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Domestic wastewater treatment and agricultural reuse progress and reporting challenges

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Abstract
Safely treated wastewater is critical to water-related sustainable development. With a focus on the domestic wastewater component of SDG 6.3, this study synthesized the latest country-level data on domestic wastewater generation and treatment, aggregated by geographic regions and income classifications, and subsequently addressed the challenges for monitoring safe water reuse (wastewater use). The data synthesis reveals that the domestic sector generates 267.5 billion $m^3\ yr^{-1}$ of wastewater globally, of which 63% (168.8 billion $m^3\ yr^{-1}$) is collected in sewers and septic tanks, and 54.7% (146.3 billion $m^3\ yr^{-1}$) is treated. In comparison, 45.3% (121.2 billion $m^3\ yr^{-1}$) is released to the environment in untreated form, either uncollected (98.7 billion $m^3\ yr^{-1}$) or collected but untreated (22.5 billion $m^3\ yr^{-1}$). Although these data, compiled by the World Health Organization (WHO), show progress in view of SDG 6.3.1, the proportion of safely treated wastewater remains strongly uneven between geographic regions and income groups. On the water reuse front, while there is significant progress in industrial (e.g. China) and agricultural (e.g. Egypt) reuse of treated wastewater, untreated water reuse remains a dilemma that requires special attention where it is most common, i.e., in low-income and lower-middle-income countries. Considerable challenges in assessing the state-of-affairs remain because of its terminology, informal status and the limited availability (and usefulness) of reported reuse volumes or areas for WHO's health-based targets.

Keywords Water resources, Wastewater treatment, Water recycling, Water reuse, SDG 6.3.1

1 Introduction

Climate change is impacting water availability and quality, with consequences that extend across all land uses and economic sectors [1, 2]. Estimates reveal that about 40% of the world's largest cities are likely to suffer competition with agricultural water needs [3]. Consequently, agriculture increasingly relies on marginal-quality water resources while gradually yielding its share of high-quality water to non-agricultural uses, such as the domestic sector [4, 5]. The increasing use of water for household activities comes with the tradeoff of generating larger volumes of domestic wastewater, which requires safe management to protect the environment and human health [6]. Given the rising volumes of wastewater production, there is a proactive interest in the potential to recover water, nutrients and energy from domestic wastewater, supported by innovations in resource recovery [7, 8].

Considering the water-related sustainable development challenges, wastewater collection, treatment, and safe and productive reuse can narrow the gap between water supply and demand [9–11]. Moreover, safely treated wastewater helps protect freshwater systems with significant food supply, health and environmental benefits. There are demonstrated examples of safe use of wastewater in agriculture, industry, aquaculture, agroforestry and aquifer recharge [12, 13].

The 2030 Agenda for Sustainable Development calls on national governments to introduce, adopt, and integrate measures aimed at reducing by half the proportion of untreated wastewater discharged into the environment by the year 2030. Such aspirations are based on the Sustainable Development Goal (SDG) 6, its water quality protection and improvement target (SDG 6.3), and its wastewater-specific indicator SDG 6.3.1, which tracks the proportion of wastewater flows from households, services, economic and industrial activities that are safely treated before discharged into the environment or ideally productively reused [14]. Wastewater treatment can occur at the household or industry scale or through centralized or decentralized wastewater treatment plants, which receive effluent through a network of sewer channels or trucks from septic tanks [10, 15]. Wastewater can also be treated in septic tanks with soak pits in specific cases with supportive design for treatment. Constructed wetlands have also emerged as a promising opportunity to treat wastewater as a natural and cost-effective alternative, particularly for smaller communities and towns with available land [16].

The aim of tracking monitoring progress on SDG 6.3.1 is to assess the status of wastewater management in all the countries. This process provides essential and up-to-date data and information to support policymakers and relevant stakeholders in making informed decisions to decrease water quality deterioration, limit the discharge of hazardous substances, and enhance safe collection, treatment, reuse or disposal of wastewater [14].

