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Review

Riverine Plastic Pollution in Asia: Results from a Bibliometric Assessment

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Abstract: Rivers are important ecosystems, vital to the livelihoods of hundreds of millions of humans and other species. Despite their environmental, social, and economic importance, current use of rivers is unsustainable, due to a combination of solid waste and high levels of pollutants. Plastic materials are among the most predominant of such pollutants. Based on the need for additional research in this area, this study examines pressures put to rivers and explores trends related to riverine plastic pollution, with a focus on Asia. Apart from the bibliometric analysis, and relying on the collected information, examples describing the drivers of riverine plastic pollution in a sample of Asian countries are described, outlining the specific problem and its scope. Among some of the results obtained from it, mention can be made to the fact that much of the literature focuses on plastic pollution as a whole and less on one of its most significant ramifications, namely microplastics. Additionally, there is a need related to data availability on riverine plastic data and improving the understanding of transport mechanisms in relation to riverine plastic emission into the ocean. The results from this study illustrate the significance of the problems posed by plastic waste to Asian rivers and point out the fact that there are still significant gaps in respect of regulations and standards, which prevent improvements that are highlighted in this study. Based on the results of this bibliometric assessment, specific measures via which levels of riverine plastic pollution may be reduced are presented, bringing relevant new insights on this topic beyond the existing reviews.

Keywords: Asia; plastic pollution; rivers; riverine ecosystems; sustainability

1. Introduction: The Many Pressures Posed to Rivers

The significant problems faced by rivers have many different implications. The fact is that reductions in the volume and quality of river water affects the provision of ecosystem services for other dependent species, including recipient lakes and seas. Studies have highlighted that river ecosystems are under threat due to the increasing human pressure [1–3], but the problem continues [4].

The increasing need for water for irrigation of arable land, domestic use, hydropower production, and industries has increased the demand for brackish water resources [5], including river water. More than 20% of the world's river basins have experienced severe impacts due to abstraction of water, changed land use, or declined surface water area, as well as floods over the past 20 years, and several million people, particularly in the developing world, are suffering due to the shortage of water of sufficient quality, which may satisfy their needs for safe drinking water, sanitation, and basic human rights [6]. It has been estimated that 68% of all water withdrawals are used by agriculture, 19% by industries, and 12% by municipalities for households and services [7]. Freshwater withdrawals for irrigation include groundwater that is used in 38% of the total area used for irrigation [8]. Used water that returns to water bodies, including rivers, as treated or untreated municipal and industrial wastewater, and diffuse runoff from agriculture, is often contaminated with chemicals and other compounds. About 48% of globally produced wastewater is still untreated [9]. Moreover, the world's rivers transport up to 2.41 million tons of plastic waste a year to the sea [10].

Rivers have traditionally been valued quite narrowly as providers of some resources, e.g., drinking water, water for irrigation, and fish [11]. The Common International Classification of Ecosystem Services (CICES) version 5.1 that has been developed in the context of work on the System of Environmental and Economic Accounting (SEEA) has identified the paradox when defining ecosystem services, grouped into three major sections, i.e., provisioning, regulating, and cultural, as "the contributions that ecosystems make to human well-being, and distinct from the goods and benefits that people subsequently derive from them" [12] are largely overlooked. Provisioning services of rivers involve water for drinking, material for the production of goods, and flowing water used as an energy source, for fish and aquaculture, as well as for cultivation of aquatic plants for nutrition. The majority of the water used to satisfy human needs for drinking water, for industrial and agricultural goods and products, including for irrigation, comes from rivers [13]. Despite being affected by the COVID-19 pandemic, the hydropower market is expanding, and hydropower accounts for 16.8% of global electricity generation [14]. Moreover, hydro-energy production in most cases requires damming of rivers. AQUASTAT, FAO's Global Information System on Water and Agriculture, estimates the number of dams on earth's rivers to be over 14,000 [15]. The water reservoirs upstream of the dams often cover large surface areas, including agricultural lands and human infrastructures. Water stress, i.e., the ratio of water that is needed and what is available downstream of the dam, is quite high in many regions of the world, particularly during the dry season. Shortage of water could have a severe impact on biota, including fish populations. Given that rivers produce 40% of the world's seafood consumption, any shortage represents a direct threat to food security [16].

Another important service provided by rivers is water flow regulation and control of excess floods. Water residence time largely determines the in-stream biogeochemical processes and recycling of pollutants and depends on hydromorphological characteristics of the river, e.g., relief, floodplains, meandering, availability of healthy wetlands in the catchment, etc. [11]. Increased residence time allows more efficient mediation of pollutants and toxic substances by inorganic chemical and physical processes, as well as organic processes by bio-remediation, filtration, storage, and uptake by microorganisms, algae, and plants [17–20]. The water residence time is partly enhanced by human infrastructures, e.g., dams installed for hydro-energy production or for collecting water during the rainy season, which can have a specific impact on river ecosystems, as described previously. Rivers deliver large quantities of sediments and nutrients that sustain agriculture in delta floodplains. Consequently, rivers provide crucial buffering services for human-induced pollutants that could otherwise reach the recipient lakes or seas. Rivers also provide some direct services for various aquatic plant and animal species by seed dispersal and maintaining habitats [11]. In addition, rivers also sustain suitable conditions for recreation, enjoyment, tourism, and hobby fishing [12], which are mostly underestimated. Furthermore, river landscapes enable intellectual and spiritual interactions, education, and research. Satisfaction of the needs for these cultural services could severely impact the availability of provisioning services, e.g., for good quality bathing water or maintaining habitats for aquatic species.

In 2015, the United Nations agreed upon the Sustainable Development Goals (SDGs) to be achieved by 2030 [21]. One of the goals (Target 6.6) addresses the need to protect the endangered values of waters and rivers, requiring specific policies and management measures. Recent studies point out to "a disproportional contribution of Asian rivers to global plastic emissions" [22]. With the need to protect the threatened services provided by rivers in mind, this study aims to map the peer-reviewed articles published between 2000–2021 with a specific focus on riverine plastic pollution in Asia. This study thus attempts to show how the unsustainable relationship between humans and rivers in the region has been documented so far and report on emerging trends, with a focus on Asia. To achieve it, a bibliometric analysis was employed, alongside a meta-analysis of selected case studies. The second section of this article presents the scope of the unsustainable use of rivers. The third section summarizes the methods used. The fourth section describes the results of the study and its analysis and discussion, whereas the final section presents the conclusions and outlines specific measures that may be implemented in order to address the topic of riverine pollution in Asia and its implications.

2. Unsustainable Use of Rivers in Asia: Plastic Pollution

The significant increase in plastic production and use, which is expected to reach 34 billion metric tons by 2050 [23,24], has become a major environmental issue. Riverine plastic pollution, here defined as the portion of plastic that finds its way to rivers, has evolved to become a global environmental problem, associated with the creation of waste patches across the world's oceans [25].

