion of the total MiP load, with black, blue, and brown colours representing 56–85 % for MiPCS Pump and 7.7–86 % for the net method. White or transparent MiPs were constituted approximately 24 % and 28 % of the total for the MiPCS Pump and net methods, respectively. Variations in colour distribution were observed across different water layers and locations, with surface waters exhibiting a broader range of colours (Fig. S4).

3.3. Operational and environmental efficiency

A summary of the operational characteristics of the two methods is provided in Table 1. The MiPCS Pump method offered several advantages over the net method, including ease of use, portability, accurate volume measurements, and adaptability to varying depths, turbidity, and hydrodynamic conditions. However, the net method was more suitable for specific scenarios, such as capturing larger meso-plastics (5–25 mm) in deeper, low-turbidity waters.

The MiPCS Pump system demonstrated flexibility and efficiency, requiring fewer personnel and less operational time, making it well-suited for extensive field studies. Concentrations and abundances of MiPs reported by the MiPCS Pump method were up to 50 times higher than those detected by the net method (Fig. 3A & B). Despite these differences, both methods revealed that fibre-shaped MiPs were the most prevalent type across the study area (Fig. 4A & B).

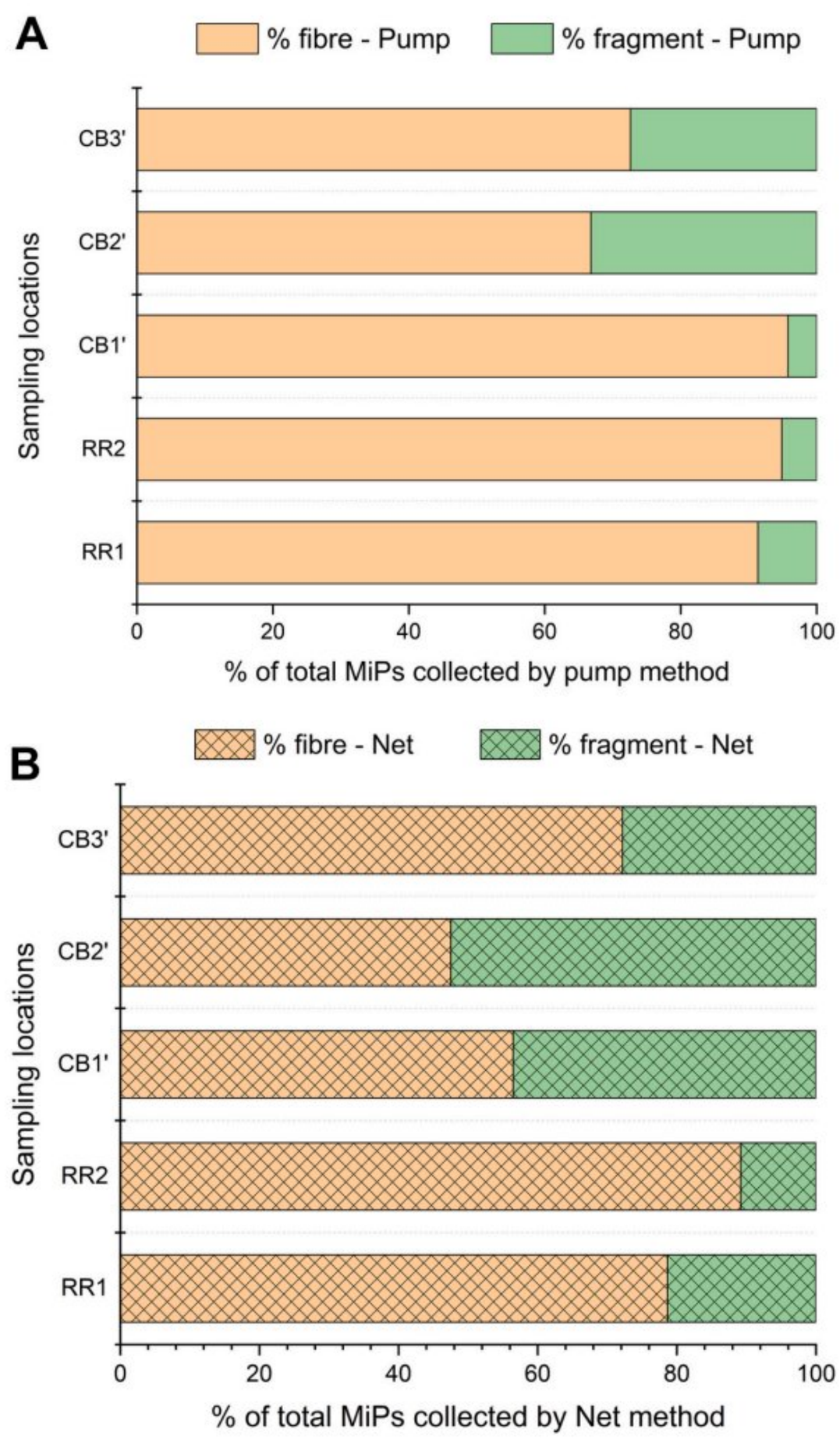

Fig. 4. Overall proportions of fibre and fragments of microplastic collected by two sampling methods: (**A**) Pump and (**B**) Net.

4. Discussion

Numerous studies have explored the efficiency of various MiP sampling methods by altering mesh sizes or sampling depths (Karlsson et al., 2020; Liu et al., 2020; Zhang et al., 2021). Our findings coincide with the previous study (Karlsson et al., 2020), which underscore the performance of the MiPCS Pump system in enabling precise volume measurements and flexible filter size options. Similarly, Zhang et al. (2021) also found notable discrepancies between sieve and plankton net methods with different mesh sizes in the Lijiang River, China. The differences were primarily attributed to variations in filtered volumes, which differed by up to three orders of magnitude, and this aligns closely with our study.

To evaluate the influence of sampling methods on MiP data, we made every effort to keep variables like sample depth and navigation speed constant. Our analysis can identify and assess the benefits and drawbacks of each method by focusing on three key issues influencing MiP data***: (1) Operational conditions,*** such as how easy each method was to use, how portable it was, and how well it could adapt to different environmental conditions***; (2) Sampled volume,*** which showed that MiPCS Pump method gives more accurate and controlled volume

