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Microplastics in global rivers: Sustainable practices

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Abstract

Sustainable Development Goals (SDGs) call for implementing sustainable practices by 2030, but their effects on microplastic pollution over time are limited. Here, we aimed to understand better the effects of improved centralized-sanitation and reduced production and consumption on point-source inputs of microplastics into rivers from 2010 to 2100 with a 10-year time step for 10,226 sub-basins globally. We developed scenarios with sustainable practices and implemented them into the MARINA-Plastics model. Our baseline scenario followed the "middle-of-the-road" socioeconomic pathway, where global microplastics (MIPs) in rivers will almost triple by 2100. European and Asian rivers were major MIP pollution hotspots in the past whereas Africa will join them in the future. Better centralized-sanitation may reduce MIPs in rivers globally in the long-term by 2100, while controlled waste generation may reduce MIPs in rivers in the short-term by 2030. Our insights could guide policy-making in implementing SDG 6 and 12. We argue that combined sustainable practices could reduce MIP in global rivers in the short- and long-term.

KEYWORDS
Global, Long and short terms, MARINA-plastics model, Microplastics, Rivers, SDGs

1 | INTRODUCTION

With economic development and population growth, urbanization has become a global phenomenon with a strong sustainability impact the environment, economy, and society (Nagendra et al., 2018). Rapid urbanization often results in increased sewage connections discharging more pollutants from cities into rivers. This poses threats to human and animal health and can lead to varying degrees of ecosystem damage, such as eutrophication (WWAP, 2018). Urbanization has increased the production of urban waste. This may lead to more contamination of water with multiple pollutants from sewage systems. This especially holds for microplastics that is often generated in urban households via laundry, personal care products, and dust.

Microplastic is one of the micropollutants. Particles with a grain size lower than 5 mm are usually referred to as microplastics (Browne et al., 2015). There are two main sources for microplastics in rivers: point and diffuse (Strokal et al., 2023). Point sources include microplastics in rivers from sewage systems. Sewage systems collect wastewater with microplastics from personal care products (PCP), detergents, household dust and car tire wear. These are the primary sources of microplastics in wastewater. Microplastic wastewater is transported by pipes to wastewater treatment plants (WWTPs). After treatment, some microplastics can enter rivers. Sometimes, sewage waste with microplastics can be directly discharged to adjacent water bodies without treatment (Siegfried et al., 2017). Once microplastics in rivers, they are transported further downstream to coastal waters (Avio et al., 2017). Recent studies showed that many rivers worldwide are polluted by microplastics from PCP, laundry, car tire wear, and household dust (Strokal et al., 2021). These happen often in areas with a lot of urbanization (e.g., Europe, North America). In contrast, in areas with a lot of mismanaged solid waste (e.g., Asia, and Africa), rivers are reported to have microplastics from mismanaged macroplastic waste (e.g., packaging materials in the environment) (Strokal et al., 2023).

To our knowledge, it is not well understood how the sources of microplastics in rivers may change in the 21st century when considering urbanization trends and socioeconomic developments. This information is especially needed to formulate effective reduction options and inform policymaking. A global focus is needed to better understand where (e.g., sub-basins) and how (sources) microplastics are expected to enter rivers in the future to prioritize areas and sources for pollution reduction. Such information is lacking but needed to support a debate between different countries to reduce future pollution for transboundary rivers crossing more than one country.

Scenario analysis is a tool to assess the potential long-term consequences of decisions made today, the uncertainty of future global change, and the stress of the environment, including water resources (Dellink et al., 2017; van Vuuren et al., 2014). Different scenarios vary in several aspects, such as rates of urbanization, degree of water scarcity, and wastewater treatment efficiencies (Strokal et al., 2021). The Shared Socio-economic Pathways (SSP) have been defined as plausible alternative scenarios by considering socioeconomic and urbanization trends during the 21st century. Five SSPs have been developed with different degrees toward adaptation and mitigation to societal challenges (Dellink et al., 2017; O'Neill et al., 2014; Rozenberg et al., 2014). SSP1 is more oriented toward sustainability whereas SSP5 takes economy as a priority. SSP2 assumes a moderate development in the economy following the historical trends (Dellink et al., 2017). In other words, the current developmental trends of society, economy, and technology are expected to continue. In this SSP2 scenario, some areas might be more developed than others, limiting the achievement of sustainable development goals (SDGs) on a global scale (Dellink et al., 2017). SSP3 and SSP4 assume the socioeconomic development that is in-between of the other SSPs. SSP3 assumes a fragmented world whereas SSP4 focuses on inequality (Calvin et al., 2017; Fujimori et al., 2017; O'Neill et al., 2014; Samir, 2020). These five SSPs have been widely applied in various studies, like agriculture, biology, climate change, earth science, and social science (Brunner et al., 2020; Li et al., 2022; Molotoks et al., 2021; Samir & Lutz, 2017; Wiebe et al., 2015). However, their application has been limited especially for microplastics. Future scenarios could help to analyze water quality and support advice for water pollution control but lacking for microplastics.

SDGs were created by the United Nations with the aim of "peace and prosperity for people and the planet, now and into the future" (Nilsson et al., 2016; Pakkan et al., 2023). In total, 17 specific goals were created. Among them, SDG6 (Clean Water and Sanitation) and SDG12 (Responsible Consumption and Production) are highly correlated to microplastic pollution from point sources in rivers under the urbanization trends. To correspond to the SDGs, several sustainable practices are called to be implemented by 2030. For example, SDG6 can be reflected by better-centralized sanitation with wastewater treatment levels. Better centralized sanitation may bring more microplastics to sewage systems, while improved levels of wastewater treatment may remove more microplastics in wastewater. Sustainable practices of SDG12 can be related to microplastic consumption and production reduction. For example, sustainable practices could be oriented to produce and consume less goods with microplastics. As a result, sewage systems may collect wastewater containing less microplastics.

However, our knowledge is still limited in the relationship between sanitation (improved centralized systems and wastewater treatment), production and consumption patterns, and microplastic pollution in rivers. Some studies discussed the importance of achieving SDG6 for sanitation by assessing the current situation, technical feasibility, possible environmental impacts, or the mitigation for policies (dos Santos Silva et al., 2024; Jiang et al., 2022; Omoregie et al., 2023; van Wijnen et al., 2019; Zhao & You, 2024). Other studies illustrated the necessity to reduce microplastic consumption patterns by assessing the current situation, improvements in waste management, and relevant policies (Winton et al., 2022; Zhuo et al., 2023). Studies that connect both sanitation and consumption are lacking for microplastics especially at the sub-basin scale worldwide for rivers. Our knowledge is still limited in how the implementation of SDG strategies will influence microplastic pollution in rivers in the future at a global scale. Besides, the existing models (Jambeck et al., 2015; Lebreton et al., 2017; Lebreton & Andrady, 2019; Meijer et al., 2021; Micella et al., 2024; Nakayama & Osako, 2023; Schmidt et al., 2017; Siegfried et al., 2017; Strokal et al., 2023; van Wijnen et al., 2019) are also limited in their scenarios and do not fully address the effects of SDG6 and 12 on the future microplastic pollution reduction. There is a gap in our knowledge to explore the SDG's effectiveness in reducing microplastic in rivers worldwide in the short- (2030) and long-term (2100).

Global water quality models exist but are limited to microplastics and specific to regions or periods. For example, Jambeck et al., 2015 presented a framework to calculate the annual inputs of plastics to oceans from 2010 to 2025 based on the relationship between waste generation and populations. Jang et al., 2015 estimated the annual marine plastic pollution from 1950 to 2013 based on the annual plastic consumption in 2012. Lebreton et al., 2017 used a global ocean surface mass balance model to calculate the mass of buoyant macroplastics and microplastics from 2000 to 2050 in three future scenarios based on different emission situations. Schmidt et al., 2017 evaluated global plastic debris inputs from rivers to seas based on the mismanaged plastic waste and regression models. Siegfried et al., 2017 used an integrated modeling approach to estimate microplastic export by rivers to coastal waters for 2000 and two scenarios in 2050 at the European scale. Lebreton & Andrady, 2019 projected global mismanaged plastic waste generation from 2010 to 2060 under three different scenarios based on Gross Domestic Product and waste management efforts. van Wijnen et al., 2019 estimated the total river export of microplastics to coastal areas in 2050 under four future scenarios based on waste management. Nihei et al., 2020 estimated the plastic emissions from land to sea based on a water balance analysis. Mai et al., 2020 projected global plastic pollution in 2050 based on mismanaged plastic waste and the Human Development Index. Meijer et al., 2021 projected riverine plastic emissions into oceans using a probabilistic approach. Nakayama & Osako, 2023 simulated plastic debris from land to oceans for Japan using a process-based approach with biogeochemical cycle models.

