A Nature Portfolio journal

https://doi.org/10.1038/s43247-025-02320-2

Quantitative assessment on the distribution patterns of microplastics in global inland waters

Check for updates

Xia Jin¹, Zimin Li $\mathbb{O}^{2,3}$, Josep Peñuelas $\mathbb{O}^{4,5}$, Jordi Sardan $\mathbb{O}^{4,5}$, Qiqian Wu⁶, Yan Peng¹, Petr Heděnec⁷, Zhijie Li⁸, Chaoxiang Yuan¹, Ji Yuan¹, Zihao Chen \mathbb{O}^{1} , Zemin Zhao¹, Fuzhong Wu $\mathbb{O}^{1,9}$ & Kai Yue $\mathbb{O}^{1,9}$

Microplastics (MPs) contamination in global inland waters has raised concerns recently. However, quantitative research on the abundance of MP in these environments remains limited. Here we compiled a comprehensive dataset of MPs in global inland waters from 5365 observations across 301 publications, revealing a diverse distribution of MP abundance in inland waters, ranging from 0.00 to 4,275,800.70 items m⁻³ (mean: 25,255.47 \pm 132,808.40 items m⁻³). Human development index, evapotranspiration, cropland, and land surface runoff emerged as the primary factors influencing MPs levels in water. The predicting map showed particularly high MP abundance in China, but also relatively high abundance in Asia, Europe, Africa, and the eastern United States. Urgent action is needed to monitor and manage MPs in inland waters, especially the small-sized MPs (<1 mm). Implementing effective strategies to regulate plastic production and waste management is imperative for protecting freshwater ecosystems, particularly in countries with high MP pollution.

Human activities have triggered a series of critical environmental problems, one of which is plastic pollution. Microplastics (MPs), defined as small pieces and particles of plastic less than 5 mm in diameter¹, were first reported in inland waters of Lake Huron², Rhine River³, and Three Gorges Dam⁴ in 2011 and 2015, respectively. Since 2014, more studies have reported the distribution of MPs in global inland waters^{5–10}. These MPs, with diverse characteristics of colors, shapes, sizes, and polymer types, enter inland waters through runoff, sewage discharge, and atmospheric deposition^{11,12}.

MPs are extremely mobile in aquatic environments due to their properties of lightweight, insolubility, and durability¹³, making them easily ingested by aquatic animals. Consequently, animals may suffer from choking or starvation due to pseudo-satiety¹⁴. Smaller MPs readily accumulate through food chains, causing bioenrichment that results in reduced hatching rates, impaired growth, behavioral disruptions, and changed feeding preferences¹⁵. Additionally, MPs can adsorb pollutants such as heavy metals¹⁶, polycyclic aromatic hydrocarbons, and polychlorinated biphenyls¹⁷. Moreover, many substances added during plastic production,

such as pigments, stabilizers, and plasticizers, can continuously release toxic or even carcinogenic additives¹⁸.

Inland waters are vital for human living and the development of industry and agriculture. However, rivers are known to transport MPs from terrestrial to marine ecosystems. Lebreton et al.¹⁹ reported that the 122 polluting rivers contributed more than 90% of total plastic inputs to the ocean¹⁹. Moreover, during the long process of transportation, some MPs are intercepted on riverbanks, while many MPs remain submerged in water, affecting the health of aquatic environments²⁰. The MPs in lakes and reservoirs have also received considerable attention²¹. Due to their relatively closed characteristics, lakes also act as important sinks for MPs. Yet they can also become significant sources of MPs once being disturbed by environmental factors, such as wind exposure, and facilitate the transport of MPs to the outlet²². Artificial barriers such as dams and weirs also play a significant role in intercepting plastic into the ocean in freshwater bodies¹⁹.

MPs in inland waters have diverse potential sinks, including discharge into the sea through rivers¹⁹, deposition on riparian soils²³, and settling in sediments²⁴, or ingestion by aquatic organisms²⁵. Being a significant sink for

¹Key Laboratory for Humid Subtropical Eco-Geographical Processes of the Ministry of Education, School of Geographical Sciences, Fujian Normal University, Fuzhou, China. ²State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, China. ³National Observation and Research Station of Earth Critical Zone on the Loess Plateau of Shaanxi, Xi'an, PR China. ⁴CREAF, Cerdanyola del Vallès, Spain. ⁵CSIC, Global Ecology Unit, CREAF-CSIC-UAB, Cerdanyola del Vallès, Spain. ⁶State Key Laboratory of Subtropical Silviculture, Zhejiang A & F University, Lin'an, China. ⁷Institute of Tropical Biodiversity and Sustainable Development, University Malaysia Terengganu, Kuala Nerus, Malaysia. ⁸School of Computing, Clemson University, Clemson, USA. ⁹Fujian Sanming Forest Ecosystem National Observation and Research Station, Fujian Normal University, Sanming, China. MPs, sediments can reflect historical inputs of plastic wastes²⁶. However, MPs in sediments are prone to resuspension once influenced by hydraulic conditions and climate factors^{27,28}, thereby being released into surface water. Activities of leaching, bioturbation, and cultivation in soils may influence the migration of MPs, while this process is exceedingly slow^{29,30}. Indeed, the process of MPs deposition on riparian soils is not unidirectional. As earlier evidence suggests, water-driven soil erosion has been indicated to promote the immigration of MPs from cultivated land soils to freshwater³¹. Another study on MPs transport from headwaters to the estuary of the Yangtze River Basin also suggests that the immigration of MPs in the watershed is more pronounced in water rather than in soils or sediments³². Consequently, the complicated behaviors of MPs between water and riverine sediments and soils in freshwater ecosystems lead to greater harm to long-time transportation in freshwater systems.

Experiential settings, such as sampling methods, extraction, and purification methods, are the dominant factor to determine the MPs detection in the water, followed by the human and environmental factors³³. A previous study has indicated that there is no significant difference in MP abundance between grab sample with 0.45 μ m filter and net sample with 100 μ m mesh¹⁸. Yet, a meta-analysis has divided sampling methods into volume-reduced and bulk sample categories, with the volume-reduced samples overlooking smaller-sized MPs than the bulk samples³³. Human activities, such as industrial, agricultural, washing, road usage, fishing, and wastewater treatment plants³⁴⁻³⁸, are often direct sources of MPs, increasing their abundance in inland waters. Additionally, agricultural activities, such as plastic mulching, may produce MPs in the soil³⁹. MPs could move in soils affected by soil erosion, and the input of plant processes as well as various animals³⁹, and may also be exported to freshwater systems through irrigation or stormwater runoff^{18,34,40}. Natural environmental factors, such as the hydrology of rivers with climate variability, play significant roles in affecting MPs dispersal in the water. Inherent properties of MPs, including the density, size, shape, and polymer type, can also influence their transportation and distribution patterns in aquatic environments⁴¹.

Although many studies have examined MPs in inland waters, most focus on specific locations or review global freshwater data about sampling methods, presence, and impacts^{12,42–47}. Only a few studies have assessed MP abundance in water globally^{48,49}. Since the definition of MPs pollution is only recently proposed, the limitation that MP pollution goes unreported in some areas leads to a lack of knowledge about the global spatial distribution of MP abundance in inland waters⁴⁹. A recent review study⁴⁹ summarized the MP pollution in global freshwater systems including river, lake, estuary, and wetland, but it mainly focused on the global efforts, knowledge gaps, and research priorities for MP monitoring, providing limited information on the spatial distribution and the associated driving factors of MPs in global inland waters. Machine learning, an essential technique in ecology, has the potential to establish models and predict global distributions^{50,51}. Here, we present a comprehensive meta-analysis of MP distributions, characteristics, influencing factors, and predicting maps for MP abundance in global inland waters and China. Given that China is the world's largest producer of plastic materials, it was imperative to explore MP abundance in inland waters within the country and apply machine learning to understand MPs distribution in other unstudied regions. Our research addresses several research questions, including the identification of MP research hotspots, the most significant factors influencing MP abundance, and regional differences in MP abundance across predicting maps. We, thus, aim to provide the understanding and predicting MP distribution that can be used to prioritize efforts to mitigate MP concentration, especially the smaller particles, in global inland waters.

Results

Distribution and characteristics of microplastics in global inland waters

The number of articles reporting MP contamination in inland waters has steadily increased since 2014, particularly from 2018 to 2021 (Fig. 1b), indicating the growing concerns about MP pollution in these environments.

