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Review

Microplastics in Asian rivers: Geographical distribution, most detected types, and inconsistency in methodologies☆

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A B S T R A C T

Microplastics pose a significant environmental threat, with potential implications for toxic chemical release, aquatic life endangerment, and human food chain contamination. In Asia, rapid economic growth coupled with inadequate waste management has escalated plastic pollution in rivers, positioning them as focal points for environmental concern. Despite Asia's rivers being considered the most polluted with plastics globally, scholarly attention to microplastics in the region's freshwater environments is a recent development. This study undertakes a systematic review of 228 scholarly articles to map microplastic hotspots in Asian freshwater systems and synthesize current research trends within the continent. Findings reveal a concentration of research in China and Japan, primarily investigating riverine and surface waters through net-based sampling methods. Polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET) emerge as the predominant microplastic types, frequently observed as fibers or fragments. However, the diversity of sampling methodologies and reporting metrics complicates data synthesis, underscoring the need for standardized analytical frameworks to facilitate comparative analysis. This paper delineates the distribution of microplastic hotspots and outlines the prevailing challenges and prospects in microplastic research within Asian freshwater contexts.

1. Introduction

Plastics, among the most versatile materials engineered by humanity, have significantly eased aspects of daily life, albeit with considerable environmental repercussions (Andrady and Neal, 2009). The mismanagement of plastic waste has emerged as a grave environmental concern, tarnishing natural aesthetics and bequeathing persistent pollution to succeeding generations (Yang et al., 2011). Misplaced plastics, migrating from terrestrial to aquatic realms, jeopardize essential water resources and amplify human exposure to pollutants, notably microplastics.

Microplastics, categorized into primary and secondary types, originate from various sources (UN-Water, 2018). Primary microplastics directly enter ecosystems through industrial and domestic activities, including textile and plastic production, agriculture, and personal care products, cumulatively releasing billions of particles annually (Tan et al., 2019; Praveena et al., 2018). Secondary microplastics result from the degradation of larger plastic items through environmental factors, contributing to pollution across ecosystems (Kabir et al., 2021).

The omnipresence of microplastics in environmental

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matrices—sediments, surface waters, and organisms—poses significant risks to the health of humans, animals, and ecosystems. Human exposure occurs via ingestion, inhalation, and dermal contact (Prata et al., 2020), predominantly through contaminated food (Mamun et al., 2023; Danopoulos et al., 2020; Rochman et al., 2015; Walkinshaw et al., 2020; Liao et al., 2021; Van Cauwenberghe and Janssen, 2014; Lee et al., 2019; ohnson et al., 2020; Pivokonsky et al., 2018; Mamun et al., 2023). The health implications of long-term exposure remain a concern, with potential for inflammation, metabolic disruptions, and compromised barrier functions, dependent on individual clearance rates (Yan and Peng, 2021).

Furthermore, direct human contact with microplastics, through skin (Rubio et al., 2020; Magrì et al., 2018) and respiratory systems (Enyoh et al., 2019; Donaldson et al., 2002), introduces additional exposure pathways, with certain plastics posing greater risks due to their size and physical properties (Flament et al., 2015; Allen et al., 2019; Rubio et al., 2020). Despite this growing understanding, freshwater plastic pollution, especially in Asia, remains underexplored compared to marine environments. Recent studies in various countries have begun addressing this gap, highlighting the critical role of rivers in transporting plastics to oceans.

Freshwater plastic pollution is a relatively new field, with most efforts concentrated in Europe and North America's industrialized nations (Talbot and Chang, 2022). Research on microplastics was initially more focusing on marine areas (Collignon et al., 2012; Dubaish and Liebezeit, 2013; Fries et al., 2013; Leslie et al., 2013). Recently, the presence of microplastics in rivers was rapidly investigated in some countries, such as England (Horton et al., 2018), Germany (Klein et al., 2015), France (Dris et al., 2015), Switzerland (Faure et al., 2015), USA (McCormick et al., 2014), Canada (Ballent et al., 2016), Austria (Lechner et al., 2014), India (Sarkar et al., 2019; Sarkar et al., 2021a; Sarkar et al., 2021b), South Korea (Eo et al., 2019), China (Wang et al., 2017), Japan (Kabir et al., 2021; Kataoka et al., 2019; Nihei et al., 2020), Vietnam (Lahens et al., 2018), Indonesia (Lestari et al., 2020), and Taiwan (Kunz et al., 2023; Wong et al., 2020a). The information of microplastics in rivers are necessary regarding as plastics and other debris pollution that ended up in the ocean (Lebreton et al., 2017; Meijer et al., 2021; Schmidt et al., 2017).

Asia, with its high plastic usage and production, particularly in countries like China and Japan, is a major contributor to global microplastic pollution (Meijer et al., 2021; PlasticsEurope, 2021). Asian rivers, laden with plastics due to rapid industrialization and inadequate waste management, serve as significant conduits of marine pollution (Lebreton and Andrady, 2019; Jambeck et al., 2015; Vriend et al., 2021; Razeghi et al., 2021). While studies in marine environments predominate, the scarcity of research on freshwater systems, particularly in Asia, underscores the urgent need for comprehensive studies to inform risk assessments and policy formulation.

This study aims to bridge the knowledge gap on microplastic pollution in Asian inland waters, emphasizing the necessity for extensive research to grasp the full scope of microplastic impacts and guide effective mitigation strategies.

2. Materials and methods

To systematically investigate the prevalence of microplastics in Asian freshwater systems, we conducted a thorough literature search via the Scopus database in March 2022. Employing key phrases "microplastic*", "river*", and "Asia*", and subsequently substituting "Asia*" with names of 50 countries within the region as defined by the 2022 Index of Economic Freedom (Miller et al., 2022). The detailed search strategy and results are documented in the **electronic supplementary materials (ESM)**.

From an initial totally of 457 studies, we identified 36 overlaps across searches. After removing duplicates, the authors reviewed the literature list based on their own knowledge and experience, identifying 7 missing studies which were added to the search results. The identified studies were then compared against references from recent microplastics literature reviews, namely (Razeghi et al., 2021; Raha et al., 2021; Ouda et al., 2021; Weiss et al., 2021; Vriend et al., 2021; Petersen and Hubbart, 2021), which revealed one additional study of relevance that was added to the search results. This process is visually summarized in Fig. 1.

After the identification, full-text documents for all of the 429 indexed publications were sought (Fig. 1). While one study was not accessible online and could not be retrieved from its authors. The 428 publications were examined for eligibility, excluding 199 for reasons such as geographical irrelevance, focus on unrelated topics (e.g., biofilms, risk assessments), or methodological discrepancies. This left 228 studies for inclusion in our review, detailed screening criteria are available in the **ESM**.

2.1. Data extraction and analysis

For data extraction, we developed a Google Sheets template with three main sections. Initially, we documented the country, freshwater system type, sampling year, compartment, microplastics size range, and equipment used. While rivers were our primary focus, other water bodies like canals and lakes were also considered. Sampling methods varied from nets and traps for water to manual techniques for sediments, and the approach for biota collection ranged from fishing to direct purchase.

Next, we collated river and compartment-specific data, including microplastics abundance, and their predominant shapes, materials, colors, and size classes. We also noted potential microplastic sources and other relevant observations.