Plastics found in the rivers can be classified based on their size ranges. According to the classification adopted by the National Oceanic and Atmospheric Administration (NOAA), there are three main size classes provided: micro- (≤5 mm), meso- (5 mm to 2.5 cm), and macroplastic (>2.5 cm) [26]. Macroplastics can be identified either by resin type using the International Resin Identification Coding system (ASTM D7611) or by their functional origin based on the NOAA Technical Memorandum. Table 1 presents the macroplastics classification by type of resin, functional origin, and plastic type.

Table 1. Macroplastics' classification, adapted from Lippiatt, Opfer, and Arthur [26].

Resin	Item	Type
Poly(ethylene terephthalate) (PET)	Beverage bottles, other jugs, or containers	Hard
High-density polyethylene (HDPE)	Bags, other jugs or containers, bottle or container caps, buoys, fishing lures, and baits	Film, hard
Poly(vinyl chloride) (PVC)	Rope floats	Hard
Low-density polyethylene (LDPE)	Bags, cigar tips, 6-pack rings, fishing lures, and baits	Film, hard
Polypropylene (PP)	Food wrappers, bottle or container caps, disposable cigarette lighter, plastic rope/small net pieces, straws	Film, hard
Polystyrene (PS)	Disposable cigarette lighter, floats, cups, plastic utensils	Hard, foam
Other resins	Cigarette filter, balloons	-

Meso- and microplastics are rather complicated to identify by resin type or functional origin because of the smaller size, which obstructs the identification. According to Blettler, et al. [27], meso- and microplastics can be classified into hard plastic fragments, foam, films, and others. For microplastic identification, lines of fibre-type plastic pieces can also be recognized. Furthermore, the number of items, weight, area, volume, length, and colour are important properties that can be recorded for detailed identification of meso- and microplastic pieces found in rivers and oceans. Some of the most important sources of environmental pollution involving microplastics are:

- Plastic pellets;
- Synthetic textiles (abrasion and shedding during laundry);
- Abrasion of tires while driving;
- Weathering and abrasion by vehicles of road markings;
- Weathering of ship marine coatings.

Additionally, the fragmentation of larger plastic objects after the dispersion in the environment should be considered. In addition, microscopic particles of polymers are often components of personal care products (plastic microbeads can be used as ingredients in personal care and cosmetic products for a variety of purposes), resulting in the direct introduction of the plastic particles into wastewater streams from households, hotels, hospitals, and sports facilities [28].

As emphasized by Andersen [29], the Executive Director of the UN Environment Programme, plastic pollution in surface water, as well as in seas and oceans, poses one of the greatest problems and challenges to life on the Earth. Global marine plastic pollution has received a lot of interest lately, and studies confirm that river plastic pollution has a significant negative impact on the environment and human health (see citations in van Emmerik and Schwarz [30]), as well as contributing to pollution in the oceans. In the recent study by Nelms, et al. [31], fishing gear-related debris was documented as causing a significant threat to biodiversity in one of the world's largest plastic pollution contributing river catchments, the Ganges.

Asian rivers are highly polluted with plastics, which increases the mortality of aquatic animals through entanglement and microplastic ingestion. Macro- and microplastics also contaminate seafood, increase water turbidity, render freshwater unfit for human consumption, contributes to seawater pollution, and causes water stagnation and floods in urban areas, which is a condition that favours the breeding of harmful pests and insects, such as mosquitoes [32,33]. Factors that cause riverine plastic pollution include improper waste management, unsustainable human attitudes of dumping plastic in rivers and waterways, proximity of cities to rivers, the presence of dams and litter traps, seasonality of rainfall, river discharge, and floods [34]. For instance, the presence of microplastics has been detected, originating mainly from wastewater effluents in the case of the Pearl River [35].

Malaysia, Indonesia, Thailand, and Vietnam are among the top 10 countries in the world that release the most plastics to surface water bodies. According to the van Calcar and van Emmerik [34] study, rivers in Indonesia and Vietnam comprise up to fourfold more plastic than those in some European countries in terms of plastic items per hour. Variations in cultures, economic development, educational levels, and enforcement of environmental regulations are the likely causes of the differences. Six of the eight rivers studied in these Southeast Asian countries collectively contain 7100 plastic items/hr, compared to only 250 items/h found in the rivers in France, Italy, and The Netherlands, combined. For example, the Ciliwung River located in the Java region of Indonesia ranked the most polluted by microplastics as measured in total observed items (2000 floating items/h). Concerning the composition of plastics found in the rivers in the Southeast Asian countries, soft polyolefin (POsoft) is the most dominant, averaging 37%, with Indonesian rivers having the highest percentage. For the two rivers studied in Vietnam, expanded polystyrene plastic (EPS) constitutes 30% to 55%. The hard polyolefin (POhard) and EPS contribute to about 10% of plastics found in Malaysian rivers and one river in Vietnam and Indonesia.

Overall, polystyrene (PS) and polyethylene terephthalate (PET) were found in rivers but in little proportions.

In Indonesia, high population densities in coastline regions, plus improper waste disposal, have been attributed to a high level of riverine pollution. For example, the Ciliwung River in Jakarta is among the most polluted rivers in the country [33]. Among the most abundant plastic particles, fragments, fibres, and films are the shapes that are more frequently found in Indonesian rivers. The country is sited on an area significant for global marine biodiversity that is very vulnerable to the negative impacts of plastic pollution. The Indonesian government set an ambitious target of reducing plastic waste by 70% by 2025. In order to achieve the set target, the government established the National Action Plan for Marine Debris Management 2018–2025.

In India, residents treat rivers like open drains by directly discharging solid waste, including plastics, into them. For example, the rivers Ganges (861,452 km^2), Mithi (68,839 km^2), Sabarmati (21,674 km^2), and Yamuna (366,323 km^2) are considered sacred and contain significant biodiversity. However, these rivers, covering 4272 km and passing through major urban centres, such as Delhi, Mumbai, and Ahmedabad, are highly contaminated by plastics and organic wastes, chemicals, and sewage [36]. These cause waterlogging damage to the ecosystem and deteriorate water quality, thereby rendering them unfit for human consumption, with substantial risks to those dependent on rivers' public health and livelihoods. For example, in July 2005, prolonged plastic disposal into the Mithi River resulted in waterlogging and floods in Mumbai city, especially around the airport. In addition, according to Chakraborty [32], during daily religious practice and annual events, such as the Hindu Idols immersion, substantial quantities of plastic idols, flowers, and polyethylene bags are released into rivers. These plastic substances pose a significant threat to the structure and function of the river ecosystem by undermining its agricultural, recreational, aesthetic, and household functions, therefore impacting the SDGs.