Among all existing models for plastics, the MARINA-Plastics model (Model to Assess River Inputs of pollutaNts to seAs for Plastics) has been recently developed to quantify annual macroplastics and microplastics in rivers of 10,226 sub-basins in the world with SSP scenarios for trends in urbanization and wastewater treatment (Strokal et al., 2023). The MARINA-Plastics model was evaluated as part of multi-pollutant assessments of water quality (Bak et al., 2024; Micella et al., 2024; Strokal et al., 2021; Strokal et al., 2023; Ural-Janssen et al., 2023; Wang et al., 2020). This model is a promising tool and does not require a lot of data and computation time, but its application is limited to two future years (2050 and 2100) and only a few applications were done for microplastics in rivers of specific regions, such as the Black Sea (Strokal et al., 2022). Additionally, the model is limited to a few years in the period of 2010–2100 (2010, 2050, and 2100). These years are used as snapshots to analyze water pollution. This limits an analysis for the 21st century. A 10-year time step would support such analysis but needs to be integrated into the model. This 10-year information is especially needed for supporting the achievement of SDGs in the 21st century.

Here, we aimed to understand better the effects of improved centralized sanitation and reduced production and consumption on point-source inputs of microplastics into rivers from 2010 to 2100 with a 10-year time step for 10,226 sub-basins globally. This study chooses SSP2 as the baseline scenario. We develop three new future scenarios relative to the baseline socio-economic development. Our new scenarios reflect practices that are associated with SDG6 or/and SDG12 (details in Section 2). We focus on sewage-related inputs of microplastics to rivers in 10,226 sub-basins (delineated in an earlier study by Strokal et al., 2021). We quantify the distribution of microplastic pollution over the years and identify the effects of SDG-oriented practices to reduce microplastic pollution in short (by 2030) and long (by 2100) (see details in Section 3). This insight could provide temporal and spatial trends of microplastic pollution based on the development of urbanization with 10-year intervals from 2010 to 2100. Our insights could also support policy-relevant actions to reduce river pollution and facilitate the achievement of SDG6 (Clean Water and Sanitation) and SDG12 (Responsible Consumption and Production). Below, we present the modeling approach and scenario description (Section 2), followed by results and discussion on model uncertainty and policy implications (Section 3). Finally, we provide main conclusions of our study.

2 | METHODOLOGY

2.1 | Modeling approach

The MARINA-Plastics model is short for a Model to Assess River Inputs of pollutaNts to seAs for Plastics (Strokal et al., 2023). The model has been validated against available observations and evaluated using sensitivity analysis and comparisons with other studies (Strokal et al., 2023). The model quantifies the export of plastics from land to rivers and by rivers to the coastal waters from point (sewage systems) and diffuse (mismanaged solid waste) sources. In this study, we only focus on the microplastic inputs into rivers from point sources by extending the period of 2010–2100 with a time step of 10 years. Microplastics in sewage systems are derived from car tire wear, PCPs, household dust, and laundry. Point-source inputs of microplastics to rivers are quantified as a function of the urban and rural population, population with sewage connections, treatment efficiencies, and per capita microplastic consumption and production. The main equations are presented in Table S1. The descriptions of the model variables are given in Table S2.

The main equation to quantify inputs of microplastics from point source i to rivers in sub-basin j is (MARINA-Plastics, Strokal et al., 2023):

$$RS_{sew.MIP.i.j} = Pop_{sew.j} \times WShw_{cap.MIP.i.j} \times \left(1 - hw_{frem.MIP.j}\right), \quad (1)$$

$$RS_{sew.MIP.j} = \sum_{i} RS_{sew.MIP.i.j}, \quad (2)$$

where, $RS_{sew.MIP.i.j}$ is the annual input of microplastics (MIP) to rivers from point source *i* (car tire wear, PCPs, household dust, or laundry from sewage systems) in sub-basin j (kg/year).

$RS_{sew.MIP.j}$ is the annual input of microplastics (MIP) to rivers from all point sources in sub-basin *j* (kg/year).

$Pop_{sew.j}$ is the total population with sewage (sew) connections in sub-basin *j* (people/year). Population connected to sewage systems is calculated by the data of population and the fraction of population with sewage connections. The population data at the grid cell of 0.5° for rural, urban, and total population was available in the NCAR database (Jones & O'Neill, 2016). We aggregated the gridded data to sub-basins for the 10-year time step from 2010 to 2100.

$WShw_{cap.MIP.i.j}$ is the per capita (cap) consumption or production rate of microplastics (MIP) from point source *i* in sub-basin j (kg/capita/year). This data are available from previous studies (Siegfried et al., 2017; Strokal et al., 2023; van Wijnen et al., 2019).

$hw_{frem.MIP.j}$ is the removal fraction (frem) of microplastics (MIP) during wastewater treatment in sub-basin j (0–1). It is quantified following the approach of Micella et al. (2024):

$$hw_{frem.\,MIP.j} = \left(f_{p.j} \times RE_{MIP.p}\right) + \left(f_{s.j} \times RE_{MIP.s}\right) + \left(f_{t.j} \times RE_{MIP.t}\right) + \left(f_{q.j} \times RE_{MIP.q}\right) + \left(f_{no.j} \times RE_{no}\right), \quad (3)$$

$f_{p.j}$, $f_{s.j}$, $f_{t.j}$, $f_{q.j}$, and $f_{no.j}$ are the fractions of the population (urban and rural) with primary, secondary, tertiary, quaternary, and no treatment types in sub-basin *j*, respectively (0–1, details see Tables S1 and S2). The country data was available in van Puijenbroek et al. (2023). We aggregated the country data to sub-basins using the population in the following way. First, we assigned the national fractions to the corresponding grids of 0.5°. Second, we multiplied the gridded fractions with the gridded population from the NCAR database (Jones &

O'Neill, 2016) to get the gridded population with different treatment types. Third, we summed the gridded population with different treatment types over the corresponding sub-basins and then divided it by the total population at the sub-basin scale to get the fractions of the population with different treatment types at the sub-basin scale.

$RE_{MIP.p}$, $RE_{MIP.s}$, $RE_{MIP.t}$, $RE_{MIP.q}$, and $RE_{MIP.no}$ are removal efficiencies of microplastics during primary, secondary, tertiary, quaternary and no treatment respectively (0–1, details are in Tables S1, S2 and S3). The data was available in Micella et al. (2024) and was used directly in this study.

2.2 | Scenario development

Shared Socioeconomic Pathway 2 (SSP2) was selected as a Baseline Scenario (BS_{MIP}) because it follows the "middle-of-the-road" trends. This implies that socioeconomic development and income growth in countries will likely follow a path similar to the historical pattern (O'Neill et al., 2015). This means that some countries may develop faster than others following their current abilities to invest in those developments. Some countries have made progress in improving the environmental aspects while others have not done that yet over the past. Technological development will depend on income and follow the current trends (Riahi et al., 2017). The achievement of SDGs is generally limited. However, due to development disparities between regions, countries vary in their attention to environmental issues and in their abilities to address environmental problems (Fricko et al., 2017). The population growth is moderate, the rates of which are influenced by the level of education, fertility, and economic growth (Fujimori et al., 2017) (Figure S1). Asia and Africa are two major areas for which a larger increase in their population is projected compared to the other continents in the future. The Asian population is expected to increase by 2050 and after 2050 may decrease by the end of the 21st century. The African population is expected to keep increase over the entire 21st century (Figure S2). With the development of urban construction, in some urban areas over 75% of the population may become connected to centralized sanitation after 2050 (Figure S3). For the rural population, this will take time. For example, it is assumed that at least 50% of the rural population may be connected to sewage systems by 2100 (Figure S4). The level of wastewater treatment for microplastics in most areas globally will increase and may range from 25% to 50% among the sub-basins in the world for the year of 2070 (Figure S6). Besides, economic growth is expected to increase the consumption and production of daily necessities for life and vehicles for traffic, but this will likely vary among countries (van Wijnen et al., 2017). In more developed countries (e.g., Europe, and North America), people may buy more products to improve their quality of life and use traffic to go further places (van Wijnen et al., 2017). This might be different for less developed countries that are located in Africa and Asia.