After data extraction, we performed a consistency check, correcting any discrepancies found. Microplastics concentrations were standardized for comparison, and the data was then used to rank freshwater environments by pollution levels and to categorize the most common microplastics characteristics (see Table 1). This analysis facilitated the identification of methodological and spatial trends over time.

In the final section, we extracted geographic coordinates for each study's sampling locations, enabling us to map the data and highlight areas with intensive or scarce research. Of the 228 studies, 117 provided coordinates either within the text or supplementary materials. Where necessary, we derived coordinates from provided figures or contacted authors directly. This mapping effort helped pinpoint both well-studied and under-researched regions.

3. Results

3.1. Scientific publication trends

The volume of microplastics research in Asia has seen a significant increase, as depicted in Fig. 2. Starting with a single publication in 2014 and 2015, the field witnessed a tripling of output in 2018 compared to the previous year. The year 2020 marked a notable surge, with 62 publications, doubling the count from 2019. By mid-April 2022, 31 papers had been published, indicating a continuing upward trend. Leading journals in this domain include Science of the Total Environment, Environmental Pollution, and Marine Pollution Bulletin, collectively accounting for 42.8% of the total publications. Other prominent outlets are Chemosphere, Water Research, and Environmental Science and Pollution Research, alongside contributions from local journals and conference proceedings, underscoring the growing interest in microplastic research within the Asian academic community.

3.2. Investigated systems

A variety of freshwater systems have been explored for microplastics research in Asia, with rivers accounting for 70% of the studies, followed by estuaries (21%), lakes (10%), and smaller fractions examining

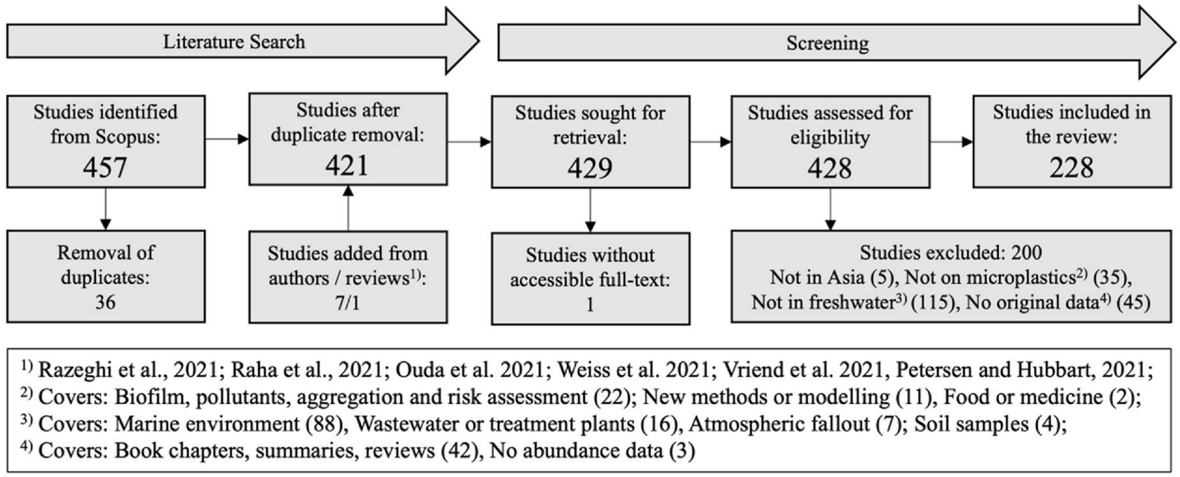

Fig. 1. Literature identification and screening approach used in this study.

Table 1
Different categories used in this study to describe microplastics in Asian rivers.

Category	Description
Shape	Fibers (Filament), Fragments (Flake), Film (Sheet), Foam, Line, Pellets (Spheres, Granules, Polyhedral), Not mentioned
Color	Transparent (Colorless), Colored (mixed), White, Blue (Purple, pigment blue), Black (Gray), Red, Green, Yellow, Not mentioned
Polymer type	PP, PE (LDPE, HDPE), PET, PVC, PS, PES, Nylon, Rayon, Other, Not mentioned
Size (μm)	<50, <100, <150, <250, <333, <500, <900, <1000, <2000, <3000, <5000

reservoirs (2.6%), canals (2.6%), wetlands (1.8%), lagoons (0.9%), and ditches (0.4%). Analysis predominantly focused on surface water (68%) and sediments (49%), with lesser attention to biota, water column, and bottom water samples.

3.3. Sampling methodologies

Diverse approaches have been employed to sample microplastics across different freshwater ecosystems, involving both bulk and volume-reduced strategies (Hidalgo-Ruz et al., 2012; Wang and Wang, 2018). The sampling methodologies are revealed in Fig. 3 and the range of sampling sizes are shown in Fig. 4.

3.3.1. Water sampling methodologies

Non-discrete sampling devices were utilized by 38% of studies on water systems, including nets such as neuston, plankton, and manta nets with varying mesh sizes, followed by pumps (12%), traps (3%), and autosamplers (3%), for collecting surface water, water column, and bottom water in freshwater systems. In contrast, 32% of microplastics in Asian freshwater studies have focused on surface water sampling using discrete sampling devices like buckets and bottles. Additionally, 7% of microplastics in Asian freshwater studies have employed alternative sampling approaches, such as hand sorting in quadrates (Battulga et al., 2020) and the use of water samplers with manual filtration through stainless steel sieves, stainless steel drums (Huang et al., 2021; Wang et al., 2020a). In 5% of the studies the sampling methodologies were not described or unclear.

Discrete sampling devices like buckets, bottles, stainless steel drums, and water samplers, along with manual filtration through stainless steel sieves, are straightforward for collecting river samples at different depths and suitable for smaller microplastics (Campanale et al., 2020). However, they collect limited water samples and require boats (Campanale et al., 2020). Nets and traps with mesh sizes of 100–500 μm allow sampling large-volumes but cannot capture particles smaller than 100 μm and may clog in freshwater (Campanale et al., 2020; Karlsson et al., 2020). Pump devices enable large volume water sampling at various depths, effectively trapping smaller microplastics like fibers (Cutroneo et al., 2020). Studies by Eo et al. (2019), He et al. (2021), Liu et al. (2020), Zhang et al. (2021) combined discrete and non-discrete devices to capture smaller microplastics in water samples.

The combination of both discrete and non-discrete sampling devices in these studies has facilitated the identification of microplastic particles ranging in size from 20 μm to 5 mm in freshwater samples (Fig. 4). Additionally, the autosampler device has been utilized primarily for water sampling in freshwater systems and has proven effective in capturing smaller microplastic samples measuring less than 45 μm (Jiang et al., 2019; Liu et al., 2020; Zhou et al., 2020a; Zhou et al., 2020b). This device offers on-site particle filtration separation,

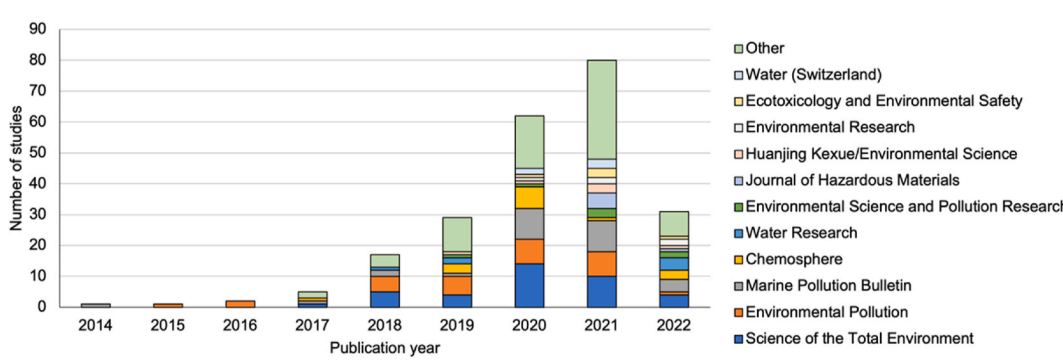

Fig. 2. Journal and publication year recordings of microplastics sampling studies in Asian freshwater environments.