The abundance of MPs in global inland waters varied from 0.00 to 4,275,800.70 items m^{-3} , with an average of 25,255.47 ± 132,808.40 items m^{-3} (mean ± standard deviation). We found significant differences between the tools used to capture MPs, as demonstrated by the pump > grab > net (p < 0.001) (Fig. 1c, see Note S1 for details of tools), while different chemistry reagents had no significant effects on detection results of MPs (Fig. S3). Higher sampling volumes led to smaller MP abundance for grab and pump sampling, and filtering size and sieving size only significantly affected MP abundance under pump sampling, showing that the smaller size leads to higher MPs abundance (Table S3). Interestingly, our analysis revealed no significant difference in MP abundance among different ecosystems (p = 0.13) (Fig. 1d), whereas it presented that MP abundance in dry season was higher significantly than wet season (p < 0.001) and that in autumn was higher significantly than other seasons (p < 0.001) (Fig. 1e). Additionally, our results indicated that MP abundance was higher at the depths of 0.00 to 0.50 m compared to 0.50 to 55.00 m (Fig. S4).

Regarding the colors of MPs, transparent, black, and blue were the most prevalent in global inland waters, with mean values accounting for 29.27%, 9.21%, and 8.02%, respectively (Fig. 2a). In terms of shape, fibers, fragments, and films comprised 38.25%, 13.28%, and 3.84%, respectively (Fig. 2b). Small-sized MPs (≤ 1 mm) constituted a significant proportion of 63.72% in inland waters (Fig. 2c). Moreover, the most prevalent polymers in the waters were polyester (PE), polypropylene (PP), and polyethylene terephthalate (PT), accounting for 15.90%, 13.90%, and 5.10%, respectively (Fig. 2d).

Drivers of microplastics in global inland waters

Our analysis using random forest showed a satisfactory prediction of MP abundance in global inland waters, explaining 86% of the variation in MPs concentration across all observations (Fig. 3a). The model identified the human development index (HDI), actual evapotranspiration (AET), potential evapotranspiration (PET), cropland extent, and land surface runoff (LSR), each of which accounted for 26.18%, 21.22%, 17.27%, 19.08%, and 16.24% of the variation of MP abundance of global predicting model (R^2 : 0.86, RMSE: 1.24), respectively (Fig. 3b). The partial dependence plots showed the non-liner relationship between variables and MP abundance (Fig. 3c–g).

Prediction of microplastics in inland waters of globe

The global predicting map revealed the regions with high MP abundance in Asia, Europe, Africa, and eastern United States (Figs. 4a, S6). In particular, the high MP abundance was predicted for China (Fig. 4a). MP pollution was lower near the Arctic Circle (Fig. 4a). MP pollution was more severe in the Northern Hemisphere, primarily concentrated between 10°N and 50°N (Fig. 4b). According to the predicting map of three sampling methods, we basically found that although there were similar trends overall, there were some differences (Figs. 57, S8). The prediction map for China indicated the highest values in central, eastern, and northwestern regions, especially in the estuary of the Yellow River (Fig. S9).

Discussion

Distributions and characteristics of microplastics in global inland waters

The study provides comprehensive and more recent insights into the extent and distribution of MP pollution in global inland waters. This finding highlights significant MP contamination in spatial distribution on a global scale based on machine learning. In comparison to global marine environments where MP abundance ranges from 0.01 to 660,000.00 items m⁻³ with an average of 20,463.30 ± 98,346.24 items m⁻³ (mean ± standard deviation)⁵², our study suggested that the average MP abundance in global inland waters was higher. Given receiving MPs from terrestrial environment and acted as conduits for MPs to the marine environment, freshwaters represent the most complex system referred to MPs transport and retention⁵³. MP behavior in freshwater depends on their properties (size, shape, density) and environmental factors (water chemistry, flow



Fig. 1 | **The microplastics (MPs) distribution of our database derived from 301 publications including 5365 observations. a** Locations of samples for MPs published in inland waters. **b** The dynamic diagram of article published year or sampling year. **c** Abundance distribution of MPs under different sampling methods. Effects of **d** ecosystem type and **e** different seasons on MP abundance in inland

waters. In the boxplot (**c**–**e**), black points are the estimated values using liner mixed-effect model. Different lowercase letters indicate significant difference among characteristics of MPs at 0.05 level. The same as below. ***p < 0.001; ns not significant.



Fig. 2 | Characteristics of microplastics (MPs) in our database. Distribution of a color, b shape, c size, d polymer of MPs in the global inland waters. In which we classify white into transparent, pellet into granular, and liner into fiber. ***p < 0.001.

conditions, UV exposure), which together control sinking, aggregation, and transport⁵⁴, ultimately prolonging MP retention in freshwater ecosystems. The average MP abundance reported by Schmidt et al.⁵⁵ for global rivers (37,659.70 particles 1000 m⁻³; standard deviation = 272,998.10; including



Fig. 3 | **Results of the predicted microplastics (MPs) based on random forest. a** Comparison of predicted and observed MPs abundance in inland waters after log transformation (the grey dashed line indicates the 1:1 line and the blue line indicates the regression line between predicted and observed values). **b** The relative importance of predictors in the model. **c**-**g** Partial dependence plots showing the dependence of MPs abundance in the global inland waters on predictors after log transformation (Blue lines presented the smooth curve fitted by LOESS regression). HDI human development index, AET actual evapotranspiration, PET potential evapotranspiration, LSR land surface runoff.

zero values) differs markedly (five orders of magnitude) from our data, in part because their study relied on literature prior to April 2017. Yet many articles related to MP pollution in inland waters were published between 2017 and 2024 (Fig. 1b). In addition, other ecosystem types (e.g., lake, wetland) also have higher pollution of MPs in the water^{49,56,57}. Therefore, considering an exhaustive data collection can significantly elevate the MP pollution level in the inland waters.

In fact, the efficiency of the sampling and processing methods can affect the abundance of MPs measured in inland waters. Pump and grab sampling were observed to be more effective than net collection, the results of which are consistent with the study of Zhao et al.⁴⁹. In terms of net sampling, net with 330 µm mesh was the popular approach to collect the top water samples¹², due to the lower size boundary of MPs of 333 µm suggested by National Oceanic and Atmospheric Administration of USA⁵⁸. Net sampling with a greater mesh size always leads to the omission of smaller MPs, underestimating MP pollution in aquatic environments⁵⁹. Lozano and Mouat (2009) found that using an 80 µm mesh yielded results 100,000 times higher than those obtained with a 450 µm mesh when concentrating water samples⁶⁰. Compared with net sampling, the filter meshes of grab (pore sizes mainly ranging from 0.20 to 200 µm, accounted for 77.42% of the grab samples in our database) and pump (pore sizes mainly ranging from 0.45 to 75 µm, accounted for 65.77% of the pump samples in our database) were smaller and can retain more MPs. However, pump sampling has a larger sampling water volumes and deeper sampling depth compared to grab sampling, which may contribute to the improved efficiency results. A study suggested that compared to plankton nets with 75 µm mesh, pump sampling with 25 µm mesh was regarded as an overvaluation of MP abundance resulting from lesser water volumes and accelerating water flow⁶¹. Despite that the smaller filtering size significantly improves the capture ability of MPs in water, especially for pump sampling, but it should be carefully considered that the blockages by zooplankton and algae can also occur⁶². A previous review has indicated that 60-90 µm mesh size is recommended to obtain samples for grab and pump sampling⁶². Lower volumes result in larger orders of magnitude for MP abundance values in pump or grab collections, being consistent with previous studies⁶³⁻⁶⁵. Consequently, sampling volumes should be large enough to minimize overestimation decreased by scaling up results⁶⁴. Large volume sampling (at least 500 liters) is recommended for the grab sampling to effectively assess the prevalence of MP in surface water⁶⁶, while 1000 liters was regarded as the adapt volumes for pump sampling⁶⁴. Unlike previous studies reporting the main method in net sampling^{12,49}, our study indicated that the grab sampling (3353



Fig. 4 | **Predicted map of microplastics (MPs) in inland waters based on random forest. a** Global prediction map of MP abundance, and **b** latitudinal pattern of MP abundance (red line indicates the locally weighted regressions and yellow ribbon spans the range between the 5% and 95% quantiles). The predicted value was the average value of the results of 100 iterations of random forest model. Predicting MP

abundance after log transformation was reserved to draw the map to avoid skewed distribution of the MPs values, while the values of the map need to log-transformed and then added to 1 for viewing. The spatial resolution of grid cells was 3 arcmin-by-3 arcmin.

observations from 188 publications) had dominated the database, the analytical results of which demonstrate the importance of data updating and set the stage for the next step in global prediction. Consequently, our findings support that future research should use the grab sampling with larger volumes (at least 500 liters) and a $60-90 \,\mu\text{m}$ mesh size. This is because the grab sampling is more common in freshwater samples and easier for the individual comparisons across regions, while the pump sampling is largely dependent on sampling volumes and filter pore size, leading to an overestimation.