Table 1
Comparison between MiPCS Pump and net sampling methods.

Evaluating parameters	Net method	Pump method
Operating condition	- Operate with different mesh size: No - **Flexibility and Portability**: need more supporting equipment. - **Operate with varying depths:** difficult, require two sampling systems: for surface and deeper water layers. **Manpower:** more manpower required, at least 3–4 operating persons.	- Operate with different mesh size: Yes - **Flexibility and Portability**: a flexible and portable solution for microplastic sampling. - **Operate with varying depth:** possible, ensures data homogeneity across water depths. **Manpower**: can be operated with less manpower: 2 people.
Sampled volume		
- Collected volumes	0.81–37.21 m^3	0.4–1.6 m^3
- Volume precision (%)	>1	< 0.05
- Required volumes for trace metal*, POPs**	0.43–300.33 m^3	0.13–10 m^3
Mesh size of net	300–330 μm	80 μm
Collected MiP concentrations	0.06–2.71 mg m^{-3} 0.78–26.62 particle m^{-3}	0.22–7.81 mg m^{-3} 16.25–114.58 particle m^{-3}
MiP size and shape	- Better for capturing larger MiPs (meso-size) - Not ideal for capturing MiP fibres.	- Better for micron-sizes MiPs - 3–50 times better at capturing MiP fibres than the net method.

* Requiring at least 1 mg MiPs for analysis.
** Volume calculated based on the minimum weight of MiPs in studied locations.

measurements than the net method; and ***(3) mesh size of the net,*** which can influence the capture of MiPs of different sizes (Table 1). This evaluation highlights the potential of selecting the most suitable method to enhance the reliability of MiP concentration estimates and uncover essential environmental relationships that might otherwise lead to misinterpretations.

4.1. Operational versatility

Both the Manta-Apstein nets and our MiPCS Pump system were effective in collecting MiPs, but the MiPCS Pump demonstrated greater adaptability. Which integrates a pump with phytoplankton nets and a mixing chamber, facilitates sampling in challenging conditions, including shallow (net only partially submerged), low-flow environments, or aquaculture settings lacking structures for net fixation. The MiPCS Pump also outperformed nets in deep waters and under turbulent hydrodynamic conditions, where nets may face submersion errors and challenges from strong waves or sediment layers.