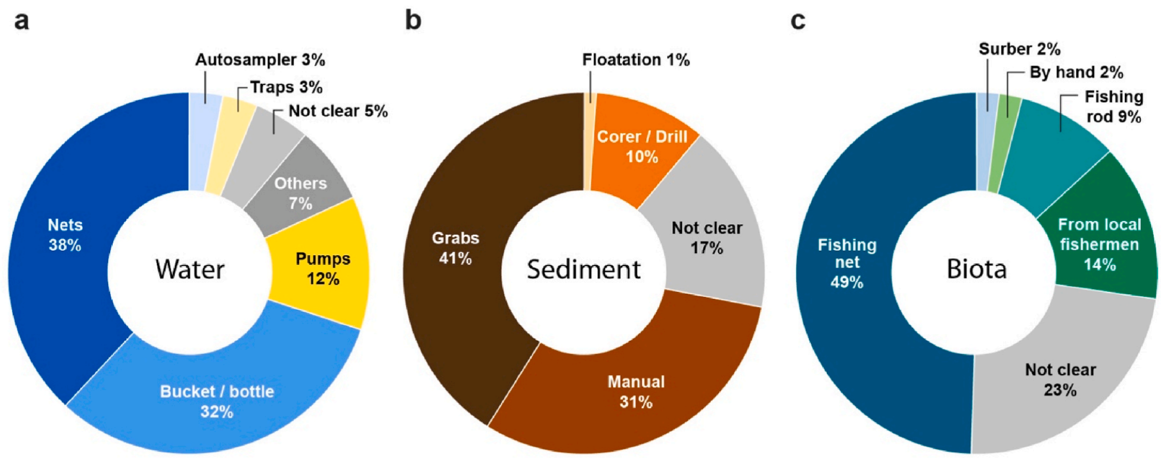

Fig. 3. Sampling methodologies adopted for microplastics analysis in Asian freshwater studies (a) water, (b) sediment and (c) biota samples in Asian freshwater systems.

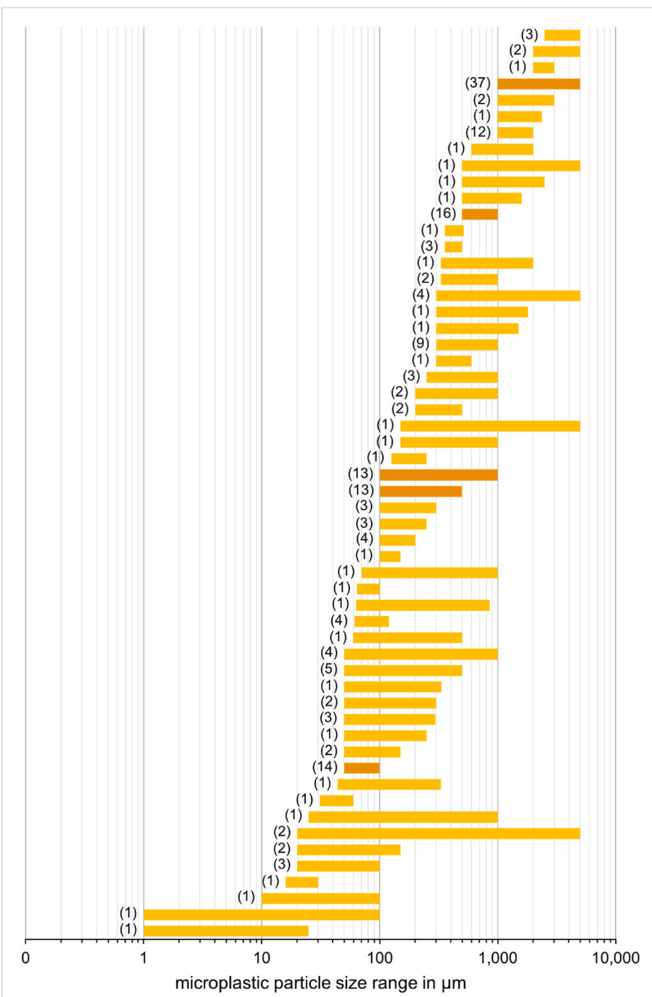

Fig. 4. Size ranges of microplastic particles from analyzed studies, with the number of studies in parentheses. Top five frequently reported size ranges are shaded darker.

minimizing the risk of contamination (Zhou et al., 2020b). However, the autosampler device is the least commonly employed in freshwater sampling in Asian countries due to logistical challenges, including transportation and deployment difficulties, the need for electricity supply, and high costs (Campanale et al., 2020).

3.3.2. Sediment sampling methodologies

Sediment sampling in freshwater environments, including rivers, canals, lakes, reservoirs, estuaries, and wetlands, has predominantly relied on grab samplers. Among the studies, 41% utilized grab samplers to collect sediment samples, acknowledging the potential accumulation of microplastics over time in these environments. Alternatively, 31% of the studies opted for manual collection of bulk sediment samples from riverbanks, lakeshores, and estuary shorelines using tools such as shovels, spatulas, or trowels (Hu et al., 2018; Kumkar et al., 2021; Li et al., 2021a; Xiong et al., 2018). To understand the vertical distribution of microplastics, 10% of the studies collected sediment core samples with corer or drills at depths ranging from 0 cm to 80 cm (Abbasi and Turner, 2022; Fraser et al., 2020; Li et al., 2020; Sarijan et al., 2019; Wicaksono et al., 2021; Wu et al., 2020; Xia et al., 2021). One study (1%) adopted flotation techniques. 17% of the studies did not clearly specify the sampling devices used for sediment sampling.

Sediment sampling methods offer different advantages and limitations in capturing microplastics. Grab samplers are commonly used to collect sediment samples and effectively capture smaller microplastics. However, their effectiveness is influenced by variables such as sediment composition, unpredictable penetration, and riverbed agitation caused by the opening and closing of grab sampler jaws (Hastuti et al., 2019).

Alternatively, manual sediment sampling using tools like shovels, spatulas, or trowels is a cost-effective method for collecting bulk samples. However, this method lacks consistency in sampling depth or sediment volume and may exclude smaller plastics (Wang and Wang, 2018). Another approach is the core sampler, which is a handheld device designed for collecting deeper samples at specific points and depths. Nevertheless, it is crucial to carefully manage potential sediment distortion when inserting the tube into high-velocity locations (Adomat and Grischek, 2021; Brander et al., 2020).

