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Baseline concentration of microplastics in surface water and sediment of the northern branches of the Mekong River Delta, Vietnam

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ABSTRACT

The Mekong River Delta in Vietnam, is concerned by numerous microplastic-related issues such as a lack of wastewater treatment facilities and mismanagement of plastic waste released from agriculture, aquaculture and related activities. This study aimed to examine the presence of microplastics in surface water and sediment by collecting samples from six sites along the Tien River and its distributaries in February 2019. The results showed that the average concentration of microplastics over the entire area was 53.8 ± 140.7 items m^{-3} in surface water and 6.0 ± 2.0 items g^{-1} dried weight in sediment, with a predominance of microplastic fibres rather than fragments, respectively 85 % and 98 % in surface water and sediment. In the main flow of surface water, the concentration of microplastics was stable; however, in the sediment, microplastic concentration was affected by the high dynamic flow regime rather than the sources where microplastics are released.

1. Introduction

Since the first evidence of microplastic presence in sediment samples collected from beaches around Plymouth City, England (Thompson et al., 2004), microplastics – plastic particles <5 mm in size (GESAMP, 2019) – and the pollution caused by them have become a ubiquitous environmental issue. Over the last decade, knowledge on microplastic pollution, i.e., abundance in different environments, sources, transport, and ecotoxicity, has been remarkably elucidated. Microplastics have been found across the globe at different levels and in most of different environmental compartments as water, sediment, atmospheric fallout and biota (Yusuf et al., 2022; Perumal and Muthuramalingam, 2022; Yuan et al., 2022; Ugwu et al., 2021; Kumar et al., 2021a). Compared to other regions, Asia countries, the biggest contributors to marine plastic wastes due to mainly waste mismanagement (Jambeck et al., 2015; Meijer et al., 2021) are encountering the most vulnerable abundance levels of microplastics (Kumar et al., 2021a; Yang et al., 2022). The presence of microplastics in the environments is related to local development and economic structures and mainly originated from the release of treated or untreated waste water and landfill leachate to the

environment, the improper treatment of plastic wastes, and from other activities such as aquaculture, agriculture, and shipping (Xiang et al., 2022; Yang et al., 2022). Microplastics in the water can deposit to the bottom sediments or can be transported over a short or long distance, ingested by the organisms. The bioaccumulation and biomagnification of microplastics through the food chain have been alarmed in various research. The potential toxicity of microplastics could come from the additives added during the production of plastics or adsorbed pollutants, i.e. organic pollutants and heavy metals, on microplastic surface (Nam et al., 2022; Xiang et al., 2022). The coexistence of microplastics and these pollutants may lead to a more vulnerable threats to human health and the environment at two folds: (i) a higher accumulation of the pollutants in microplastics than in the ambience up to two to three orders of magnitude and (ii) a higher level of toxicity of the combination of microplastics and some pollutants compared to the toxicity of individual pollutants (Verla et al., 2019; Campanale et al., 2020b; Xiang et al., 2022). This interaction could be affected by the characteristics of microplastics, i.e., type, size, aging degree, etc., and of the pollutants and the conditions of the environment (Nam et al., 2022; Xiang et al., 2022).

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Microplastics in the environment exist in different forms, such as microbeads, pellets, films, foams, fragments, and fibres. They are usually divided into primary or secondary microplastics based on their source (Lusher et al., 2017). Primary microplastics are often pellets, micro-sized spherical plastic particles added to personal care products, microbeads, or multi-faceted plastic particles used as input materials in the plastic industry. Secondary microplastics include films, foams, fragments, and fibres and are generated from the fragmentation of larger plastics or from the protective coating of ships and boats. This is primarily caused by weather agents such as ultraviolet radiation, or other mechanical, chemical, and biological degradation processes. Fibres are the most dominant form and are primarily released from untreated domestic wastewater through the laundries of synthetic clothes and from industrial wastewater generated by the textile and apparel industries (Bui et al., 2020; Auta et al., 2017; Duis and Coors, 2016). Secondary microplastics are estimated to occupy the majority of microplastics in the environment and become more difficult to tackle because of the large amount of macroplastics entering the oceans every year (Meijer et al., 2021). The role of coastal zones and rivers as the main input of plastic debris to oceans is now recognised (Meijer et al., 2021; Lebreton et al., 2017). It was estimated that between 1.15 and 2.41 million tons of plastic annually enters the oceans from global river systems, of which the top 20 contributing rivers were from Asia (67 %). The Mekong River, which is the world's second richest river basin in terms of biodiversity (World Wide Fund for Wildlife, 2016) and is considered the lifeline for the entire basin of five Southeast Asian developing countries, was ranked at 11 out of 20 (Lebreton et al., 2017).

In 2015, the mismanagement of solid waste brought Vietnam in the list of the top countries emitting most plastics to the global oceans (Jambeck et al., 2015). Microplastics were measured in various aquatic environments including rivers, lakes, bays, and beaches in Vietnam, indicating the link of microplastic concentration to the plastic-related anthropogenic activities of the surrounding areas (Doan et al., 2021; Lahens et al., 2018; Strady et al., 2020, 2021; Tran Nguyen et al., 2020). Located downstream of the Mekong River, the Mekong River Delta (MRD), hosting 17.3 million inhabitants, contributes to more than half of the country's production of rice, fruits, and aquaculture products (GSO, 2020). The MRD is especially vulnerable to climate change, facing issues such as sea level rise, salinity intrusion, and flooding, and its aquatic environment is already contaminated by various pollutants such as trace metals and organic pollutants originated from aquaculture, agriculture, craft villages, households, and industrial activities (ADB, 2015; Le et al., 2016; MDP-team, 2013; MONRE, 2018, 2014; Pham et al., 2013; Strady et al., 2017). So far, little is known about the microplastic pollution status in the Mekong Delta. The presence of both dense urban areas (with numerous cities above 100,000 inhabitants) and rural areas dominated by agriculture and aquaculture activities raises the hypothesis of contrasted microplastic concentrations along the river watershed. This study aims thus to evaluate the microplastic contamination level in surface waters and intertidal riverine sediments of this environment and discuss their distribution relative to local activities and features. The Tien River system, the Mekong's northern branch, was selected for collecting surface water and sediment to represent the different anthropogenic activities and pressure observed at the scale of the MRD.

2. Materials and methods

1. Study area

The northern branch of the Mekong River Delta (40,000 km², the largest delta in Vietnam) has a total length of 230 km and flows to the East China Sea through three main distributaries: Tien River, Ham Luong River, and Co Chien River. In the MRD, the climate is tropical with two distinct seasons: the rainy season from May to November, and the dry season from December to April, with flooding occurring

primarily between August and November, when a high volume of water from upstream of the Mekong River flows to the delta, leading to a change in the livelihood of local people. More specifically, the Tien River system is flowing through urban dense cities (e.g., Cao Lanh, My Tho, Cho Lach, and Ben Tre), agriculture area (rice, fruit), industrial zones and aquaculture area (shrimp). The six sampling sites were located along the Tien River system distributaries: Cao Lanh, My Tho, Cho Lach, Ben Tre, Vinh Long, and Tra Vinh (Fig. 1). Among the sampling sites, the Cao Lanh site was in the Cai Sao Thuong River, a secondary tributary of the Tien River; it flows through the urban area of Cao Lanh City. Other sites were located in primary tributaries of the Tien River system with My Tho on the Tien River; Cho Lach and Ben Tre on the Ham Luong River; and Vinh Long and Tra Vinh on the Co Chien River (Table 1).