Environmental parameters such as turbidity, salinity, and hydrodynamic regime are known to influence MiP distribution, although their specific mechanistic effects were not explicitly examined in this study. Nevertheless, the operational advantages of the MiPCS Pump were particularly evident in turbid waters, where traditional nets are susceptible to rapid clogging, reduced filtration efficiency, and backflow, leading to uncertainties in filtered volume estimation. In contrast, the pump system's active filtration and direct flow measurement allow for more stable and quantifiable sampling performance across varying turbidity levels. Another key strength of the MiPCS Pump is its depth flexibility. While Manta nets are largely restricted to surface waters, the pump system can sample across the full water column by adjusting intake depth. In this study, successful sampling at surface, mid-depth (4–8 m), and near-bottom layers enabled the assessment of vertical MiP distribution without the need for multiple specialized net deployments.

From an operational perspective, the system improves field efficiency through simultaneous multi-sample collection using five parallel nets, reducing deployment time and costs. Real-time flow monitoring further ensures adequate sample volumes during collection, minimizing under-sampling risks. The MiPCS Pump also performed consistently across freshwater-to-marine gradients despite substantial variation in salinity, turbidity, and productivity, highlighting its suitability for comparative studies. Although turbidity may reflect enhanced vertical mixing (Ugwu et al., 2024), no clear linear relationship between turbidity and MiP abundance was observed, suggesting complex, non-linear controls on MiP transport.

Finally, the MiPCS Pump system provides direct volume measurement using calibrated mechanical flow meters. Calibration with volumetric containers prior to field deployment showed <5 % deviation between measured and actual volumes across the operational flow-rate range. This direct measurement eliminates backflow-related uncertainties inherent to geometric volume calculations used in net-based methods, where the standard formula ($V = A \times D$) assumes 100 % filtration efficiency and cannot account for water deflected or expelled due to clogging. Visual observations during net towing indicated progressive clogging in turbid waters, suggesting that backflow likely contributed to volume-related uncertainties, although its magnitude was not quantified in this study.

4.2. Enhanced volume accuracy and correlated pollutant analysis

One of the key differences between the net and MiPCS Pump methods is the volume of water sampled. Two aspects that may influence the correct estimation of MiPs concentration are: (1) the certainty of knowing the volume of filtered water; (2) the right volume destined for various analyses, such as to determine MiP composition, chemical pollutants sorbed to the surfaces of MiPs, etc. (Table 1).

4.2.1. Accuracy of sampling volume

Accurate quantification of sampling volume is essential for MiP analysis because environmental concentrations are typically low, requiring large water volumes (Huppertsberg and Knepper, 2018; Peng et al., 2020; Qiu et al., 2015). Although net-based method allows for large volumes of water to be sampled (in cubic meters), accurately quantifying the filtered volume can be a challenge, as influenced by wave-induced immersion and depth fluctuations, wind, boat movement, and net clogging-induced backflows (Hamidian et al., 2021; Pasquier et al., 2022; Razeghi et al., 2021). Consequently, volume uncertainty represents a significant limitation of net approaches (Karlsson et al., 2020). Net methods estimate filtered volume using a geometric formula (V = net mouth area × towing distance), which assumes 100 % filtration efficiency. In practice, clogging and associated backflow reduce the effective filtered volume, potentially leading to biased MiP concentration estimates. The magnitude of this error varies with turbidity, deployment duration, and hydrodynamic conditions, and is difficult to quantify under field settings without dedicated flow-measurement devices.

In contrast, by using a pump with small pore-sized plankton nets, it is possible to reduce the sample volume while still collecting smaller MiP particles (Delgado-Gallardo et al., 2021). Besides, our MiPCS Pump system, equipped with the 80 μm mesh size phytoplankton nets, required a smaller sampling volume of 400-2000 L, depending on the analytical purpose, much less than the 10 to 30 m^3 volumes required by the manta trawl method. By incorporating an electronic flow meter, the MiPCS Pump minimizes sampling errors and ensures reproducibility, providing reliable data for various analyses. These advantages position the pump method as an alternative for obtaining accurate concentration data compared to the net method, which is prone to inconsistencies from environmental variability and net clogging.

4.2.2. Beyond MiP analysis: other pollutants

To comprehensively assess the health risks linked to MiP contamination, it is crucial to analyse other contaminants, such as toxic metals and POPs that are commonly found sorbed onto MiPs, alongside MiP composition. The MiPCS Pump system facilitates simultaneous collection of MiPs and associated pollutants, such as toxic metals or persistent organic pollutants (POPs). A comparison between MiPCS Pump and net methods, including the MiP quantities required to be recovered using either method for analysing various contaminants that could be sorbed to them were presented (Table 1). It also illustrates the flexibility of the MiPCS Pump in adjusting to various sampling conditions and ensuring adequate sample volumes for comprehensive analyses. The MiPCS Pump method we developed and employed allows us to easily adjust to different field conditions and sampling quantities, ensuring the acquisition of important data for various investigations, including environmental risks assessments.

