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Microplastic Pollution in High Population Density Zones of Selected Rivers from Southeast Asia

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Abstract

Southeast Asia (SEA) faces significant environmental challenges due to rapid population growth and economic activity. Rivers in the region are major sources of plastic waste in oceans. Concerns about their contribution have grown, but knowledge of microplastics in the area is still limited. This article compares microplastic levels in sediment and water from urban zones of three major rivers in SEA: Chao Phraya River (Thailand), Saigon River (Vietnam), and Citarum River (Indonesia). The study reveals that in all three rivers, microplastics were found, with the highest concentrations in Chao Phraya's water (80 ± 60 items/m^3) and Saigon's sediment (9167 ± 4559 items/kg). The variations in microplastic sizes and concentrations among these rivers may be attributed to environmental factors and the exposure duration of plastic to the environment. Since these rivers are important water supply sources, rigorous land-use regulations and raising public awareness are crucial to mitigate plastic and microplastic pollution.

Keywords Microplastics · Southeast Asia · Chao Phraya river · Saigon river · Citarum river

Introduction

With a rapidly expanding population and booming economic growth, the Southeast Asia (SEA) region faces significant challenges in managing its water resources sustainably (Strazzabosco 2020). In addition to persistent issues, microplastics (MPs) are becoming an emerging concern due to their long-term persistence and potential environmental risks (Sheng et al. 2021). MPs are plastic debris measuring less than 5 mm in size and can be categorized as primary or secondary based on their sources. Primary MPs, such as microbeads found in resin pellets and cosmetic products, are intentionally manufactured to be this size. Secondary MPs result from physical and chemical processes that cause the fragmentation of big plastics.

The widespread presence, persistence, and potential adverse impacts of MPs, characterized by their small size, pose a significant environmental concern as they are easily ingested by various aquatic species, such as plankton, fish, and other organisms (Ta et al. 2022; Vandermeersch et al. 2015). Microplastics enter various ecosystems, disrupting food webs, altering habitats, and adversely affecting aquatic and terrestrial organisms. This ingestion can disrupt physiological functions, hinder nutrient absorption, and impede growth and reproduction (Aljaibachi and Callaghan 2018). Additionally, MPs serve as vectors for other contaminants in the marine environment, including persistent organic pollutants (e.g., DEHP and bisphenol A) and heavy metals (Sheng et al. 2021; Ta and Babel 2023a). As these particles accumulate in the tissues of aquatic organisms, there is a potential for bioaccumulation and biomagnification in the food chain, ultimately reaching humans (Yuan et al. 2022). Moreover, the particles can become airborne, posing risks through inhalation (O'Brien et al. 2023). The persistence of MPs in the environment, their ubiquity in remote areas, and their presence in treated wastewater and drinking water underscore the need for global efforts to mitigate plastic pollution.

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Previous studies by Meijer et al. (2019) and Jambeck et al. (2015) have identified that rivers in Southeast Asian countries are among the leading contributors to plastic waste in the oceans (0.15–1.29 million tonnes, annually). However, a Web of Science literature search reveals a lack of information regarding the prevalence of MPs in these rivers. For instance, a recent study on the Wanquan River estuary in Hainan Island (Wang et al. 2023) addresses the abundance and characteristics of MPs, shedding light on the urgency of investigating similar concerns in other key rivers of the region. The Chao Phraya River stretches 372 km through nine provinces in Thailand and provides drinking water to over 10 million people. However, due to rapid industrialization, urbanization, and inadequate waste management practices, the Chao Phraya has become a microcosm of the intricate interplay between human activities and environmental degradation, including plastics and MP pollution. Similarly, the Saigon River, which extends 256 km through Ho Chi Minh City (Vietnam), reflects the region's complex urbanization and industrial growth dynamics. The deltaic landscape and the interconnected waterways make the Saigon River a focal point for diverse human activities. This confluence of factors expands the challenges associated with MP and plastic pollution, as the river becomes a conduit for plastic debris from various sources. In West Java, Indonesia, the Citarum River is essential for agriculture, electricity, fisheries, and industry, but it has also been reported as one of the world's most polluted river, posing a significant threat to the region (Sembiring et al. 2020). As Indonesia contends with rapid economic development, the Citarum bears the brunt of industrial discharges, agricultural runoff, and inadequate waste disposal practices. Moreover, according to Meijer et al. (2021), the Chao Phraya, Saigon, and Citarum Rivers are estimated to be among the top 15 rivers releasing plastics into oceans.