With a focus on the domestic wastewater part of SDG 6.3.1, this study investigates the latest data (2023) on wastewater generated by household activities and its treatment across countries grouped into global regions and income groups, with particular attention to the challenges for monitoring safe water reuse. The study contributes new data, information, trends, and insights into the use of treated wastewater for crop production. It expands on the progress made in certain countries, including China, Mexico and India, and across regions such as the Middle East and North Africa.

2 Methodology

The domestic wastewater component of SDG 6.3.1 includes both sewage and fecal sludge, either collected and treated on-site at the household level, such as via septic tanks, or collected and carried through a sewerage network to wastewater treatment plants and treated off-site. The World Health Organization (WHO) serves as the United Nations agency in charge of overseeing the domestic wastewater component of SDG 6.3.1. This portion of total wastewater is tracked within the sanitary system. It is directly linked to SDG 6.2.1, which focuses on access to safely managed sanitation services.

WHO oversees and facilitates data collection efforts to support the Joint Monitoring Programme for Water Supply, Sanitation, and Hygiene (JMP). The official statistics are produced on behalf of WHO and United Nations International Children's Emergency Fund (UNICEF) for SDG 6.2.1a, which tracks the status of safely managed sanitation referred to as the proportion of population using an improved sanitation facility, which is not shared with other households. The published estimates of JMP on the percentage of households connected to sewer systems and septic tanks are also used as a data source to estimate the volume of household wastewater generated and collected. Wastewater generated by the industrial sector is not part of domestic wastewater and is, hence, out of the scope of this study. For the reuse terminology, like direct and indirect reuse, we followed the FAO Water Report [17]. We made one exception and used the popular wording of 'wastewater reuse' in addition to the technically correct terms of either wastewater **use** or water **reuse**, all meaning the same in this paper.

2.1 Data synthesis on wastewater generation and treatment

The datasets that underpin this study are developed by WHO for monitoring SDG 6.3.1, containing estimates of domestic wastewater generation and treatment at the country scale for 2023 [14]. Country-level data collection is commonly undertaken by the federal and provincial line ministries and institutions dealing with, for example, water and sanitation, environment and climate change, public health services, housing, infrastructure, and production; utilities and on-site service providers; the National Statistical Offices (household surveys and registers of economic activities); and planning commissions dealing with national-level strategic planning and allocation of resources to different sectors [14].

The quality and robustness of the datasets on domestic wastewater have gone through different periodic steps, which improved data quality significantly since the first report on SDG 6.3.1 in 2018. While data coverage for the household component of SDG 6.3.1 is high and global and regional aggregate estimates have been established for 2020 and 2022, WHO's methodological approach of computing country estimates based on a snapshot of the most recent country data on household wastewater occasionally results in significant variability in the estimates between reporting years – most often due to new, revised, or reinterpreted data [14]. To tackle these data challenges, WHO plans to enhance its methodology and approach in tracking domestic wastewater, enabling the generation of time series estimates by incorporating all pertinent and up-to-date historical datasets from the UN Member States.

Estimates for the total annual volumes of household wastewater from a country are calculated as a sum of the annual volume of sewage in the sewerage system, the annual volume of wastewater generated by septic tanks, and the volume of sewage generated by other sources, such as pit latrines, other sanitation facilities, or in some cases, generated by open defecation, with all volumes are expressed as million $m^3\ yr^{-1}$. The estimates of total annual volumes of domestic wastewater at the national level are based on data from 231 countries and territories. Domestic wastewater generation per capita volumes were calculated as the volume of wastewater generated ($m^3\ yr^{-1}$) at the national level in a country or a territory in 2023 divided by its population in the same year.