Three new alternative scenarios are developed in this study based on the BS_{MIP} (Table 1). New scenarios include the interpretation of sustainable practices for centralized sewage systems (reflecting SDG6), reduced microplastic consumption and production to avoid waste generation (reflecting SDG12) and a combination of these practices.

The first new scenario is called the Fair Sanitation & Treatment scenario (FST_{MIP}, Table 1). It reflects SDG6 sanitation practices for centralized sewage systems. SDG6 aims to provide "adequate and equitable sanitation for all by 2030" and "halving the proportion of untreated wastewater by 2030" (Nilsson et al., 2016). We interpret this formulation into our scenario with a focus on microplastics. This implies that open defecation will end in all our sub-basins. Since urban areas develop generally faster, all urban populations in all sub-basins will be connected to sewage systems by 2030 (100% of the urban population with sewage connections) to maintain fairness among urban sub-basins. For the rural population, the development in the future will not be as rapid as for the urban population. To achieve the goal that at least half of the rural population is connected to sewage systems (Arora & Mishra, 2022), we assume that the sewage connection will increase by 50% in 2030 relative to the BS_{MIP} scenario in all sub-basins. For other years (2040, 2050, 2060, etc.), we also assume a 50% increase in the sewage connection rates relative to the baseline scenario in those years. If sewage connections for the rural population in some sub-basins are still below 50%, then we increased the connections to 50% for those sub-basins. These assumptions influence the following model input: the total population with sewage connections in sub-basins ($Pop_{sew.j}$, see Equation (1), Table S1, and Figure S5). To reflect on "halving untreated waste" from one of the SDG6 targets, we assumed that the removal fractions of microplastics during wastewater treatment will increase by 50% (to the maximum of 88% based on Micella et al., 2024) in all sub-basins relative to the BS_{MIP} value in 2030 (Arora & Mishra, 2022). The same holds for the other years (2040, 2050, 2060, etc.). This assumption influences the following model inputs: the removal fractions of microplastics during wastewater treatment in sub-basins ($hw_{frem.MIP.j}$, see Equation (1) above, and Figure S7).

The second new scenario is called the Waste Generation Control scenario (WGC_{MIP}, Table 1). It reflects SDG12 waste-generation practices for microplastic consumption and production. SDG12 aims to "substantially reduce waste generation through prevention, reduction, recycling and reuse by 2030" (Nilsson et al., 2016). We interpreted this formulation into our scenario with a focus on microplastics. The urban and rural populations with sewage connections and the treatment removals for microplastic will be the same as in the BS_{MIP} scenario. In contrast, the consumption or production rate of microplastics per person in this scenario will decrease by 50% relative to BS_{MIP} for each 10-year step. This decrease is assumed to be realized through restrictions on plastic production and use, and reductions in the purchase of plastic products (Hughes, 2020). In detail, per capita production rates of microplastic by PCPs, household dust, laundry, and car tire wear will decrease by 50% from 2030 to 2100 relative to BS_{MIP} (see Table 1). This assumption influences the following model input: per capita (cap) consumption or production rates of microplastics ($WShw_{cap,MIP,i,j}$, see Equation 1 above).

TABLE 1 Scenario assumptions for the period of 2020–2100 with a time-step of 10 years.

Model inputs	Population	Baseline scenario BS_{MIP}	Assumptions for alternative scenarios relative to BS_{MIP}		
			FST_{MIP}	WGC_{MIP}	CWM_{MIP}
Removal fractions of microplastics during treatment* (%)	Rural	0–88	+50%	BS_{MIP}	+50%
	Urban	0–88	+50%	BS_{MIP}	+50%
Population with sewage connections (%)	Rural	0–100	+50%**	BS_{MIP}	+50%**
	Urban	0–100	100%	BS_{MIP}	100%
Per capita consumption rates of microplastics via personal care products (kg/capita/yr)	Rural	0.0071	BS_{MIP}	−50%	−50%
	Urban	0.0071	BS_{MIP}	−50%	−50%
Per capita production rates of microplastics during household dust (kg/capita/yr)	Rural	0.08	BS_{MIP}	−50%	−50%
	Urban	0.08	BS_{MIP}	−50%	−50%
Per capita production rates of microplastics during laundry (kg/capita/yr)	Rural	0.12	BS_{MIP}	−50%	−50%
	Urban	0.12	BS_{MIP}	−50%	−50%
Per capita production rates of microplastics through car tire wear (kg/capita/yr)	Rural	0.18 (HDI >0.785); 0.018 (HDI ≤0.785)	BS_{MIP}	−50%	−50%
	Urban	0.18 (HDI >0.785); 0.018 (HDI ≤0.785)	BS_{MIP}	−50%	−50%

Note: BS_{MIP} is a Baseline scenario reflecting Shared Socioeconomic Pathway 2 (SSP2). FST_{MIP} is a Fair Sanitation & Treatment scenario reflecting SDG6-oriented practices for sanitation. WGC_{MIP} is a Waste Generation Control scenario reflecting SDG12-oriented practices for the consumption and production of microplastics. CWM_{MIP} is a Comprehensive Waste Management scenario reflecting both SDG6- and SDG12-oriented practices. HDI is short for the Human Development Index. "+" refers to increases and "−" refers to decreases in model inputs relative to the BS_{MIP} values for every 10-year time step. "*" The maximum removal fractions of microplastics during treatment is set (88%) based on Micella et al. (2024). "**" We assumed that the rural population with sewage connections will increase by 50% relative to the baseline scenario; however, if this sewage connection stays below 50%, we increase the connections to 50%.

The third new scenario is called the Comprehensive Waste Management scenario (CWM_{MIP}). It reflects the combination of SDG6 (from the FST_{MIP} scenario) and SDG12 (from the WGC_{MIP} scenario) practices to reduce microplastic pollution. This scenario combines the assumptions of the previous two scenarios (see Table 1).

3 | RESULTS

3.1 | Microplastic inputs to rivers in the past

Globally, around 460 kton of microplastics entered all rivers from sewage systems in 2010 (Figure 1). By 2020, this amount increased by 16% globally. However, this point-source inputs of microplastics to rivers differed among continents (Figure 2).

Asian and European rivers were the most polluted compared to the other continents (Figure 3). For example, Asian rivers received over 100 kton of microplastics, and European rivers received around 50 kton of microplastics in 2010. These loads increased by 2020 (Figure 3 and Table S5). High pollution levels for Asian rivers were associated with a high population density (Figure S2) and poor wastewater treatment (Figures S6 and S7). High pollution levels in Europe could be explained by relatively higher per capita consumption and production of microplastics in PCPs, household dust, laundry, and car tire wear compared to continents such as Africa (Figure S9). Europe had one of the best treatments (Figure S8), and a relatively lower population in 2010 compared to Asia (Figure S2).

Among other continents, Africa had a relatively lower contribution to global microplastic pollution in the past (2010 and 2020). This could be associated with lower microplastic consumption and production, lower connections to sewage systems, and poor treatment in Africa compared to Europe and Asia in 2010 and 2020 (Figures S3, S7). North America and South America had lower levels of microplastics in their rivers because of the lower population with sewage connections compared to Europe (Figure S1) and medium to high levels of wastewater treatment efficiencies compared to Africa (Figure S6).

Microplastics in rivers (kg/km^2/year) varied among 10,226 sub-basins in the past years (Figure 2). Sub-basins in Asia, Europe, North America, and South America experienced higher levels of microplastics in their rivers compared to the other sub-basins (Figure 3). Some individual sub-basins around the Mediterranean Sea and the Black Sea had also high inputs of microplastics (Figure 3). These high inputs of microplastics were largely associated with lower wastewater treatment, compared to the sub-basins in Western and Northern Europe (Figure S6). Other examples are the St Lawrence, Mississippi, and Parana sub-basins located in North America which were calculated to receive 5–50 kg/km^2 of microplastics to their rivers in the past years. This was caused by higher societal development (a higher human development index) because of more microplastic production and thus more microplastics in sewage (Figure S8).