With the above situation, this study examined the occurrence of MPs in three major rivers in SEA: the Chao Phraya River (Thailand), the Saigon River (Vietnam), and the Citarum River (Indonesia). The primary objective of this research is to assess the levels of MPs in both surface water and sediment, particularly in densely populated regions along these rivers. The study also aimed to identify the types and characteristics of MP polymers, including size and morphology, to determine their sources. Given these rivers' pivotal roles in their respective countries' economies and societies, the outcomes of this study provide crucial insights into MP pollution. This information serves as foundational data for future research endeavors and the development of effective management strategies. Additionally, the research aims to inform strategies such as regulatory measures, policy instruments, and environmental education to mitigate MP pollution in the river ecosystems.

Materials and Methods

Study Area

The study focused on three important rivers in rapidly developing countries of the SEA region (Thailand, Indonesia, and Vietnam) (Fig. 1). The Chao Phraya River samples were taken from Bangkok's Tha Pra Chan area on September 19, 2019. This study location is in the heart of Bangkok's central area, with a high population density of local people and a diverse range of popular tourist attractions in the vicinity. For the Citarum River, samples were taken on October 8, 2019, from the Oxbow Dayeuhkolot area in West Java Province. This region exhibits a high population density, characterized by numerous residential and industrial activities. Regarding the Saigon River, water and sediment samples were taken near Nhieu Loc - Thi Nghe Canal's inlet on August 24, 2019. Various anthropogenic activities, including industrial pollution and urban development, have significantly impacted the area's water quality.

Sampling and Sample Analysis

The study employed consistent methods across three research partners. The sampling, analysis methods, and contamination control were adapted from Ta and Babel (2023b). Researchers from various institutions conducted the study: the Sirindhorn International Institute of Technology for the Chao Phraya River, Van Lang University for the Saigon River, and the Institute Teknologi Bandung for the Citarum River.

Water samples were collected using a volume-reduced technique employing a manta trawl. The trawl featured a rectangular aluminum frame measuring 50 cm in width and 20 cm in height, connected to a 2-meter-long net with an aperture size of 0.3 mm. The trawl also had a cod-end with dimensions of 25 cm in height and 10 cm in diameter. The manta trawl was towed behind a research boat to avoid the turbulence of the boat engine. Samples were collected on the superficial layer of the water column (6–10 cm surface layer). Sediment samples were collected using a Van Veen grab sampler. All collected materials, including water and sediment samples, were transferred to glass bottles and stored at 4 °C until analysis.

Water samples were sieved through a series of stainless-steel sieves to separate particles into four different size ranges. The solids in size classes of 0.5–1.0 mm and 1.0–5.0 mm underwent manual sorting using tweezers and were cleaned with deionized (DI) water. Subsequently, the particles were filtered on Whatman glass fiber filter GF/C and dried at 60 °C. Morphological and color inspections were conducted using an optical microscope. Polymer types of all

Fig. 1 Sampling sites at urban zones of the Chao Phraya River (**A**), Citarum River (**B**), and Saigon River (**C**)

particles were analyzed using Attenuated Total Reflection (ATR) Fourier Transform Infrared (FTIR) spectroscopy. Particles in size classes of 0.05–0.3 mm and 0.3–0.5 mm underwent wet peroxide oxidation (Fenton reaction). The treated samples were separated by density using a sodium iodide solution (1.5 g/cm^3) to remove undesirable particles. The supernatants were filtered on Whatman™ glass microfiber filters (GF/C) and dried at 60 °C. The fractions were then analyzed similarly to the 0.5–1.0 mm size class. For sediment, a triplicate of 100-gram wet samples was dried at 60 °C to determine the total solids. After that, MPs were separated from the sediment using a density separation technique (NaI, 1.5 g/cm^3). The extracted particles were then analyzed according to the water samples' procedures.

To assess the variability and dispersion of the collected data, Microsoft Excel was utilized for calculating standard deviations, offering a fundamental measure of the spread within the dataset. Moreover, an independent t-test analysis was conducted to compare the number and characteristics of MPs found in three rivers, if they are statistically different.