Contrary to our assumption, the abundance of MPs in inland waters during the dry season was higher than in the wet season. This effect may be attributed to a combination of various factors, such as hydroclimate, hydrodynamic factors, land-use types, MP properties, and sampling times. Among these factors, the frequency and intensity of rainfall may have continually changed the MPs level in water. Early in the wet season, rainfall may result in flush event to transport MPs from land to the aquatic environment⁶⁷ or re-suspend and transport river bottom MPs caused by fast water flow⁶⁸, resulting in the higher MP abundance in this period. With the extended rainy season, MPs in waters may be diluted or washed downstream through increasing river water volume in the wet season^{69,70}, especially after heavy rainstorm events37,71-73, leading to more than input of plastic waste from surface runoff. As being evidenced by Cheung et al.74, MP abundance in waters under a storm event dropped significantly within just two hours⁷⁴. Additionally, compared to high precipitation in the wet season, reducing river flow and low velocity in the dry season may decrease the river water volume (i.e., surface-water area ratio to be smaller), resulting in a higher amount of MPs in the surface water⁷⁰. Physical characteristics of MPs (e.g., size, shape, and density) also contributed to MPs with smaller size to remain in the surface water during periods of low flow⁷⁵. Noteworthily, landuse types are dominant in MP pollution. Fan et al. has demonstrated that seasonal differences in MP abundance in an urban river network could be explained by the combined effect of the urban plastic production and regional precipitation⁷¹. Industrials and urban areas are higher producers of plastic production, where impervious surfaces could contribute to the formation of surface runoff and aid MPs from diverse sources (including point and nonpoint pollution) in the region to the aquatic environment during rainfall periods^{76,77}, resulting in the higher accumulation of MPs. The MP abundance in urban water bodies during dry season may also be higher than that in the wet season, which is related to the point source associated with domestic and industrial land uses (e.g., direct dumping of waste, domestic sewage effluent)78,79.

The abundance of small-sized MPs (<1 mm) tends to increase, as larger plastic waste undergoes the weathering⁸⁰. Our results revealed that the small-sized MPs constituted an average proportion of 64% in global inland waters, which can pose greater harm, including facilitating their translocation in aquatic organism tissues^{81,82}, delayed development of nauplii to cyprids⁸³ and even caused acute inflammation of human blood cells⁸⁴. Being similar to marine environments, fibers and fragments were the predominant shapes of MPs in inland waters⁵². The shape of MPs can be indicative of their parent material, with fibers, for instance, primarily originating from textiles and related to washing processes⁸⁵. Besides, fibers and fragments may be generally more dangerous than other shapes of MPs. It is worth that fibers of MPs pose greater dangers to Ceriodaphnia dubia compared to beads⁸⁶. Fragmentation processes change surface features such as cracks, fractures, scratches, pits, and grooves⁸⁷, resulting in exacerbating biofouling processes and further influencing particle distribution and pollution in the waters. The colors of MPs may originate from their parent plastic products, but the differences in colors can also arise from processes such as solar radiation, microbial degradation, and mechanical forces⁸⁸. Additionally, different colors of MPs may be ingested by different fish species³⁸. Polyester (PE), polypropylene (PP), and polyethylene terephthalate (PT) were the most prevalent polymers in the waters, largely because of their widespread use in packaging, pipes, agricultural film, fishing gears, electronic appliances, and other applications⁸⁹.

Divers of microplastics abundance in global inland waters

Human activities (open dumping, unreasonable waste management, sewage discharge, landfill, and agricultural activities, etc.) dominate the generation and emission of MPs. Climatic factors such as temperature, precipitation, evaporation, and land surface runoff affect the distribution of MPs in inland waters. Being consistent with our hypothesis, HDI indeed acts as the most important driver to influence the MP abundance in inland waters.

The HDI represents crucial aspect of development, including education, economy, and health⁹⁰. The non-liner relationship between HDI and MP abundance indicated that the higher HDI did not mean richer MP abundance in their countries. In other words, HDI is an indispensable but not absolute driver to explain abundance of MPs in freshwater. Areas with higher development and plastic consumption tend to have higher MP abundance. Additionally, unreasonable and disturbed plastic managements and the lack of environmental awareness among the public are another important reason⁹¹, such as poorly managed waste treatment plants (WWTP)^{12,92}. Some countries have a higher HDI, such as Britain and Canada (both with average HDI values exceeding 0.80)⁹⁰, while the predictions revealed that the abundance of MPs in these regions ranked in the middle or lower range on our prediction map. These countries took strong action to ban the production of cosmetics containing plastic beads in 2017 and 2018⁴². Despite of the United States with high HDI values, few regions still have revealed higher MP production. Higher population density and urbanization in the eastern United States are more direct input sources of MPs. Indeed, it is estimated that the 110 million people living within 50 km of the Unite State coasts can produce 0.1 million metric tons of plastic litter to the nation surface waters each year⁹³. Noteworthily, tire wear particles are the major contributor of MPs in urban land use⁹⁴. It is reported that the United State emitted an estimated 1,797,480 metric tons of tire wear and tear annually, resulting in a per capita emission rate of 4.70 kg per year and ranking as the largest contributor of tire wear and tear globally³⁵. However, early strict policies on MPs in some cities of the United State have appropriately mitigated pollution. For example, California (revealing lower MPs prediction abundance) banned use of the plastic bags in 2007 and California also became the first state to ban plastic bag related to retail stores in the entire state in 2014⁹⁵.

Evapotranspiration is related to diverse climate variables such as surface temperature, ultraviolet radiation, and precipitation. Raising air temperature leading to one of nonnegligible results is increasing of freshwater evaporation⁹⁶, giving birth to the enlargement of MP concentration in the water. Temperature is also considered as an influencing factor of the bacterial diversity on plastic debris, as it alters the average growth rate of biofilm⁹⁷, then affecting biodegradation progress of MPs. Chang et al.⁴⁸ has also reported that global warming is projected to potentially increase MP abundance and alter the share of small-size MPs by impacting on evaporation, precipitation patterns, and ultraviolet radiation intensity⁴⁸. Additionally, the change of temperature and precipitation may also disturb adsorption between MPs with sediments or other pollutants and then impact the MP concentration in surface water.

In general, the MP abundance in water showed a decreasing trend with the increase of land surface runoff (mainly including urban runoff, industrial runoff and agriculture runoff), supporting our previous statement that dilution of MPs with heavy rainfall in water bodies might be greater than the input of plastic waste from land surface runoff. Urban runoff is the great contributor of MPs transfer to aquatic environments⁹⁸, and the larger potential cause is the poor plastic waste management⁹⁹. Additionally, urban land has the greater potential to product wear-derived MPs particles, which are easily transported into aquatic water from roadsides and stormwater runoff⁹⁴. Indeed, treated or untreated industrial runoff including effluent of WWTP are the importance pathway for MPs, as being early demonstrated¹⁰⁰. In the agricultural areas, biosolids and compost, wastewater irrigation, mulching film, polymer-based fertilizer and pesticides, and atmospheric deposition are the sources of MPs in agricultural soils¹⁰¹, then entering surface water through stormwater runoff or irrigation. Among them, plastic mulching, sewage sludge, and application of fertilizers and

compost are the main sources of MPs in agricultural soils³⁹, and runoff in storm events have been regarded as the important channel of MPs into surface water^{18,34}. It is reported that 1.44 million metric tons of plastic mulch in China are used to contribute to increase the crop yield, the remaining plastic mulch in soils of which varies from 7190 to 25,910 kg·km⁻²⁴⁷, and partly can be transported into aquatic water through runoff. Besides, approximately 50% of sewage sludge in Europe and North America was utilized as economical fertilizer on farmlands, contributing to an influx of up to 850 tons of MPs per million inhabitants into European agricultural soils¹⁰². Zhang et al.¹⁰³ found that the content of MPs in soil was significantly higher after adding sludge compost every year¹⁰³, while another study reported that in Germany alone, approximately 0.035-2.20 trillion MPs are added to agricultural soil through organic fertilizer annually¹⁰⁴. Although irrigation has been shown to intensify differences in MPs between different compartments, leading to a significant difference of MP abundance in surface water which is significantly higher after irrigation than before irrigation. This migration process also occurs through runoff⁴⁰.

Global patterns of microplastics in inland waters

Being consistent with our hypothesis, the variation of global patterns of MP abundance in inland waters was clearly presented, especially in Asia. This contrasting distribution variation in global inland waters was attributed to the high demand and production of plastics and the poor management of plastic waste, especially in underdeveloped or developing countries. Indeed, the production and consumption of plastics, particularly in packaging, building, and construction applications, significantly contribute to global plastics production, therefore leading to their pollution in terrestrial and aquatic ecosystems. As recently estimated, 6.10 Mt of plastic waste will maintain for decades to leak into the ocean even if not improving the ability to manage waste in the future¹⁰⁵.