The solid waste in MRD was estimated of 5852 and 3577 tons day⁻¹, with collection rates of 49 % and 88 %, in rural and urban areas, respectively (MONRE, 2019). In many rural areas, household waste is buried in open and unsanitary landfills, burnt, or discarded into the environment (Nguyen and Le, 2011). Plastic waste from agricultural activities (e.g. plastic bottles and bags containing pesticides, herbicides, and fertilizers, Le, 2019) and aquaculture activities (e.g. fishing equipment such as nets, lines, and plastic floats, and plastic sheets used as the bottom layer of shrimp ponds) are thrown in the aquatic environment.

2. Sampling

Sampling campaign was carried out in October 2018. At each site of the six sites, surface water and sediment samples were collected near the low tide. Duplicate surface water samples were collected in the middle of the river, using a plankton net 300 µm mesh size and 50 cm diameter, during 5 min. At each sampling, the net was placed perpendicularly to the current and towed by a local boat to ensure the current speed entering the net at about 0.5 m s⁻¹. The volume of the collected water was measured using an Oceanics flowmeter attached to the plankton net, after which the net was rinsed from the outside, and the sample was collected in a 500 mL glass bottle.

Sediment samples were collected using an Ekman grab sampler in the intertidal zone. At each sampling site, two to four sub-samples were collected and homogenised into a single sample. Approximately 1 kg of sediment was collected at each site and kept in a Ziploc plastic bag. After being transported to the laboratory, the samples were stored in a 4 °C cooler for later analysis.

3. Laboratory analysis

Analysis of surface water samples was carried out based on the five step treatment protocol proposed by Strady et al. (2021): (1) sample preparation: The samples were processed through a 1 mm mesh size sieve to discard all larger fractions; suspected microplastics smaller than 5 mm were kept and stored in Petri dishes. (2) Sample digestion: To reduce the high density of interfering particles such as leaves, wood, sand, and minerals, a two-step sample digestion was conducted comprising of digestion of interfering matter, and density separation. For each 350 mL sample, 1 g of sodium dodecyl sulphate (Merck®) was added to the bottles and heated at 55 °C for 24 h. Next, 1 mL of biozyme SE (protease and amylase, Spinnrad®) and 1 mL of biozyme F (lipase, Spinnrad®) were added to the samples and heated at 40 °C for 48 h. The samples were subsequently oxidised using 15 mL of H₂O₂ (30 %, Merck®) at 40 °C for a further 48 h. After five days of digestion, the treated samples were sifted through a 250 µm mesh size sieve to remove all fractions smaller than 250 µm in size. (3) Density separation: The overflow was performed using filtered NaCl solution ($d = 1.18 \pm 0.02 \text{ g mL}^{-1}$) until all plastic were retrieved. (4) Sample filtration: The supernatant of the overflow solution was then filtered through GF/A filters (1.6 µm porosity, Whatman®) using a glassware filtration unit. After that, the filters were kept separately in sterile Petri dishes until the

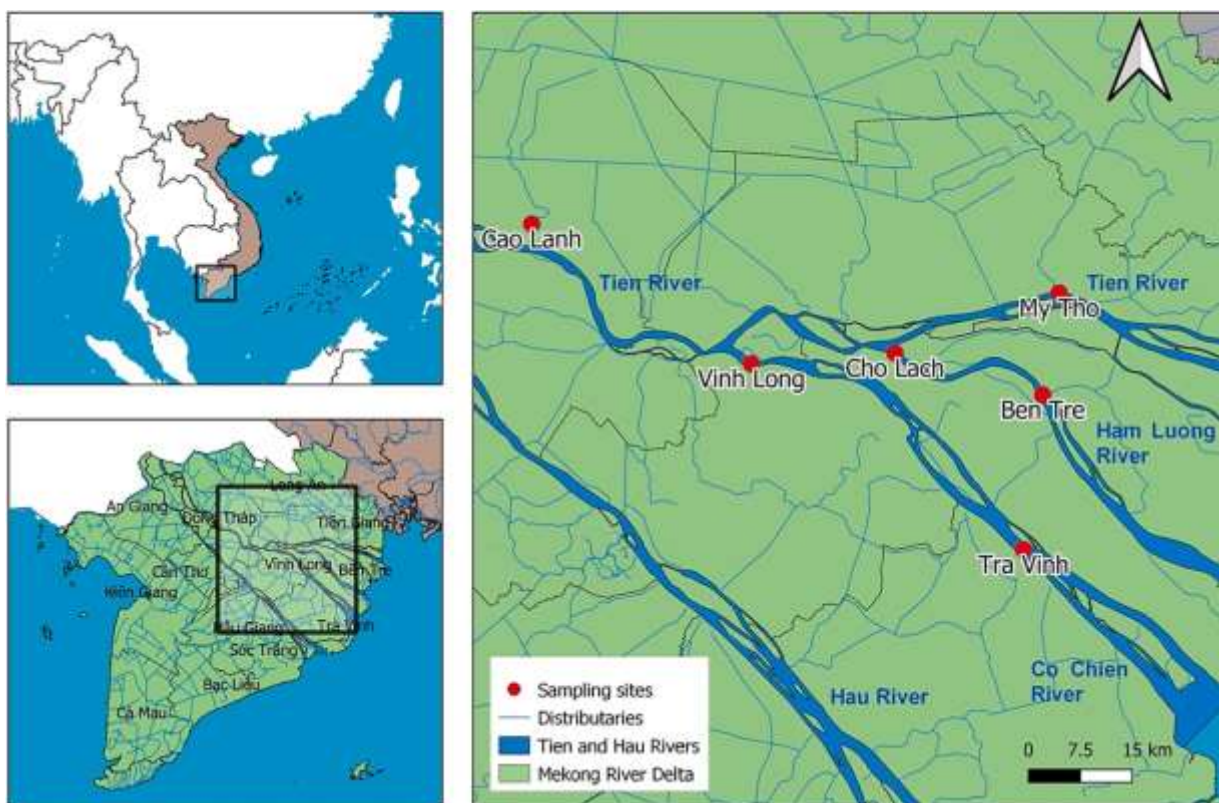


Fig. 1. Study area map showing the surface water and sediment sampling sites along the Tien River.

Table 1

Description of sampling sites with the population of nearby urban in 2016 and the description of each site.

Sampling site	Coordinate	River	Site description
Cao Lanh	10°27'05"N, 106°27'05"E	Cai Sao Thuong River (small secondary tributary, low water discharge)	Closed to a residential area (My Tra residential area, 500 households). This urban river flow through the center of Cao Lanh City (population 163,892 inhabitants)
My Tho	10°21'04"N, 106°22'07"E	Tien River (main distributaries)	Near the fishing raft area My Tho City (population 228,385 inhabitants) is on the left bank
Cho Lach	10°16'29"N, 106°09'17"E	Ham Luong River (main distributaries)	Fishing activities Cho Lach Town (population 109,516 inhabitants) is on the right bank
Ben Tre	10°15'22"N, 106°19'48"E	Ham Luong River (main distributaries)	Ben Tre City (population 122,482 inhabitants) is on the left bank
Vinh Long	10°15'34"N, 105°58'20"E	Co Chien River (main distributaries)	Near stilt house area and market Vinh Long City (population 142,761 inhabitants) is on the right bank
Tra Vinh	10°01'47"N, 106°18'19"E	Co Chien River (main distributaries)	Tra Vinh City (population 108,700 inhabitants) is on the right bank

observation step (5), which is discussed in [Section 2.4](#).