Results and Discussion

Microplastic Abundance

MP concentrations in the Chao Phraya River exhibit a notable spatial variation, with the highest concentration (155 ± 16 items/m^3) observed in the middle position and lower concentrations (48 ± 11 and 38 ± 30 items/m^3) along the banks. This variation is likely influenced by the river's morphology, turbulence, and boat activity. The increased concentration in the middle of the river suggests a potential correlation with boat traffic at this location, as suspended materials may be transported towards the center. Anthropogenic activities, combined with the dynamic nature of the river, contribute to the observed distribution of microplastics. Further research is needed to confirm these hypotheses and explore the broader environmental implications.

In the Oxbow Dayeukolot area of the Citarum River, MP concentrations at different locations were 16, 15, and 4 items/m^3 at bank 1, middle position, and bank 2, respectively. The mean MP count in the study area was 12 ± 6 items/m^3, emphasizing the influence of human activity and population density. Higher concentrations near the banks, particularly at bank 1, may indicate increased human presence and activities in densely populated areas. This underscores the necessity of understanding these localized patterns for implementing targeted mitigation strategies in areas with heightened human impact.

The Saigon River study area reveals MP concentrations of 68 ± 20 items/m^3, with the highest concentration (90 items/m^3) observed on bank 2. This higher concentration is attributed to the influx of raw sewage through combined sewers and the Doi-Te canal. In contrast, bank 1, characterized by a buffer zone with trees, exhibits a lower concentration of MPs. The middle stream also registers lower concentrations, potentially due to the influence of cargo ships, which may push suspended solids/particulates toward the banks. These findings also highlights the direct link between human activities, industrial processes, and MP pollution in river ecosystems.

As shown in Fig. 2 (A), the concentration of MPs in water samples from the Tha Pra Chan area of the Chao Phraya River and the Nhieu Loc – Thi Nghe area of the Saigon River is significantly higher than that in the Oxbow Dayeukolot area of the Citarum River ($p < 0.05$, t-Test). This difference may be attributed to higher population density in the Tha Pra Chan area compared to these urban zones along the Citarum and Saigon Rivers. The population density in the Tha Pra Chan area is notably higher at 5,536 people/km^2 compared to Oxbow Dayeukolot (1,272 people/km^2) and Nhieu Loc – Thi Nghe (4,292 people/km^2). High population density areas often experience increased plastic consumption, waste generation, and with inadequate waste management practices, it can potentially lead to elevated MP levels in water bodies. (Napper et al. 2023; Ta and Babel 2023b). Beyond population density, specific anthropogenic activities such as tourism play a pivotal role. With its higher MP concentration, Tha Pra Chan is characterized by intense tourist activities. Tourist influxes may contribute to increased plastic usage and littering, amplifying the introduction of MPs into the aquatic environment. While these initial observations offer insights, a comprehensive understanding requires further investigation. Future studies could employ advanced statistical analyses to establish correlations between MP concentrations and specific anthropogenic factors. Additionally, qualitative assessments of local waste management practices, plastic consumption patterns, and tourist behaviors would aid in providing valuable information.

The observed variations in MP concentrations across the studied rivers highlight the intricate interplay between anthropogenic activities, river morphology, and natural features. Higher concentrations in specific areas underscore the need for targeted interventions, especially in regions with heightened human impact. Furthermore, the effectiveness of natural barriers, such as buffer zones with trees, in mitigating microplastic transport suggests the importance of incorporating ecological approaches into pollution control strategies. Understanding these nuances is crucial for formulating informed policies and practices to reduce microplastics' environmental impact on river ecosystems.

The MP number in sediment samples differed between the three studied rivers. As shown in Table 1, the Saigon River had a significantly higher MP number than the Citarum and Chao Phraya Rivers (independent samples t-test, $p < 0.05$). The variations in the MP number in sediment across the three rivers could be due to several reasons. The rivers' hydrodynamics, pollution levels, and the types of plastic polymers may all contribute to these variations. The high concentrations of MPs found in sediment samples from these rivers indicate widespread plastic pollution in aquatic environments, highlighting the urgent need for effective plastic waste management strategies.