4.3. Mesh size and microplastic capture efficiency

Net-based methods using mesh sizes of 300–330 μm, such as the Manta–Epstein net (300 μm) applied in this study, are inherently limited in retaining smaller MiPs. In contrast, the MiPCS Pump system, equipped with 80 μm phytoplankton nets, captured a broader size range (80–5000 μm), including particles missed by conventional nets. Consistent with our results, Vermaire et al. (2017) reported substantially higher MiP concentrations using smaller-mesh nets (100 μm; 0.1 particle L^{-1}) than manta nets (333 μm; 0.00135 particle L^{-1}). In addition, net-based sampling is susceptible to clogging-induced backflow, which reduces filtration efficiency and introduces uncertainty in geometric volume estimates that assume unobstructed flow (Kataoka et al., 2019). These combined size-selective and hydrodynamic constraints explain the lower concentrations, particularly of fibres, observed with traditional net methods.

Previous studies have shown that mesh size strongly influences MiP capture efficiency (Alfaro-Núñez et al., 2021; Yu et al., 2025). Larger mesh sizes (such as the 330 μm used in our traditional nets) often fail to retain smaller MiPs, resulting in concentration estimates that underrepresent the actual pollution levels. Our comparison focuses on the practical performance of each method under field conditions. The higher MiP concentrations obtained using the pump system can be attributed to (i) its ability to sample a broader particle size range (80–5000 μm vs. 330–5000 μm for nets) and (ii) more accurate volume determination through direct flow metering, which avoids backflow-related errors inherent in geometric volume calculations. Consistent with Range et al. (2023), mass-based quantification provides a more representative measure of environmental MiP loads than particle counts when comparing methods with different size cut-offs and operational constraints. Our results further indicate that smaller MiPs (80–330 μm) constitute a substantial fraction of total environmental MiP loads and are systematically missed by conventional net-based approaches due to unavoidable physical constraints. Even for particles theoretically capturable by both methods (>330 μm), net-based concentrations may remain underestimated because of differences in retention efficiency associated with particle shape, hydrodynamic effects, and backflow-induced losses.

Consistent with previous reports, plankton nets with smaller mesh sizes (~80–100 μm) yield substantially higher MiP concentrations than manta nets, capturing up to 30-fold higher abundances in shorter sampling durations (Dris et al., 2018a, 2018b). For example, an 80 μm mesh net can retain up to 250 times more fibres than a 330 μm net (Dris et al., 2018a). This evidence supports the superior performance of the MiPCS Pump system, which integrates smaller-mesh phytoplankton nets with an active pumping configuration that mitigates clogging and backflow, thereby enabling more efficient capture across a wider MiP size spectrum (Fig. S1B).

4.4. Differences in particle characteristics

The MiPCS Pump system captured a higher proportion of fibrous MiPs (≈20 %) compared to the net-based method, indicating differences in particle-type selectivity between sampling approaches. These differences can be attributed primarily to two methodological factors: (i) mesh size effects, whereby finer meshes are more efficient at retaining small and flexible fibres, and (ii) sampling geometry, as horizontal surface towing and vertical pump-based sampling may access distinct water column fractions.

Previous studies have reported pronounced vertical heterogeneity in MiP distributions (Liu et al., 2022; Zong et al., 2024), suggesting that sampling geometry can substantially influence particle capture. In the present study, however, vertical profiles and detailed hydrodynamic parameters were not measured, preventing direct attribution of the observed differences to specific environmental mechanisms. Consequently, the contrasting particle characteristics between methods likely reflect a combined influence of mesh selectivity and sampling geometry, with their relative contributions requiring further investigation.

At the surface layer, both systems sampled horizontally at comparable depths, allowing direct comparison under similar conditions. Nevertheless, MiPs collected by manta nets were driven by vessel-induced flow, whereas those captured by the MiPCS Pump were influenced by active suction in combination with ambient hydrodynamics, potentially contributing to differences in particle shape distributions. In deeper waters, methodological divergence was more pronounced: net sampling remained horizontally oriented, while the MiPCS Pump operated vertically with a downward intake, enabling integration across broader depth intervals. Similar effects of vertical sampling on MiP distributions have been reported previously (Zong et al., 2024; Liu et al., 2022).