Our findings clearly illustrate that Asia was a dominant region regulating the global patterns of MP abundance in inland water. This corresponds with the previous study of Lebreton et al.¹⁹, analytically estimating that plastic releases from Aisa rivers accounted for 86% of the total global input, and followed by Africa¹⁹. Lin et al.¹⁰⁶ have also evidenced the high MPs abundance of rivers within some Asia countries, exceeding 10,000 items m^{-3106} . Asia is home to about 60% of the world's population due to about 30% of Earth's total land area, while nearly most of them are developing countries, experiencing rapid development and simultaneously facing growing environmental problems¹⁰⁷. Consequently, plastic production in Asia has been at a high level, accounting for 52% of the world's total production in 2021 (390.70 million tonnes)⁸⁹. Especially, the recycling rate of plastic waste in these developing countries is much lower than that of developed countries. Meanwhile, these developing countries usually have a high percentage of mismanaged plastic waste, 12 Asian countries (China, Indonesia, and Philippines ranked the top three) of which had ranked by the mass of mismanaged plastic waste among the top 20 countries for 201093.

China plays a substantial role in the global plastics market, accounting for approximately 32% of total world production in 2021⁸⁹. Despite playing an important role in the production of the world, the per capita consumption in China is low. According to the reports from 2014, the per capita consumption in China was 45 kg, comparing to 65 and 109 kg per person in Europe and the United States¹⁰⁸. However, poor waste management in China may be a key reason, leading to a considerable amount of plastic waste, especially in the form of widely used packaging plastics⁴⁷. Compared to the western regions, the eastern regions of China generally have higher population density because of faster social and economic improvement¹⁰⁹. This disparity results in more sources and opportunities for plastic production and leakage into the environment in the eastern regions, leading to higher MP abundance. The lower section of Yellow River was the most prosperous region in ancient China, and its catchment goes through rapid urbanization, industrialization and agricultural activities recent decades^{110,111}. Additionally, natural processes in rivers, such as turbulent diffusion and MPs resuspension, can transfer the resuspended MPs from

sediment to surface water, contributing to MP abundance in water bodies^{92,112}, these processes of which may be more pronounced in the Yellow River because of high sediment in the river.

The production of the European Union, as well as the United Kingdom, Norway, and Switzerland, only accounted for 15% of the world plastic production in 2021, slightly decreasing 4% compared to 2017⁸⁹. Siegfried et al.¹¹³, combining with many MP sources, calculated river export of MPs from the European rivers to coastal seas and indicated the high yields in Israel and Lebanon, Turkey, southern France, western Portugal, northern as well as eastern Spain, and the United Kingdom¹¹³. Our findings are consistent with MP pollution in western Asia, as well as Central and eastern Europe. These subtle differences are attributed to a variety of natural factors, such as climate (i.e., rainfall). Yet plastic pollution in Europe and the Middle East should be taken seriously. In 2020, the ratios of recycling in Poland, Slovakia, Latvia, and Hungary were 27%, 30%, 34%, and 22%, respectively, but for landfill, 41%, 45%, 64%, and 57%, respectively⁸⁹. In contrast, Germany, Denmark, Norway, and the Netherlands had over 40% recycling and less than 2% landfill⁸⁹. A study mapping the mismanaged plastic waste (MPW) distribution in the Carpathians of East-Central Europe has suggested that most of MPW accumulation hotspots occur along rivers in Romania, Hungary, and Ukraine¹¹⁴. Russian-Ukrainian war may aggravate the MP pollution in rivers from untreated waste¹¹⁵. Additionally, tire and road wear particles constituted the largest source of MPs in European rivers, accounting for 42% of the total measured MP load, while plastic polymerbased textiles ranked second at 29%¹¹³. Previous study estimated that Africa contributed 24% of the global emissions of mismanaged plastic waste¹¹⁶. Despite of its relatively low production and consumption of plastics (5% and 4% respectively) compared to that of China, North America, Western Europe, and India, but Africa has the highest global environmental emissions of plastics due to poor waste management, contributing 24% of the global emissions of mismanaged plastic waste¹¹⁶. Many cities in Africa have experienced rapid urban development¹¹⁷. Indeed, the sub-Saharan urban expansion averaged 140% between the 1960s and 1990s, which is ten times faster than in OECD countries and 2.5 times faster than in the rest of the developing world¹¹⁸. This, to a certain extent, accelerates the MP pollution. Besides, it is not overlooked that most African countries have insufficient budgets to plan and execute governmental projects including research activities¹⁰⁷, overlooking the MP pollution to some extent.

Human activities in the Arctic are relatively low, greatly reducing the source of MP pollution. The Northern Hemisphere (10°N-50°N) accounts for most of the world's population and urban development^{119,120}, significantly increasing the potential sources of MPs. Asia notably contributes to MP pollution in the 10°N-50°N latitude region. At the same time, we excluded the desert and glacier areas, including northern Africa, Arabian Peninsula, and Greenland, which may have introduced a considerable error in this range.

We also predicted three global maps of MPs through different sampling methods to assist the global tendency. The trends of grab sampling and net collection are consistent with the map patterns generated by the three methods. However, the pump collection method is more efficient in collecting MPs. Additionally, the samples are small and extremely uneven. Observations from pump sampling are concentrated in Central Asia, while there are no observations in Africa, making the higher trend in Asia and lower in Africa, leading to differences in the maps generated by the three methods.

Limitations and prospects

Despite our considerable effort to obtain data and predict MP abundance in global inland waters, some limitations remain. The research on MP abundance in inland waters in Canada, Australia, South America, and Africa is still insufficient, which may affect the accuracy of our predicting map. For example, Aragaw et al.¹²¹ have reported that Africa, as a rapidly developing continent, has consumed a substantial amount of plastic production¹²¹, but contributes 24% of the global emissions of mismanaged plastic waste¹¹⁶. However, the studies based on MPs in African freshwater ecosystems are

still insufficient. Additionally, our database exhibits a severely right-skewed pattern with some extreme maxima, such as those observed in the Yellow River and small-scale rivers in Japan, potentially leading to lower prediction accuracy for these high-abundance areas.

In our prediction model, data related to WWTP, mismanaged plastic waste, and atmosphere deposition, are not included due to the lack of globally available and published distribution data on these. Therefore, these factors were not incorporated into the study and are only mentioned in the Discussion Section. Additionally, the lack of unified standards for experimental methods, including sampling, purification, extraction, and identification, has impacted the range distribution of MP abundance. Our analysis clearly demonstrated that MP abundance is influenced by the sampling method and tools used, which was consistent with previous studies^{122,123}. Harmonizing these methods is essential for accurately assessing MP pollution globally. Our results suggested that grab sampling with larger volumes (at least 500 liters) and a 60–90 μ m mesh size would be recommended, since grab sampling is more common in freshwater samples and comparisons across regions are easier, and pump sampling is too affected by sampling volumes and filter pore size, leading to overestimation.

Recently, mass concentrations of MPs in water have emerged as a reasonable unit, particularly due to the breakdown of microplastics in the environment. For example, Kooi and Koelmans¹²⁴ and Koelmans et al.¹²⁵ proposed a method to convert items to mass of MPs based on three key components: (1) a power-law distribution of MP-particle sizes, (2) formratios representing the height and width of MP particles, which are expressed as triangular distributions with specified lower and upper ratioboundaries for forms-various, and (3) triangular distributions of polymerdensities that take into account the observed density ranges of polymers in the environment. However, the research is currently unable to estimate the mass concentration, because of the varying sampling methods employed in our database leading to discrepancies in MP abundance. Additionally, different studies of our database define MP size classifications differently. Estimating global mass concentrations of MPs is indeed a worthwhile direction for future research, which can further promote the knowledge for us to grasp the MPs global distribution.

According to our results, the world should make collective efforts to manage MPs pollution in freshwater ecosystems, particularly in Asia, East and Central Europe, Africa, South America, and the eastern United States. Developing a circular plastic economy (i.e., where plastics are reused, recycled, and redesigned to minimize waste) and stricter waste management are key to mitigating MP pollution. Among them, the primary mitigation strategy is to improve plastic waste management, such as restricting open dumping, improving plastic recycling, raising public awareness and education, implementing strict waste management and waste sorting, and enhancing the management of landfills and incineration plants. Besides, it needs to strengthen the management of urban surface plastic waste to reduce the ratio of MPs entering freshwater bodies through land surface runoff, particularly in the dry season. Given the low flow during the dry season, it is essential to enhance the collection of plastic waste in water bodies and their surrounding areas. Moreover, constructed wetlands in urban could be emphasized to consider the movement of MPs in surface waters by a combination of promoting gravitational settling, microbial adhesion, plant retention, and sediment adsorption⁵⁶. In terms of cropland, organic (e.g., grass clippings, straw, compost, sawdust, dry leaves, bark and even paper) and inorganic mulches (e.g., consisting of stones and gravel) can be substituted for conventional plastic mulch films¹²⁶. Additionally, there has also been some progress in experiments related to the removal of MPs from water bodies¹²⁷. For example, using 1.3 g L⁻¹ of Fe₃O₄ magnetic nanoparticles and letting it sit for 150 minutes can remove over 80% of MPs¹²⁸. Additionally, some colloidal silica minerals (e.g., kaolinite, smectite, montmorillonite, or Al/Fe-oxyhydroxides) can adsorb dissolved organic matter via electrostatic/covalent interactions¹²⁹. Since oxidized or biofilm-coated MPs often have negative charges (-COOH/-OH) like that of organic matter, this may suggest that these colloidal silica minerals may act as similar adsorption processes in aiding MP removal from aquatic systems. Yet this still needs to be further validated in future.