Recent estimates of microplastics amount in the world ocean are 93 to 268,000 tons [37,38]. However, microplastics have been found also in freshwaters [39] and drinking water [40]. Adverse impacts of microplastics on aquatic living organisms due to impaired reproduction, malnutrition, internal abrasions, and blockages have been demonstrated [41–43], and adverse human health impacts have also been identified [44]. Considering the high surface area and hydrophobicity of their surfaces, microplastics can act as sorbents for other environmental pollutants, persistent organic pollutants [45], hydrocarbons [46], pharmaceuticals [47], and other pollutants [48]. Sorption of pollutants, if the particles enter the living body, is one of the microplastics' toxicity mechanisms [43].

3. Materials and Methods

In order to explore trends in plastic riverine pollution in Asia, a bibliometric methodological approach was applied, further allowing an investigation into a set of examples illustrating the problem under study.

Bibliometric analysis is useful to summarize the status of scientific literature in a given period and area, as well as to present trends in the growth of publications, leading authors, and the main journals and countries exploring the topics in the investigation. The database Web of Science (WoS) was used to perform the search, as it represents an important and relevant source for scientific search analyses [49,50].

The search string was composed of terms associated with plastic pollution and riverine contexts, based on Kasavan, et al. [51], and contained reference to Asia and a list of Asian countries among the 20 countries with the highest numbers of mismanaged plastic waste worldwide [52], as presented in Table 2.

Table 2. Search string and selection criteria.

Search String	((“plastic pollution” OR “plastic contamination” OR “plastic debris”) AND (“coastal” OR “freshwater” OR “river” OR “riverine” OR “estuary” OR “stream” OR “inland water” OR “continental water” OR “creek” OR “brook”) AND (“Asia” OR “Asian Countries” OR “Indonesia” OR “China” OR “Thailand” OR “Philippines” OR “Vietnam” OR “India” OR “Sri Lanka” OR “Malaysia” OR “Pakistan” OR “Burma” OR “Myanmar” OR “North Korea”))
Timespan	2000–2021
Language	English
Search	Topic (title, abstract, and keywords)

All results were screened (title, abstract, and keywords) to remove articles not related to the scope of this investigation. The final set of articles (*n* = 281) was then analysed through research assessment and science mapping [51]. For the research assessment, the investigation included growth pattern by year, most productive journals, and main categories in the WoS database. The science mapping was performed with the support of the VOSviewer software and investigated keyword co-occurrences and co-authorships. Results of the term co-occurrence analysis are shown as a combination of nodes and links. Node size is proportional to the frequency of co-occurrence of a term with other terms, and link strength is proportional to the strength of connections between two terms. Terms that have co-occurred more frequently form clusters that indicate thematic focus areas.

In addition to term co-occurrence analysis, VOSviewer and its co-citation analysis were used to identify the most influential journals, authors, and institutions. Co-citation refers to the connection between two documents that are simultaneously cited by another document. Additionally, bibliographic coupling refers to the “link between two items that both cite the same document” [53].

Subsequently, the mapping outcomes (through publication clusters) were applied to classify the set of collected examples from the literature, which illustrate the rivers mostly affected by plastic pollution in the Asian countries sampled. These describe trends in the amount of plastic pollution, allowing to list some of the concerns related to the studied rivers.

4. Results and Discussion

4.1. Research Assessment and Science Mapping

This section presents both the research assessment and the science mapping performed through the use of the VOSviewer software. The mapping is organized in two subsections: main thematic areas and the most influential journals, authors, and institutions.

4.1.1. Research Assessment

Figure 1 shows the trends in publication growth around plastic riverine pollution in Asia in the analysed period (2000–2021). The first article appeared only in 2010, published in *Biodiversity and Conservation*, on “Impacts of pollution on marine life in Southeast Asia” [54]. Between 2012 and 2014, no publications were recorded, based on the keywords used in this study. However, since then, exponential growth was observed. Over 75% of all publications of the last decade are concentrated in the last three years. Figure 1 also illustrates the number of publications per year of the top five most productive journals, with expressive representation and growth of the *Marine Pollution Bulletin* and the *Science of the Total Environment*. Together, these journals have published 58% of all publications of the period: *Marine Pollution Bulletin* (*n* = 58, 21%), *Science of the Total Environment* (*n* = 55, 20%), *Environmental Pollution* (*n* = 29, 10%), *Chemosphere* (*n* = 12, 4%), and *Environmental Science and Pollution Research* (*n* = 8, 3%). As far as the publication (WoS) categories are concerned, Environmental Sciences applies to 94% of the published studies (*n* = 236), followed by 26% under Marine Freshwater Biology (*n* = 73). The other three categories among the most common ones are Environmental Engineering (n = 26, 9%), Water Resources (n = 19, 7%), and Multidisciplinary Sciences (n = 13, 5%).