Safely treated domestic wastewater is the effluent from household activities that has undergone thorough treatment to remove contaminants, making it suitable for discharge or reuse without harming human health and the environment. Based on the treatment type and contaminants in the effluent, the treatment may involve physical, chemical and biological processes to eliminate pathogens, organic matter and pollutants. Considering the quality of the wastewater treated, it can be used for purposes including agriculture, aquaculture, agroforestry systems or aquifer recharge. Advanced wastewater treatment technologies such as disinfection can further improve the quality of treated wastewater. Safely treated domestic wastewater supports water sustainability, minimizes pollution, and contributes to climate resilience by promoting efficient water reuse and resource recovery.

The proportion of domestic wastewater safely treated was calculated as the total annual volume of safely treated domestic wastewater divided by the total yearly volume of domestic wastewater generated in a country or a territory. The estimates on the proportion of domestic wastewater safely treated are based on 140 countries and territories, suggesting that 91 countries and territories have insufficient, incomplete or inaccurate data to assess the status of wastewater treatment. In some cases, the estimation for the generation of household wastewater and its treatment percentage are not reported directly by the countries and territories. The nationally representative data for all the domestic wastewater management chain variables are unavailable. In such cases, WHO employs a set of default assumptions to fill some data gaps. In addition, the national-level estimates draw on the data directly reported to the United Nations Statistics Division (UNSD), the Organisation for Economic Co-operation and Development (OECD), and Eurostat in addition to national sources of data directly collected by WHO into domestic wastewater databases [14].

2.2 Data aggregation by geographic regions and income groups

The total volumes of domestic wastewater generated at the national level were aggregated into two major categories based on (1) physical location of a country or territory – seven global regions defined as Asia, Europe, Latin America and Caribbean, Middle East and North Africa, North America, Oceania and Sub-Saharan Africa, and (2) gross national income per capita based on World Bank classification into four categories consisting of high-income, upper-middle-income, lower-middle-income and low-income countries. High-income countries have gross national income per capita ≥ $14,006, upper middle-income countries ($4,516 to $14,005), lower-middle-income countries ($1,146 to $4,515) and low-income countries (≤ $1,145). Factors such as economic strength, investment capacity and gross domestic products also provide useful information but are also related to the gross national income levels, directly or indirectly.

2.3 Data synthesis on wastewater irrigation

Data on wastewater reuse is focused on by far the largest reuse sector, i.e. agriculture. Such data on the reuse of tertiary treated wastewater is increasingly available for high-income countries, as well as from private-sector intelligence platforms or internationally operating companies involved in the construction of wastewater treatment plants. For other countries and treatment levels, the availability of reuse data is minimal, as treated wastewater is often mixed, e.g., with untreated wastewater before it is reused. Here, reported data are based on a targeted literature survey, which covered academic papers, national statistics, FAO-AQUASTAT, private-sector reports and news articles using standard search engines. The specific challenges are based on the described terminology issues and the fact that many academic publications cite old data, while media reports require careful data scrutinization. Considering the fact that the estimates on the use of untreated wastewater in the informal sector are scattered and limited, this assessment consists of combining datasets on wastewater reuse from the compilation of the data by the International Water Management Institute (IWMI), private (business) data sources [18–20] and public databases [21].