Microplastic Characteristic

Size of Microplastics

In the Chao Phraya River, the prevalent sizes of 0.3–0.5 mm (29%) and 0.5–1 mm (31%) suggest a notable proportion of

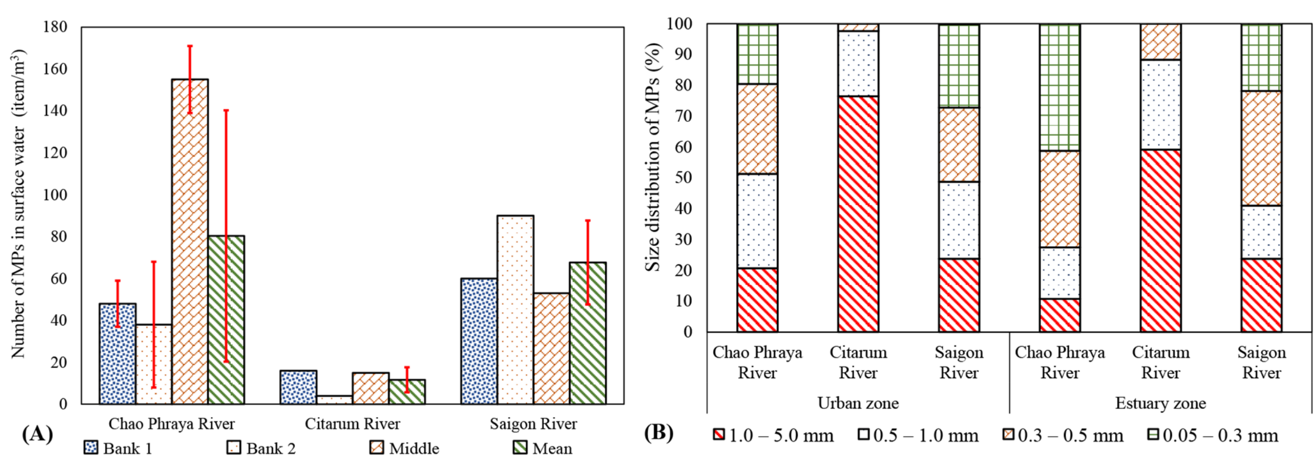

Fig. 2 (**A**) Number of MPs in surface water; (**B**) Variation of MP sizes at Chao Phraya (Thailand), Citarum (Indonesia), Saigon (Vietnam)

Table 1 Number of MPs in sediment samples at the Chao Phraya, Citarum, and Saigon River

Rivers	Number of MPs			
	Bank 1	Bank 2	Middle	Mean
Chao Phraya River (Thailand)	72 ± 2	53 ± 3	-	62 ± 11
Saigon River (Vietnam)	12,391	5943	-	9167 ± 4559
Citarum River (Indonesia)	300	850	350	500 ± 304

Saigon and Citarum Rivers, Bank 1 and Bank 2 values are averages from duplicate samples: standard deviations not applicable

smaller MPs in water samples. Similarly, the Saigon River shows a preponderance of small-sized MPs, particularly in the ranges of 0.05–0.3 mm (30%) and 0.3–0.5 mm (26%). This similarity in size distribution between the Chao Phraya and Saigon Rivers may signify comparable environmental conditions, potentially related to exposure duration, high UV index and increased weathering effects.

In contrast, the Citarum River in Indonesia exhibits a significantly higher percentage of larger-sized MPs, particularly in the range of 1.0–5.0 mm (76%). This finding raises intriguing questions about the factors influencing the size distribution of MPs in this river. Notably, Boyle and Örmeci (2020) reported that MP size decreases over time due to environmental exposure. To substantiate this, Song et al. (2017) conducted control experiments and observed a gradual breakdown of certain polymers, such as PP, PE, and EPS, into sizes less than 0.3 mm over 2 to 12 months.

The lower proportion of larger MPs (> 0.3 mm) in the Chao Phraya and Saigon Rivers may suggest extended environmental exposure, allowing for more significant degradation. This aligns with the findings of Ta et al. (2020), who proposed that plastic waste in these rivers has undergone prolonged weathering and degradation compared to that in the Citarum River. The latter, with its higher percentage of larger MPs, may indicate a relatively shorter exposure duration or different environmental conditions that favor the persistence of larger plastic particles (Zhang et al. 2021). The observed variations in MP size distributions among the studied rivers reflect the current state of plastic pollution and offer insights into the potential impacts of weathering and degradation on plastic particles over time. Further research and in-depth analysis are warranted to unravel the interplay between environmental factors, plastic degradation processes, and MP size variations.