3.3.3. Biota sampling methodologies

A total of 43 studies have included biota (fish, wild fish, mudskipper fish, shellfish, oyster, blood cockle, tadpoles) sampling in Asian freshwater environments. Fish nets were the most commonly utilized sampling method (49%) for biota sampling in rivers, lakes, and estuaries. Biota samples were also obtained through purchasing from local fishermen (14%), manual collection by hand (2%), and the use of fishing rods (9%) (Frank et al., 2020a; Heshmati et al., 2021; Karaoglu and Gul, 2020; Makhdoumi et al., 2021; Sembiring et al., 2020; Wang et al., 2020b; Xiong et al., 2018; Yuliati et al., 2021; Zhu et al., 2019). Only one study by Lin et al. (2021) used the Surber sampler, placed on a stone-based riverbed, for biota sampling in freshwater systems. In 23% of the studies, there was unclear information about the biota sampling method employed.

Fish nets are commonly used for aquatic biota sampling in various aquatic environments. However, they are not suitable for collecting macroinvertebrates above the sampler's height (around 40 cm) and can allow free-floating biota to escape (Di Sabatino et al., 2018; Guild et al., 2014; Shull and Lookenbill, 2017). Efficiency in sampling is influenced by the time taken to obtain biota samples, as longer durations are less preferred due to increased costs, labor, and predator exposure (Ghani et al., 2016). In Asian freshwater studies, there is no universally accepted standard for sampling procedures, leading to variations in equipment, sample volume, size, and depth. These differences result in inconsistencies in reporting units, hindering findings comparison and assessing microplastics extraction methods' sensitivity (Peller et al., 2019; Talbot and Chang, 2022; Yang et al., 2021).

3.4. Microplastic size ranges and concentrations

From the analysis of 228 studies in this review, a diverse range of reported size ranges and concentrations emerged. The majority of studies (44%) presented size ranges with both upper and lower boundaries, while a smaller fraction (27%) reported only upper size boundaries. A few studies (7%) indicated different size ranges due to various sample types, and surprisingly, a significant number (21%) provided no information about the size range. In Fig. 4, the summarized size ranges illustrate their wide spectrum. The analyses revealed a predominant use of the large microplastics range (1–5 mm) by 37 of the examined studies. Other frequently reported size ranges include 0.5–1 mm, 0.1–1 mm, 0.1–0.5 mm, and 0.05–0.1 mm.

Similarly, there was a broad spectrum of ways to report microplastic quantities, with 30 different methods identified (Fig. 5). These units fall into four main categories: by volume (e.g., pcs/m^3, used by 61% of the studies), by weight (e.g., pcs/kg, 26%), by individual (e.g., pcs/fish, 7%), and by area (e.g., pcs/km^2, 3%). A small percentage of studies (3%) reported findings in absolute numbers, concentration (mg/g), or frequency of occurrence. However, even within each of these main categories, there exist a wide range of different units. For example, various terms are used to represent the amount, such as item/items, mg, MP/MPs, n, part. P/Particles, and pcs/pieces. When it comes to weight, some studies specify the use of dry weight (e.g., Eo et al. (2019), Gupta et al. (2021), while others do not mention it (e.g., Jian et al. (2020); Li et al. (2019)). In certain studies, authors indicate that the number of particles is related to wet weight (e.g., Su et al. (2016); Zhao et al. (2020)). The lack of clarification regarding the relationship between mass and dry or wet weight poses a challenge when interpreting the data without context. In some cases, highly specific units are used, such as n/10 g dry mud (Nakao et al., 2019); n/piece of polystyrene foam (Battulga et al., 2020); or n x 1000/kg (Xia et al., 2021). While these specific units may be suitable for the particular study, they make it nearly impossible to compare data across different studies. In such cases, authors are encouraged to convert their units into a more standardized format for better comparability. Overall, it would be preferable for authors to employ commonly used and easily convertible units in their reporting.

Ideally, microplastics concentrations should be reported based on mass for samples collected from solids (e.g., particles/g dry weight) or on volume for samples taken from liquids (e.g., particles/m^3). Additionally, it is preferable to report size ranges using the actual particle sizes rather than relying on a hypothetical range based on the sampling equipment or filters used during sample preparation. Kunz et al. (2023) demonstrated that true particle sizes may deviate from the expected range due to the use of a manta net. This is particularly crucial for the upper size range. In many instances, the upper size limit is conventionally set at 5 mm according to the standard definition of

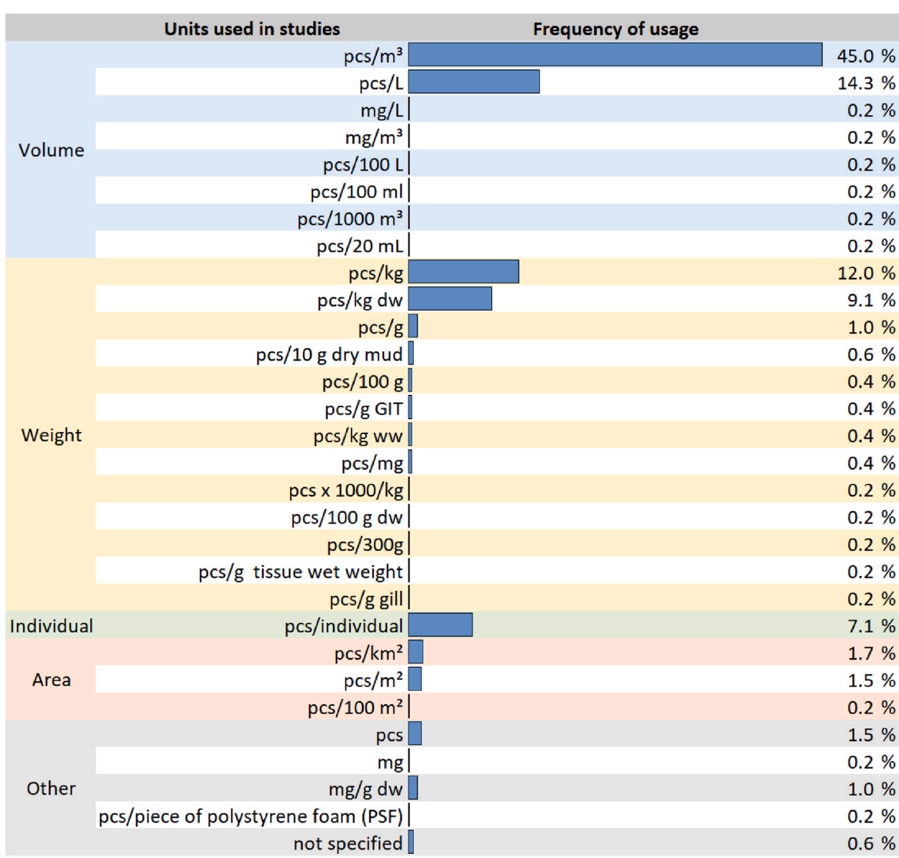

Fig. 5. Unit and occurrence of the unit used from analyzed studies.

microplastics. However, as evidenced by Kunz et al. (2023), the actual maximum particle size can be lower.