Conclusion

By synthesizing global datasets, this study was to evaluate the differences in MP abundance among different ecosystem types, seasons, and sampling processes, revealing the characteristic distribution of MPs to fill the gap in the spatial distribution of MP abundance in global freshwater bodies. Our findings demonstrate that MP abundance ranges over six orders of magnitude (0.00 to 4,275,800.70 items m⁻³), with small-sized MPs (<1 mm) dominating freshwater systems. This is a previously underquantified threat that demands urgent attention due to its potential to disrupt aquatic ecosystems.

In contrast to the initial hypotheses (1), the MP abundance in inland waters during the dry season was significantly higher than that in the wet season. This variation is attributed to the alteration of hydrodynamic factors (such as rainfall duration and intensity), land-use types, and sampling time. This underscores the need for time-sensitive monitoring strategies, particularly in regions with pronounced climatic variability. Methodologically, we identify that standardized grab sampling (≥500 liters, 60–90 µm mesh size) is essential for accurate cross-regional comparisons, because of pumpbased methods risk overestimation induced by the sampling volumes and filter pore size dependencies. As expected, our analytical results highlight that the human development index plays a crucial role in the distribution of MPs in global inland waters, being consistent with our hypothesis (2). Despite that HDI does not directly cause plastic waste or emissions, it serves as a proxy for development patterns that drive these environmental impacts. The distribution of MPs in inland waters is further regulated by climate factors such as temperature, precipitation, evaporation, and land surface runoff. In agreement with our hypothesis (3), Asia, Europe, Africa, and eastern United States face the highest burdens of MPs in inland waters, particularly China, exemplifying the nexus of high plastic consumption and inadequate waste management.

Indeed, human activities and social development have brought about the varying degrees of MPs pollution. To manage plastic waste, some effective measures should be implemented to reduce emissions into the environment. Our research highlights the importance of enhancing waste management policies and public awareness and improving plastic waste management in urban areas and freshwater ecosystems, particularly during the dry season, as well as addressing agricultural MP emissions (such as by replacing plastic films with organic or inorganic mulches). These measures are crucial for reducing environmental emissions and mitigating MPs pollution in inland waters. This finding will serve as a valuable resource for further studies and the development of effective management measures for inland waters.

Methods

Data source and processing

We conducted a thorough search for peer-reviewed literature on microplastics (MPs) in inland waters using the Web of Science and China National Knowledge Infrastructure (CNKI) in April 2024. The search theme included terms such as "microplastic," "microplastics," and "MPs," combined with keywords related to inland waters ("watercourse," "stream," "river," "creek," "lake," "reservoir," "dam," "inland water," "watershed," and "freshwater"). We applied the following criteria to filter the articles: (1) The study was conducted on inland waters; (2) At least one record of MPs abundance was reported; (3) The unit of MPs abundance in water was measured in items m⁻³ or items L⁻¹; and (4) Data from wastewater treatment plants (WWTP) were excluded.

Our database included a total of 5365 observations from 301 articles (Fig. 1a; Appendix 1). In addition to MP abundance, we also collected the following information: (1) Longitude and latitude of sampling sites, article publication year, sampling year, sampling season, sampling volume, and ecosystem type; (2) Methods used for obtaining MPs, including sampling, extraction, and purification methods (Note S1); (3) Characteristics of MPs,

including particle colors, shapes, sizes, and polymers; and (4) The abundance unit of MPs was uniformly converted to items·m⁻³. We hypothesized that (1) the abundance of MPs in inland waters during the wet season was higher than in the dry season, due to the input of MPs from rainfall through land surface runoff; (2) human development index (HDI) is the most important drivers to promote MP emissions of inland waters; and (3) MP abundance would show a clear global patterns across inland waters, which was higher in areas with higher human activities, especially in Asia. Our study consists of two modeling parts: assessing the differences in microplastics at different taxonomic levels and global predictions. The overall process is shown in the supplementary file (Fig. S1).

Modeling of assessing the differences within the different division

Prior to analysis, we conducted a log transformation (log (abundance+1)) on our data to obtain normal distribution data (Fig. S2). First, we used univariate linear mixed models in the *lme4* package¹³⁰ to assess the effects of ecosystems, different seasons, experimental settings on MP abundance in global inland waters, and also explore the differences within the different characteristics of MPs. Next, we will conduct global predictions, and the specific process is as follows.

Global predicted variables

Based on our database coordinate information, we extracted 23 candidate predictor variables from the HydroSHEDS data¹³¹ (https://www.hydrosheds.org) (Table S1) to establish and predict MP abundance in global inland water environments using machine learning. This study resampled all variables in EPSG:4326 (World Geodetic System 1984) at 0.05-degree grid resolution. We also conducted log(abundance+1) transformation for the response variable to facilitate modeling in the predicting map. To avoid collinearity, we eliminated predictors with low contributions one by one until the variance inflation factors (VIFs) of all predictors were less than five. After that, we conducted the *VSURF* package for model selection¹³², which used the random forest permutation-based score of importance and conducted using a stepwise approach, adding variables only if they significantly reduced the out-of-bag error (OOB) by more than the average change after adding the noise variables. Finally, there are the remaining 5 variables used for modeling (Fig. S5).

Modeling of prediction

Based on our database, we conducted random forest regression model based on *randomForest* package¹³³ to explore the relationship between environmental predictors and MP abundance. As a supervised learning algorithm, random forest combines multiple decision trees to make predictions, reducing the risks of overfitting and improving the generalization performance. To determine the best-performing model, we tuned a series of parameters to optimize model performance¹³⁴, using the train function from the *caret* package¹³⁵. We fulfilled repeated random 10-fold repeated crossvalidation. The process was trained 10 times, each time using 90% of the data for training and leaving the remaining 10% for validation. Finally, we select the optimal parameters to build the final model.

Model test and predictors importance assessment

In each model, we evaluated the root-mean-square error (RMSE) and R²_Accuracy to summarize the cross-validation results and assess the predictive performance of the model. R²_Accuracy (R²_Accuracy = 1 – SSE/ SST) represents the amount of variation explained by the model¹³⁶, where SSE is the squared error between observation and prediction, and SST is the total sum of squares¹³⁷. The model with the lowest RMSE and highest R²_Accuracy was considered the best performance for predicting MP abundance in specific environments. We assessed the variable importance using "caret" package for the best parameter random forest model, and the results of variable importance with normalization within a range of 0–100% in the model indicated the effects of predictors on the model results.

Global prediction and uncertainty

We extracted data on these five predictor variables for the global scale, excluding glaciers and desert regions. Based on this data, the model with best parameter was conducted to predict and generate the global map of MPs, the process of which were performed 100 iterations. Notably, we generated 100 global maps related to MPs, and by averaging the results over these 100 iterations, we obtained the per-pixel mean values and standard deviations. Afterwards, we calculated the coefficient of variation (standard deviation divided by mean value).

Analysis of differences MP abundance among sampling methods

In terms of MPs in water, sampling methods largely affect the abundance values of MPs in water samples, which can be easily overestimated or underestimated. We divided all the methods into three categories (grab, net, and pump), and modeled as well as predicted world maps for the three methods with the same processes as above. Additionally, owing to major sampling points in China, we also modeled and predicted these properties for China using the same processes.

Data availability

Raw data were deposited in figshare at https://doi.org/10.6084/m9.figshare. 28784873.v1.

Code availability

R code for generation of the results were deposited in figshare at https://doi. org/10.6084/m9.figshare.28784873.v1.

Received: 19 August 2024; Accepted: 22 April 2025; Published online: 30 April 2025

References

- 1. Thompson, R. C. et al. Lost at sea: where is all the plastic? *Science* **304**, 838–838 (2004).
- Zbyszewski, M. & Corcoran, P. L. Distribution and degradation of fresh water plastic particles along the beaches of Lake Huron, Canada. Water Air Soil Pollut. 220, 365–372 (2011).
- Mani, T., Hauk, A., Walter, U. & Burkhardt-Holm, P. Microplastics profile along the Rhine River. Sci. Rep. 5, 17988 (2016).
- Zhang, K., Gong, W., Lv, J., Xiong, X. & Wu, C. Accumulation of floating microplastics behind the Three Gorges Dam. *Environ. Pollut.* 204, 117–123 (2015).
- Bordós, G. et al. Identification of microplastics in fish ponds and natural freshwater environments of the Carpathian basin, Europe. *Chemosphere* 216, 110–116 (2019).
- Campbell, S. H., Williamson, P. R. & Hall, B. D. Microplastics in the gastrointestinal tracts of fish and the water from an urban prairie creek. *FACETS* 2, 395–409 (2017).
- Di, M. & Wang, J. Microplastics in surface waters and sediments of the Three Gorges Reservoir, China. *Sci. Total Environ.* 616–617, 1620–1627 (2018).
- Huang, D. et al. The occurrence and abundance of microplastics in surface water and sediment of the West River downstream, in the south of China. *Sci. Total Environ.* **756**, 143857 (2021).
- Wang, G. et al. Occurrence and pollution characteristics of microplastics in surface water of the Manas River Basin, China. Sci. Total Environ. 710, 136099 (2020).
- Wang, W., Ndungu, A. W., Li, Z. & Wang, J. Microplastics pollution in inland freshwaters of China: a case study in urban surface waters of Wuhan, China. Sci. Total Environ. 575, 1369–1374 (2017).
- Gall, S. C. & Thompson, R. C. The impact of debris on marine life. Mar. Pollut. Bull. 92, 170–179 (2015).
- Li, J., Liu, H. & Paul Chen, J. Microplastics in freshwater systems: a review on occurrence, environmental effects, and methods for microplastics detection. *Water Res.* **137**, 362–374 (2018).