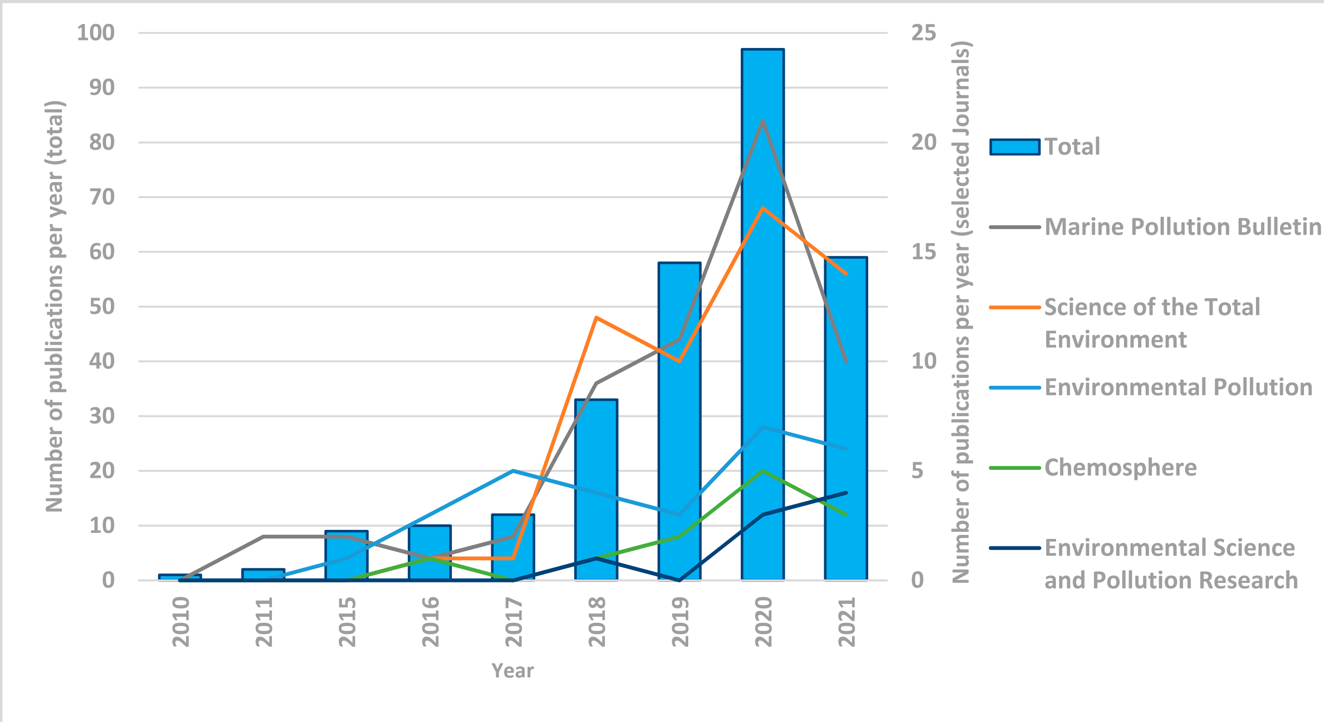

Figure 1. Number and percentage of publications per year in the last decade (total and most productive journals).

Regarding the number of citations per analysed article, Table 3 summarizes the top 10 most cited publications. In total, the set of 281 articles had 11,398 citations to date, and 89% of these happened between 2019 and 2021. Of those 10 publications, six are in the most productive journals (four in *Environmental Pollution* and two in *Science of the Total Environment*), and all have Impact Factors of over 7000, with the highest being *Nature Geoscience* and *Nature Communications* (16,908 and 14,919, respectively).

The most cited study is "Microplastics in freshwater systems: A review of the emerging threats, identification of knowledge gaps, and prioritization of research needs" from Eerkes-Medrano, Thompson, and Aldridge [40], published as a review in *Water Research*. It explores the topic of microplastics in freshwater systems to present knowledge gaps and future study opportunities and support policy and management decisions.

The second most cited study is also the one with the highest average number of citations per year (160.2), published by Lebreton, Van der Zwet, Damsteeg, Slat, Andrady, and Reisser [10] in *Nature Communications*. With a total of 801 citations to date, "River plastic emissions to the world's oceans" indicates "a global model of plastic inputs from rivers into oceans based on waste management, population density, and hydrological information". The findings also point out that the most polluting rivers are located in Asia.

Completing the top 3 most cited studies is the review "Distribution and importance of microplastics in the marine environment: A review of the sources, fate, effects, and potential solutions", published in *Environment International* by Auta, Emenike, and Fauziah [55]. With 584 citations in total and an average of 116.8 per year, it discusses the distribution of microplastics in oceans around the globe, as well as the main transportation routes and sources, and proposes possible solutions to microplastic pollution.

Table 3. The top 10 most cited publications.

Title	Reference	Source	Year	Total Citations	Average per Year
Microplastics in freshwater systems: A review of the emerging threats, identification of knowledge gaps, and prioritization of research needs	Eerkes-Medrano, Thompson and Aldridge [40]	Water Research	2015	832	118.86
River plastic emissions to the world's oceans	Lebreton, Van der Zwet, Damsteeg, Slat, Andrady and Reisser [10]	Nature Communications	2017	801	160.2
Distribution and importance of microplastics in the marine environment: A review of the sources, fate, effects, and potential solutions	Auta, et al. [55]	Environment International	2017	584	116.8
Microplastics in Taihu Lake, China	Su, et al. [56]	Environmental Pollution	2016	339	56.5
Atmospheric transport and deposition of microplastics in a remote mountain catchment	Allen, et al. [57]	Nature Geoscience	2019	297	99
Microplastics pollution in inland freshwaters of China: A case study in urban surface waters of Wuhan, China	Wang, et al. [58]	Science of the Total Environment	2017	277	55.4
Microplastics and mesoplastics in fish from coastal and fresh waters of China	Jabeen, et al. [59]	Environmental Pollution	2017	270	54
Microplastic in three urban estuaries, China	Zhao, et al. [60]	Environmental Pollution	2015	252	36
Microplastics in sediments of the Changjiang Estuary, China	Peng, et al. [61]	Environmental Pollution	2017	236	47.2
Microplastics in surface waters and sediments of the Three Gorges Reservoir, China	Di and Wang [62]	Science of the Total Environment	2018	215	53.75

Interestingly, 9 out of these top 10 cited articles cover the topic of microplastics, having this important keyword in the title. Of these, six refer to case studies in China [56,58–62].

4.1.2. Science Mapping

Plastics are considered to represent about 50% to 80% of marine litter [63]. While the most contaminated plastic rivers are in Asia [22], only a small percentage of studies address the continent. This is a concern, specifically when considering that the world's main inland fisheries are found in Asian rivers. Furthermore, studies have mostly been focusing on marine ecosystems, and there is an urgent need to increase the knowledge on freshwater systems. Most freshwater studies have been carried out in Europe and North America [27,34,64,65], and van Calcar and van Emmerik [34] claim to have published the first study providing a transcontinental overview of plastic transport, underlining that Asian rivers transport more plastics towards the ocean (Asian rivers studied transport almost 30 times more macroplastics than the European rivers studied). As a result, substantial amounts of plastic debris are found in the Pacific region [66].

The outputs of the term co-occurrence analysis are presented in Figure 2 and allow for insights into the main thematic areas (clusters) of the analysed publications. Three major clusters can be observed (shown in red, green, and blue). The biggest ones, in red and green, cover a wide range of terms and have similar contexts, supporting the overall picture of plastic riverine pollution in Asia portrayed in the second section. The analysis of the clusters in Figure 2 also allows for the identification of different publication trends: while the red cluster seems to have a focus slightly directed towards environmental pollution and its aspects, e.g., contamination, debris, and impact, the green cluster covers more physical aspects/zones and transportation routes, e.g., particles, sediments, and surface waters. The smaller cluster, in blue, has terms that also directly connect with microplastics, referring to their ingestion by aquatic species, e.g., zooplankton, ingestion, and demersal fish [67–69]. The national focus on China has been the subject of several publications, as highlighted by terms associated with the region in the co-occurrence map (Bohai Sea, Yellow Sea, and Pearl River, among others) [70,71].