3.5. Sampling points

The distribution of sampling locations shows that the largest number of samples was collected in China followed by Indonesia, Japan and India (Fig. 6). Regional clusters are apparent. Clustering follows two patterns. Either a certain region is intensively studied or river sections are sampled in great detail. Regions with large clusters of sampling locations can be lakes (e.g., Qinghai Lake in China), large urban agglomerations (e.g., Shanghai in China or Tokyo in Japan), and the mouth of large river systems, e.g., the Pearl River and the Yangtze River. River sections that have been intensively studied are mainly the Yangtze River in China and southern Japan. Other rivers have been sampled multiple times, but mostly in limited areas or only once. The map also reveals that data from freshwater reservoirs of certain countries or regions are largely missing.

3.6. Concentration of microplastics

Fig. 7 illustrates the concentration of microplastics in Asian rivers. Due to the variety of concentration reporting methods, only the results from surface water, water column, and bottom water reporting by n/m^3 are illustrated here. Rivers reported with microplastic concentration exceeding 100,000 n/m^3 include Krukut River (Azizi et al., 2022) and Deli River (Harpah et al., 2021) in Indonesia, Yellow River (Han et al., 2020), Cao'e River (Zhou et al., 2020b), Pearl River (Li et al., 2021b), and Yangtze River (Zhang et al., 2015; Zhang et al., 2017) in China, Saigon River (Lahens et al., 2018; Strady et al., 2020) in Vietnam, and Majime River, Awano River, Asa River, and Ayaragi River in Japan (Kabir et al., 2020; Kabir et al., 2021). The highest concentration of microplastics was found in the Krukut River in Indonesia, followed by the Yellow River in China and the Cao'e River in China. It should be noted that the concentrations presented in this review, as illustrated in Fig. 7, exhibit a certain degree of bias. While it may appear that China and Japan exhibit the highest concentrations of microplastics in freshwater systems, this does not necessarily imply that these regions are the most polluted in Asia. The over-representation of research from China and Japan can be attributed to a scarcity of studies and data from other Asian countries.

Table 2 shows the list of Asia's 20 longest river systems and the number of review studies and surface water MPs number. Although Yangtze, Ganges, and Pearl River are intensively studied, most major rivers in Asia have not yet been studied. This result also shown a knowledge gap in many areas.

3.7. Microplastic shape, type, color, and size in Asian rivers

The concentration of microplastics, the size, shape, color, and type of polymer were further explored and analyzed based on the 228 articles on the existence of microplastics in Asian freshwater bodies (Fig. 8). The

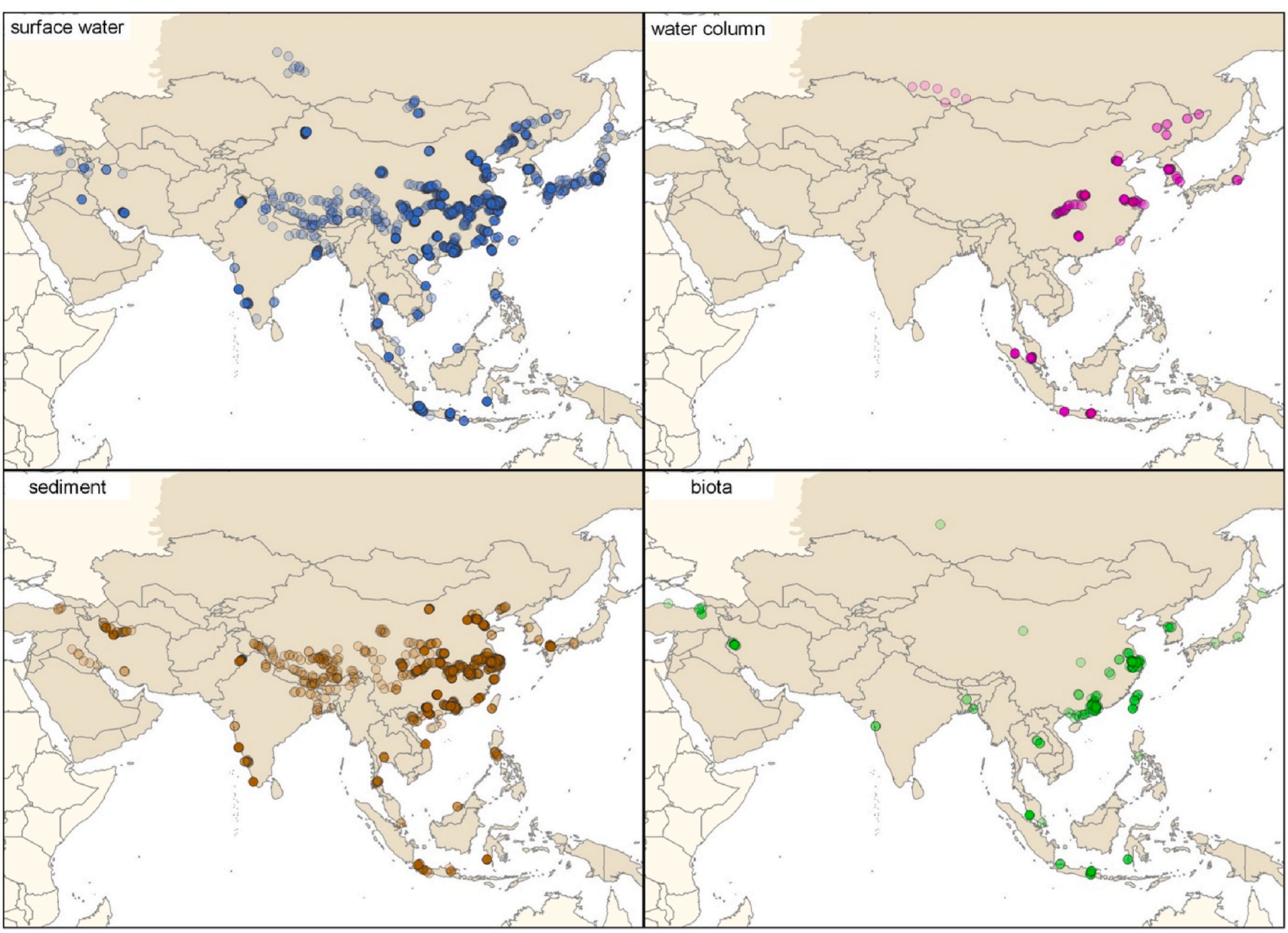

Fig. 6. Sampling location for microplastic in freshwater environments throughout Asia for each compartment. Some locations have been sampled for surface water, sediment or biota simultaneously and hence appear multiple times in this map.