These findings demonstrate that both mesh size selectivity and sampling geometry influence the particle characteristics captured by different methods. Understanding these methodological effects is essential for selecting the most appropriate sampling method and ensuring accurate MiP concentration estimations.

4.5. Limitations and future research directions

This study describes a new MiPCS Pump to ensure more accurate, precise and simultaneous multi-sample collection for assessing MiP concentrations compared to conventional methods. However, as with all these methods we would like to highlight some limitations with the MiPCS Pump method. Firstly, sampling was limited to the Red River Delta and Cat Ba Archipelago, which may restrict the applicability of results to other environments with different hydrodynamics. Secondly, although the MiPCS Pump's low-pressure and pre-screening design reduces mechanical stress, some pump-induced fragmentation of weathered MiPs may still occur. Our dual quantification (mass and particle count) indicates this effect is minor, but further tests under varied operating conditions are needed. Thirdly, limited sampling prevented a full assessment of seasonal variation in MiP distribution.

Additional methodological limitations include (1) the absence of systematic size-fractionated analyses, (2) limited characterization of variability among the five parallel nets, and (3) the lack of formal uncertainty quantification and error propagation for either sampling approach. Moreover, (4) backflow-related volume errors in net-based methods were not directly measured, despite visual evidence of clogging, and (5) environmental parameters (e.g., salinity, turbidity, hydrodynamics) were not quantified in a manner allowing hypothesis-driven evaluation of their influence on MiP distributions.

Future studies should validate the MiPCS Pump across diverse aquatic settings (e.g., varying depths, salinity, turbidity) and conduct long-term monitoring to capture seasonal trends. Integration with advanced spectroscopic and machine learning methods could improve MiP identification. Establishing standardised inter-laboratory protocols

and conducting cost-benefit analyses will also support broader and more consistent use of this system in research and monitoring programs.

5. Conclusion

This study has developed and evaluated an innovative pump system integrated with plankton nets for microplastic (MiP) sampling in various aquatic environments, comparing its performance with the established Manta-Apstein net method. The findings highlight the substantial influence of the sampling method on the accuracy and reliability of MiP concentration estimates.

Both the Manta-Apstein net and the advanced MiPCS Pump system offer distinct advantages and limitations. While the net method is effective for capturing larger MiPs, particularly mesoplastics in surface waters, its susceptibility to clogging and reliance on substantial time and human resources limit its efficiency.

In contrast, the MiPCS Pump method represents a notable advancement in MiP sampling technology. Its flexibility and adaptability to varying environmental conditions, combined with its ability to capture a broad size range of MiPs with precision and consistency, make it an invaluable tool for environmental monitoring. By employing smaller mesh-sized nets, the MiPCS Pump system also enhances the collection of fibres, which pose a hidden ecological risk.

The system's operational efficiency and versatility support its adoption as a standardised method for global MiP assessments. Its consistent and accurate data collection can inform pollution mitigation strategies, enhance environmental policies, and contribute to a deeper understanding of the ecological and human health impacts of microplastic contamination.

CRediT authorship contribution statement

Thao Thanh Le: Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis. **Hoa Thi Tran:** Writing – original draft, Visualization, Investigation. **Van Thuong Truong:** Supervision, Methodology, Investigation. **Tien Trung Chu:** Methodology, Investigation. **Thi Hanh Tien Nguyen:** Investigation. **Ryan Pereira:** Writing – review & editing, Supervision. **Tony Gutierrez:** Writing – review & editing, Supervision. **Thomas Wagner:** Writing – review & editing, Supervision, Investigation. **Michel J. Kaiser:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Huong Thi Thuy Ngo:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

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

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References

Al-Azzawi, M.S.M., Kefer, S., Weißer, J., Reichel, J., Schwaller, C., Glas, K., Knoop, O., Drewes, J.E., 2020. Validation of Sample Preparation Methods for Microplastic Analysis in Wastewater Matrices—Reproducibility and Standardization. Water 12 (9), 2445. https://doi.org/10.3390/w12092445.

Alberghini, L., Truant, A., Santonicola, S., Colavita, G., Giaccone, V., 2023. Microplastics in fish and fishery products and risks for human health: a review. Int. J. Environ. Res. Public Health 20 (1), 789.