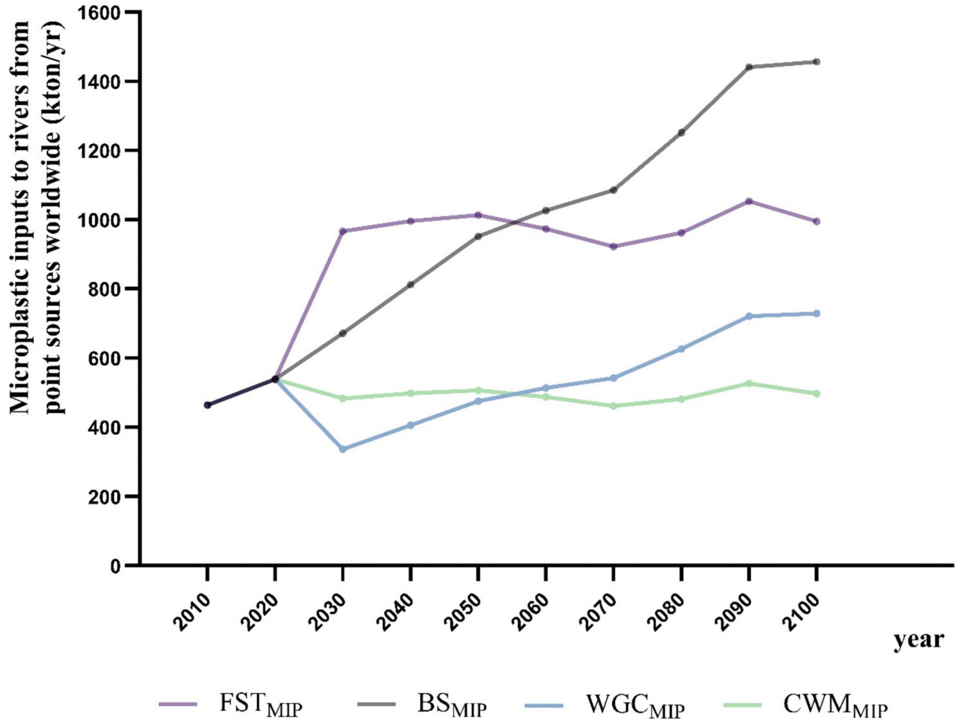

FIGURE 1 Total annual inputs of microplastics to rivers from point sources worldwide during the period of 2010–2100 with a time step of 10 years according to the baseline and three alternative scenarios (kton/year). Point sources are sewage systems including microplastics from personal care products, laundry, household dust, and car tire wear. The baseline scenario (BS_{MIP}) is based on the shared socio-economic pathway 2. FST_{MIP}, WGC_{MIP}, and CWM_{MIP} are three alternative scenarios relative to the baseline and assume increased sewage connections with improved treatment (FST_{MIP} reflecting SDG6 sanitation practices), reduced microplastic consumption and production (WGC_{MIP} reflecting SDG12 practices) and the combination of these two scenarios (CWM_{MIP}). SDG is short for Sustainable Development Goal. Source: The MARINA-Plastics model (see Section 2).

3.2 | Microplastic inputs to rivers in the future

3.2.1 | The baseline scenario (BS_{MIP})

Globally, microplastics in rivers are expected to almost triple between 2020 and 2100. However, these trends differ *among continents* and years (Figure S10). In 2030, Asia and Europe are projected to remain major contributors to global microplastic pollution in rivers (Figure 2, Section 3.1). This can be explained by more urbanization and the developed societal and economic level in Europe and the large population in Asia. From 2030 to 2100, the contribution of Africa to global microplastic pollution is expected to increase considerably (Figure 4) and exceed the contribution of Europe (Figure 3b). This could be associated with a projected fast increase in the human population and urbanization in the future in Africa (Figures S1, S2, and S8). Urban facilities are expected to be improved and more people will be connected to the centralized sewage systems in Africa (Figure S6). Meanwhile, the level of environmental development in Africa may not catch up with the development in Europe and Asia. This implies that the level of microplastic treatment in Africa is expected to stay relatively low in the future compared to the treatment level in Europe and Asia (Figure S6). For the other continents, their contribution to global microplastic pollution in rivers is expected to increase slowly because of the slow increase in the human population, and sewage connections (Figure 3b).

Among the sub-basins, different trends are projected for microplastic inputs to rivers (Figure 3). By 2030, for many sub-basins in Asia (e.g., Godavari, Mekong, Hong), Europe (e.g., Glama, Kuban), and Africa (e.g., Nile, Niger, and Orange) inputs of microplastics to their rivers are projected to increase compared to the past (Section 3.1, Figure S14). Between 2030 and 2050, increases are projected for microplastic inputs into the Rhine, Po, Seine, Ganges, Mississippi, Nile, and Niger rivers. Between 2050 and 2070, the Congo, Cauweri, and Jubba rivers may receive more microplastics. Between 2070 and 2100, increases in microplastics in rivers may continue for the Ob, Irrawaddy, and Parana sub-basins.

3.2.2 | Reducing future microplastic pollution

SDG-oriented practices for centralized sewage sanitation (FST_{MIP} reflecting SDG6) and microplastic consumption and production (WGC_{MIP} reflecting SDG12) may reduce future microplastic pollution in many rivers in the world. However, their effects differ over time and continents. Some practices seem to be more effective in the long term (by 2100) while others are in the short term (by 2030, Figure 4).

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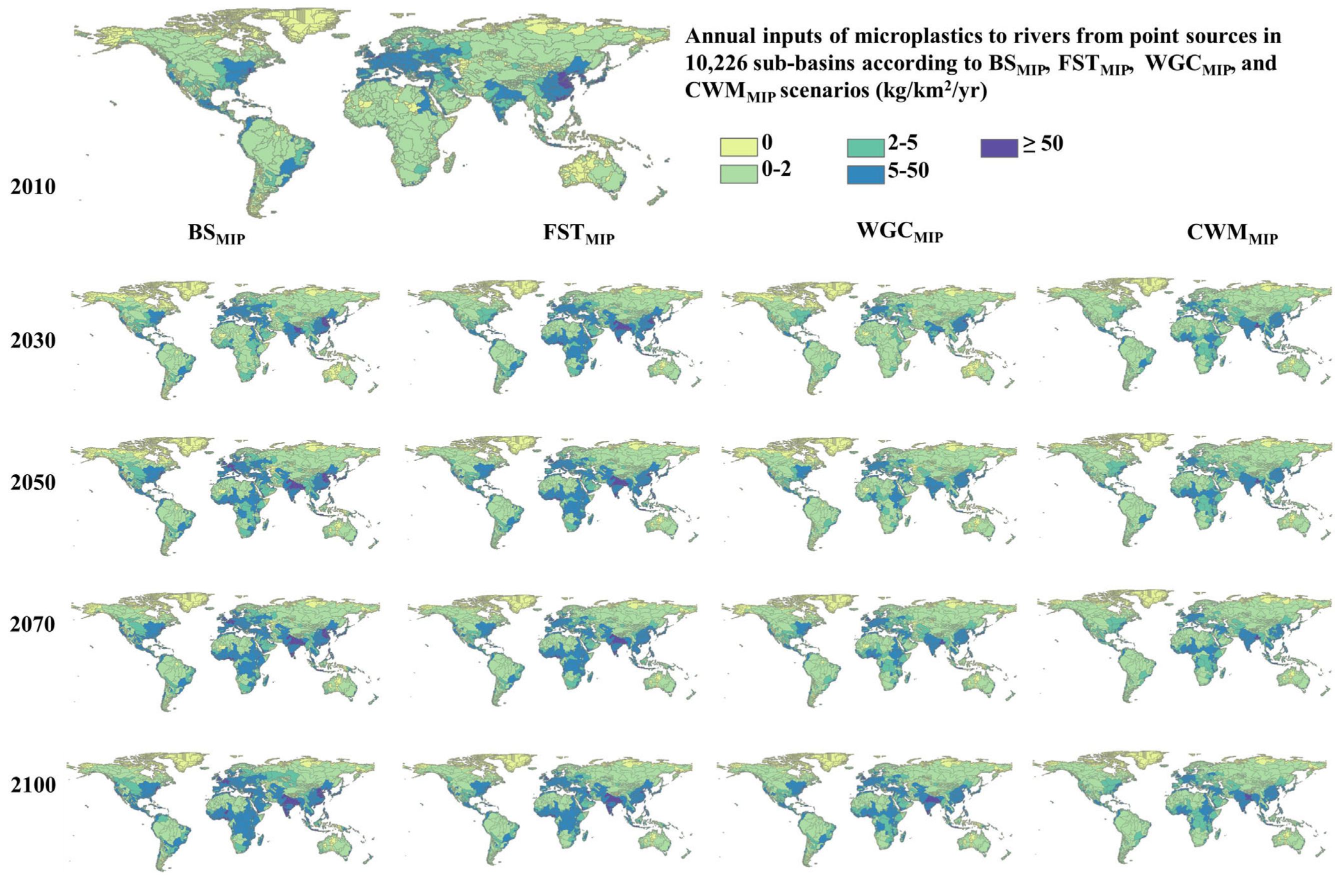