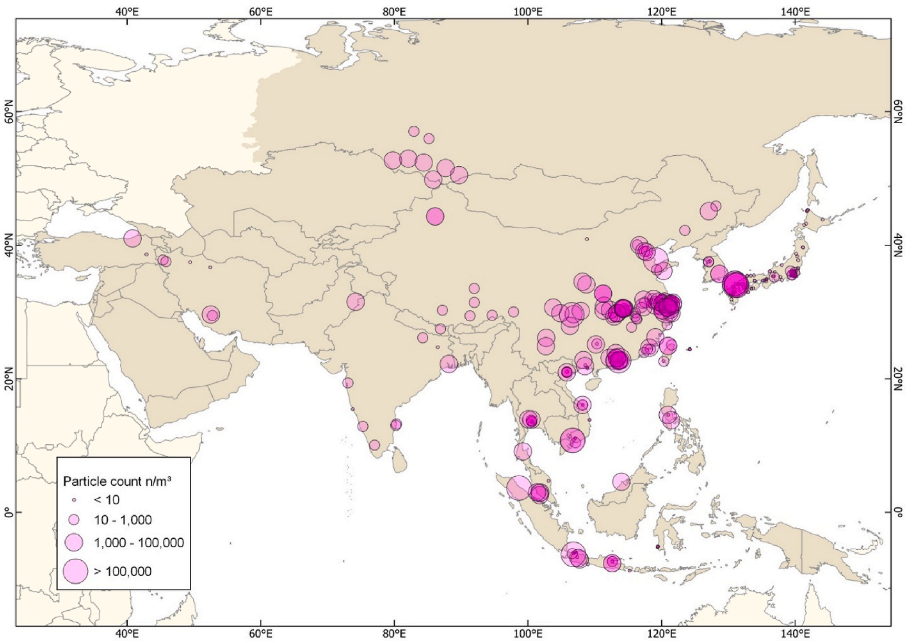

Fig. 7. The water bodies and the concentration of plastic particles per m^3 water.

Table 2
Microplastics studies that cover Asia's 20 longest river systems.

River name	Length [km]	Basin area [km^2]	Countries	Reviewed studies [number]	Surface water MPs [n/m^3]
Yangtze	6,300	1,722,193	China	17	129–125,350
Yellow River	5,464	832,238	China	3	886,000
Mekong	4,909	805,604	China, Myanmar, Laos, Thailand, Cambodia, Vietnam	0	–
Lena	4,294	2,306,743	Russia	0	–
Irtysh	4,248	1,673,470	Mongolia, China, Kazakhstan, Russia	0	–
Brahmaputra River	3,969	1,999,000	China, India, Bangladesh	1	–
Ob	3,650	2,982,493	Russia	1	51.2
Indus River	3,610	1,081,718	China, India, Pakistan	1	–
Yenisey	3,487	2.554,388	Mongolia, Russia	0	–
Nizhnyaya Tunguska	2,989	473,000	Russia	0	–
Ganges	2,900	1,200,000	India, Bangladesh	5	0.5–1,111
Yarlung Tsangpo	2,840	241,691	China, India, Bangladesh	0	–
Amur	2,824	1,929,955	Russia, China	0	–
Salween River	2,800	271,888	China, Myanmar, Thailand	0	–
Euphrates	2,760	532,739	Iraq, Syria, Turkey	1	–
Vilyuy	2,650	454,000	Russia	0	–
Amu Darya	2,500	534,739	Afghanistan, Tajikistan, Turkmenistan, Uzbekistan	0	–
Ishim	2,450	189,000	Kazakhstan, Russia	0	–
Ural	2,428	231,000	Kazakhstan, Russia	0	–
Pearl River	2,320	453,700	China, Vietnam	18	0.028–135,100

most common microplastic sizes reported by Asian countries were 500 μm, 1000 μm, and 5000 μm (Fig. 8a). Fibers were the predominant shape in all three river samples, followed by fragments (Fig. 8b). Freshwater systems typically contain a higher number of microplastic fragments/flakes due to their ease of separation by filtration. This disparity may also result from variations in study regions, sampling methods, and microplastic emission sources. Domestic sewage has been identified as a major source of fiber and particle release into the environment (De Falco et al., 2018; Hernandez et al., 2017). Additionally, river washing practices in some regions release clothing fibers and fragments directly into the river water.

The majority of microplastics observed in river water, sediment, and biota samples were colored (Fig. 8b). Transparent microplastics were dominant in water and sediment samples. In contrast, Asian river studies reported the highest percentage of black and blue biota samples. It's important to note that the color of microplastics is not permanent, and bleaching into the environment may occur (Stolte et al., 2015). The use of a wide range of colored plastics in plastic production contributes to the diversity of colors observed. The attractive colors of microplastics may entice plankton, fish, and other organisms to consume them, potentially leading to toxic effects across multiple trophic levels in food chains. However, reporting colors is a new trend, so 44% of microplastics studies in rivers of Asian nations did not include information about the colors of microplastics.

Microplastics found in Asia's rivers encompass various polymer types, including nylon, rayon, polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polyvinyl chloride (PVC), polystyrene (PS), polyether sulfone (PES), and polyethylene (PE) (Fig. 8d). However, in some reports, the identification of polymer types is vaguely described, likely due to limitations in the testing apparatus.

3.8. The microplastic studies in Asian countries

An overview of available microplastics in Asian freshwater systems is

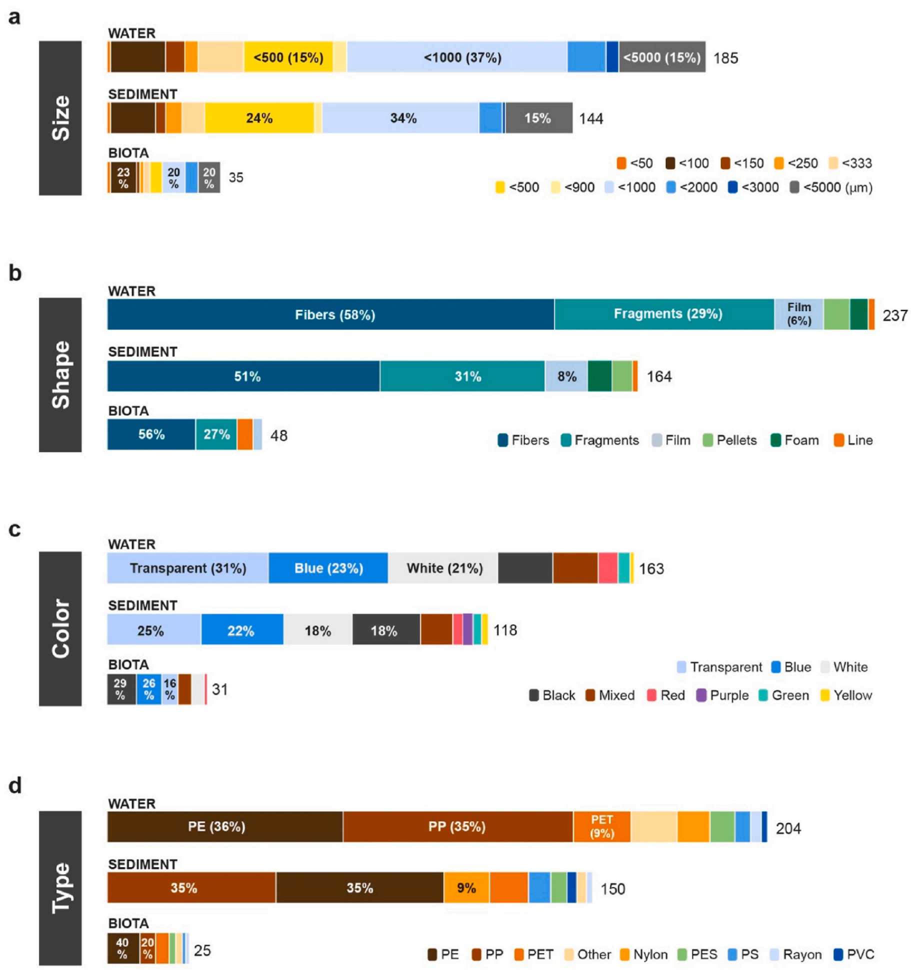

Fig. 8. The most common detected top (a) size, (b) shape, (c) color, and (d) type of microplastics in Asian freshwater bodies. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

given in Table 3.