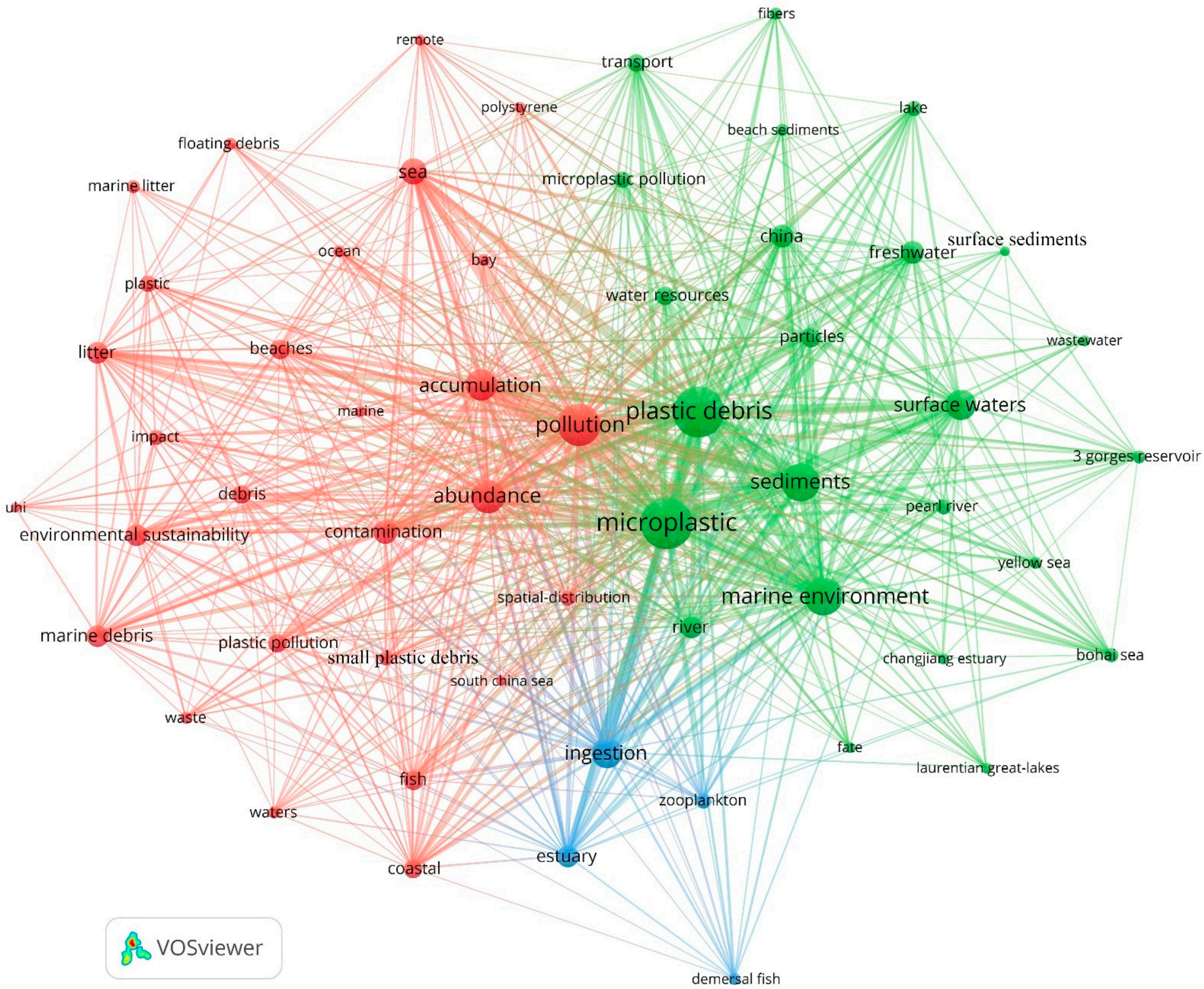

Figure 2. Co-occurrence analysis on terms associated with plastic pollution and riverine contexts in Asia (Derived from VOSviewer).

Among the central terms in the co-occurrence map in Figure 2 are microplastic and accumulation, which are important outcomes of the analysis because these terms were not originally included in the search string. The aspect of accumulation covers mostly the increase of plastic waste/debris in specific spatial zones [72–75] but also the bioaccumulation in fauna [76,77]. Microplastics are extensively studied in the set of analysed articles, representing an important research focus on matters related to plastic waste and management strategies. Most studies focus on investigating the occurrence and distribution of microplastics in riverine regions [78], especially in China [35], but in other Asian countries as well, such as Vietnam [63], India [79], Thailand [80], the Philippines [81], and Malaysia [82].

Regarding the most influential journals, Figure 3 presents the results of the co-citation analysis and groups the journals that have been most frequently cited together in the analysed articles. Three clusters were identified based on the frequency of co-citation: Cluster 1 (red), with 21 journals (including *Marine Pollution Bulletin and Science*), with profiles dedicated to the physical sciences of plastic pollution; Cluster 2 (green), with 19 journals (including *Environmental Pollution*, *Environmental Science & Technology* and *Science of the Total*

Environment), with varied profiles within the Environmental Sciences; and Cluster 3 (blue), with *Archives of Environmental Contamination and Toxicology* and *Environmental Research*, both with strong characteristics of multidisciplinarity. By correlating these results with those previously presented in Figure 1, it is observed that the three most productive journals are also most frequently cited together (*Marine Pollution Bulletin*, *Science of the Total Environment*, *Environmental Pollution*). Although *Environmental Science & Technology* is not among the top five most productive journals, the co-citation analysis has shown that it has a central role among the other sources.