- Holland, E. R., Mallory, M. L. & Shutler, D. Plastics and other anthropogenic debris in freshwater birds from Canada. *Sci. Total Environ.* 571, 251–258 (2016).
- 14. Cole, M. Microplastics as contaminants in the marine environment: a review. *Mar. Pollut. Bull.* **62**, 2588–2597 (2011).
- Ivleva, N. P., Wiesheu, A. C. & Niessner, R. Microplastic in aquatic ecosystems. *Angew. Chem. Int. Ed. Engl.* 56, 1720–1739 (2017).
- Guo, X. & Wang, J. The phenomenological mass transfer kinetics model for Sr²⁺ sorption onto spheroids primary microplastics. *Environ. Pollut.* 250, 737–745 (2019).
- Bouhroum, R. et al. Concentrations and fingerprints of PAHs and PCBs adsorbed onto marine plastic debris from the Indonesian Cilacap coast and the North Atlantic gyre. *Reg. Stud. Mar. Sci.* 29, 100611 (2019).
- Kapp, K. J. & Yeatman, E. Microplastic hotspots in the Snake and lower Columbia rivers: a journey from the Greater Yellowstone ecosystem to the Pacific Ocean. *Environ. Pollut.* 241, 1082–1090 (2018).
- Lebreton, L. C. M. et al. River plastic emissions to the world's oceans. *Nat. Commun.* 8, 15611 (2017).
- Barboza, L. G. A., Dick Vethaak, A., Lavorante, B. R. B. O., Lundebye, A.-K. & Guilhermino, L. Marine microplastic debris: an emerging issue for food security, food safety and human health. *Mar. Pollut. Bull.* 133, 336–348 (2018).
- 21. Nava, V. et al. Plastic debris in lakes and reservoirs. *Nature* **619**, 317–322 (2023).
- Liu, Y. et al. Application of a microplastic trap to the determination of the factors controlling the lakebed deposition of microplastics. *Sci. Total Environ.* 843, 156883 (2022).
- Zhou, Y. et al. Microplastic contamination is ubiquitous in riparian soils and strongly related to elevation, precipitation and population density. *J. Hazard. Mater.* **411**, 125178 (2021).
- Xue, B. et al. Underestimated microplastic pollution derived from fishery activities and "Hidden" in deep sediment. *Environ. Sci. Technol.* 54, 2210–2217 (2020).
- Vendel, A. L. et al. Widespread microplastic ingestion by fish assemblages in tropical estuaries subjected to anthropogenic pressures. *Mar. Pollut. Bull.* **117**, 448–455 (2017).
- Matsuguma, Y. et al. Microplastics in sediment cores from Asia and Africa as indicators of temporal trends in plastic pollution. *Arch. Environ. Contam. Toxicol.* **73**, 230–239 (2017).
- Ballent, A., Purser, A., De Jesus Mendes, P., Pando, S. & Thomsen, L. Physical transport properties of marine microplastic pollution. *Biogeosciences Discuss.* 9, 18755–18798 (2012).
- Fischer, E. K., Paglialonga, L., Czech, E. & Tamminga, M. Microplastic pollution in lakes and lake shoreline sediments – a case study on Lake Bolsena and Lake Chiusi (central Italy). *Environ. Pollut.* 213, 648–657 (2016).
- 29. Cao, L. et al. Occurrence, distribution and affecting factors of microplastics in agricultural soils along the lower reaches of Yangtze River, China. *Sci. Total Environ.* **794**, 148694 (2021).
- 30. Rillig, M. C. & Lehmann, A. Microplastic in terrestrial ecosystems. *Science* **368**, 1430–1431 (2020).
- Wang, Y. et al. Soil erosion is a major drive for nano & micro-plastics to enter riverine systems from cultivated land. *Water Res.* 256, 121597 (2024).
- Yuan, W. et al. Environmental fate of microplastics in the world's third-largest river: basin-wide investigation and microplastic community analysis. *Water Res.* **210**, 118002 (2022).
- Guo, Z. et al. Global meta-analysis of microplastic contamination in reservoirs with a novel framework. *Water Res.* 207, 117828 (2021).
- 34. Eriksen, M. et al. Microplastic pollution in the surface waters of the Laurentian Great Lakes. *Mar. Pollut. Bull.* **77**, 177–182 (2013).

- Kole, P. J., Löhr, A. J., Van Belleghem, F. & Ragas, A. Wear and tear of tyres: a stealthy source of microplastics in the environment. *IJERPH* 14, 1265 (2017).
- Xiong, X. et al. Sources and distribution of microplastics in China's largest inland lake—Qinghai Lake. *Environ. Pollut.* 235, 899–906 (2018).
- Fan, Y., Zheng, K., Zhu, Z., Chen, G. & Peng, X. Distribution, sedimentary record, and persistence of microplastics in the Pearl River catchment, China. *Environ. Pollut.* **251**, 862–870 (2019).
- Sarijan, S., Azman, S., Said, M. I. M. & Jamal, M. H. Microplastics in freshwater ecosystems: a recent review of occurrence, analysis, potential impacts, and research needs. *Environ. Sci. Pollut. Res.* 28, 1341–1356 (2021).
- Jin, T. et al. Activities of microplastics (MPs) in agricultural soil: a review of MPs pollution from the perspective of agricultural ecosystems. J. Agric. Food Chem. 70, 4182–4201 (2022).
- 40. Liu, Y. et al. Effects of irrigation on the fate of microplastics in typical agricultural soil and freshwater environments in the upper irrigation area of the Yellow River. *J. Hazard. Mater.* **447**, 130766 (2023).
- Eerkes-Medrano, D., Thompson, R. C. & Aldridge, D. C. Microplastics in freshwater systems: a review of the emerging threats, identification of knowledge gaps and prioritisation of research needs. *Water Res.* **75**, 63–82 (2015).
- 42. Li, C., Busquets, R. & Campos, L. C. Assessment of microplastics in freshwater systems: a review. *Sci. Total Environ.* **707**, 135578 (2020).
- Kabir, A. H. M. E. et al. Assessing small-scale freshwater microplastics pollution, land-use, source-to-sink conduits, and pollution risks: perspectives from Japanese rivers polluted with microplastics. *Sci. Total Environ.* **768**, 144655 (2021).
- Tibbetts, J., Krause, S., Lynch, I. & Sambrook Smith, G. Abundance, distribution, and drivers of microplastic contamination in urban river environments. *Water* **10**, 1597 (2018).
- Gao, S., Orlowski, N., Bopf, F. K. & Breuer, L. A review on microplastics in major European rivers. WIREs Water 11, e1713 (2024).
- Razeghi, N., Hamidian, A. H., Wu, C., Zhang, Y. & Yang, M. Microplastic sampling techniques in freshwaters and sediments: a review. *Environ. Chem. Lett.* **19**, 4225–4252 (2021).
- 47. Zhang, K. et al. Microplastic pollution in China's inland water systems: a review of findings, methods, characteristics, effects, and management. *Sci. Total Environ.* **630**, 1641–1653 (2018).
- Chang, M. et al. Changes in characteristics and risk of freshwater microplastics under global warming. *Water Res.* 260, 121960 (2024).
- 49. Zhao, B., Richardson, R. E. & You, F. Microplastics monitoring in freshwater systems: a review of global efforts, knowledge gaps, and research priorities. *J. Hazard. Mater.* **477**, 135329 (2024).
- Raymond, P. A. et al. Global carbon dioxide emissions from inland waters. *Nature* 503, 355–359 (2013).
- 51. Liu, S. et al. The importance of hydrology in routing terrestrial carbon to the atmosphere via global streams and rivers. *Proc. Natl. Acad. Sci. USA* **119**, e2106322119 (2022).
- Tang, L. et al. Global occurrence, drivers, and environmental risks of microplastics in marine environments. *J. Environ. Manag.* 329, 116961 (2023).
- Horton, A. A. & Dixon, S. J. Microplastics: an introduction to environmental transport processes. *WIREs Water* 5, e1268 (2018).
- Guo, M., Noori, R. & Abolfathi, S. Microplastics in freshwater systems: dynamic behaviour and transport processes. *Resour. Conserv. Recycl.* 205, 107578 (2024).
- 55. Schmidt, C., Krauth, T. & Wagner, S. Export of plastic debris by rivers into the sea. *Environ. Sci. Technol.* **51**, 12246–12253 (2017).
- Xia, F., Liu, H., Zhang, J. & Wang, D. Migration characteristics of microplastics based on source-sink investigation in a typical urban wetland. *Water Res.* 213, 118154 (2022).