The major size range of MPs in sediment samples collected from the Saigon and Chao Phraya Rivers were 0.05–0.3 mm. This may be attributed to the fact that these samples were obtained from a depth of 2–4 m below the surface water, at which the smaller-sized MPs are likely to sink to the river bottom through agglomeration or cake filtration rather than by density. Conversely, large MPs with a size range of 1.0–5.0 mm were predominantly detected in the Oxbow zones of the Citarum River, followed by 0.5–1.0 mm and 0.3–0.5 mm, which is similar to the MP size ranges found in water samples from this river (Fig. 2B). Overall, MP sizes in the Citarum River were larger than those observed in the Saigon and Chao Phraya Rivers, also reflected in the water samples (Fig. 2B).

Morphologies of Microplastics

Based on morphological characteristics, MPs were classified into four types: pellets, fragments, fibers, and films. Pellets typically exhibit an ovoid, spherical, disk-shaped, or cylindrical form, while fibers are characterized by their slender and elongated structure. Films refer to thin sheets of plastic debris; fragments lack a defined shape. The analysis of water samples from the Citarum, Chao Phraya, and Saigon Rivers, as illustrated in Fig. 3 (A), revealed similarities in MP morphologies, with fragments being the predominant type. However, the Saigon River exhibited more fibers than the other two rivers, while pellets were the least typical morphology in all three.

The various MP morphologies observed are often indicative of their sources. Fibers are commonly associated with textile materials, fishing gear, or airborne deposition (Ta and Babel 2023b), while film-shaped MPs are primarily derived from plastic bags and packaging materials. According to Ta and Babel (2020), pellets may originate from microbeads or plastic resin, and the degradation of larger plastic products due to mechanical stress and exposure to UV radiation is likely to produce fragments (Horton et al. 2017). Understanding these sources is crucial for assessing the environmental implications of MP pollution. In the Saigon, Chao Phraya, and Citarum Rivers, the prevalence of fibers and fragments in water and sediment samples suggests a significant contribution from secondary sources. Fibers dominating in sediment samples from the Saigon and Chao Phraya Rivers (44% and 78%, respectively) imply a potential influx of textile-related pollutants. Conversely, the higher proportion of fragments in the Citarum River sediment (61%) may indicate a more substantial contribution from degraded larger plastic items. The environmental implications of these findings extend beyond the mere characterization of MP morphologies. The presence of specific types may indicate varying degrees of environmental persistence, transport, and potential harm to aquatic ecosystems. Further research into the specific sources and their contribution to

MP pollution in these rivers is warranted for effective mitigation strategies.

Figure 3A presents the various MP morphologies discovered in sediment samples from the three rivers. In the sediment samples from the Saigon and Chao Phraya Rivers, fibers were the most prevalent morphology, accounting for 44% and 78%, respectively. Conversely, in the Citarum River, fragments were the dominant morphology, comprising 61% of the MPs. The MP morphologies found in the Citarum and Saigon Rivers sediment were similar to those observed in their corresponding water samples. However, in the Chao Phraya River, fragments were the predominant morphology in water samples, whereas fibers were dominant in the sediment samples.

Polymer Types

Chao Phraya River's surface water MPs were mainly polypropylene (PP), followed by polyethylene (PE). Other polymers such as PP-PE copolymer, polyurethane, polyester (PES), polybutylene, and cellophane were present but accounted for less than 5% of the total. Similarly, in the Oxbow area of the Citarum River, most MPs consisted of PP and PE, likely originating from food packaging, daily-use plastics, and industrial waste. In the Saigon River, the identified MPs included PP, PE, polyethylene terephthalate (PET), and polystyrene (PS), with PP being the most abundant (65–70%), followed by PE (24–37%), and PET having the lowest proportion. These findings indicate a high concentration of MPs in these rivers, likely due to the population density and resident activities in the surrounding areas.

The high PP and PE numbers in the Chao Phraya, Saigon, and Citarum Rivers can be attributed to their widespread usage in Thailand, Vietnam, and Indonesia (VPAS 2019; WB 2020). These polymer types are commonly produced in everyday products, including tableware, containers, bags, and bottles. PP and PE are also widely found as MPs in marine and freshwater environments due to their low densities, which allow them to float easily on surface water. High-density polymers like PES (1.40 g/cm³) were also detected in the surface water, suggesting that their density may decrease during weathering (Lv et al. 2017). Tides and waves may also resuspend denser MPs from the bottom sediment.