The analytical procedure for sediment samples was the same as that used for treating surface water samples, except for some differences in the preparation step and digestion step. Prior analysis, for each site, the moisture content of the sediments was firstly determined by drying approximately 20 g of sediment sample at 55 °C during 72 h until the sample weight became constant. Then, duplicate samples were analysed for microplastics. For each replicate, after a thorough homogenisation of the sample, a known mass of moist sediment equivalent to 10 g of dry sediment was placed in a 250 mL beaker and digested with 30 % H₂O₂ at 40 °C. The volume of the digestion solution was in the range of 20–25 mL and was gradually added until the sediment was completely digested. The oxidised solution was then sifted through a 250 µm mesh size sieve and separated by NaCl solution before filtration.

2.4. Observation

Microplastics observation and evaluation of their size, colour, nature, and shape was carried out, using a Leica stereoscope S6D (0.5× to 80×) coupled with LAS software®. In this study, the criterion proposed by [Nor'en \(2007\)](#) and used by [Strady et al. \(2021\)](#) were followed to identify the microplastic particles in terms of appearance and internal structure among other materials such as fine and coarse sand, phytoplankton, and zooplankton. For the purpose of this study, the microplastic fibres were defined as elongated lines with three-dimensional bending and an equal thickness throughout their entire length. In contrast, microplastic fragments were defined in one of three ways. Firstly, as irregular hard particles that appeared to be broken from larger pieces of macroplastics. Secondly, as flat flexible particles with smooth or angular edges, or finally, as near spherical or granular particles which deform readily under pressure and can be partly elastic ([Nor'en, 2007](#)). All microplastic fibres and fragments had an absence of visible cellular or organic structures and exhibited a clear and homogeneous colour throughout ([Fig. 2](#)). Based on the GESAMP recommendations, a

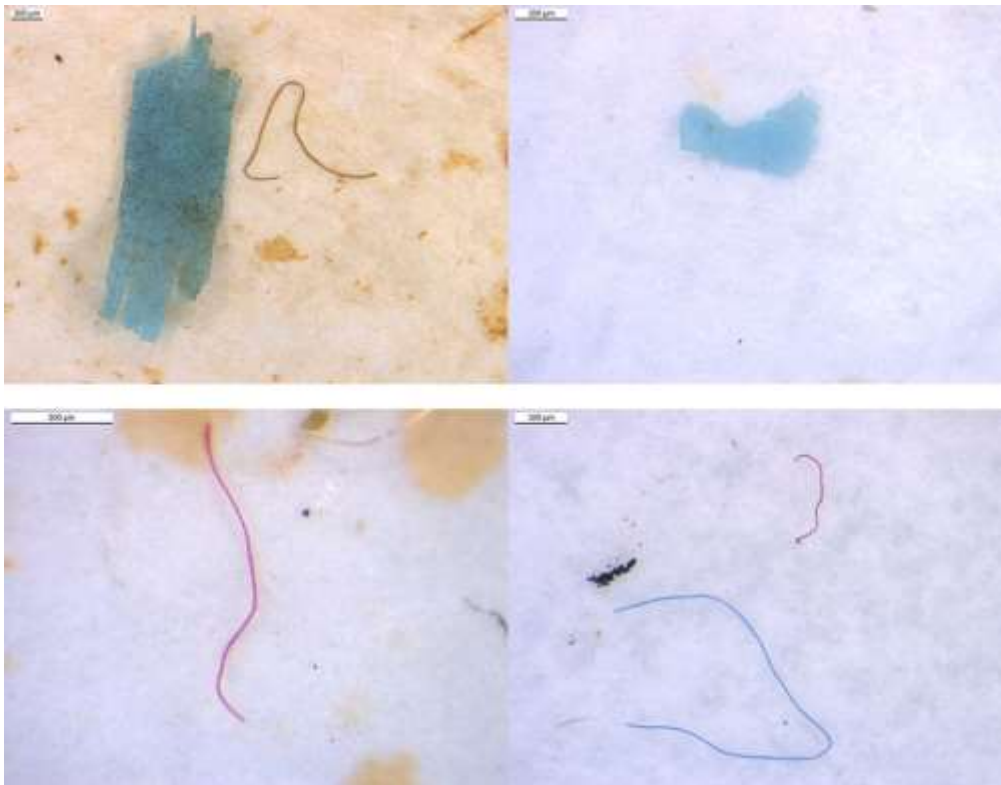


Fig. 2. Stereomicroscopic images of microplastics collected in the Tien River.

minimum length of 300 μm for microplastic fibres and a minimum surface area size of 45,000 μm^2 for microplastic fragments were chosen to identify each during the visual observation (GESAMP, 2019).

2.5. Quality control

Several quality control steps were taken during the sample treatment and observation process to prevent contamination from outside microplastics and control the data quality. Work areas were cleaned with alcohol and filtered tap water at the beginning of the procedure. Laboratory operators wore cotton laboratory coats, masks, and sterile latex gloves. All glassware was washed with filtered tap water (GF/A filters; 1.6 μm porosity, Whatman®) and covered with aluminium foil before use. Further, three control steps based on those used by Strady et al. (2021) were implemented. These were: positive extraction control (PEC), digestion atmospheric control (DAC), and observation atmospheric control (OAC). The PEC was conducted by adding 10 pieces of yellow polyethylene microplastics (CARAT®) into the samples after the sample preparation step. This control step aimed to evaluate the recovery efficiency of the added microplastics after the digestion step in the laboratory. The DAC and OAC were then conducted to check the contamination of microplastics by placing a virgin GF/A filter close to the sample over the course of the digestion step and observation step, respectively. The PEC recovery efficiency ($n = 12$) was 98 %. The DAC ($n = 24$) and OAC ($n = 24$) evidenced an average quantity of 4.4 and 0.3 fibres per filter, respectively. No correction was applied to the results based on the PEC, DAC, or OAC values.

2.6. Fourier transform infrared spectrometry (FTIR)

To prepare the tested particles for the FTIR-ATR tests, we wetted the shank of a sewing needle with filtered tap water and carefully touched it to the particle on the filter before transferring it to the microscopic slide. This step was performed under the restriction of having a ventilation fan

in the testing area. The chemical composition of the microplastics was analysed by Fourier transform infrared spectrometry using an FTIR-ATR iS50 Thermo Fisher Scientific®. In total, 87 suspected particles (51 fragments and eight fibres in surface waters and seven fragments and 21 fibres in sediments) were tested. They were chosen according to different criteria, such as their possibility of being easily picked up and analysed by FTIR-ATR; their representativeness of the sample selection as a whole; and our uncertainty regarding their composition, as FTIR-ATR was sometimes necessary for particles which could not be classified through only visual observation. The composition of the tested particles was confirmed when the match between the tested and reference spectra was over 70 %.

2.7. Analysis

The concentrations of microplastics were calculated in units of items m^{-3} for surface water and items g^{-1} dry weight (d.w.) of sediment. The concentrations of fragments and fibres and their part of the total microplastics at each sampling site were also determined. Statistical Kruskal Wallis tests were conducted using XLSTAT® to compare the size of microplastics in surface water and sediment.

3. Results

1. Abundance of microplastics

In surface water, the average concentration of microplastics across the entire river system was 53.8 ± 140.7 items m^{-3} . Microplastics were observed in both replicates at all the sampling sites (Table 2a). Among the sampling sites, microplastic concentrations for both fibres and fragments were always observed to be lowest at Ben Tre and highest at Cao Lanh, with concentrations fluctuating from 1.2 ± 0.6 items m^{-3} at Ben Tre to 303.9 ± 259.9 items m^{-3} at Cao Lanh (Fig. 3a). The average concentration of fibres in the surface water of the whole river system

Table 2a

Concentrations of microplastics, fibres, and fragments in surface waters of each replicate at each sampling site.