FIGURE 2 Annual inputs of microplastics to rivers from point sources for 2010, 2030, 2050, 2070, and 2100 in 10,226 sub-basins according to the BS$_{MIP}$, FST$_{MIP}$, WGC$_{MIP}$, and CWM$_{MIP}$ four scenarios (kg/km^2/year). Point sources are sewage systems including microplastics from personal care products, laundry, household dust, and car tire wear. Inputs of microplastics to rivers for each 10 year from 2010 to 2100 are in Figures S10–S13. The baseline scenario (BS$_{MIP}$) is based on the shared socio-economic pathway 2. FST$_{MIP}$, WGC$_{MIP}$, and CWM$_{MIP}$ are three alternative scenarios relative to the baseline and assume increased sewage connections with improved treatment (FST$_{MIP}$ reflecting SDG6 sanitation practices), reduced microplastic consumption and production (WGC$_{MIP}$ reflecting SDG12 practices) and the combination of these two scenarios (CWM$_{MIP}$). SDG is short for Sustainable Development Goal. Source: The MARINA-Plastics model (see Section 2).

It may be possible to stay below the baseline pollution level, but not for all sub-basins, alternative scenarios, and years. However, it may be challenging to reduce the river pollution levels to below 2020 or 2010 by 2100, especially on a global scale. Asian and European rivers were the most polluted compared to the other continents in the past years but Africa will join them in the future (Figure 3). Below, we describe the results for our alternative scenarios.

The scenario reflecting SDG6 centralized sanitation practices (FST$_{MIP}$)

Increased centralized sewage systems with improved treatment may be effective in reducing river pollution by microplastics in the longer term *worldwide and at the continental scales* (Figures 4 and 5). By 2030, globally, microplastics in rivers will almost double compared to 2020 (Figure 1), and Africa will become the second largest contributor to this global pollution (Figure 3c). These increases are associated with a large increase in sewage connections (especially for the urban population) with higher population growth (Figures S1 and S6). However, assumed treatment improvement may not be sufficient to reduce microplastic inputs to rivers from sewage in 2030 to below the baseline and 2020 levels globally (Figure 1). After 2030, global microplastic pollution levels will stabilize by 2100 and will be below the baseline (after 2060), but still higher than in 2020 (Figures 1 and 5). During this period, the sewage connections are also projected to increase, especially for the rural population. Removal fractions of microplastics during treatment will further increase at the same speed as in 2030. As a result, between 2030 and 2050, global microplastic inputs to rivers will increase slightly. In contrast, between 2050 and 2070, the global pollution levels will decline and then slightly increase by 2090 and again decrease by 2100 (Figures 1 and S5).

Among the sub-basins, trends in microplastic inputs to their rivers differ over the years (Figure 2). By 2030, microplastic inputs to rivers are projected to increase for many sub-basins located in Asia (e.g., Ganges, Indus, Chao Phraya), and Africa (e.g., Congo, Niger, and Nile). For the other sub-basins located in North America (e.g., the Hay sub-basin), South America (e.g., Pilcomayo), and Asia (e.g., Aldan), microplastic pollution in their rivers is projected to increase slightly by 2030 (Figure S15). Between 2030 and 2050, microplastic inputs to

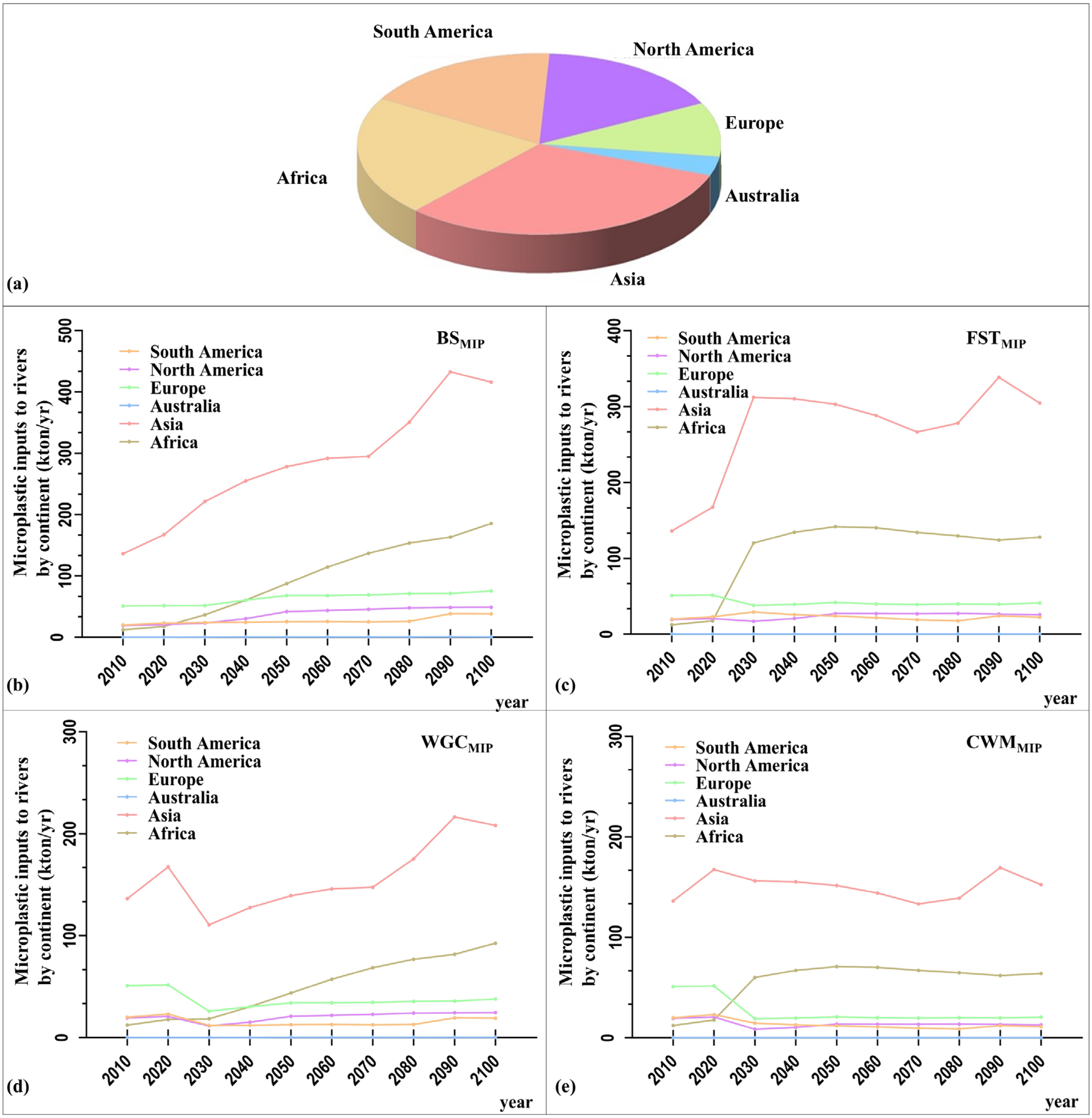

FIGURE 3 Total annual inputs of microplastics to rivers from point sources by continents during the period of 2010–2100 with a time step of 10 years according to the baseline and three alternative scenarios (kton/year). (a) A Pie shows the proportion of the surface area of each continent (0–1). (b–e) Graphs show river pollution by microplastics according to the four scenarios. The baseline scenario (BS$_{MIP}$) is based on the shared socio-economic pathway 2. FST$_{MIP}$, WGC$_{MIP}$, and CWM$_{MIP}$ are three alternative scenarios relative to the baseline and assume increased sewage connections with improved treatment (FST$_{MIP}$ reflecting SDG6 sanitation practices), reduced microplastic consumption and production (WGC$_{MIP}$ reflecting SDG12 practices) and the combination of these two scenarios (CWM$_{MIP}$). SDG is short for Sustainable Development Goal. Source: The MARINA-Plastics model (see Section 2).

rivers are projected to further increase, but not for all sub-basins in the world (Figure S11). The increasing trends will continue between 2070 and 2090 for rivers in some Asian and European sub-basins. However, after 2090, those sub-basins may receive less microplastics (Figure S11).