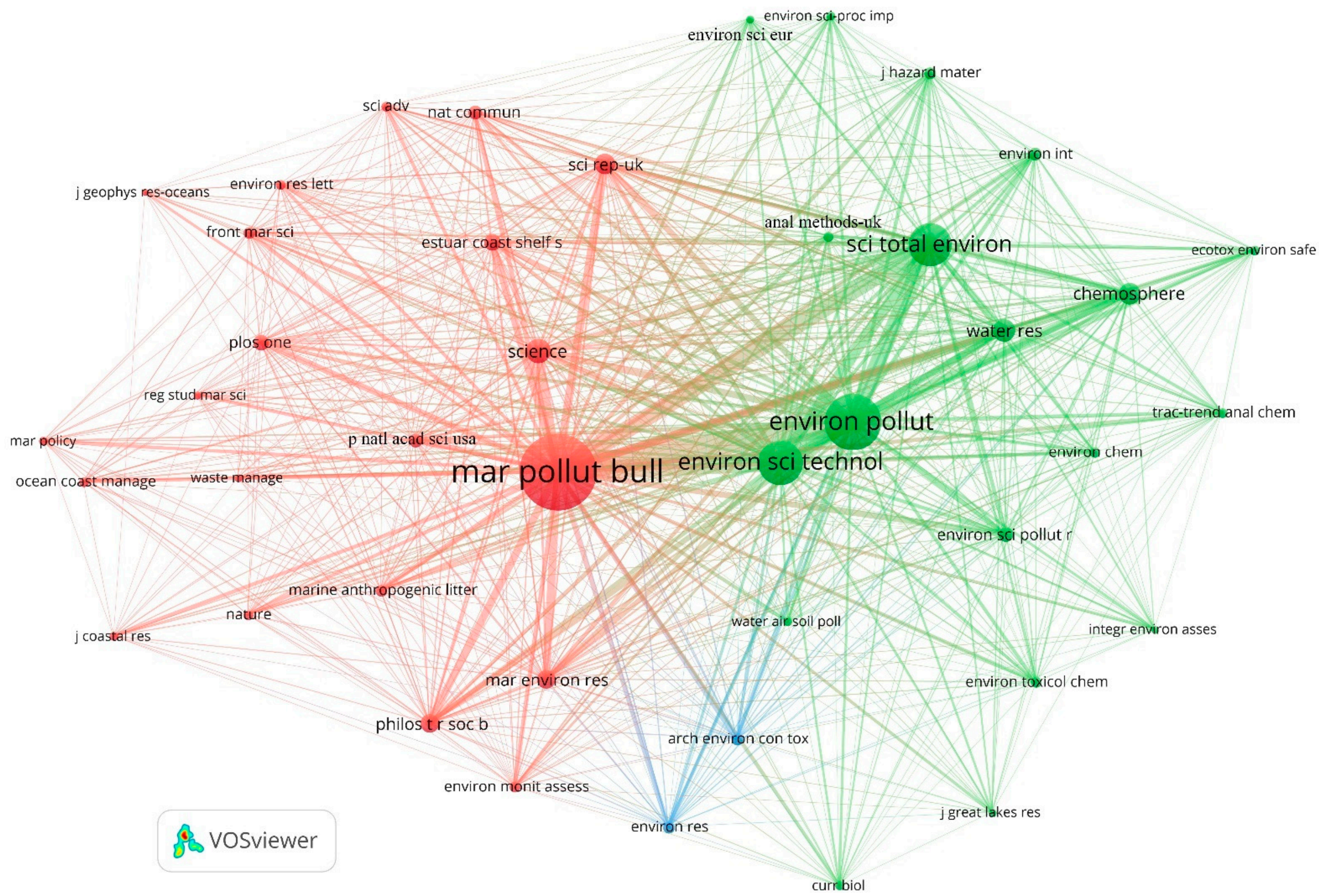

Figure 3. Main publication sources.

4.2. Examples of Riverine Plastic Pollution Resulting from the Literature

4.2.1. The Emerging Topic of Riverine Pollution

The top 20 polluting rivers in the world represented 67% of the global annual river input. In total, 103 out of 122 top polluting rivers are located in Asia [34]. Asia alone represents 86% of the annual global plastic inputs from rivers into the ocean; therefore, Asia is a hotspot and a major emitter of global plastic pollution [83]. A set of examples illustrating riverine pollution are presented in this section. They aim to illustrate the topics that have been addressed in terms of concern in studies involving pollution in Asian rivers. The selection was based on three WoS search strings, including the terms “plastic debris”, “Asia”, and “river”; “plastic pollution”, “Asia”, and “river”, and finally “riverine plastic pollution” and “Asia” in the topic. For each example, the cross-cutting issues are presented, ending with the studies’ identified concerns, actions, insights, and/or gaps. Accordingly, Table 4 summarizes the addressed topics, cross-cutting issues, scope, and authors for the 15 selected articles, focusing on plastic pollution in Asian Rivers at various levels of analysis, as shown below.

Although recent, plastic pollution is an increasing environmental problem worldwide, with a particular emphasis on marine systems, the persistence of plastic at sea [10], and its spread globally to remote habitats [40,55,84], which have various adverse consequences to biota and human life [10,85]. Particles with less than 5 mm, called microplastics, are becoming a huge problem, also due to high density and interaction with organisms [40,64,80,83,85,86], particularly in Europe, North America, and Asia [40,78,87]. According to the study of van Wijnen, Ragas, and Kroeze [78], the fragmentation of poorly managed plastic waste, i.e., macroplastics, is the main source of microplastics. Alongside climate change, plastic debris is considered an emerging issue affecting biodiversity in the near future [83]. In water systems, it mainly originates from land activities [34,88], also due to poor waste management practices [10,55,63,86]. The presence of microplastics in the marine environment [25] impacts oceans, lakes, seas, rivers, coastal areas, and even the Polar Regions [84]. They are easily ingested by microorganisms, being accumulated in tissues, the circulatory system, and the brain [55].

According to Strokal, et al. [89], it is necessary to further develop multi-pollutant models at the global scale, intending to improve the water quality assessment and to better identify these risks. Lebreton, Van der Zwet, Damsteeg, Slat, Andrady, and Reisser [10] also emphasize the need to standardize methodologies. The connection between policy and science [90] through participatory modelling and scenario analysis will contribute to a better assessment of global water quality issues [89]. It is crucial to create public, private, and government-based sector awareness through education, intending to reduce the entry of microplastics, in particular, into the environment [55,90] and to encourage consumers to use alternatives [91]. The focus on studying the most polluted rivers, particularly in countries with rapid economic development and poor waste management is essential [10,27,78]. Finnegan and Gouramanis [65] show that when projecting waste loss scenarios between 2000 and 2030, the biggest single decreases of microplastics are observed with plastic bags representing the largest plastic-type. This illustrates the importance of the consequences of consumption trends to the environment.

4.2.2. The Need for a Comprehensive Monitoring of Plastic Fate

The Meijer, van Emmerik, van der Ent, Schmidt, and Lebreton [22] model shows that countries with a relatively small land surface area, compared to the length of their coastline, and with high precipitation rates, are likely to emit more plastics. Accordingly, Asian countries with similar mismanaged plastic waste (MPW) concentrations contribute different riverine plastic emissions depending on their geographical and climatological conditions. For example, China generates 12.8 million metric tons (MT) per year of MPW, over 10 times more than Malaysia (0.8 million MT/year). However, the fraction of total plastic waste reaching the rivers is 9% in Malaysia, but only 0.6% in China. Using this model, the study identified the Philippines (356,371 MT/year in 4820 rivers, 8.8% of the total generated MPW in the country) as the largest country with plastically polluted rivers. The subsequent Asian countries are India (126,513 MT/year, 1% of total generated MPW in 1169 rivers), Malaysia (73,098 MT/year in 1070 rivers), and China (70,707 MT/year in 1309 rivers).

Several of the SDGs are linked to the conditions of rivers, and their maintenance depends on their flows, water quality, and the general environment. Although there may be concerted efforts by relevant authorities in addressing river pollution in the region, there are still significant gaps within the areas of regulations and standards, which are herewith highlighted, identified in Table 4:

- The urgent need for more long-term monitoring efforts on plastic debris across Europe and Asian rivers [34];
- The need to improve riverine plastic data availability and improve the understanding of transport mechanisms in relation to riverine plastic emission into the ocean [88];
- The concentrations of microplastics in the marine environment, as seen in East Asian seas around Japan [55];

- Policy measures aimed at decreasing or reducing plastic pollution resulting from river export of microplastics from land to sea and the marine environment [78];
- The flow of plastic towards the ocean, which accounts for 67% of the global total, covering 2.2% of the continental surface area and representing 21% of the global population [10];
- Microplastics contamination in fish [80];
- Potential risks of microplastics for humans and biota and high levels of microplastics found in the water and sediments of the Chao Phraya River [85];
- The urgent need for global conservation actions and policy initiatives;
- The alarming rate of microplastics pollution in major freshwaters over Asia [64];
- The need to assess microplastics' impacts on ecosystem services.