Site	Microplastic concentration (items m ⁻³)		Fragment concentration (fragments m ⁻³)		Fibre concentration (fibres m ⁻³)	
	Rep. 1	Rep. 2	Rep. 1	Rep. 2	Rep. 1	Rep. 2
	Cao Lanh	120.1	487.7	15.1	33.4	105.0
My Tho	2.9	11.9	0.9	2.3	1.9	9.6
Cho Lach	2.1	3.7	0.3	0.9	1.8	2.9
Ben Tre	0.8	1.6	0.1	0.1	0.7	1.4
Vinh Long	5.4	4.2	0.6	0.6	4.8	3.6
Tra Vinh	1.9	2.8	0.2	0.4	1.7	2.4

was 49.2 ± 130.9 items m⁻³, with concentrations varying from 1.1 ± 0.5 fibres m⁻³ at Ben Tre to 279.6 ± 247.0 fibres m⁻³ at Cao Lanh (Table 2a; Fig. 3b). The average concentration of fragments was 4.6 ± 10.0 fragments m⁻³, varying from 0.1 ± 0.03 fragments m⁻³ at Ben Tre to 24.3 ± 13.0 fragments m⁻³ Cao Lanh (Fig. 3c).

In sediment, the average concentration of microplastics over the whole river system was 6.0 ± 2.0 items g⁻¹. Microplastics were observed in both replicates at all the sampling sites (Table 2b). Microplastic concentration fluctuated from 3.3 ± 1.1 items g⁻¹ at Tra Vinh to 7.9 items g⁻¹ at My Tho (Fig. 3a). The average concentration of fibres in the sediment of the entire river system was 5.8 ± 1.9 fibres g⁻¹, varying from 3.3 ± 1.1 fibres g⁻¹ at Tra Vinh to 7.6 ± 1.1 fibres g⁻¹ at Ben Tre (Fig. 3b). The average concentration of the fragments was 0.1 ± 0.2 fragments g⁻¹. No fragments were observed in Cao Lanh, Cho Lach, and Tra Vinh, and for the other sites, fragment concentrations varied from 0.2 ± 0.0 fragments g⁻¹ at My Tho to 0.4 ± 0.3 fragments g⁻¹ at Vinh Long (Fig. 3c).

2. Morphology of microplastics

1. Microplastic shapes

In both surface water and sediment, the observed microplastic shapes included fibres and fragments, with fibre being predominant. Both fibres and fragments were observed in surface water at all sites, with fibres representing 85 % and fragments the remaining 15 %. Fibres varied slightly from 77 % at My Tho to 91 % at Cao Lanh (Fig. 4a). In sediment, fibres represented 98 % of the microplastics over the river system and varied from 95 % at My Tho to 100 % at Cao Lanh, Cho Lach, and Tra Vinh (Fig. 4b), suggesting that only a few fragments were observed in the sediment, with no fragments being found in Cao Lanh, Cho Lach, and Tra Vinh.

2. Microplastic size

In surface water, the median fibre length over the river system was 1235 µm (Fig. 5a) and varied from 1041 µm at My Tho to 1914 µm at Tra Vinh (Fig. 6a). The median fragment area over the river system was 142,174 µm² (Fig. 5b) and varied from 108,424 µm² at Cao Lanh to 228,042 µm² at Tra Vinh (Fig. 6b).

In the sediment, the median fibre length over the river system was 1060 µm (Fig. 5a) and varied between sampling sites from 845 µm at Tra Vinh to 1316 µm at My Tho (Fig. 6c). The median fragment area over the river system was 179,672 µm² (Fig. 5b).

3.2.3. Microplastic colour partition

In surface water, microplastics of six colours were observed over the river system (blue, red, white, green, yellow, and grey). Colour partition of microplastics showed a dominance of blue fibres (50 % to 69 %), followed by red fibres (24 % to 29 %) and white fibres (4 % to 29 %). Other colours included green, yellow, and grey with a total percentage of 3 % to 15 % (Fig. 7a). Over the whole river system, seven colours were observed in sediment (blue, red, white, green, yellow, grey, and black). Colour partition of microplastics showed a dominance of blue fibres (67

% to 87 %) followed by red fibres (10 % to 23 %), with the total percentage of other colours was lower, between 3 % to 18 % (Fig. 7b).

3.3. Chemical composition of microplastics

In surface water, FTIR-ATR results showed that 88 % of the tested particles were microplastics, including 67 % polyethylene (PE) and polypropylene (PP), 19 % polyester, 14 % other polymers (Table 3). In sediment, 64 % of the tested particles were microplastics, including 33.3 % polyester, 33.3 % PE, PP, and PE-PP, 16.7 % rayon, 16.8 % other polymers.

4. Discussions

1. Comparison to worldwide and local contamination level

The observation of microplastics in all replicates of both surface water and sediment across sampling sites confirmed the contamination of microplastics in the northern branches of the MRD. The average

microplastic concentration over the entire area was 53.8 ± 140.7 items m⁻³ in surface water and 6.0 ± 2.0 items g⁻¹ d.w. in sediment. Compared to other river systems in Vietnam (Table 4), microplastic concentrations in surface water of the Tien River was higher than that of the Red River, Dong Nai River, and Han River in Da Nang, which had concentrations of 2.3 items m⁻³, 3.9 items m⁻³, and 2.7 items m⁻³, respectively (Strady et al., 2021). Microplastic abundance in the sediment of the Tien River was higher than that of the sandy sediment in Dau and Sau Beaches in Vung Tau City, Vietnam ($1.5\text{--}2.0$ items g⁻¹; Strady et al., 2021), and approximately equal to that of shoreline sediment in Da Nang Beach (9.2 ± 2.1 items g⁻¹ d.w.; Tran Nguyen et al., 2020). This study was based on the same protocols and observation range size (300–5000 µm) as the aforementioned studies carried out by Strady et al. (2021) and Tran Nguyen et al. (2020) and therefore the comparison is more reliable when the protocols are identical. In comparison to the Saigon River, highly impacted by the anthropogenic activities in this water basin, the Tien River, located in the neighboring basin, had approximately three orders of magnitude lower (Lahens et al., 2018; Strady et al., 2020).

When compared with worldwide river systems (Table 4), microplastic levels in the surface water of the Tien River was approximately that same as that of the Qing River, China ($170\text{--}260$ items m⁻³; Wang et al., 2020), and the Seine River, France ($3\text{--}106$ items m⁻³; Dris et al., 2015). Further, it was higher than that of the Chao Phraya River Estuary, Thailand (48 ± 8 items m⁻³; Ta and Babel, 2020), 29 assorted rivers in Japan (1.6 ± 2.3 items m⁻³; Kataoka et al., 2019), and Northern Dvina River in Russia ($0.004\text{--}0.01$ items m⁻³; Zhdanov et al., 2022), and lower than that of the Orange-Vaal River system in South Africa (0.23 ± 0.27 items L⁻¹; Weideman et al., 2019), and the Thames river in the United Kingdom ($87,750$ items m⁻³; Devereux et al., 2022). Sediment in the Tien River also presented higher microplastic levels than that in the Ciwalengke River, Indonesia ($1.4\text{--}3.5 \times 10^{-3}$ items g⁻¹ d.w.; Alam et al., 2019), the Chao Praya River, Thailand (0.04 items g⁻¹ d.w.; Ta and Babel, 2020), the Barrow River in Iceland (172.5 ± 116 items kg⁻¹ w.w., Murphy et al., 2022), and the Qin River in Beibu Gulf, China ($0\text{--}0.1$ items g⁻¹ d.w.; Zhang et al., 2020). It was approximately the same with that of the St. Lawrence River in Canada ($65\text{--}7562$ items kg⁻¹ d.w., Crew et al., 2020).