- 57. Dusaucy, J., Gateuille, D., Perrette, Y. & Naffrechoux, E. Microplastic pollution of worldwide lakes. *Environ. Pollut.* **284**, 117075 (2021).
- Arthur, C., Baker, J. E. & Bamford, H. A. Proc. International Research Workshop on the Occurrence, Effects, and Fate of Microplastic Marine Debris (University of Washington Tacoma, 2009).
- Löder, M. G. J. & Gerdts, G. Methodology used for the detection and identification of microplastics – a critical appraisal in *Marine Anthropogenic Litter* (eds Bergmann, M. et al.) 201–227 (Springer, 2015).
- 60. Lopez Lozano, R. & Mouat, J. Marine Litter in the Northeast Atlantic Region: Assessment and Priorities for Response (OSPAR Commission, 2009).
- 61. Zhang, L. et al. Microplastics in freshwater and wild fishes from Lijiang River in Guangxi, Southwest China. *Sci. Total Environ.* **755**, 142428 (2021).
- Liu, K. et al. Elucidating the vertical transport of microplastics in the water column: a review of sampling methodologies and distributions. *Water Res.* 186, 116403 (2020).
- Lusher, A. L., Burke, A., O'Connor, I. & Officer, R. Microplastic pollution in the Northeast Atlantic Ocean: validated and opportunistic sampling. *Mar. Pollut. Bull.* 88, 325–333 (2014).
- 64. Tamminga, M. On the representativeness of pump water samples versus manta sampling in microplastic analysis. *Environ. Pollut.* **254**, 112970 (2019).
- Watkins, L., Sullivan, P. J. & Walter, M. T. What you net depends on if you grab: a meta-analysis of sampling method's impact on measured aquatic microplastic concentration. *Environ. Sci. Technol.* 55, 12930–12942 (2021).
- Koelmans, A. A. et al. Microplastics in freshwaters and drinking water: critical review and assessment of data quality. *Water Res.* 155, 410–422 (2019).
- Liu, F., Olesen, K. B., Borregaard, A. R. & Vollertsen, J. Microplastics in urban and highway stormwater retention ponds. *Sci. Total Environ.* 671, 992–1000 (2019).
- Hurley, R., Woodward, J. & Rothwell, J. J. Microplastic contamination of river beds significantly reduced by catchmentwide flooding. *Nat. Geosci.* **11**, 251–257 (2018).
- 69. Wang, C. et al. Microplastics profile in a typical urban river in Beijing. *Sci. Total Environ.* **743**, 140708 (2020).
- Wicaksono, E. A., Werorilangi, S., Galloway, T. S. & Tahir, A. Distribution and seasonal variation of microplastics in Tallo River, Makassar, Eastern Indonesia. *Toxics* 9, 129 (2021).
- 71. Fan, Y. et al. Spatiotemporal dynamics of microplastics in an urban river network area. *Water Res.* **212**, 118116 (2022).
- Barrows, A. P. W., Christiansen, K. S., Bode, E. T. & Hoellein, T. J. A watershed-scale, citizen science approach to quantifying microplastic concentration in a mixed land-use river. *Water Res.* 147, 382–392 (2018).
- Stanton, T., Johnson, M., Nathanail, P., MacNaughtan, W. & Gomes, R. L. Freshwater microplastic concentrations vary through both space and time. *Environ. Pollut.* 263, 114481 (2020).
- Cheung, P. K., Hung, P. L. & Fok, L. Microplastic contamination and dynamics upon a rainfall event in Hong Kong. *China Environ. Process.* 6, 253–264 (2019).
- 75. de Carvalho, A. R. et al. Urbanization and hydrological conditions drive the spatial and temporal variability of microplastic pollution in the Garonne River. *Sci. Total Environ.* **769**, 144479 (2021).
- Su, L. et al. Superimposed microplastic pollution in a coastal metropolis. *Water Res.* 168, 115140 (2020).
- Rosso, B. et al. Quantification and characterization of additives, plasticizers, and small microplastics (5–100 μm) in highway stormwater runoff. *J. Environ. Manag.* **324**, 116348 (2022).
- Huang, Y. et al. Coupled effects of urbanization level and dam on microplastics in surface waters in a coastal watershed of Southeast China. *Mar. Pollut. Bull.* **154**, 111089 (2020).

- 79. Li, T. et al. Environmental fate of microplastics in an urban river: spatial distribution and seasonal variation. *Environ. Pollut.* **322**, 121227 (2023).
- Lambert, S. & Wagner, M. Formation of microscopic particles during the degradation of different polymers. *Chemosphere* **161**, 510–517 (2016).
- Browne, M. A., Dissanayake, A., Galloway, T. S., Lowe, D. M. & Thompson, R. C. Ingested microscopic plastic translocates to the circulatory system of the mussel, *Mytilus edulis* (L.). *Environ. Sci. Technol.* 42, 5026–5031 (2008).
- 82. Van Cauwenberghe, L. & Janssen, C. R. Microplastics in bivalves cultured for human consumption. *Environ. Pollut.* **193**, 65–70 (2014).
- 83. Nousheen, R., Rittschof, D. & Hashmi, I. Toxic effects of pristine and aged polystyrene microplastics on selective and continuous larval culture of acorn barnacle *Amphibalanus amphitrite*. *Environ. Toxicol. Pharmacol.* **94**, 103912 (2022).
- Hwang, J., Choi, D., Han, S., Choi, J. & Hong, J. An assessment of the toxicity of polypropylene microplastics in human derived cells. *Sci. Total Environ.* 684, 657–669 (2019).
- Salvador Cesa, F., Turra, A. & Baruque-Ramos, J. Synthetic fibers as microplastics in the marine environment: a review from textile perspective with a focus on domestic washings. *Sci. Total Environ.* 598, 1116–1129 (2017).
- Ziajahromi, S., Kumar, A., Neale, P. A. & Leusch, F. D. L. Impact of microplastic beads and fibers on waterflea (*Ceriodaphnia dubia*) survival, growth, and reproduction: implications of single and mixture exposures. *Environ. Sci. Technol.* **51**, 13397–13406 (2017).
- 87. Zhang, H. Transport of microplastics in coastal seas. *Estuar. Coast. Shelf Sci.* **199**, 74–86 (2017).
- Abaroa-Pérez, B., Ortiz-Montosa, S., Hernández-Brito, J. J. & Vega-Moreno, D. Yellowing, weathering and degradation of marine pellets and their influence on the adsorption of chemical pollutants. *Polymers* 14, 1305 (2022).
- 89. Plastic Europe. *Plastics The Facts 2022*. https://plasticseurope. org/knowledge-hub/plastics-the-facts-2022-2/ (2022).
- Kummu, M., Taka, M. & Guillaume, J. H. A. Gridded global datasets for Gross Domestic Product and Human Development Index over 1990–2015. Sci. Data 5, 180004 (2018).
- 91. Geyer, R., Jambeck, J. R. & Law, K. L. Production, use, and fate of all plastics ever made. *Sci. Adv.* **3**, e1700782 (2017).
- Eo, S., Hong, S. H., Song, Y. K., Han, G. M. & Shim, W. J. Spatiotemporal distribution and annual load of microplastics in the Nakdong River, South Korea. *Water Res.* 160, 228–237 (2019).
- Jambeck, J. R. et al. Plastic waste inputs from land into the ocean. Science 347, 768–771 (2015).
- Wagner, S. et al. Tire wear particles in the aquatic environment—a review on generation, analysis, occurrence, fate and effects. *Water Res.* 139, 83–100 (2018).
- 95. Sorensen, R. M., Kanwar, R. S. & Jovanovi, B. Past, present, and possible future policies on plastic use in the United States, particularly microplastics and nanoplastics: a review. *Integr. Environ. Assess. Manag.* **19**, 474–488 (2023).
- Liu, Q. & McVicar, T. R. Assessing climate change induced modification of Penman potential evaporation and runoff sensitivity in a large water-limited basin. *J. Hydrol.* 464–465, 352–362 (2012).
- Li, W. et al. Colonization characteristics of bacterial communities on plastic debris influenced by environmental factors and polymer types in the Haihe estuary of Bohai Bay, China. *Environ. Sci. Technol.* 53, 10763–10773 (2019).
- García-Haba, E., Hernández-Crespo, C., Martín, M. & Andrés-Doménech, I. The role of different sustainable urban drainage systems in removing microplastics from urban runoff: a review. *J. Clean. Prod.* **411**, 137197 (2023).
- 99. Fan, J. et al. Occurrence and distribution of microplastics in surface water and sediments in China's inland water systems: a critical review. *J. Clean. Prod.* **331**, 129968 (2022).