3 Results

3.1 Wastewater generation and treatment

The synthesis of domestic wastewater data suggests household activities in 2023 generated 267.5 billion m^3 (billion $m^3 = km^3$) of wastewater. This wastewater volume represents 8,019 million people, covering almost the entire global population. Averaged globally, domestic wastewater generation per capita is 33.4 $m^3\ yr^{-1}$ or 92 $L\ d^{-1}$. Of the 267.5 billion m^3 of domestic wastewater generated in 2023, 168.8 billion m^3 was collected while 98.7 billion m^3 remained uncollected, i.e., 63.1% of the generated domestic wastewater is collected (Table 1). The treatment status of domestic wastewater suggests that 54.7% (146.3 billion $m^3\ yr^{-1}$) of the generated wastewater undergoes treatment. In comparison, 45.3% (121.2 billion $m^3\ yr^{-1}$) is released to the environment in untreated form, i.e., as uncollected wastewater (98.7 billion $m^3\ yr^{-1}$) or collected but untreated wastewater (22.5 billion $m^3\ yr^{-1}$). Previous global assessments estimated a generation of municipal wastewater in a similar order ranging from 359 billion m^3 [11] to 380 billion m^3 [15], however it should be noted that these studies considered a combination of domestic and manufacturing wastewater. Such wastewater is generated by (1) domestic effluent consisting of greywater and black water, (2) effluent from commercial and business entities, (3) effluent from industries in areas where such wastewater is not collected instead discharged into the municipal wastewater management systems, (4) stormwater

Table 1 Annual volumes of domestic wastewater generation per capita, and collection and treatment of wastewater across geographic regions and country income groups

	Population (million)	Domestic wastewater generation ($m^3\ capita^{-1}\ yr^{-1}$)	Wastewater management	
			Collection (%)	Treatment (%)
Global	8,019	33.4	63.1	54.7
Geographic region				
Sub-Saharan Africa	1,196	15.1	25.6	17.2
Oceania	46	35.4	83.1	78.4
North America	379	103.4	99.1	96.1
Middle East and North Africa	562	34.8	66.2	57.2
Latin America and the Caribbean	665	41.7	62.9	39.4
Europe	741	41.5	89.3	74.4
Asia	4,431	29.5	50.7	45.4
Income level				
Low-income	724	13.8	10.2	5.8
Lower-middle-income	3,257	22.6	35.4	29.4
Upper-middle-income	2,808	36.3	63.1	48.0
High-income	1,230	66.7	94.5	91.5

Based on the 2023 country files developed by WHO for SDG 6.3.1 [14] and other urban runoff ending up in municipal wastewater systems, and (5) a possible combination of waste streams as mentioned above.

There is a distinct heterogeneity in wastewater management practices across world regions, with countries in North America, on average, generating the most significant volumes of domestic wastewater per capita (103.4 m^3 yr^{-1}), while those in Africa generating the smallest volumes of wastewater per capita (15.1 m^3 yr^{-1}), a 7-fold difference between the regions. All other global regions generate less than half of the wastewater per capita in North America. The sequence of the regions generating per capita domestic wastewater from the largest to the smallest volumes follows North America (103.4 m^3 yr^{-1}), Latin America and the Caribbean (41.7 m^3 yr^{-1}), Europe (41.5 m^3 yr^{-1}), Oceania (35.4 m^3 yr^{-1}), Middle East and North Africa (34.8 m^3 yr^{-1}), Asia (29.5 m^3 yr^{-1}), and Sub-Saharan Africa (15.1 m^3 yr^{-1}).

Wastewater collection and treatment numbers follow a somewhat different pattern than wastewater generation. North America has the highest percentage of domestic wastewater treatment (96.1%), followed by Oceania (78.4%), Europe (74.4%), Middle East and North Africa (57.2%), Asia (45.4%), Latin America and the Caribbean (39.4%), and Sub-Saharan Africa (17.2%). Among all regions, North America generates the most significant volumes of domestic wastewater per capita, with the highest proportions of wastewater collection and treatment. At the same time, Sub-Saharan Africa holds the lowest proportions of wastewater collection and treatment (Table 1).