Alfaro-Núñez, A., Astorga, D., Cáceres-Farías, L., Bastidas, L., Villegas, C.S., Macay, K., Christensen, J.H., 2021. Microplastic pollution in seawater and marine organisms across the Tropical Eastern Pacific and Galápagos. Sci. Rep. 11 (1), 6424. https://doi.org/10.1038/s41598-021-85939-3.

Amélineau, F., Bonnet, D., Heitz, O., Mortreux, V., Harding, A.M.A., Karnovsky, N., Walkusz, W., Fort, J., Grémillet, D., 2016. Microplastic pollution in the Greenland Sea: Background levels and selective contamination of planktivorous diving seabirds. Environ. Pollut. 219, 1131–1139. https://doi.org/10.1016/j.envpol.2016.09.017.

Cai, Y., Li, C., Zhao, Y., 2021. A review of the migration and transformation of microplastics in inland water systems. Int. J. Environ. Res. Public Health 19 (1), 148. https://doi.org/10.3390/ijerph19010148.

Cho, Y., Shim, W.J., Jang, M., Han, G.M., Hong, S.H., 2019. Abundance and characteristics of microplastics in market bivalves from South Korea. Environ. Pollut. 245, 1107–1116. https://doi.org/10.1016/j.envpol.2018.11.091.

Delgado-Gallardo, J., Sullivan, G.L., Esteban, P., Wang, Z., Arar, O., Li, Z., Watson, T.M., Sarp, S., 2021. From sampling to analysis: a critical review of techniques used in the detection of micro- and nanoplastics in aquatic environments. ACS EST Water 1 (4), 748–764. https://doi.org/10.1021/acsestwater.0c00228.

Dris, R., Gasperi, J., Rocher, V., Saad, M., Renault, N., Tassin, B., 2015. Microplastic contamination in an urban area: a case study in Greater Paris. Environ. Chem. 12 (5), 592–599. https://doi.org/10.1071/EN14167.

Dris, R., Gasperi, J., Rocher, V., Tassin, B., 2018a. Synthetic and non-synthetic anthropogenic fibers in a river under the impact of Paris Megacity: sampling methodological aspects and flux estimations. Sci. Total Environ. 618, 157–164. https://doi.org/10.1016/j.scitotenv.2017.11.009.

Dris, R., Imhof, H.K., Löder, M.G.J., Gasperi, J., Laforsch, C., Tassin, B., 2018b. Chapter 3 - microplastic contamination in freshwater systems: methodological challenges, occurrence and sources. In: Zeng, E.Y. (Ed.), Microplastic Contamination in Aquatic Environments. Elsevier, pp. 51–93.

Fava, M., 2022. Ocean plastic pollution an overview: data and statistics. https://oceanliteracy.unesco.org/plastic-pollution-ocean/.

Hamidian, A.H., Ozumchelouei, E.J., Feizi, F., Wu, C., Zhang, Y., Yang, M., 2021. A review on the characteristics of microplastics in wastewater treatment plants: a source for toxic chemicals. J. Clean. Prod. 295, 126480. https://doi.org/10.1016/j.jclepro.2021.126480.

Hanvey, J.S., Lewis, P.J., Lavers, J.L., Crosbie, N.D., Pozo, K., Clarke, B.O., 2017. A review of analytical techniques for quantifying microplastics in sediments. Anal. Methods 9 (9), 1369–1383. https://doi.org/10.1039/C6AY02707E.

Hermabessiere, L., Dehaut, A., Paul-Pont, I., Lacroix, C., Jezequel, R., Soudant, P., Duflos, G., 2017. Occurrence and effects of plastic additives on marine environments and organisms: a review. Chemosphere 182, 781–793. https://doi.org/10.1016/j.chemosphere.2017.05.096.

Huppertsberg, S., Knepper, T.P., 2018. Instrumental analysis of microplastics—benefits and challenges. Anal. Bioanal. Chem. 410 (25), 6343–6352. https://doi.org/10.1007/s00216-018-1210-8.

Karlsson, T.M., Kärrman, A., Rotander, A., Hassellöv, M., 2020. Comparison between manta trawl and in situ pump filtration methods, and guidance for visual identification of microplastics in surface waters. Environ. Sci. Pollut. Res. 27 (5), 5559–5571. https://doi.org/10.1007/s11356-019-07274-5.

Kataoka, T., Nihei, Y., Kudou, K., Hinata, H., 2019. Assessment of the sources and inflow processes of microplastics in the river environments of Japan. Environ. Pollut. 244, 958–965. https://doi.org/10.1016/j.envpol.2018.10.111.