Furthermore, the elevated concentrations of PP and PE in sediment samples underscore their persistence in river ecosystems. In the Chao Phraya, Saigon, and Citarum Rivers, PP dominates the sediment MPs, constituting approximately 70% of the total. PVC, characterized by its higher density, is more abundant in sediment than in water samples, as it tends to sink to the river bottom. Additionally, the presence of PE, PP, and PE-PP copolymers in sediment samples, despite their lightweight nature, suggests potential interactions such as cake filtration or biofouling altering their density (Ta and Babel 2020).

The widespread distribution of these polymers in river ecosystems raises concerns about their environmental significance. The ubiquity of PP and PE, stemming from their extensive use in various consumer products, highlights the need for targeted efforts to reduce plastic consumption, improve waste management practices, and mitigate the release of these pollutants into water bodies. Additionally, detecting high-density polymers like polyethene terephthalate (PET) in the Saigon River suggests potential weathering effects, emphasizing the dynamic nature of polymer densities in aquatic environments. Future research should delve into the specific sources of these polymers, their transport mechanisms, and the potential ecological and human health risks associated with their presence in river ecosystems.

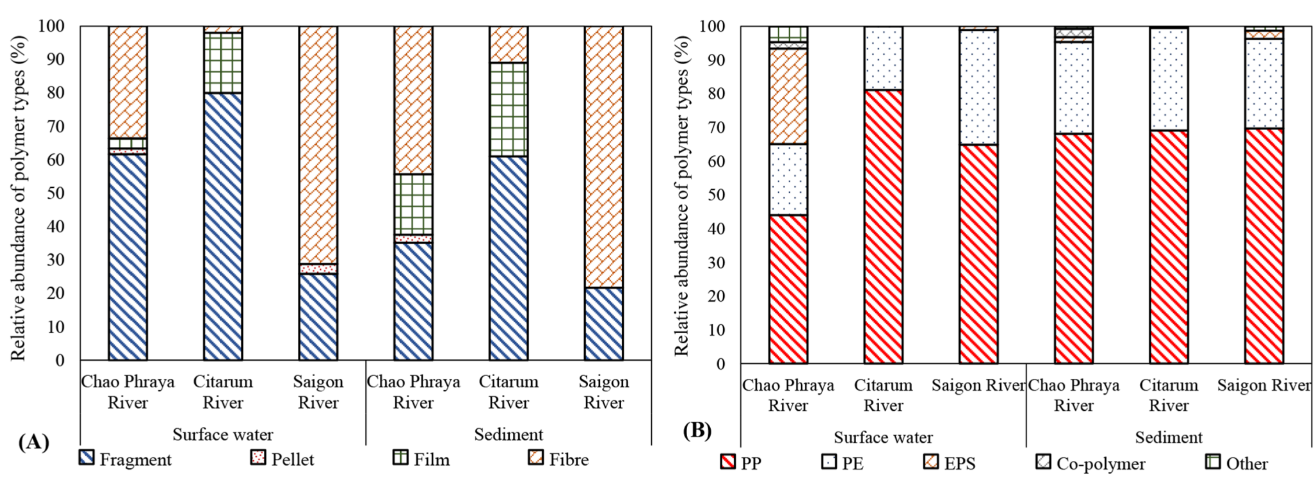

Fig. 3 Variability of MP morphology (**A**) and polymer types (**B**) at selected rivers in urban zones of the Chao Phraya (Thailand), Citarum (Indonesia), Saigon (Vietnam)

Furthermore, previous research has highlighted the presence of various harmful substances, such as persistent organic pollutants (POPs) and heavy metals, that can adsorb onto the surfaces of MPs composed of PP and PE, potentially allowing them to enter the aquatic food chain. Notably, these MPs can become more toxic after absorbing heavy metals from the surrounding environment (Khalid et al. 2021; Liu et al. 2022).