4.2. Spatial variation of microplastic abundance in the surface water of the Tien River

Among the sampling sites, Cao Lanh was the only site in a secondary tributary of the Tien River, situated in a small secondary tributary flowing through the urban area of Cao Lanh City, the Cai Sao Thuong River. Thus far, only the main distributaries of the Tien River have been used to account for the spatial variation of microplastic contamination

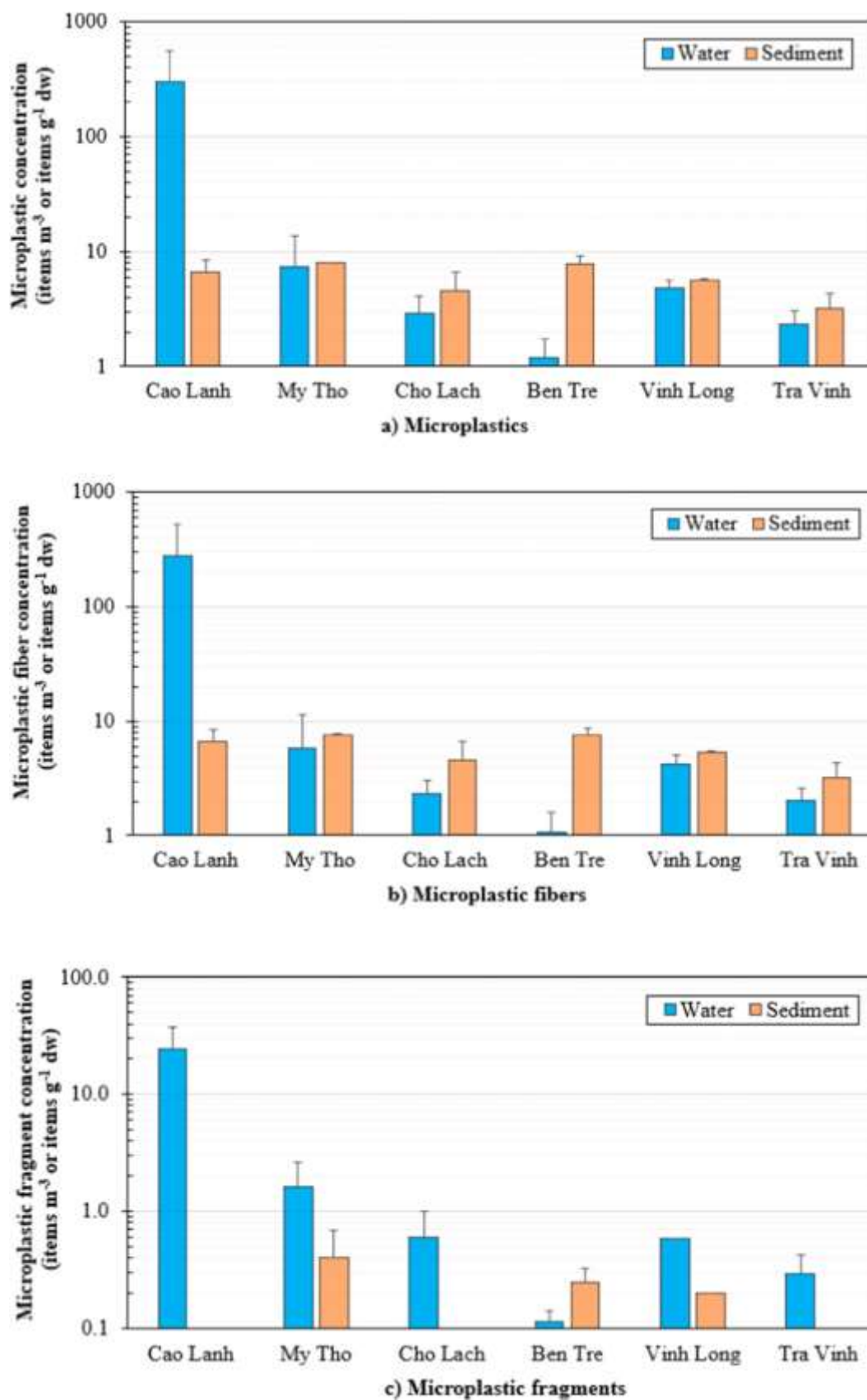


Fig. 3. Average concentrations of a) microplastics, b) fibres, and c) fragments in surface waters (blue) and sediments (orange) at each sampling site along the Tien River. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2b

Concentrations of microplastics, fibres, and fragments in sediments of each replicate at each sampling site.

Site	Microplastic concentration (items g^{-1})		Fragment concentration (fragments g^{-1})		Fibre concentration (fibres g^{-1})	
	Rep. 1	Rep. 2	Rep. 1	Rep. 2	Rep. 1	Rep. 2
Cao Lanh	5.5	7.9	0	0	5.5	7.9
My Tho	7.9	7.9	0.2	0.6	7.7	7.3
Cho Lach	3.2	6	0	0	3.2	6
Ben Tre	7	8.7	0.2	0.3	6.8	8.4
Vinh Long	5.7	5.5	0.2	0.2	5.5	5.3
Tra Vinh	2.5	4	0	0	2.5	4

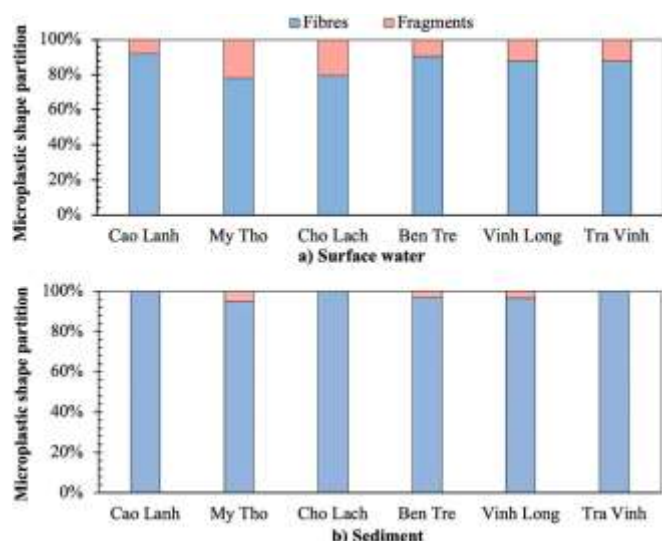


Fig. 4. Microplastic shape partition, i.e. fibres and fragments, in a) surface water and b) sediment at each sampling site in the Tien River.

in this area. These are, the Tien River (My Tho), the Ham Luong River (Cho Lach and Ben Tre), and the Co Chien River (Vinh Long and Tra Vinh). The concentration of microplastics maintained a stable level over the entire area, varying from 1.2 ± 0.6 items m^{-3} at Ben Tre to 7.4 ± 6.4 items m^{-3} at My Tho for surface water and from 3.3 ± 1.1 items m^{-3} at Tra Vinh to 7.9 items m^{-3} My Tho for sediment. We hypothesise that the concentrations of microplastics in this area originate from two factors: (i) the release of microplastics from anthropogenic activities, and (ii) water discharge. Previous studies have demonstrated the influence of anthropogenic factors such as population distribution, land use, waste

management, and wastewater treatment plant effluent on the abundance of microplastics in surface water (Amrutha and Warriar, 2020; Kataoka et al., 2019; Strady et al., 2021; Talbot and Chang, 2022). Urban areas are evenly scattered on both banks of the Tien River and its tributaries and fall within our study area. These urban areas have a population of approximately 100,000 inhabitants in Tra Vinh City to over 220,000 inhabitants in My Tho City (Table 1). These urban areas may be main sources of microplastics that are released into the environment through wastewater discharge. In 2020, after a sampling survey, a centralised wastewater treatment plant was put in place to treat domestic wastewater, which was before directly flowing into the urban canals and rivers without treatment. The remarkable concentration of microplastics at the Cao Lanh site can be taken as an example of direct microplastic release from an urban area. In the MRD, aquaculture and agriculture are the main livelihoods of local residents. In the Tien River, there were many fish raft villages that use fishing nets and floats. Outside of the urban areas along the river are large areas of agricultural activities, such as rice paddy fields and other agricultural products. Accordingly, along its flow to the estuary, the Tien River and its tributaries may continuously receive microplastics released from wastewater effluents, aquaculture, and agriculture. Concerning river water discharge, several publications presented it as one of the hydrodynamic factors dominating the presence of microplastics in water such as in nival tributaries of the Rhine River in Switzerland and the pluvial Lower Rhine River in Germany (Mani and Burkhardt-Holm, 2020) and in the torrential Ofanto River of Italy (Campanale et al., 2020a, 2020b).