Kovač Viršek, M., Palatinus, A., Koren, Š., Peterlin, M., Horvat, P., Kržan, A., 2016. Protocol for microplastics sampling on the sea surface and sample analysis. J. Vis. Exp. 118. https://doi.org/10.3791/55161.

Kvale, K., Prowe, A.E.F., Chien, C.T., Landolfi, A., Oschlies, A., 2020. The global biological microplastic particle sink. Sci. Rep. 10 (1), 16670. https://doi.org/10.1038/s41598-020-72898-4.

Liu, Y., Zhang, J., Cai, C., He, Y., Chen, L., Xiong, X., Huang, H., Tao, S., Liu, W., 2020. Occurrence and characteristics of microplastics in the Haihe River: an investigation of a seagoing river flowing through a megacity in northern China. Environ. Pollut. 262, 114261. https://doi.org/10.1016/j.envpol.2020.114261.

Liu, Y., Cao, W., Hu, Y., Zhang, J., Shen, W., 2022. Horizontal and vertical distribution of microplastics in dam reservoir after impoundment. Sci. Total Environ. 832, 154962. https://doi.org/10.1016/j.scitotenv.2022.154962.

Malinowski, C.R., Searle, C.L., Schaber, J., Höök, T.O., 2023. Microplastics impact simple aquatic food web dynamics through reduced zooplankton feeding and potentially releasing algae from consumer control. Sci. Total Environ. 904, 166691. https://doi.org/10.1016/j.scitotenv.2023.166691.

Mikulec, V., Adamović, P., Cvetković, Ž., Ivešić, M., Gajdoš Kljusurić, J., 2023. Green techniques for detecting microplastics in marine with emphasis on FTIR and NIR spectroscopy—short review. Processes 11 (8), 2360.

Monique, M., Giuseppe, P., Francesca, F., Davide, D.P., Savoca, S., Gioele, C., Teresa, R., Giovanni, P., Eleonora, G., Nunziacarla, S., Gioacchino, B., Giuliano, S., Teresa, B., 2022. Investigating the effects of microplastic ingestion in Scyliorhinus canicula from the South of Sicily. Sci. Total Environ. 850, 157875. https://doi.org/10.1016/j.scitotenv.2022.157875.

Montoto-Martínez, T., Meléndez-Díez, C., Melián-Ramírez, A., Hernández-Brito, J.J., Gelado-Caballero, M.D., 2022. Comparison between the traditional Manta net and an innovative device for microplastic sampling in surface marine waters. Mar. Pollut. Bull. 185, 114237. https://doi.org/10.1016/j.marpolbul.2022.114237.

Pasquier, G., Doyen, P., Carlesi, N., Amara, R., 2022. An innovative approach for microplastic sampling in all surface water bodies using an aquatic drone. Heliyon 8 (11), e11662. https://doi.org/10.1016/j.heliyon.2022.e11662.

Peng, L., Fu, D., Qi, H., Lan, C.Q., Yu, H., Ge, C., 2020. Micro- and nano-plastics in marine environment: Source, distribution and threats — a review. Sci. Total Environ. 698, 134254. https://doi.org/10.1016/j.scitotenv.2019.134254.

Prata, J.C., da Costa, J.P., Duarte, A.C., Rocha-Santos, T., 2019. Methods for sampling and detection of microplastics in water and sediment: a critical review. TrAC Trends Anal. Chem. 110, 150–159. https://doi.org/10.1016/j.trac.2018.10.029.

Qiu, Q., Peng, J., Yu, X., Chen, F., Wang, J., Dong, F., 2015. Occurrence of microplastics in the coastal marine environment: first observation on sediment of China. Mar. Pollut. Bull. 98 (1), 274–280. https://doi.org/10.1016/j.marpolbul.2015.07.028.

Range, D., Scherer, C., Stock, F., Ternes, T.A., Hoffman, T.O., 2023. Hydro-geomorphic perspectives on microplastic distribution in freshwater river systems: a critical review. Water Res. 245, 120567. https://doi.org/10.1016/j.watres.2023.120567.

Razeghi, N., Hamidian, A.H., Wu, C., Zhang, Y., Yang, M., 2021. Microplastic sampling techniques in freshwaters and sediments: a review. Environ. Chem. Lett. 19 (6), 4225–4252. https://doi.org/10.1007/s10311-021-01227-6.