However, in highlighting the gaps and fostering an effective approach for sustainable river use:

- There is more need for dedicated monitoring efforts of plastics in water systems (micro and macro plastics);
- Presence of plastics in water has a wide range of potential harms on the environment, and many of these are not yet well understood;
- Plastic emissions from Asia are severe and are larger than from other continents;
- Large-scale, collaborative action is needed to reduce plastic emissions into waters.

Additionally, it is possible to restore the ecosystem to a level that can be seen to be an asset rather than a liability and can thus provide attractive and safe river areas for recreation. This can be achieved by involving the public, stakeholders, and waste management companies [55].

4.2.3. Selected Studies Addressing Riverine Pollution in Asia

The study has allowed to identify a wide range of case studies addressing riverine pollution in Asia. A selection of relevant ones is outlined in Table 4.

The 15 case studies' alarming worries are broad and they contribute to understanding why, along with climate change, plastic litter is regarded as an emerging issue that will impact the planet's biodiversity in the near future, being critical for continuing to develop global multi-pollutant models in order to improve water quality assessment and better detect plastic pollution, as well as standardizing procedures. Through interactive modelling and scenario analysis, policy and research together will assist and support decision-making processes and mitigate plastic pollution.

Table 4. A total of 15 selected studies addressing riverine pollution in Asia (sorted by publication year).

Topic	Cross-Cutting Issues	Scope	Reference
Microplastics in freshwater systems	Microplastics are being detected in Asia Identified gaps: § optimal methodology for microplastics monitoring in water systems § quantification of microplastics presence, abundance, and distribution § study microplastics lifetime and fate § assess river potential as a microplastic source to oceans § assess microplastics interactions with biota § assess microplastics impact on ecosystem services § assess microplastics impact on humans	Lake Hovsgol, Mongolia	Eerkes-Medrano, Thompson and Aldridge [40]

Table 4. *Cont.*

Topic	Cross-Cutting Issues	Scope	Reference
Microplastics in the marine environment	Concentrations of microplastics total particle of about 1.72 million pieces km^{-2} (10 times greater than in the North Pacific and 27 times greater than in the world oceans) Identified concerns/actions: § the degree of ingestion by marine biota is associated with the hazard represented to the entire ecosystem § microplastics reduce recreational, aesthetic, and heritage environmental value § microplastic reduction cannot take place without involving the public, stakeholders, and waste management companies § microplastics degradation by microorganisms is a promising sustainable environmental option in favour of contaminated environments	East Asian seas around Japan	Auta, Emenike and Fauziah [55]
River plastic flow towards the oceans	The top 20 polluting rivers, mostly located in Asia, account for 67% of the global total, covering 2.2% of the continental surface area and representing 21% of the global population. 103 out of 122 top polluting rivers are located in Asia. Asian rivers represented 86% of the total global estimated plastic releases. 1.15 to 2.41 million tonnes of plastic currently flow from the global riverine system into the oceans every year, with 74% of emissions occurring between May and October. Identified concerns/gaps: § most of the river plastic pollution comes from Asia § besides rivers, plastics also enter the oceans through direct littering near beaches, followed by tidal or wind transport § plastic sources, deposition, and degradation processes need further study § the seasonality of inputs needs systematic sampling § standardization of methodologies and units necessary across assessments § plastics need to be categorized into classes (e.g., polymer types, debris sizes) § studies should focus on mass estimates rather than numbers of particles per units of volume (or surface area) § weight is critical to compare estimates with plastic production statistics § physical and geological characterization of plastic loads will refine estimates § monitoring and mitigation efforts must focus on Asian countries, particularly those with rapid economic development and weak waste management	Global	Lebreton, Van der Zwet, Damsteeg, Slat, Andrady and Reisser [10]
Freshwater plastic pollution	Holistic vision of plastic pollution within freshwater ecosystems. Identified concerns/actions: § the major inland fisheries of the world are located in Asia's plastics-polluted rivers § to estimate river plastic emissions to the world's oceans, the field-data bases about plastics (all size fractions) in freshwater environments need to be increased § although representing a significant input in terms of plastics weight, macroplastics data from most polluted and larger rivers are extremely scarce § the potential damage caused by macroplastics on a wide range of freshwater fauna remains undetermined § studies addressing the presence of plastic debris in freshwater environments are scarce § even if it cannot be assumed that freshwater ecosystems are unaffected by macro-debris, studies addressing microplastics largely exceed those addressing macroplastics § monitoring efforts in most polluted rivers worldwide, with particular emphasis in countries with rapid economic development and poor waste management	Global	Blettler, Abrial, Khan, Sivri and Espinola [27]

Table 4. *Cont.*

Topic	Cross-Cutting Issues	Scope	Reference
Global Pattern of Microplastics	Sea salt as an indicator of seawater microplastics pollution. Identified concerns/innovation: § monitoring of seawater, sediments, and organisms show high microplastics extent in Asia § inconsistencies in measurement and sampling make it difficult to identify microplastics geographical distribution § seawater monitoring is financially expensive and labour intensive and has limitations relating to the mesh size (>300 µm) of the nets used § microplastics in salt differ with the brand but are particularly high in Asian countries § commercially sea salt is an indicator of microplastic pollution in the surrounding seawater environment unless filtered	16 countries/ regions on six continents	Kim, Lee, Kim and Kim [83]
Macroplastic and microplastic contamination assessment	Assessment of a tropical river. Identified concerns/actions: § microplastic and microplastic contamination identified in Saigon River § land-based macroplastics seem to be related to local habits and waste management § high concentrations of microplastics in surface waters are related to textile and plastics industries and paucity of wastewater treatment in Vietnam	Saigon river (Vietnam)	Lahens, Strady, Kieu-Le, Dris, Boukerma, Rinnert, Gasperi and Tassin [63]
Ecotoxicological Risk Assessment of Microplastics	Comparison of available hazard and exposure data in freshwaters. Identified concerns/gaps: § ecological risk due to microplastics cannot be excluded in Asia § lower cut-offs when sampling microplastics and more secondary microplastics testing for ecotoxicity are needed to obtain better results § improved microplastics quantifying analytical methods will allow excluding non-validated methods § to reduce the amounts of particles released into freshwater, better waste and wastewater management is necessary	Asia, Europe, and North America	Adam, Yang and Nowack [86]
Global multi-pollutant modelling of water quality	Challenges and future directions in water quality modelling. Identified concerns/actions: § there is a limited understanding of interactions of pollutants in rivers at the larger scale § global water quality studies often focus on individual pollutants and water quality assessments are largely incomplete in many world regions, preventing the formulation of effective solutions § multi-pollutant modelling for comprehensive water quality assessments at the global scale should include analyses of hotspots with multiple pollutants (e.g., plastic debris, nutrients, chemicals), causes and solutions § to better understand how pollutants interact bio-geochemically in rivers further research is needed § better link the results of multi-pollutant river modelling with water scarcity or risk assessments, is needed § policy and science need to be interconnected through participatory modelling and scenario analysis	Global	Strokal, Spanier, Kroeze, Koelmans, Florke, Franssen, Hofstra, Langan, Tang, van Vliet, Wada, Wang, van Wijnen and Williams [89]
Plastic debris across Europe and Asian rivers	Plastic pollution as an urgent global environmental challenge Identified concerns/insights: § urgent need for more long-term monitoring efforts § accurate data on riverine plastic debris considered to be crucial to improve global and local modelling § the studied Asian rivers transport almost 30 times more macroplastics than the studied European rivers § first transcontinental overview of plastic transport showing Asian rivers to transport more plastics towards the ocean § further study necessary on riverine plastic pollution hotspots in West Africa, Central America, China, India, and the Philippines	Europe and Asian rivers	van Calcar and van Emmerik [34]
Riverine plastic emission from Jakarta into the ocean	Plastic emission into the ocean. Identified concerns/insights: § macroplastics in Jakarta consists of films and foils, reflecting the consumption trends § 2.1×10^3 tonnes of plastic waste are transported from land to sea annually, representing 3% of the total annual disposed plastic waste in Jakarta, with the majority being discarded through drains of the Pesanggrahan and Ciliwung rivers § riverine plastic data availability must increase to improve understanding of transport mechanisms	Jakarta (Indonesia)	van Emmerik, Loozen, van Oeveren, Buschman and Prinsen [88]