The data on domestic wastewater reveals that gross national income per capita is strongly correlated to wastewater generation per capita and wastewater collection and treatment. The countries in the high-income category generate almost 5-fold more wastewater than the volumes generated in low-income countries (Table 1). The treatment numbers follow the same pattern, with high-income countries treating 91.5% of wastewater, followed by upper-middle-income countries (48.0%), lower-middle-income countries (29.4%), and low-income countries (5.8%). Other studies based on municipal wastewater have also shown substantial differences in its production, collection and treatment by the status of economic development. Sato et al. [22] estimated municipal wastewater treatment to be 70%, 38%, 28% and 8% for high-income, upper-middle-income, lower-middle-income and low-income countries, respectively, while Jones et al. [11] quantified these sets of countries in the sequence of 74%, 43%, 26% and 4%. While similar, these estimations could potentially indicate that percentage collection and treatment have increased in the developed world but have decreased in the developing world. This could be caused by wastewater production, particularly in the developing world, rising at a faster pace than the development of collection infrastructure and treatment facilities [13, 21].

On a volumetric basis, Asia, containing 55.3% of the global population, generates the most significant volume of domestic wastewater (130.7 billion m^3 yr^{-1}), which is 49% of the global domestic wastewater generation. There are two extreme cases of domestic wastewater generation at the regional level. With 4.7% of the global population, North America generates 14.6% of the wastewater generated globally, while Sub-Saharan Africa, with 14.9% of the worldwide population, generates 6.8% of the wastewater generated globally.

Regarding wastewater management, half of the domestic wastewater generated in Asia is released into the environment untreated. In addition, 7.0 billion m^3 yr^{-1} of wastewater collected in sewers or septic tanks is also not treated (Fig. 1), which is 5.4% of the wastewater generated in the region. By contrast, of the 18.1 billion $m^3\ yr^{-1}$ of wastewater produced in Sub-Saharan Africa, 13.5 billion $m^3\ yr^{-1}$ still needs to be collected, i.e., 74.4% of the wastewater generated in the region. In the case of North America, less than 1% of domestic wastewater is not collected (Fig. 1).

The countries grouped into four gross national income per capita categories present large differences regarding wastewater management practices (Fig. 2). Wastewater collection and treatment rates are highest in high-income countries (collection 94.5% and treatment 91.5%), followed by upper-middle-income (collection 63.1% and treatment 48.0%), lower-middle-income (collection 35.4% and treatment 29.4%) and low-income (collection 10.2% and treatment 5.8%). Although low-income countries generate a small volume of wastewater (10.0 billion $m^3\ yr^{-1}$ or 3.7% of the globally generated wastewater), about 90% of wastewater produced is released untreated to the environment. The significant differences between collection and treatment in upper-middle-income and lower-middle-income countries are also noteworthy.

Using a ternary plot and displaying the proportions of three variables (treated wastewater, sewers; treated wastewater, septic tanks; and untreated wastewater), all high-income countries (blue dots) are closer to the highest proportions of wastewater treatment from sewers, while low-income countries (red dots) are closer to the lowest proportions of wastewater treatment from sewers. Similarly, low-income countries are closer to the highest levels of untreated wastewater (Fig. 3). Lower-middle-income and upper-middle-income countries (orange and green dots) show a more varied distribution across all three categories, with some leaning towards higher proportions of untreated wastewater and others more balanced.

While the data on wastewater generation is available for 231 countries and territories, the proportions of domestic wastewater safely treated are available for only 140,