Rochman, C.M., Tahir, A., Williams, S.L., Baxa, D.V., Lam, R., Miller, J.T., Teh, F.-C., Werorilangi, S., Teh, S.J., 2015. Anthropogenic debris in seafood: plastic debris and fibers from textiles in fish and bivalves sold for human consumption. Sci. Rep. 5 (1), 14340. https://doi.org/10.1038/srep14340.

Sambolino, A., Herrera, I., Álvarez, S., Rosa, A., Alves, F., Canning-Clode, J., Cordeiro, N., Dinis, A., Kaufmann, M., 2022. Seasonal variation in microplastics and zooplankton abundances and characteristics: the ecological vulnerability of an oceanic island system. Mar. Pollut. Bull. 181, 113906. https://doi.org/10.1016/j.marpolbul.2022.113906.

Silva, A.B., Bastos, A.S., Justino, C.I.L., da Costa, J.P., Duarte, A.C., Rocha-Santos, T.A.P., 2018. Microplastics in the environment: challenges in analytical chemistry - a review. Anal. Chim. Acta 1017, 1–19. https://doi.org/10.1016/j.aca.2018.02.043.

Soares, M.O., Rizzo, L., Ximenes Neto, A.R., Barros, Y., Martinelli Filho, J.E., Giarrizzo, T., Rabelo, E.F., 2023. Do coral reefs act as sinks for microplastics? Environ. Pollut. 337, 122509. https://doi.org/10.1016/j.envpol.2023.122509.

Tagg, A.S., Sapp, M., Harrison, J.P., Ojeda, 2015. Identification and quantification of microplastics in wastewater using focal plane array-based reflectance micro-FT-IR imaging. Anal. Chem. 87, 6032–6040. https://doi.org/10.1021/acs.analchem.5b00495.

Ugwu, K., Vianello, A., Almeda, R., Iordachescu, L., Rotander, A., 2024. Comparison of two pump-based systems for sampling small microplastics (>10 μM) in coastal waters. Environ. Pollut. 363, 125192. https://doi.org/10.1016/j.envpol.2024.125192.

UNEP, 2023. Turning Off The Tap: How the World Can End Plastic Pollution and Create a Circular Economy.

Vermaire, J.C., Pomeroy, C., Herczegh, S.M., Haggart, O., Murphy, M., 2017. Microplastic abundance and distribution in the open water and sediment of the Ottawa River, Canada, and its tributaries. FACETS 2, 301–314. https://doi.org/10.1139/facets-2016-0070.

Wright, S.L., Kelly, F.J., 2017. Plastic and human health: a micro issue? Environ. Sci. Technol. 51 (12), 6634–6647. https://doi.org/10.1021/acs.est.7b00423.

Xia, W., Rao, Q., Liu, J., Chen, J., Xie, P., 2024. Occurrence and characteristics of microplastics across the watershed of the world's third-largest river. J. Hazard. Mater. 480, 135998. https://doi.org/10.1016/j.jhazmat.2024.135998.

Xia, F., Yang, W., Zhao, H., Cai, Y., Tan, Q., 2025. Occurrence characteristics and transport processes of riverine microplastics in different connectivity contexts. NPJ Clean Water 8, 1. https://doi.org/10.1038/s41545-024-00424-4.

Yu, M., Herrmann, B., Liang, H., Sistiaga, M., Zhu, Z., Brčić, J., Tang, L., Liu, C., Tang, Y., 2025. Size selection in sampling nets leads to underestimation of microplastic pollution. Environ. Pollut. 372, 126007. https://doi.org/10.1016/j.envpol.2025.126007.

Yuan, C., Almuhtaram, H., McKie, M.J., Andrews, R.C., 2022. Assessment of microplastic sampling and extraction methods for drinking waters. Chemosphere 286, 131881. https://doi.org/10.1016/j.chemosphere.2021.131881.

Zhang, L., Xie, Y., Zhong, S., Liu, J., Qin, Y., Gao, P., 2021. Microplastics in freshwater and wild fishes from Lijiang River in Guangxi, Southwest China. Sci. Total Environ. 755, 142428. https://doi.org/10.1016/j.scitotenv.2020.142428.

Zong, C., Zhu, L., Jabeen, K., Li, C., Wei, N., Wang, X., Dong, X., Li, D., 2024. Vertical distribution of microplastics in the Western Pacific Warm Pool: in situ results comparison of different sampling method. J. Hazard Mater. 479, 135722. https://doi.org/10.1016/j.jhazmat.2024.135722.