Table 4. *Cont.*

Topic	Cross-Cutting Issues	Scope	Reference
Modelling global river export of microplastics to the marine environment	River export of microplastics from land to sea. Identified concerns/insights: § the fragmentation of microplastics is the main source of microplastics § collection, processing, and recycling of plastic waste and by wastewater treatment optimization are needed to reduce microplastics export to the seas § policy measures leading to a decreased use of plastics will contribute to further reduce plastic pollution § combating microplastics in the aquatic environment requires additional region-specific analyses	Global	van Wijnen, Ragas and Kroeze [78]
Microplastics ingestion by freshwater fish	Microplastics contamination in fish Identified concerns: § fishing nets and fish cages are major sources of microplastic contaminants in the Chi river § microplastics ingested by fish in the Chi River indicate middle-level contamination	Chi river (Thailand)	Kasamesiri and Thaimuangphol [80]
Microplastic contamination on the lower Chao Phraya	Microplastics abundance in Chao Phraya river Identified concerns: § high levels of microplastics found in the water and sediments of the Chao Phraya river § high concentration of Pb and Cu heavy metals found adsorbed on microplastics § potential risks of microplastics for humans and biota	Chao Phraya river (Thailand)	Ta and Babel [85]
Freshwater fish health assessment posed by microplastics	Toxicokinetic/toxicodynamic-based risk assessment framework Identified concerns/actions: § alarming microplastics pollution in major freshwaters over Asia § microplastics pollution to likely enhance fish health risk due to metabolic disturbances § urgent need for global conservation actions and policy initiatives § toxicokinetic/toxicodynamic-based risk assessment important to support decision-making processes and to mitigate microplastic pollution benefiting freshwater	Global	Chen, Lu, Yang and Liao [64]
Plastic waste loss scenarios between 2000 and 2030	Plastic waste loss projection scenarios (2000–2030) Identified concerns/actions: § freshwater plastic pollution critically understudied in Southeast Asia § policy interventions can reduce microplastics up to 76% between 2021 and 2030 § in the scenarios presented, the biggest single decreases of microplastics are observed with plastic bags representing the largest plastic type	Largest freshwater-lake system in Southeast Asia	Finnegan and Gouramanis [65]

5. Conclusions

This study aimed at describing the problems associated with plastic pollution in rivers, illustrating the scope and seriousness of this problem, specifically in Asia. World rivers and its water quality are essential for the existence of humans and more-than-humans, considering river water significance for drinking water supply, agriculture, and industry, as well as supporting aquatic ecosystems and aquatic and terrestrial biodiversity. However, the various types of waste reaching rivers, especially plastic waste, impair river water quality and negatively influence their ability to provide healthy ecosystem services. These impacts are most significant for densely populated parts of Asia, where the levels of riverine plastic pollution are among the highest in the world, as clearly demonstrated through this extensive bibliometrics assessment.

The bibliometric analysis has confirmed the exponential growth in publications related to plastic riverine pollution in Asia. Nine out of 10 of the most cited articles cover the topic of microplastics, and case studies in China, a major pollutant contributing country, are also dominant in the list. When it comes to the main areas covered by the literature, as shown by the co-occurrence analysis, the main clusters refer to environmental pollution (e.g., contamination, debris, impact), physical aspects/zones, transportation routes (e.g., particles, sediments, surface waters), and impacts of microplastics.

The alarming concerns raised by the 15 selected case studies are extensive and help us to understand that, together with climate change, plastic debris is considered an emergent issue affecting the planet's biodiversity in the near future. It is essential to further develop multi-pollutant models at a global scale, to improve water quality assessment and better identify the risks posed by plastic pollution, as well as standardize methodologies, relying on accurate data. The integration of policy and science through interactive modelling and scenario analysis will aid in the evaluation of this issue.

This study has some limitations. First, the bibliometric analysis focused on the literature on plastic pollution, without further in-depth assessment of other solid waste contaminants. Secondly, the case studies only report a set of relevant polluting rivers, a small sample of the many rivers affected by pollution caused by plastics. Despite these constraints, this study provides relevant new insights and perspective beyond the available existing reviews, gathering and documenting a comprehensive set of data and evidence, which shows the extent to which Asian riverine ecosystems are being influenced by plastic pollution.

In terms of practical implications, the present study on plastic pollution in Asian rivers stresses how crucial it is to create public, private, and government-based sectors to promote awareness through education, aiming to reduce the entry of plastics into the environment, especially stressing the risks posed by the impacts of microplastics in the affected ecosystems. Additionally, since the existing plastic pollution is already of alarming magnitude, dedicated efforts should be made to foster effective waste removal, which has direct implications in riverine plastic pollution. While different technologies have been proposed for extraction under various conditions and targeting different types of waste, the coming years will show the efficacy of some of these technologies and reveal whether there is a need for additional approaches. Further research is needed on how to foster changes in consumption trends and how to optimize waste management approaches, centring on the recovery, reuse, and recycling and at the same time stressing the need for innovation in the area of development of new plastic materials from renewable resources.

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