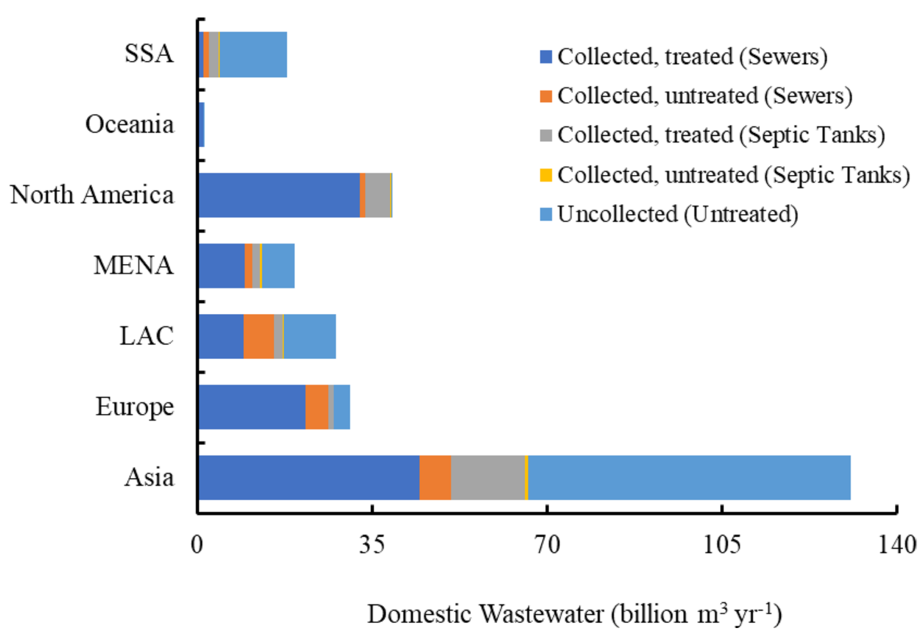

Fig. 1 Volumes of domestic wastewater collected and treated (sewers and septic tanks), collected but untreated (sewers and septic tanks), and uncollected (untreated) across geographic regions. SSA stands for Sub-Saharan Africa, MENA for Middle East and North Africa, and LAC for Latin America and Caribbean

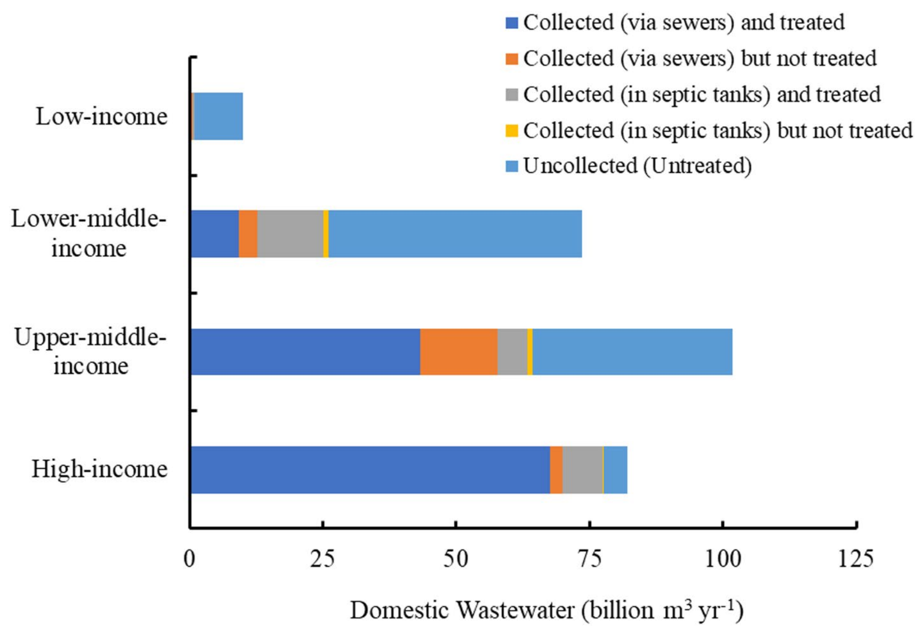

Fig. 2 Volumes of domestic wastewater collected and treated (sewers and septic tanks), collected but untreated (sewers and septic tanks), and uncollected (untreated) across country income groups

revealing that 39% of the countries and territories have insufficient, incomplete, inaccurate, or no data on wastewater treatment. However, considering the population statistics, these 140 countries and territories contain 7.156 billion people (89% of the population), suggesting that the 91 countries and territories lacking data have relatively small populations (0.863 billion people; 11% of the global population). Figure 4 considers these countries under the category 'insufficient data'. Many low-income and lower-middle-income countries are part of such countries with insufficient data, which may refer to incomplete, inaccurate or no data on wastewater treatment. On regional dimensions, several countries from Sub-Saharan Africa, some from Southeast Asia and Central Asia still need to establish efficient monitoring mechanisms to assess and report on the status of wastewater treatment at the national level (Fig. 4).