The scenario reflecting SDG12 consumption and production practices (WGC$_{MIP}$)

Reducing microplastic consumption and production (SDG12) may be effective in reducing river pollution by microplastics in the shorter term *worldwide and at the continental scales* (Figures 1 and 4). By

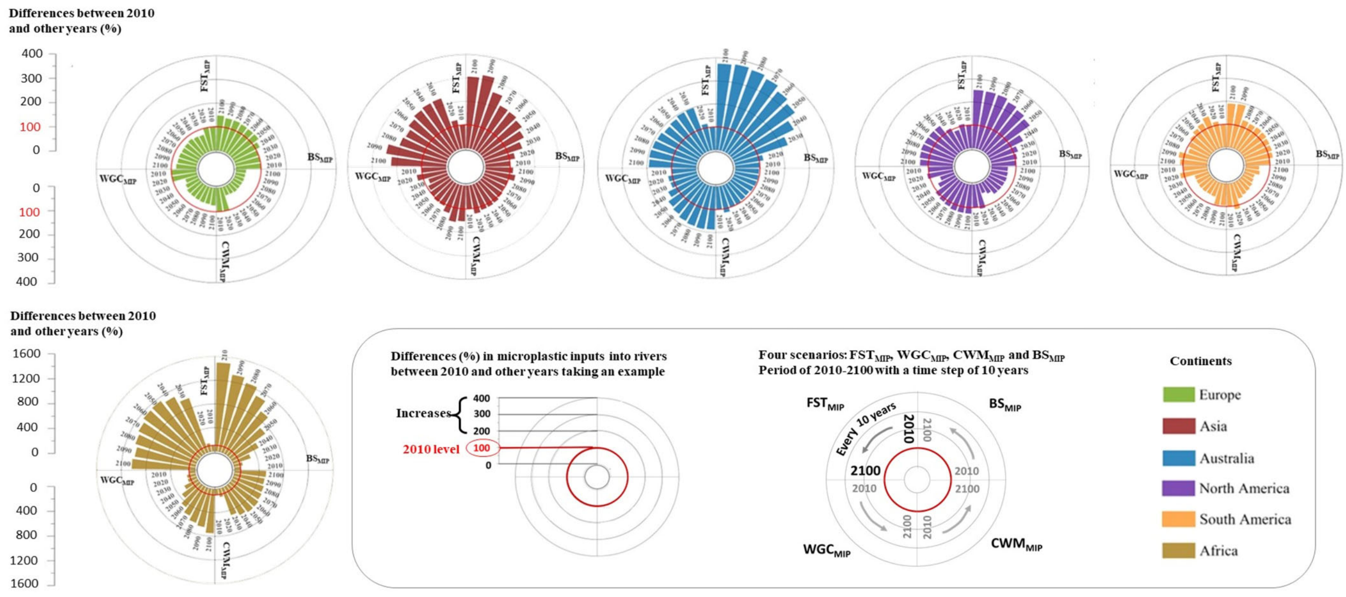

FIGURE 4 Differences in annual microplastic inputs into rivers between 2010 and other years in the period of 2010–2100 with a time step of 10 years for four scenarios and six continents (Europe, Asia, Australia, Africa, North America, and South America, %). The 2010 level is set at 100% and indicated by the red circle in the pies. For Africa, the differences in microplastic inputs to the rivers between the 2010 level and other years are much higher than for other continents. Thus, the scale for Africa differs in this figure. Source: The MARINA-Plastics model (see Section 2).

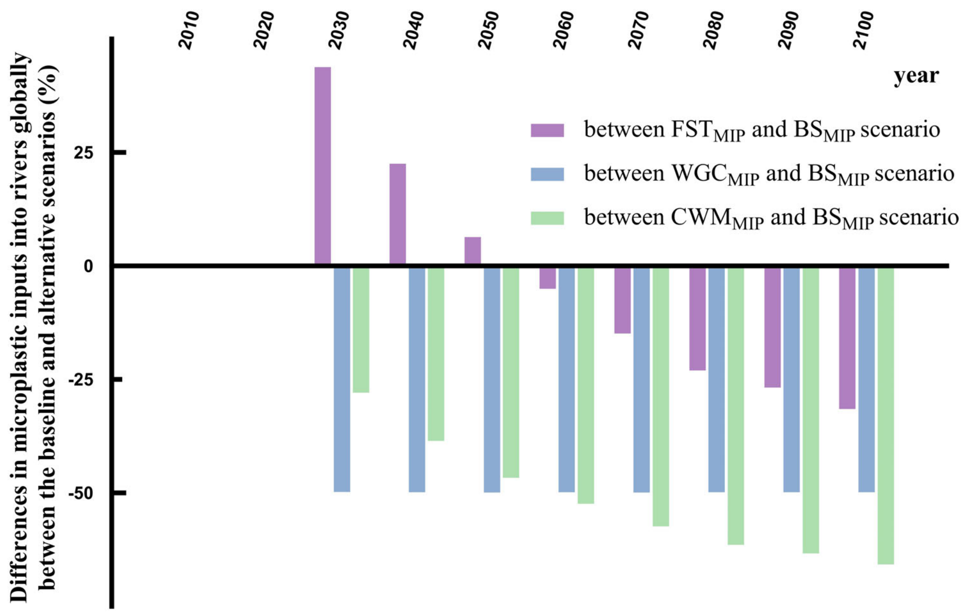

FIGURE 5 Differences in annual inputs of microplastics into rivers from point sources worldwide between the baseline (BS$_{MIP}$) and alternative three scenarios for the period of 2010–2100 with a time step of 10 years (%). The baseline scenario (BS$_{MIP}$) is based on the shared socio-economic pathway 2. FST$_{MIP}$, WGC$_{MIP}$, and CWM$_{MIP}$ are three alternative scenarios relative to the baseline and assume increased sewage connections with improved treatment (FST$_{MIP}$ reflecting SDG6 sanitation practices), reduced microplastic consumption and production (WGC$_{MIP}$ reflecting SDG12 practices) and the combination of these two scenarios (CWM$_{MIP}$). SDG is short for Sustainable Development Goal. Source: The MARINA-Multi model (see Section 2).

2030, globally, microplastics in rivers will decrease by almost 40% (Figure 1) because of a 50% reduction in consumption and production rates of microplastic per capita (Figure 2 and Table S4). However, after 2030, global pollution levels will increase by 2100 and will be above the level of 2020 (after 2060) but around 30% below the baseline in 2100 (Figure S12). This is because the population will keep increasing in the future, so the usage of plastic products will increase accordingly (Figure S1). Africa will exceed the contribution of Europe and will become the second contributor to global microplastic pollution from 2040 to 2050 (Figure 3d). The reduced per capita consumption and production of microplastics may not help to decrease microplastics in rivers by 2100 because of the increasing trend in population, societal development, and sewage connections (Figures 1 and 5).