As reported by the MRC-KOICA (2000), the Tien River had high water discharge of 3720 m^3 s^{-1} in February 2000, which may have diluted the concentration of microplastics. The dilution effect can be evidenced by comparing the concentration of microplastics at the Cao Lanh site with other sites. Cao Lanh City has a population of 163,892 inhabitants, and the Cai Sao Thuong River's surface water had a concentration of 303.9 ± 259.9 items m^{-3} , (no water discharge data available). Although the Tien River received microplastics from not only the Cai Sao Thuong River but also from other urban cities which are similar in size to Cao Lanh City (Table 1) and from agriculture and aquaculture areas along its flow, the concentration of microplastics was substantially smaller than that of the Cao Lanh site. Accordingly, it can be assumed that the high water discharge in the river serves to dilute the effect of the continuous release of microplastics as it flows into the estuary.

4.3. Factors affecting the abundance of microplastics in sediment

The accumulation of microplastics in sediments is primarily affected by (i) anthropogenic activities, (ii) hydrodynamic conditions of the environments (water dynamics, water depth, flow velocity), (iii) physical

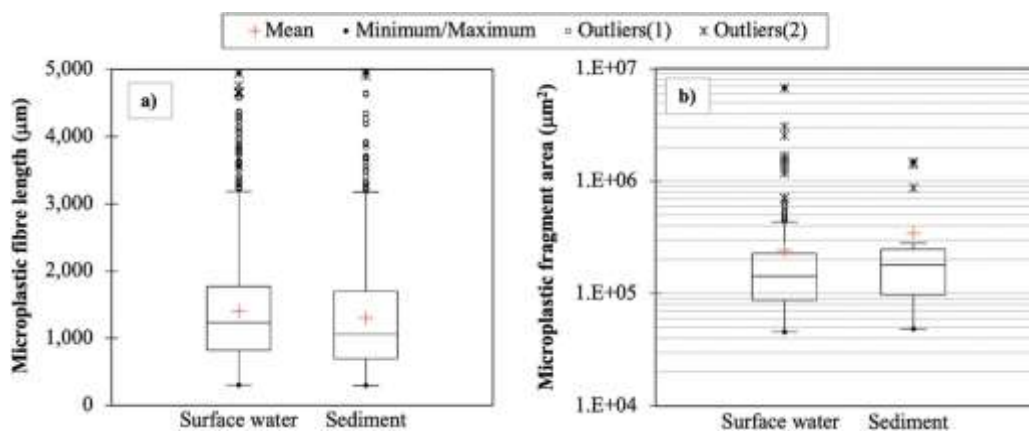


Fig. 5. Boxplots of a) microplastic fibre length (μm) and b) microplastic fragment area (μm^2) observed in all samples of surface water and sediment in the Tien River.

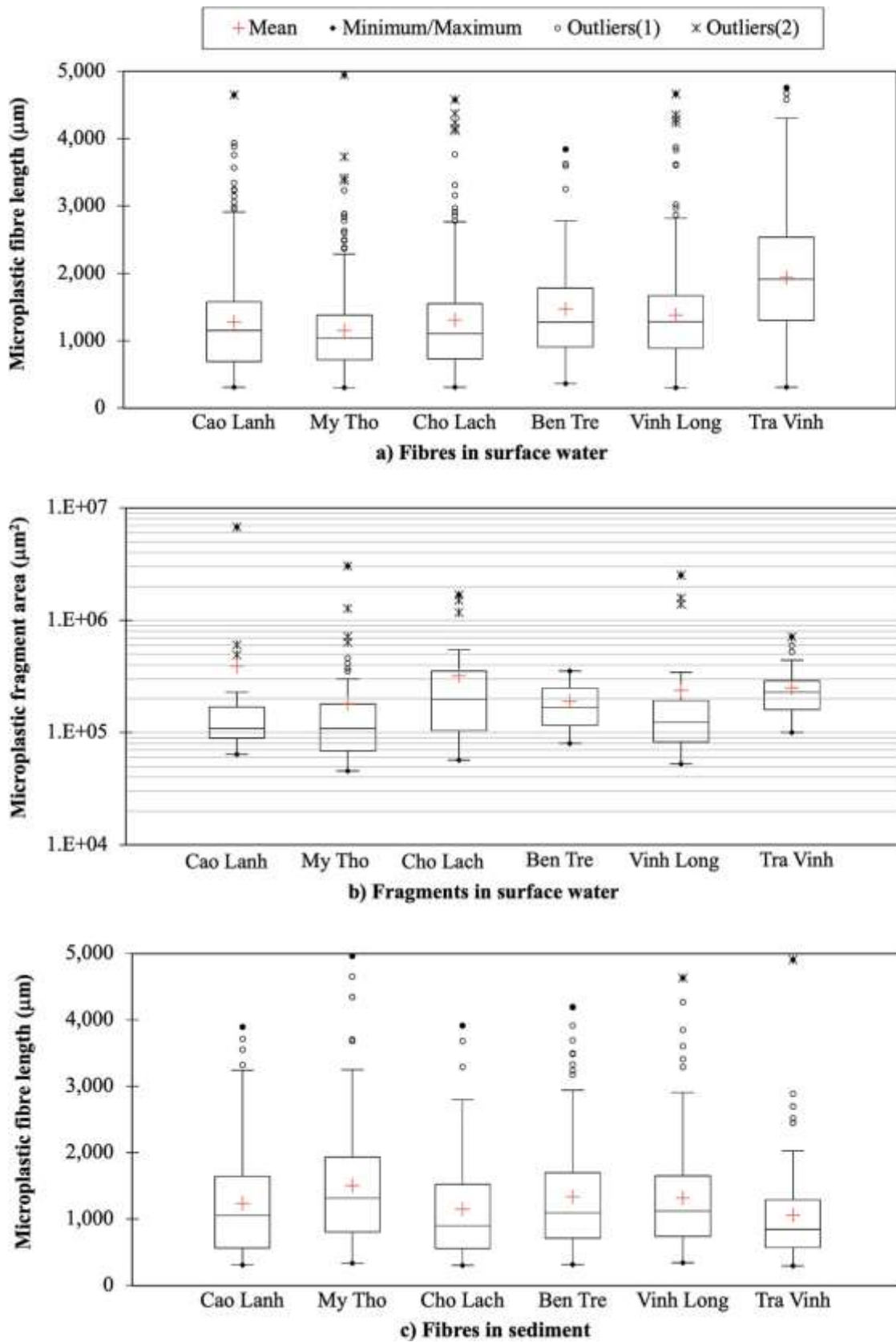


Fig. 6. Boxplots of a) microplastic fibre length (µm) and b) microplastic fragment area (µm²) in surface water and c) microplastic fibre length (µm) in sediment observed at each sampling site in the Tien River.