Rivers represent the majority of the ecosystems studied for microplastics, followed by lakes, estuaries, some lagoons, and wetland areas. China (261 studies) is the top-ranking country in terms of microplastics research, accounts for more than 50% of the reported studies coming from Asia. The rivers Yangtze, Pearl (China), Brantas, Citarum (Indonesia), and Ganges (India & Bangladesh) as well as Pangong Lake and Dongting Lake have all been the subject of extensive research. Most other regions have only reported studies on one or two freshwater ecosystems.

4. Discussion

4.1. Sources of microplastic in Asian rivers

4.1.1. Population density and industrial activities

In general, the presence of microplastics pollution in rivers and other freshwater bodies is closely tied to human activities. Rivers in areas with higher population density, increased urbanization, and elevated levels of industrial and agricultural activities tend to exhibit higher concentrations of microplastics pollution (Talbot and Chang, 2022). This pattern is also evident in numerous Asian countries, as reflected in the studies reviewed in this analysis. For instance, the extensive study of the Yangtze River in China revealed a significant increase in microplastics concentrations near large cities (Xiong et al., 2019; Yuan et al., 2022). Similarly, lakes in China, particularly in the Wuhan region, displayed a comparable trend, with microplastics concentrations rising in lakes closer to the city center (Wang et al., 2017). In India, (Amrutha and Warrier, 2020) demonstrated an increase in microplastics concentrations in the Netravathi River in southern Karnataka near urban areas. Similar trends were observed in the Surabaya River in Indonesia (Lestari et al., 2020), the Nakdong River in South Korea (Eo et al., 2019), the Saigon River in Vietnam (Lahens et al., 2018), the Wu River in Taiwan (Kunz et al., 2023), and in a comprehensive investigation of 29 rivers in Japan (Kataoka et al., 2019). However, not all reviewed studies were able to identify a clear correlation between microplastics concentration and factors such as population density or industrial activities. For instance, Wang et al. (2021) did not observe a relationship between microplastics concentration and land use patterns and human activities in the river network in Shanghai, China. Similarly, results from Wong et al. (2020a) could not establish a correlation between population density and microplastics concentrations in the Tamsui River in Taipei, Taiwan.

It is crucial to note that, even though some studies show associations between microplastics concentrations and population density or industrial activities, the majority of the analyzed studies in this review did not focus on studying relationships between microplastics abundances and anthropogenic factors. Most studies provided information solely about regional microplastics concentrations and particle characteristics in different compartments. Only a few studies, such as Chen et al. (2020b), Kunz et al. (2023), Lahens et al. (2018), Wang et al. (2021), actually focused on investigating the relationship between anthropogenic activities, such as population density, urbanization, land use patterns, and microplastics concentrations in rivers and other freshwater bodies. For

Table 3
Microplastics studies in various countries and their characterization.

No.	Country	Studies	Compartment			Freshwater System					Top Shape	Top Material	Top Colour
			Biota	Sediment	Water	Rivers	Lakes	Estuary	Wetland	Others			
1	China	261	15	113	133	119	83	40	4	9 (5 Canal, 4 Various)	microfiber	PP	Transparent
2	Japan	117	3	7	107	113	-	4	-	-	N/A	N/A	N/A
3	Indonesia	44	11	10	23	36	1	6	-	1 (Lagoon)	Fragment	N/A	N/A
4	Vietnam	21	-	3	18	8	7	2	-	4 (2 Lagoon, 2 Canal)	microfiber	N/A	N/A
5	India	20	1	9	10	17	-	3	-	-	Fragment	PE	Black
6	Thailand	15	2	4	9	10	-	3	-	2 (Lagoon)	Fragment	PP	White
7	Iran	13	2	5	6	5	3	3	2	-	microfiber	N/A	Black
8	Taiwan	13	7	1	5	7	-	6	-	-	microfiber	PE	N/A
9	South Korea	11	3	2	6	11	-	-	-	-	microfiber	PE	N/A
10	Malaysia	10	2	2	6	6	-	4	-	-	microfiber	N/A	N/A
11	Russia	9	1	-	8	3	6	-	-	-	microfiber	N/A	N/A
12	Philippines	7	1	3	3	7	-	-	-	-	microfiber	PE	N/A
13	Turkey	6	3	1	2	2	1	-	-	3 (Ditches)	microfiber	PE	White
14	Bangladesh	3	2	-	1	2	-	1	-	-	microfiber	N/A	Transparent
15	Iraq	2	-	1	1	2	-	-	-	-	microfiber	PE	Transparent
16	Pakistan	2	-	1	1	2	-	-	-	-	Fragment	PE	N/A

future research, there is a need to shift the focus from merely reporting microplastics concentrations towards investigating the relationships between anthropogenic factors and microplastics concentrations in rivers and other freshwater bodies in Asia.

4.1.2. *Textile and apparel industries*

From our review, the most found microplastics in the freshwater are PE, PP, and PET and they were mostly found in fibers or fragment shape as shown in Fig. 8. In Saigon River canal system in Southern Vietnam, 92% synthetic fibers such as PET, PE, PP, rayon, PP-vistalon, viscose and acrylic were found among the anthropogenic fibers. This is closely related to the presence of many textile and apparel industries in Ho Chi Minh City with large amounts of polyester production. On the other hand, the high population density nearby Lich River, Hanoi (Northern Vietnam) where the high release of fibers was noticed, was due to the release of fibers from washing machines. An earlier study by Napper et al. (2021) reported that up to 728,789 fibers could be released from laundering of 6 kg clothes. Interestingly, the release of fibers from synthetic materials (PE and acrylic) was found significantly higher than the PE-cotton blended material.

4.1.3. *Plastic packaging and consumer goods*

Fragment is the second most abundant shape of microplastic found in the freshwater (Fig. 8). In the Philippines, Limbago et al. (2021) also identified a large portion of fragments of PE at the banks and channels of Molawins River. Similar findings were reported in rivers in northern (Wong et al., 2020a) and southern (Chen et al., 2020a) Taiwan. These studies suggested that these fragments originated from the PE plastic bags, degraded from larger plastic materials. According to PlasticsEurope (2021), the plastic demand is the highest in the packaging sector (39.6%). Furthermore, among the plastics, PE consisted of 29.8%, followed by PP with 19.4%. In Pakistan, 250–500 kg of plastic bags are produced daily, and the majority are from the cottage industry. From the country's statistics, around 55 billion plastic shopping bags are consumed every year with a 15% increment per annum (Alvi, 2018). As PE bags are commonly used in the country to carry materials in the market, the inappropriate disposal of the bags will end up in the environment as reported by (Irfan et al., 2020) in their sampling research on Ravi River, Pakistan. For microspheres, they are believed to originate from personal care products such as facial cleaners or body scrubs (Wong et al., 2020b).