Among the sub-basins, trends differ in microplastic pollution for their rivers over time. By 2030, rivers in several sub-basins may receive less than 50 kg/km^2/year, which is lower than in the past (Figure 2). Examples are the Yellow and Yangtze rivers in Asia, the Volga, Danube, and Douro rivers in Europe, the Mississippi, St_Lawrence, and Parana rivers in America, and the Nile River in Africa (Figure 2). Between 2030 and 2050, rivers in several sub-basins in the world (e.g., the Nile, Mississippi, St_Lawrence, Godavari, and Loire rivers) may continue receiving more microplastics from sewage systems. Between 2050 and 2070, increasing trends in microplastics are also projected for rivers such as the Ganges, Volta, Niger, and Douro. Similar trends are projected from 2070 to 2100 for the Pearl, Ganges, Mississippi, and Parana rivers and sub-basins draining into the Mediterranean Sea (Figure S16).

The combined scenario (CWM$_{MIP}$)

Combined implementations of improved centralized sewage systems and reduced microplastic consumption and production may be the most effective in reducing future microplastic pollution in the short- and long-term *worldwide and at the continental scales* (Figures 1 and 4). By 2030, globally, inputs of microplastics in rivers are projected to decrease by almost 20%. It is a result of a combination of higher population growth, higher sewage connections, higher levels of removal efficiencies of wastewater treatment, and reductions in per capita microplastic consumption and production rates (Table 1). Africa will remain the second contributor to global microplastic pollution in 2030 as in the other scenarios (Figure 3). After 2030, globally, inputs of microplastics to rivers will stabilize by 2100 and stay slightly below the level of 2020 for most years (Figure 1).

Among sub-basins, trends in microplastic inputs to rivers are different as in the other scenarios (Figure 2). By 2030, for some sub-basins river pollution may increase (e.g., Mekong, Godavari, Ganges, Nile, and Niger rivers) while for other sub-basins river pollution may decrease (e.g., Yangtze, Danube, Volga, St_Lawrence, and Mississippi rivers, Figure 6). After 2030, microplastic inputs to rivers are projected to fluctuate depending on sub-basins (Figure S13). Between 2030 and 2050, in some sub-basins of Africa and South America, rivers may receive slightly more microplastics. In contrast, between 2050 and 2070, microplastics in the Parana, Irrawaddy, and Congo rivers at the sub-basin scale are projected to decline. However, between 2070 and 2090, some rivers in Asian sub-basins (like the Ganges Rivers) may continue receiving more microplastics. This may change by 2100 with a decreasing trend in their river pollution (Figure S17).

4 | DISCUSSION

4.1 | Model evaluation and comparisons

We developed the MARINA-Plastics model with three new scenarios for a time step of 10 years from 2010 to 2100. The previous model versions (Micella et al., 2024; Strokal et al., 2021; Strokal et al., 2023) were run mainly for 2010, 2050, and 2100 ignoring trends in between. We started from the existing version for the year 2010 (Strokal et al., 2023) that was evaluated using the "building trust circle" approach (Micella et al., 2024; Strokal et al., 2021). This approach was applied to compare model values and the spatial variability with other studies (Micella et al., 2024; Strokal et al., 2023), perform a sensitivity analysis in which 25 model inputs were changed to test the sensitivity of model outputs (Strokal et al., 2021), and validate the model outputs with available observations for river mouths (Micella et al., 2024). Micella et al. (2024) compared the model results with observation datasets from 120 stations close to river months. Validation results show that model results and observation data share the same order of magnitude ($R_2 = 0.94$). We used this evaluated model and expanded it to 2020 and other future years. Then we further compared our results with other studies.

The total microplastic input to rivers in 2010 from our research is 460 kton (Table S5), which is much higher than in other studies: for example, 6.1–6.6 kton from Weiss et al. (2021), 47 kton from Van Wijnen et al. (2019), 236 kton from Van Sebille et al. (2015), 35–66 kton from Eriksen et al. (2014). Those studies did not only calculate microplastics from sewage sources but also accounted for riverine exports, while we did not. We focused on point-source inputs into the rivers. Microplastics can be lost during river transport explaining why our values are much higher than in those studies. Besides, the estimated mass of mismanaged plastic waste generated in 2010 by Jambeck et al. (2015) presented that Aisa countries are the main contributors of plastic waste. Lebreton et al. (2017) did a global projection and focused on all types of plastic showing that 67% of polluted rivers are located in Asia. This is consistent with the result of our research that Asia is a hotspot area for microplastic pollution (Table S5). Estimates from Schmidt et al. (2017) showed that 80% of catchments delivering the highest plastic loads to the ocean are from Asia, confirming Asian rivers as hotspots, which also shares similar results from our research (Figure 2). The total microplastic export from Van Wijnen et al. (2019) showed that more Asian areas export total microplastic over 1000 ton/year. under the future scenario, and this future trend is consistent with our results (Figure 2). Mai et al. (2020) presented that Asia is the major contributor of plastic in the present, which is a similar result to our research (Table S5).

4.2 | Model uncertainties and limitations

This research relied heavily on data collected for 10,226 sub-basins and for every 10 years from 2010 to 2100. The availability of data and its processing to sub-basins may introduce uncertainties. Many