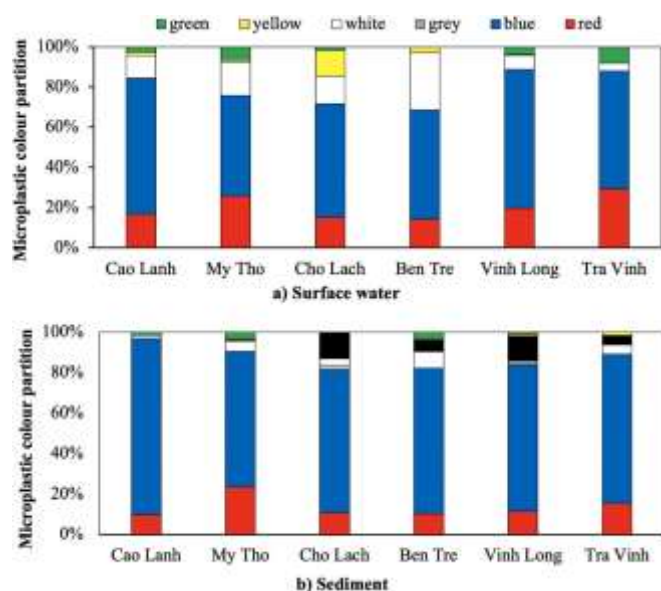


Fig. 7. Microplastic colour partition, i.e. red, blue, grey, white, black, yellow, and green, in a) surface water and b) sediment in the Tien River. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3

Chemical compositions of microplastics in surface water (a) and sediment (b) of the Tien River from FTIR-ATR analysis.

Polymer type	Quantity	Percentage among plastics
(a) Surface water		
Plastic (88 %)		
PE, PP	35	67 %
Polyester	10	19 %
Acrylic	3	6 %
Alkyd	1	2 %
Polysterene	2	4 %
PhenoXy resin	1	2 %
Non-plastic (12 %)		
Mineral, calcium carbonate, unidentified	7	
(b) Sediment		
Plastic (64.3 %)		
Polyester	6	33.3 %
PE, PP, PE-PP	6	33.3 %
Rayon	3	16.7 %
Acrylic	1	5.6 %
Polysterene	1	5.6 %
PhenoXy resin	1	5.6 %
Non-plastic (35.7 %)		
Cellulose, cotton, mineral	10	

characteristics of microplastics (such as density, shapes, and size), and the aggregation process due to microbial colonization and biofilm development (Crew et al., 2020; Gerolin et al., 2020; Huang et al., 2021; Kumar et al., 2021b; Tien et al., 2020; Wu et al., 2020; Xu et al., 2020).

The impact of anthropogenic activities on microplastic contamination in sediment was observed at higher concentrations due to the industrial wastewater discharge, sewage release, and high population density and urbanisation (Alam et al., 2019; Horton et al., 2017; Huang et al., 2021). In the MRD sediment, the concentrations of microplastics were stable across different areas, varying from 3.3 ± 1.1 items g^{-1} d.w. at Tra Vinh to 7.9 items g^{-1} d.w. at Ben Tre (Fig. 3a and Table 2b). Although the concentration of microplastics in surface water at Cao Lanh was hundreds of times higher than that at the other sites, the microplastic concentration in sediment at Cao Lanh (5.5 – 7.9 items g^{-1} d.w.) was in the same range as that at the other sites (2.5 – 8.7 items g^{-1}

d.w.), as shown in Fig. 3a. Zhang et al. (2021) compiled the published results of 624 sampling sites in different environments of the Yangtze River Basin and observed a correlation between the socio-economic factors (e.g. population density and urbanisation rate) and microplastic abundance in surface waters. However, this was not mirrored in sediments, perhaps due to the complex mechanisms and dynamics of microplastic transport and deposition. Along the Brisbane River, Australia, He et al. (2020) reported the influence of different land use types and population density on the microplastic types rather than their concentrations in sediment collected at 22 sites. In the Tien River, the impact of anthropogenic activities indicating by high microplastic concentration in surface water at Cao Lanh were not observed via the concentrations measured in sediment, i.e. microplastic concentration in sediment at Cao Lanh was almost same as that of other sites. Accordingly, the anthropogenic activities were less important in sediment of the Tien River.

Concerning the hydrodynamic conditions, one important factor that increases the deposition of microplastics is the slowdown of the flow velocity (Ding et al., 2019; Gerolin et al., 2020); microplastics start to sink in calm environments, especially in areas with long water residence times such as dams or bays. The Tien River flow dynamics are strongly affected by the tidal regime of Vietnam's East Sea up to Cambodia during the dry season. Except Cao Lanh, the other five sites were located in the main stream and main distributaries of the Tien River and therefore the flow condition at these sites were affected by a dynamic hydrological condition. Cao Lanh, however, was located in the Cai Sao Thuong River, a small secondary tributary of the Tien River. This small river was facing the issue of water pollution due to sediment deposition inducing slow flow and obstruction and in 2020 the local government approved a plan of sediment dredging to increase the flow efficiency (VNPCCL, 2020). Thus, it can be supposed that the flow velocity at this site was much lower than that at the other sites on the main distributaries. Concerning microplastic concentration, at Cao Lanh, high concentration of microplastics in surface water, however, was not reflected in sediment which presented a similar low microplastic concentration with the other sites. Accordingly, hydrodynamics conditions may not be an important factor controlling the deposition of microplastics in sediment in this area.

Kumar et al. (2021b) reviewed recent studies on the transport and deposition of microplastics in the riverine system and discussed the physical properties of microplastics including plastic particle density, shape, and size are important factors controlling the deposition of microplastics. In addition, the aggregation process due to microbial colonization and biofilm development depending upon the microplastics properties, microorganisms species, and water environmental conditions. In the Tien River system, in comparison with microplastic fragments, fibres was found more predominant (Fig. 4). Moreover, fibres shared higher proportion in sediment (95 % to 100 %) than in surface water (77 % to 91 %). As in Fig. 5a, the median length of fibres was smaller in sediment ($1060 \mu m$) than in surface water ($1235 \mu m$), and the fibres in sediment was significantly shorter than in water (Mann-Whitney test, p -value < 0.0001). Accordingly, in the Tien River, the deposition of microplastics from the surface water to the sediments was prior to fibres, and shorter fibre length.

4.4. Future trends of microplastic abundance in the Mekong River delta: the need of a global plastic assessment

The MRD is facing various challenges which impact its sustainability: increasing sea level rise and salinity intrusion (Eslami et al., 2019), changes in flood regime dynamic (Park et al., 2020), change of land use (Vu et al., 2022), increasing urbanisation (Nguyen et al., 2022), increasing subsidence (Erban et al., 2014) agricultural transformation (Nguyen et al., 2021) and increasing tourism (Vu et al., 2022). All those challenges can be interconnected, with for example, increasing sea level rise causing land use shift, with more intensive rice cropping (increasing double rice and triple rice cropping) and the development of inland

Table 4

Synthesis of microplastic abundance in water and sediment of worldwide aquatic environments.