Comparison between the Three Rivers and Others

Compared with other urban rivers worldwide (Table 2), MP levels in the water of the Chao Phraya, Saigon, and Citarum Rivers were comparable to those in the Tamsui River in Taiwan (Wong et al. 2020). This suggests a degree of uniformity in the extent of MP pollution across these diverse geographical locations. However, rivers in China, such as the Hanjiang River (Wang et al. 2017) and Suzhou River (Luo et al. 2019), exhibited higher MP concentrations, indicating potentially elevated levels of plastic contamination in Chinese water bodies. Table 2 also shows that the concentrations of MPs in urban areas of European and North American rivers, such as the Danube River in Austria (Lechner et al. 2014) and the Ottawa River in Canada (Vermaire et al. 2017), were lower compared to the rivers investigated in this study. According to Lambert and Wagner (2018), the high level of MPs in regions is directly associated with high population density and waste management practices. Thus, the MP levels in this and other studies could indicate the state of waste management systems in each research location. Furthermore, the results may show that Asian countries have insufficient waste management systems compared to Western countries (Wu et al. 2018).

For sediment samples, MP concentrations were relatively lower in the South Korean Nakdong River (Eo et al. 2019) than those from the Citarum and Chao Phraya Rivers. Conversely, the concentrations of MPs in the Saigon River were higher than those in the South Korean River. These variations underscore the complex nature of MP distribution in different river systems and highlight the influence of regional factors. The MP number in the Milwaukee River (Lenaker et al. 2019) and the Ottawa River (Vermaire et al. 2017) in the USA showed similar values to the Chao Phraya River study but with a wider range. However, it is important to note that differences in sampling and analysis techniques may affect the comparability of results and that various factors, such as the sources and types of MPs, hydrodynamics, and other pollutants, can influence MP contamination in rivers.

The diverse MP concentrations observed among the studied rivers and those worldwide underscore the need for region-specific waste management strategies. The variations may be attributed to population density, waste disposal practices, and regional hydrodynamics. These findings emphasize the importance of targeted interventions and collaborative efforts on a global scale to mitigate the impact of microplastic pollution in urban water systems.

Potential Strategies to Minimize Plastics and MPs in the Studied Rivers

Thailand, Indonesia, and Vietnam are major sources of ocean plastic waste due to poor plastic waste management and high usage (Jambeck et al. 2015). The Chao Phraya, Citarum, and Saigon Rivers have high MPs caused by littering and untreated wastewater. Government intervention is necessary to prevent these countries from becoming hotspots for plastic waste production. Strategic actions, such as improving waste management and wastewater treatment, should be implemented by stakeholders to address the issue.

Regulatory and Policy Instruments

Land-use management must be enhanced to mitigate plastic waste in the rivers. New residential zones along the banks of the three studied rivers should be strategically positioned from the riverside, creating protection zones to mitigate plastic litter and subsequent MP pollution. Regular collection of waste within these protection zones is imperative. To ensure sustainable practices, policies for real estate

Table 2 The abundance of MPs in the studied rivers, as compared to other urban rivers worldwide

Location	Water samples (items/m^3)	Sediment samples (items/kg)	Reference
Milwaukee River, USA	0.54–11.6	32.9–6229	Lenaker et al. (2019)
Ottawa River, Canada	0.71–1.99	220–450	Vermaire et al. (2017)
Nakdong River, South Korea	293 ± 83–4760 ± 5242	1970 ± 62	Eo et al. (2019)
Danube River, Austria	0.317 ± 4.665	-	Lechner et al. (2014)
Suzhou River and Huangpu River, China	1800–2400	-	Luo et al. (2019)
Hanjiang River, China	933 ± 305.5	-	Wang et al. (2017)
Tamsui River, Taiwan	10.1–70.5	-	Wong et al. (2020)
Chao Phraya River, Thailand	80 ± 60	62 ± 11	This study
Citarum, Indonesia	12 ± 6	500 ± 304	
Saigon, Vietnam	68 ± 20	9167 ± 4559	

developers in the new resident zones should mandate proper wastewater and solid waste treatment systems. Emphasizing waste separation and adhering to the 4Rs (Refuse, Reduce, Reuse, and Recycle) within these communities is crucial for minimizing plastic release into the environment. MPs reported in three rivers are mostly secondary MPs specifically generated by the breakdown of larger plastic particles. Consequently, bolstering existing solid waste collection and treatment systems is essential to minimize the duration of plastic waste exposure in the environment. Moreover, Song et al. (2017) reported that plastics can degrade into MPs in natural conditions within 2 to 12 months, indicating that timely collection during this period becomes pivotal in reducing the prevalence of secondary MPs in the environment. Implementing efficient waste management practices and timely collection mechanisms aligns with curbing the impact of plastic pollution in the Chao Phraya, Citarum, and Saigon Rivers.