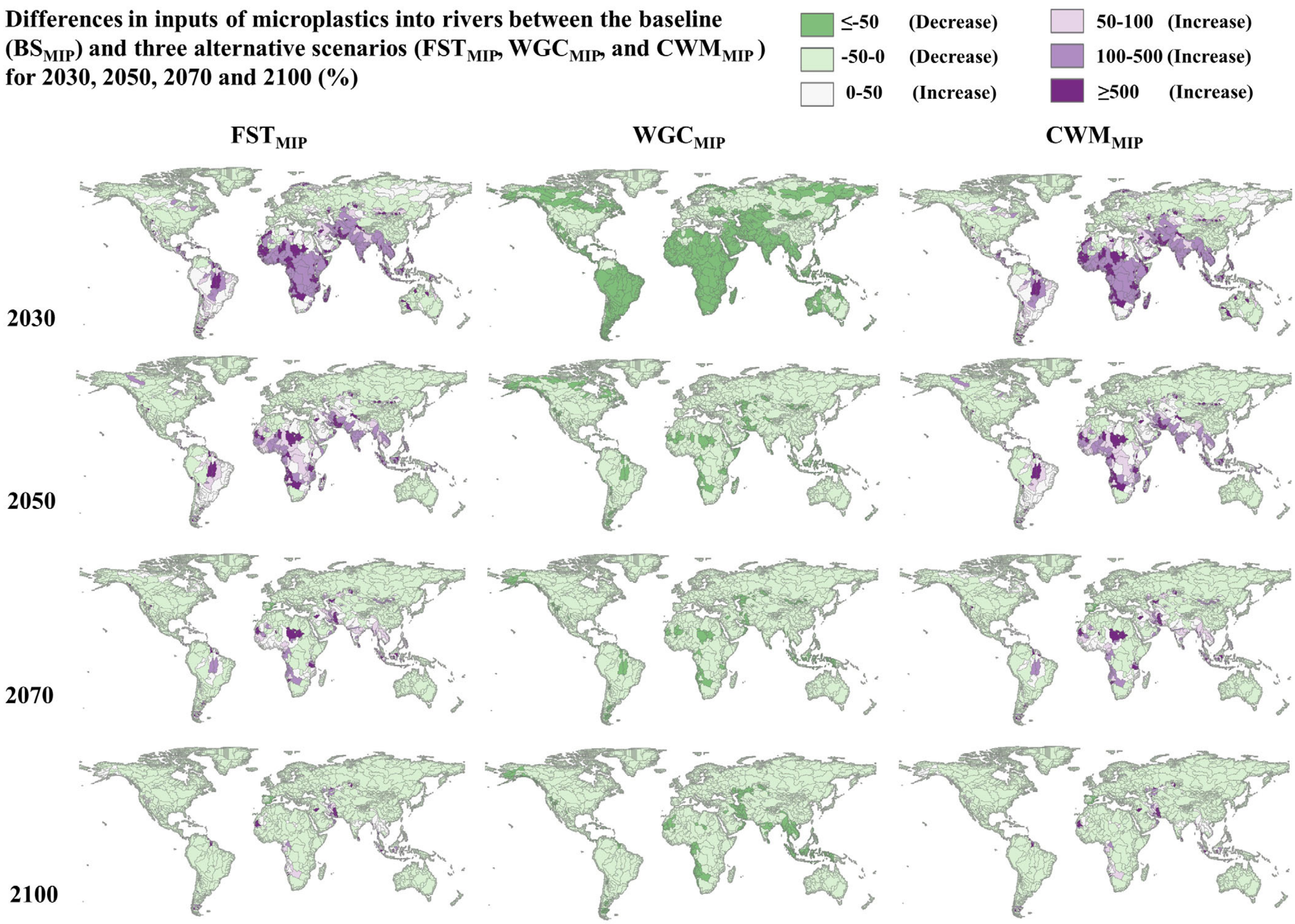

FIGURE 6 Differences in annual inputs of microplastics into rivers between the baseline (BS_{MIP}) and three alternative scenarios (FST_{MIP}, WGC_{MIP}, and CWM_{MIP}) for 2030, 2050, 2070 and 2100 (%). The baseline scenario (BS_{MIP}) is based on the shared socio-economic pathway 2. FST_{MIP}, WGC_{MIP}, and CWM_{MIP} are three alternative scenarios relative to the baseline and assume increased sewage connections with improved treatment (FST_{MIP} reflecting SDG6 sanitation practices), reduced microplastic consumption and production (WGC_{MIP} reflecting SDG12 practices) and the combination of these two scenarios (CWM_{MIP}). SDG is short for Sustainable Development Goal. Source: The MARINA-Plastics model (see Section 2).

datasets were already available at the sub-basin scale from Strokal et al. (2023) for 2010. For the other years, we had to process the data and make sure the data was consistent with the data of 2010. We used the gridded population data from the NCAR dataset and aggregated this data to sub-basins (Jones & O'Neill, 2016). We used the country fractions of the population with sewage connection and the country fractions of the population with treatment types from van Puijenbroek et al. (2023). We aggregated these fractions to sub-basins using the population, which is commonly done in other large-scale water quality studies (Micella et al., 2024; Wang et al., 2020). Country data for the Human Development Index (HDI) was from Jones and O'Neill (2016) that was also aggregated to sub-basins. A few sub-basins missed data because of the aggregations or countries for which data was not provided. We filled in those gaps in data by using the averages for continents.

The main focus of this research was point-source pollution while ignoring other sources. In urbanized and developed areas, most microplastics in rivers may come from point sources such as sewage systems. Thus our results for urbanized basins may not be underestimated to a large extent because point sources may dominate in the urban areas. This may be different for areas with other activities. Agricultural sources might be important in areas with intensive plastic mulching. Li et al. (2023) calculated that agriculture (diffuse source) contributes around 20% to plastic pollution in China as a whole. Therefore, our results may be underestimated due to a lack of diffuse sources. On the other hand, the world is expected to urbanize even more than in the past resulting in more than 3/4 of the global population living in urban areas in 2100. We can likely expect more sewage systems as one of the centralized sanitation practices for highly urbanized areas. This would imply more microplastics from urbanized areas in the future. Considering this, we believe that our study provides useful information under urbanization trends.

Another source of uncertainties is the set of assumptions i n our scenarios (see details in Section 2). We chose SSP2 as our baseline scenario as this scenario assumes that society will follow their business-as-usual environmental management approaches. This choice was made to show what may happen with river pollution by microplastics if society follows its current environmental management. This gave us the basis to develop alternative scenarios with interventions to reduce future microplastic pollution. Our three different scenarios incorporate different intervention strategies: SDG6-oriented for centralized sanitation, SGD12-oriented for reduced consumption and production of microplastics and a combination of both. The choice for those strategies is justified by the need to support SDG6 and SDG12. In our scenarios, we considered regional differences in the socioeconomic developments. However, our assumptions for improving centralized sewage systems and reducing consumption and production of microplastics waste do not differ by region. The implementation feasibility of the assumed sustainable practices may depend on various factors and differ among regions. Examples are practical, institutional, and economic feasibilities as well as inequality aspects. On the other hand, our assumptions show the technical feasibility in terms of the potential reduction in microplastic inputs into the rivers. This could already facilitate a debate on the other implementation aspects (e.g., economic, inequality, institutional, etc.). Our assumptions are also simple and transparent contributing to a better understanding of what may happen with microplastic pollution in the future if all sub-basins implement the assumed SDG practices.

4.3 | Sustainable development goals for future microplastic reduction

Our research adds to the current knowledge in the three main aspects. First, this research is the first global analysis with a time step of 10 years from 2010 to 2100 for 10,226 sub-basins when focusing on the effects of SDG6 and 12 concerning microplastics. The outputs could help policymakers to identity hotspots in different time periods. Second, we created three new scenarios that focus on the interpretation of SDG6 sanitation practices and SDG12 consumption practices for microplastics in a spatially explicit way (sub-basins). The outputs could guide national and international policymakers to adjust their regulations for reducing microplastic pollution based on different future situations. Third, this research provides new insights into the short- and long-term effects of the studied SDGs practices for reducing future microplastic pollution in rivers in an urbanizing world. It will be useful to support SDGs and their associated indicators and help policymaking to decide when over time and where in the world actions are needed to ensure microplastic reduction worldwide. For example, we learn from our analysis that African rivers are expected to receive much more microplastics by 2030 than today because of increased centralized sewage systems due to urbanization trends (Figure 3). For the African government, this shows the importance of investing in making sewage systems efficient with less pollution. Improving wastewater treatment might also be beneficial to reduce not only microplastics but also other types of pollution such as pathogens, and antibiotics. Such synergetic interventions can support even stronger SDG6 targets for clean water and bring new insights into effective solutions.

We showed what reduction strategies might be useful in the short term (by 2030) and longer (by 2100). We argue that sewage systems could be promising options to improve sanitation, but they should be with better treatment (SDG6-oriented) and combined with reductions in microplastic use (SDG12-oriented). Reducing the use of microplastics (SDG-12) showed to be the most effective in the short term. Reaching the longer-term reduction goals will be effective with improved treatment and sanitation (SDG6). This information could support policymakers to develop short- and long-term strategies to avoid microplastic pollution. For example, for Asian rivers, policymaking could invest in better sanitation and in reducing microplastic consumption products supported by environmental policies.

Our results are useful to help fill in the data gaps for SDG6 and SDG12 indicators concerning microplastics (as shown in Figure 3). Examples of indicators could be the proportion of river basins with microplastic pollution reduction. Targets could be established based on the effects of reduction options. This will assist SDGs to develop specific targets for microplastic pollution.

5 | CONCLUSIONS

Our study aimed to understand better the effects of improved centralized sanitation and reduced consumption and production on point-source inputs of microplastics into rivers from 2010 to 2100 with a time-step of 10 years and for 10,226 sub-basins in the world. To this end, we developed four scenarios and implemented them into the MARINA-Plastics Model. Our scenarios are the baseline (BS_{MIP}) following the Shared Socio-economic Pathway 2, and three alternative scenarios relative to this baseline. The first alternative scenario assumes the Fair Sanitation and improved Treatment (FST_{MIP} reflecting SDG6 practices) whereas the second alternative scenario assumes the Waste Generation Control (WGC_{MIP} reflecting SDG12 practices). The third scenario combines the previous two for Comprehensive Waste Management (CWM_{MIP}). The results showed that microplastics in rivers globally will almost triple between 2010 and 2100 in the baseline. Europe and Asia are two major contributors to the global microplastic pollution in rivers from sewage systems. Africa is expected to become the second largest contributor to global pollution in the future. Practices in FST_{MIP} may be effective in the longer term: microplastics in rivers in 2030 will almost double globally whereas it will stay 30% below the baseline in 2100. Practices in WGC_{MIP} may be effective in the shorter term: microplastics in rivers in 2030 will decrease by almost 40% globally compared to 2020 whereas after 2030 microplastics will keep increasing. Practices in CWM_{MIP} may be effective in the whole period: microplastics in rivers will fluctuate slightly over decades and by 2100, microplastics in rivers will maintain a level similar to 2010. Our results could provide a guideline to reduce microplastic pollution in the shorter term (e.g., reducing the use of microplastic products to control waste generation) and in the longer term (improving wastewater treatment to improve sanitation). Our insights could support policymakers in implementing SDG 6 (clean water achieved by fair sanitation and treatment) and 12 (waste generation control).

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CONFLICT OF INTEREST STATEMENT

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

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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