4.1.4. *Fishing activities*

In some studies, the number of microplastic fragments was higher than fibers. In the samplings performed in Ob River and Tom River in western Siberia by Frank et al. (2020b), microplastic fragments with irregular shapes consisted of 45.5% of the total plastic counts. The authors believed that the sources of the fragments in Kargasok and Kolpashevo came from fishing activities as the main industry in the areas. A similar assumption was made in another study by Lahens et al. (2018) where intense maritime and boat habitation had imported a significant amount of microplastic fragments into Kenh Te canal in Ho Chi Minh City, Vietnam. Nylon and polyethylene terephthalate (PET) were widely used in the fishing and agricultural industries. They can be released from the fishing activities when fixing fishing tools or from the abandoned nets (Amin et al., 2020). Among the 11 polymers identified by Karaoglu and Gul (2020), nylon and PET were mostly found in the surface water and tadpoles in the Rize province, Turkey. (Kabir et al., 2021) also identified an abundance of nylon 6 fibers in Awano River and they were suspected to originate from ropes used by the agricultural firms in the area. Other than that, microplastics in foam shape are mainly broken from expandable polystyrene products which are normally used in aquaculture industry and disposable tableware (Chen et al., 2020a).

4.1.5. *Wastewater treatment plants*

About 80% of the plastics present in the oceans originates from the terrestrial areas and then makes their ways into the aquatic environment (Li et al., 2018). Other than discharge from the industries, the presence of microplastics in the catchment area and freshwater system also originate from wastewater treatment plants (WWTPs). (Boucher and Friot, 2017) reported that the major land-based source of primary microplastics in marine water was road runoff (66%), followed by treated effluent from WWTPs (25%) and wind transfer (7%). Many studies revealed that discharge from WWTP contained more fiber shaped microplastics, probably originating from the washing machines (Liu et al., 2021). Furthermore, the removed fibers will accumulate in the sludge and end up released into the environment (Cao et al., 2021). On the other hand, without the WWTP facility, large amount of untreated wastewater was discharged, and floating debris was highly visible as noticed in the Kenh Te and Lo Gom canals in the Ho Chi Minh City of Vietnam. Significant reduction of microplastic was observed in Nhieu Loc and Tau Hu canals after rehabilitation, indicating mitigation of microplastic pollution in freshwater systems is possible with proper design of sanitation systems and WWTP (Lahens et al., 2018).

4.1.6. Municipal solid waste

Plastic wastes from municipal solid waste from landfill and unintentional disposal of plastic waste are also sources of microplastics in the freshwater environment. Sarijan et al. (2019) revealed that the presence of rubbish piles near the riverbank contributed to the amount of film and fragment microplastics in Skudai River. Besides, plastic wastes were observed to be discarded from vehicles on the bridge across the river (Sarijan et al., 2019). Eroded tires, fragmented road paint and other plastic wastes are also flushed into gutters from the street (Cheng et al., 2021; Wong et al., 2020a; Zhang et al., 2018). The plastic wastes undergo mechanical abrasion and degradation from weather will break into smaller fragments. These fragments will then release into the leachates or be washed away by rain runoff, and make their ways into the canals, drains or rivers. In South Korea, the highest number of microplastics was noticed during the wet season due to runoff from adjacent areas into Nakdong River. As microplastics are light, they are easily transported and deposited into the catchment areas or freshwater system easily via atmospheric fallout (Cheng et al., 2021). Dris et al. (2015) reported that the atmospheric fallout sampled in Parisian agglomeration mainly consisted of fibres with 29% of synthetic fibres. Similar findings were reported by Cai et al. (2017) that fibre was the dominant shape with 175–313 particles/m^2/day of microplastics were found in the atmospheric fallout in Dongguan city, China.

4.2. Contributions of this study

This review paper was done comprehensively based on a systematic methodology (described in Materials and Methods). All information extracted in this review paper is arranged from a total 50 countries in Asia Region consisting of 228 papers that match the study scope.

For the first time, important information of microplastics studies among the Asian Rivers was extracted and discussed systematically and compared in this study. Notably, we present a comprehensive comparison of microplastics studies, meticulously defining the color, shape, and type of microplastics to understand their distribution within Asian river systems. A key revelation is the identification of China as the leading contributor to microplastic research in Asia, followed by Indonesia and India. Among all studies extracted in Asian Rivers, 38% was conducted by using nets (neuston, plankton, and manta nets) for water sampling and 41% studies have used grab samplers for collecting sediment samples. Besides, biota samples have been collected at least on 25 studies by collecting from local fishermen. Based on the microplastics color, shape and type, white and transparent color are well-distributed the most in eight countries. While fiber shape and PE type was detected in 12 countries including Vietnam, Thailand, and Saudi Arabia. In the MENA (Middle East and North Africa) region, fiber and PE were also found dominant in the samples (Ouda et al., 2021). In conclusion, our research not only affirms the ongoing monitoring of microplastic pollution in the Asian region but also emphasizes the urgent need for further expansion in this field, especially given Asia's substantial plastic production, highlighting the significant risk of environmental contamination, particularly in rivers.

4.3. Research gaps and challenges in microplastics research

The study of microplastics is a rapidly growing field of scientific interest. There is still much to be explored to improve our understanding of the fate of microplastics in the aquatic environment, the potential toxicological impacts of microplastics on ecology at community and population levels, and the relative contribution of anthropogenic activities, fisheries and aquaculture to microplastic pollution. In view of these research gaps, future research needs to address the challenges associated with analytical methods for the recovery of microplastics in various environmental matrices. Although enormous efforts have been made to characterize microplastics in Asian freshwaters, there are still no standardized experimental protocols for identifying and quantifying microplastics in freshwater ecosystems. Therefore, there is an urgent need to standardize analytical methods to allow better quantitative comparison of microplastics in different studies. Among the many analytical methods that have been described in the literature, the most common protocols are filtration, oxidative digestion and spectroscopic confirmation using Fourier Transform Infrared (FTIR) and Raman spectroscopy. Our review also showed that studies from certain countries or regions are missing, including big river systems (Mekong river, Lena river, Irtysh river) and major rivers in Russia. More emphasizes should be put here to obtain the overview and construct strategies for microplastics pollution in Asia.

5. Conclusions

This comprehensive review underscores the critical issue of microplastic pollution in Asian rivers, exacerbated by rapid economic growth and inadequate waste management practices. Through a detailed analysis of 228 studies indexed in the Scopus database, we've witnessed an escalating focus on microplastics research within these environments. The findings reveal a concentration of studies in China, Indonesia, Japan, and India, though significant data gaps exist for numerous other regions and freshwater reservoirs.

Predominantly, microplastics identified in these studies comprise polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET), manifesting mainly as fibers or fragments. A notable challenge highlighted is the diversity of sampling methodologies employed across studies, leading to discrepancies in reporting units and difficulties in comparing results or assessing the efficacy of microplastics extraction methods. This variability complicates the analysis and interpretation of microplastic pollution using existing analytical techniques.

To advance our understanding of microplastics in freshwater systems and their ecological impacts, future research must tackle the current methodological challenges. There is an imperative need to develop and standardize analytical methods to ensure consistency and comparability across studies. Furthermore, expanded research efforts are necessary to elucidate the fate of microplastics in aquatic environments, assess their toxicological effects on ecological communities, and quantify the contributions of human activities, fisheries, and aquaculture to microplastic pollution. Addressing these research gaps is crucial for formulating effective strategies to mitigate microplastic contamination and safeguard freshwater ecosystems in Asia.

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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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