- Wang, J. et al. Runoff and discharge pathways of microplastics into freshwater ecosystems: a systematic review and meta-analysis. *FACETS* 7, 1473–1492 (2022).
- 101. Kumar, M. et al. Microplastics as pollutants in agricultural soils. *Environ. Pollut.* **265**, 114980 (2020).
- Nizzetto, L., Futter, M. & Langaas, S. Are agricultural soils dumps for microplastics of urban origin? *Environ. Sci. Technol.* 50, 10777–10779 (2016).
- Zhang, L. et al. An overlooked entry pathway of microplastics into agricultural soils from application of sludge-based fertilizers. *Environ. Sci. Technol.* 54, 4248–4255 (2020).
- Weithmann, N. et al. Organic fertilizer as a vehicle for the entry of microplastic into the environment. Sci. Adv. 4, eaap8060 (2018).
- OECD. Global Plastics Outlook: Economic Divers, Environmental Impacts and Policy Options. https://www.oecd.org/en/publications/ global-plastics-outlook_de747aef-en.html (2022).
- Lin, H.-T. et al. Microplastics in Asian rivers: geographical distribution, most detected types, and inconsistency in methodologies. *Environ. Pollut.* **349**, 123985 (2024).
- 107. Wagner, M. Freshwater Microplastics: Emerging Environmental Contaminants? Vol. 58 (Springer, 2018).
- 108. Tata Strategic Management Group. Potential of Plastics Industry in Northern India with Special Focus on Plasticulture and Food Processing – 2014. A report on plastics industry (Federation of Indian Chambers of Commerce and Industry, 2014).
- Ren, Y. H., Liu, Y. L. & Yu, L. J. Spatiotemporal changes of built-up land and population distribution patterns in China during 1990-2010. *IOP Conf. Ser. Earth Environ. Sci.* 57, 012045 (2017).
- Fu, G., Chen, S., Liu, C. & Shepard, D. Hydro-climatic trends of the Yellow River Basin for the last 50 years. *Clim. Change* 65, 149–178 (2004).
- 111. Yao, J., Wang, G., Xue, W., Yao, Z. & Xue, B. Assessing the adaptability of water resources system in Shandong Province, China, using a novel comprehensive co-evolution model. *Water Resour. Manag.* **33**, 657–675 (2019).
- 112. Waldschläger, K. & Schüttrumpf, H. Erosion behavior of different microplastic particles in comparison to natural sediments. *Environ. Sci. Technol.* **53**, 13219–13227 (2019).
- Siegfried, M., Koelmans, A. A., Besseling, E. & Kroeze, C. Export of microplastics from land to sea. A modelling approach. *Water Res.* 127, 249–257 (2017).
- Liro, M. Mountains of plastic: mismanaged plastic waste along the Carpathian watercourses. *Sci. Total Environ.* 888, 164058 (2023).
- Strokal, V., Kurovska, A. & Strokal, M. More river pollution from untreated urban waste due to the Russian-Ukrainian war: a perspective view. *J. Integr. Environ. Sci.* **20**, 2281920 (2023).
- 116. United Nations Environment Programme. *Mapping of Global Plastics Value Chain and Plastics Losses to the Environment: With a Particular Focus on Marine Environment*. https://www.unep.org/ resources/report/mapping-global-plastics-value-chain-andplastics-losses-environment-particular (United Nations Environment Programme, 2018).
- 117. Okot-Okumu, J. Solid waste management in African cities—East Africa in Waste Management—An Integrated Vision (InTech, 2012).
- Barrios, S., Bertinelli, L. & Strobl, E. Climatic change and rural–urban migration: the case of sub-Saharan Africa. *J. Urban Econ.* 60, 357–371 (2006).
- 119. CIESIN. *Gridded Population of the World, Version 4 (GPWv4): Population Count* (NASA Socioeconomic Data and Applications Center—SEDAC, 2016).
- 120. Pesaresi, M., Freire, S. & others. GHS Settlement grid following the REGIO model 2014 in application to GHSL Landsat and CIESIN GPW v4-multitemporal (1975-1990-2000-2015). JRC Data Cat http://data.europa.eu/89h/jrc-ghsl-ghs_smod_pop_globe_r2016a (2016).

- Aragaw, T. A. Microplastic pollution in African countries' water systems: a review on findings, applied methods, characteristics, impacts, and managements. SN Appl. Sci. 3, 629 (2021).
- 122. Lindeque, P. K. et al. Are we underestimating microplastic abundance in the marine environment? A comparison of microplastic capture with nets of different mesh-size. *Environ. Pollut.* **265**, 114721 (2020).
- Rist, S. et al. Quantification of plankton-sized microplastics in a productive coastal Arctic marine ecosystem. *Environ. Pollut.* 266, 115248 (2020).
- Kooi, M. & Koelmans, A. A. Simplifying microplastic via continuous probability distributions for size, shape, and density. *Environ. Sci. Technol. Lett.* 6, 551–557 (2019).
- 125. Koelmans, A. A., Redondo-Hasselerharm, P. E., Mohamed Nor, N. H. & Kooi, M. Solving the nonalignment of methods and approaches used in microplastic research to consistently characterize risk. *Environ. Sci. Technol.* 54, 12307–12315 (2020).
- Tang, K. H. D. Microplastics in agricultural soils in China: sources, impacts and solutions. *Environ. Pollut.* 322, 121235 (2023).
- 127. Gao, W. et al. Removal of microplastics in water: technology progress and green strategies. *Green Anal. Chem.* **3**, 100042 (2022).
- Shi, X., Zhang, X., Gao, W., Zhang, Y. & He, D. Removal of microplastics from water by magnetic nano-Fe₃O₄. *Sci. Total Environ.* 802, 149838 (2022).
- 129. Kleber, M. et al. Dynamic interactions at the mineral–organic matter interface. *Nat. Rev. Earth Environ.* **2**, 402–421 (2021).
- Bates, D., Mächler, M., Bolker, B. & Walker, S. Fitting linear mixedeffects models using Ime4. J. Stat. Softw. 67, 1–48 (2014).
- Lehner, B. & Grill, G. Global river hydrography and network routing: baseline data and new approaches to study the world's large river systems. *Hydrol. Process.* 27, 2171–2186 (2013).
- Genuer, R., Poggi, J.-M. & Tuleau-Malot, C. VSURF: an R package for variable selection using Random Forests. *R J.* 7, 19 (2015).
- Liaw, A. & Wiener, M. Classification and regression by randomForest. *R News* 2, 18–22 (2002).
- Bergstra, J. & Bengio, Y. Random search for hyper-parameter optimization. J. Mach. Learn. Res. 13, 281–305 (2012).
- 135. Kuhn, M. Building predictive models in R using the caret package. J. Stat. Soft. 28, 1–26 (2008).
- 136. Hengl, T. et al. SoilGrids250m: global gridded soil information based on machine learning. *PLoS ONE* **12**, e0169748 (2017).
- Cai, L. et al. Global models and predictions of plant diversity based on advanced machine learning techniques. *N. Phytol.* 237, 1432–1445 (2023).

Acknowledgements

K.Y. was funded by the Central-guided Local Science and Technology Development Fund Projects of Fujian Province (2023L3005) and the National Natural Science Foundation of China (32271633). Y.P. received funds from the National Natural Science Foundation of China (32201342) and Natural Science Foundation of Fujian Province (2022J01642). F.W. was funded by the National Natural Science Foundation of China (32171641), and J.P. was funded by the Spanish MCIN (AEI/10.13039/501100011033), and the European Union NextGenerationEU/PRTR (TED2021-132627B-I00). We confirm that no sampling permissions were required for this study, as all data were extracted from previously published literature.

Author contributions

K.Y., X.J., and Z.L. conceived the study. X.J. collected the raw data. K.Y., Z.L., and X.J. performed data analysis and wrote the first draft of the manuscript. J.P., J.S., Y.P., and P.H. discussed results. Q.W., Z.Z., and F.W. contributed to substantial revisions of the manuscript. J.Y., Z.C., and C.Y. contributed to the visualization, and all authors edited the final version.

Competing interests

The authors declare no competing interests.

Article

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-025-02320-2.

Correspondence and requests for materials should be addressed to Zimin Li or Kai Yue.

Peer review information *Communications Earth & Environment* thanks Anju Baroth and the other anonymous reviewer(s) for their contribution to the peer review of this work. Primary handling editors: Somaparna Ghosh. A peer review file is available.

Reprints and permissions information is available at

http://www.nature.com/reprints

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/bync-nd/4.0/.

© The Author(s) 2025