Site	Country	Surface water/ sediment	Concentration	Observation size range	Reference
Tien river	Vietnam	Surface water	53.8 ± 140.7 items m^{-3}	300–5000 μm	This study
		Sediment	6.0 ± 2.0 items g^{-1} d.w.		
Red River	Vietnam	Surface water	2.3 items m^{-3}	300–5000 μm	(Strady et al., 2021)
Dong Nai River	Vietnam	Surface water	3.9 items m^{-3}		
Han River	Vietnam	Surface water	2.7 items m^{-3}		
Dau and Sau Beaches in Vung Tau City	Vietnam	Beach sand	1.5 – 2.0 items g^{-1} d.w.		
Da Nang Beach	Vietnam	Shoreline sediment	9.2 ± 2.1 items g^{-1} d.w.	300–5000 μm	(Tran Nguyen et al., 2020)
Saigon River	Vietnam	Surface water	$172,000$ – $519,000$ fibres m^{-3}	50–5000 μm	(Lahens et al., 2018)
			10 – 223 fragments m^{-3}		
Qing River	China	Surface water	170 – 260 items m^{-3}	50–5000 μm	(Wang et al., 2020)
Haihe river	China	Sediment	4980 ± 2464 items kg^{-1} d.w.	1–5000 μm	(Liu et al., 2020)
Xiangjiang river	China	Sediment	288 ± 60 items kg^{-1} d.w.	50–5000 μm	(Yin et al., 2022)
Wujiang River	China	Sediment	75.6 – $1,036.2$ items kg^{-1} d.w.	0–5000 μm	(Wu et al., 2022)
Two plain rivers in Yuechen and Huangtian	China	Sediment	6060 – $37,610$ items kg^{-1} d.w.	20–5000 μm	(Ji et al., 2021)
Qin River in Beibu Gulf	China	Sediment	0 – 0.097 items kg^{-1} d.w.	300–5000 μm	(Zhang et al., 2020)
Chao Phraya River Estuary	Thailand	Surface water	48 ± 8 items m^{-3}	50–5000 μm	(Ta and Babel, 2020)
		Sediment	0.039 ± 0.014 items g^{-1} d.w.		
Cisadane River	Indonesia	Surface water	44.67 ± 24.25 items m^{-3}	1–5000 μm	(Sulistiyowati et al., 2022)
Ciwalengke River	Indonesia	Sediment	1.4 – 3.5×10^{-3} items g^{-1} d.w.	< 100 μm –5000 μm	(Alam et al., 2019)
29 assorted rivers	Japan	Surface water	1.6 ± 2.3 items m^{-3}		(Kataoka et al., 2019)
Northern Dvina River	Russia	Surface water	0.004 – 0.010 items m^{-3}	1–5000 μm	(Zhdanov et al., 2022)
Biobío river	Chile	Surface water	22 ± 0.4 items m^{-3}	50–5000 μm	(Correa-araneda et al., 2022)
Elbe river	German & Czech Republic	Sediment	2.26×10^4 – 2.27×10^7 items m^{-3}	125–5000 μm	(Scherer et al., 2020)
		Water	5.57 ± 4.33 items m^{-3}	150–5000 μm	
Seine River	France	Surface water	3 – 106 items m^{-3}	100–5000 μm	(Dris et al., 2015)
Thames River	United Kingdom	Surface water	$87,750$ items m^{-3}	200–5000 μm	(Devereux et al., 2022)
Barrow River	Iceland	Sediment	172.5 ± 116.0 items kg^{-1} d.w.	100–5000 μm	(Murphy et al., 2022)
Ottawa River	Canada	Water	1.35 fragments m^{-3}	100–5000 μm	(Vermaire et al., 2017)
		Sediment	0.22 fragments g^{-1} d.w.		
St. Lawrence River	Canada	Sediment	65 – 7562 items kg^{-1} d.w.	10–5000 μm	(Crew et al., 2020)
The Orange–Vaal River system	South Africa	Surface water	0.23 ± 0.27 items L^{-1}	25–5000 μm	(Weideman et al., 2019)
			0.04 ± 0.16 items m^{-2}	300–5000 μm	

aquaculture, which along with aggravating subsidence, is increasing floodings, especially urban flooding during equinox high tides events. Unfortunately, all those changes may also impact directly or indirectly the abundance of microplastics in the MRD receiving water systems at present and in the near future. Intensification of double and triple rice cropping can lead to a large amount of plastic and microplastic release in soils and irrigation waters, as observed in China (Zhou et al., 2020). Rice farming involves plastic from seed packaging, fertilizer and pesticide packaging, mulch, seedling trays, pesticide sprayers and storage bags. In agriculture soils from China, macroplastics ranged from 0.1 to 324.5 $kg ha^{-1}$ and were positively correlated to the mass of plastic mulch used per hectare while microplastics, dominated by fragments and fibres, were observed on all soils subjected to plastic mulching with microplastic abundance increasing with the plastic mulching use duration in the soils, being up to 1075.6 ± 346.8 pieces kg^{-1} in a soil of 24 years of continuous mulching (Huang et al., 2020; Zhou et al., 2020). The development of inland aquaculture due to salinity intrusion is also a point source of microplastic to the environment, as observed in surface sediments from aquaculture ponds in Northern Vietnam (Le et al., 2022) where high microplastic concentrations (e.g. 2767 ± 240 items kg^{-1} d.w.) were measured and might derived from plastic equipment (buoys, barrel, lines, hanging line, food bags) commonly used in aquaculture farming activity.

Anthropogenic activities taking place in urban or suburban areas are also an important source of microplastic deposition in atmospheric fallouts (71 – 917 items $m^{-2} d^{-1}$ in Ho Chi Minh City, Truong et al., 2021) and in surface road dust (19.7 ± 13.7 items m^{-2} in Da Nang, Yukioka et al., 2020). The part of microplastics reaching the aquatic environment from those sources is few, as they mainly deposit on terrestrial environment but with increasing urban flooding events during rainy season, coupled to increasing subsidence, equinox high tides are getting more

and more frequent and can remobilized deposited microplastics into the aquatic environment. In 2019, tourism activity welcomed 47 million domestic and foreign visitors in the MRD (Yu et al., 2021), leading to an important use of plastics, specifically single use ones. In Vietnam, the Extended Producer Responsibility decree (Decree 08/2022/ND-CP, 2022) is reinforcing circular economy and plastic recycling, mainly via mechanical recycling. This process, common in Vietnam, was demonstrated as a point source of microplastic pollution in the receiving environments, especially when wastewaters were not treated specifically (Suzuki et al., 2022), which is often the case at the moment.

In this complex environmental, economic and societal context, there is a need to assess microplastic concentrations in key aquatic and agricultural soil environments of the MRD in order to set up a baseline and evaluate its pollution level. Then, from this baseline, decision makers along with scientists will be able to discuss and decide adapted remediation or ban to prevent the increasing microplastic pollution of the MRD. The assessment phase through a holistic and concerted approach is a key step to prevent its pollution.

5. Conclusions

The microplastic contamination in the Tien River system predominantly comprised fibres, and was found at concentrations of 53.8 ± 140.7 items m^{-3} in surface water and 6.0 ± 2.0 items g^{-1} d.w. in sediment. The presence of stable microplastic concentration in the main streams of the Tien River indicates the role of the hydrodynamics of the river in diluting microplastics released from continuous sources along the river whereas higher concentrations in smaller streams, less affected by large hydrodynamic processes, pointed out local pollution which may affect the ecosystem. In the near future, the MRD will face important environmental and societal challenges which may reinforce its

contamination by microplastics. We therefore recommend to assess and identify the local sources of microplastic to the MRD in order to prevent the pollution.

CRedit authorship contribution statement

Thuy-Chung Kieu-Le: Conceptualization, Investigation, Supervision, Writing – original draft, Writing – review & editing. **Quoc-Thinh Thuong:** Investigation. **Tran-Nguyen-Sang Truong:** Investigation, Writing – original draft, Writing – review & editing. **Thi-Minh-Tam Le:** Investigation. **Quoc-Viet Tran:** Investigation. **Emilie Strady:** Conceptualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

Data availability

dataverse DataSudshtps://doi.org/10.23708/P9HYLM

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