Moreover, strategic interventions are paramount to mitigate this challenge. A multifaceted policy approach is recommended. To enhance solid waste management, expanding service coverage, advocating source-level waste separation, and incorporating waste-to-energy technology for non-recyclables can be pursued. Rigorous regulation of single-use plastics, including stringent bans, constitutes another vital policy avenue (Amesho et al. 2023). Moreover, imposing guidelines that curtail non-biodegradable plastic bags' production, import, and distribution through mechanisms like plastic taxes and usage charges in commercial settings could yield positive outcomes. Encouraging industries to adopt refund and refill systems for daily-use items could significantly diminish plastic packaging waste (Ta and Babel 2023a). Implementing a combination of these policies promises to curtail plastic waste and advance sustainability goals.

Environmental Education

Implementing environmental education is a crucial strategy to address MP pollution in the Chao Phraya, Citarum, and Saigon Rivers. Disseminating information regarding MP abundance in these rivers and their potential impacts on human health and the environment is essential to enhance public awareness. Elevating community knowledge is integral to the overall strategy, emphasizing responsible waste management practices. Moreover, developing skilled human resources is vital for sustainable waste handling, and monitoring groups studying plastic and MP waste at its source inform policymakers and stakeholders to safeguard the environment.

Conclusion

All water and sediment samples taken from the Chao Phraya River in Thailand, the Saigon River in Vietnam, and Citarum in Indonesia contained MPs. The Chao Phraya River had the highest MP concentration in water samples (80 ± 60 items/m^3), followed by the Saigon (68 ± 20 items/m^3) and Citarum Rivers (12 ± 6 items/m^3). Quantitative analysis confirms significantly higher MP concentrations in Tha Pra Chan (Chao Phraya) and Nhieu Loc – Thi Nghe (Saigon) compared to Oxbow Dayeukolot (Citarum), correlating with population density. For sediment samples, the Saigon River had a significantly higher average MP concentration than the Citarum and Chao Phraya Rivers (independent samples t-test, $p < 0.05$). Smaller-sized MP particles were the predominant types in the Saigon and Chao Phraya Rivers, ranging from 0.3 to 0.05 mm, whereas the size in the Citarum River was larger. Various organisms can ingest MPs' size ranges, potentially leading to bioaccumulation and disrupting food chains. Fragment and fiber morphologies were the most commonly found MPs in all three rivers, with PP and PE being the most prevalent polymer types in all collected samples. The MPs potentially leach harmful chemicals into the water, posing long-term ecological risks. Beyond ecological concerns, the implications extend to human health, as the rivers studied are crucial water supply sources and aquaculture in the region. The presence of MPs in water bodies implies the potential transfer of these pollutants into the food chain, with possible repercussions for human health through consuming contaminated living organisms.

The discovery of high MP concentrations highlights the urgency of implementing plastic management strategies to mitigate MP pollution. This study proposed measures that involve strategic land-use planning for new residential zones and establishing protection zones to combat plastic litter. Policies for real estate developers should mandate sustainable waste treatment. Emphasizing waste separation and the 4Rs (Refuse, Reduce, Reuse, Recycle) within communities is crucial. Strengthening solid waste collection systems is recommended to minimize plastic waste exposure. Efficient waste management practices are pivotal to addressing the timely generation of microplastics from larger plastics. These context-specific recommendations aim to contribute to effective interventions tailored to each river's unique environmental and socio-economic contexts. As far as we know, this study is among the first to document MP pollution in the three rivers in SEA. Therefore, it provides essential background data for shaping future research directions and guiding effective management efforts. Furthermore, the data generated enhances the scientific community's understanding of the immediate environmental concerns in these specific rivers, contributing to a more nuanced comprehension of the broader implications of microplastic pollution in SEA regions. This, in turn, will facilitate in developing appropriate policies and management of plastics.

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Author Contributions Anh Tuan Ta: Conceptualization, conducting research, writing, and revising the manuscript. Sandhya Babel: Conceptualization, supervision, review, and revision of the manuscript, corresponding author. Nguyen Thi Phuong Loan: Conducting research. Emenda Sembiring: Conducting research.

Data Availability The data supporting the findings of this study are available on request from the corresponding author.

Declarations

Consent to Participate Not applicable.

Consent for Publication All authors have read and agreed to the published version of the manuscript.

Conflict of Interest The authors declare no conflict of interest.

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