3.2 Treated and untreated wastewater reuse for irrigation

Agriculture remains by far the largest freshwater user and is also the leading sector of wastewater reuse, especially when informal reuse of primary, secondary or untreated wastewater is considered and included [23]. Only when it comes to tertiary treated wastewater, higher-value municipal and industrial applications are taking the lead from the investment perspective, i.e., market share development since 2010 (Fig. 5).

In contrast to wastewater generation data available for 231 countries and wastewater treatment status for 140 countries, JMP data on water reuse, particularly irrigation with treated and untreated wastewater, is missing, fragmented, inaccurate or inconclusive for most countries. A decade ago, Jimenez [24] described the global dearth of data on wastewater generation, treatment and use as a critical obstacle to global monitoring. As described above, a significant share of this gap has been closed due to increasing records on wastewater generation and treatment capacities. However, the numbers of covered countries and percentages of captured populations decrease along the service chain from wastewater generation to reuse. When it comes to reuse, only 37 countries

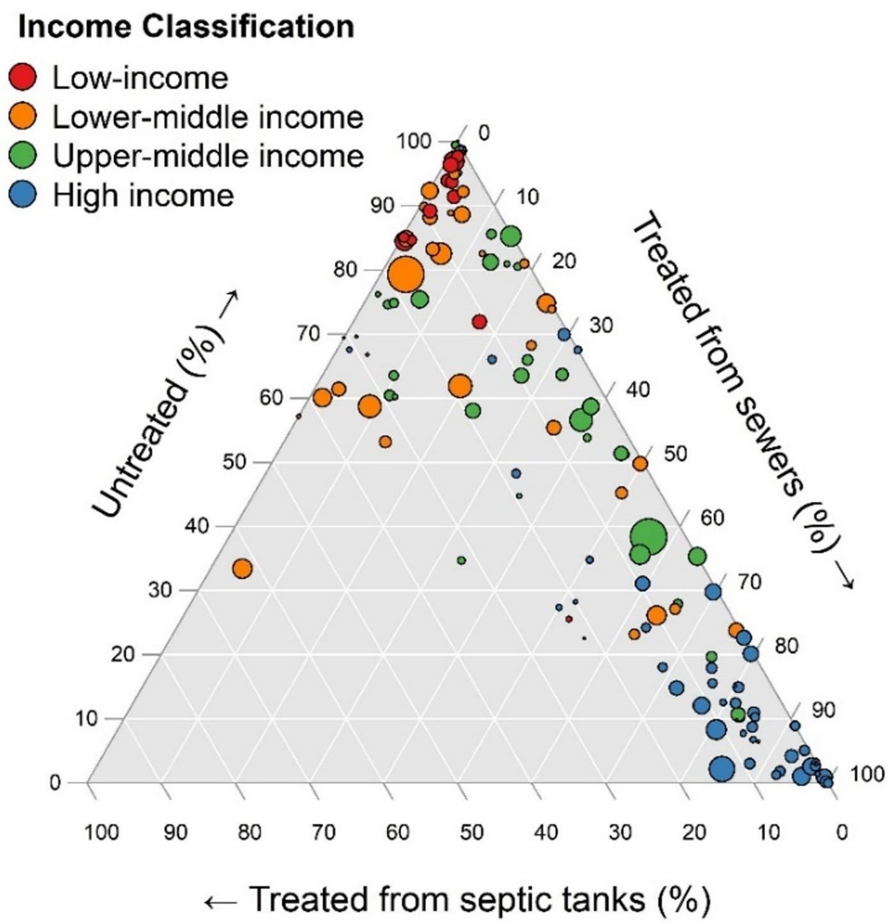

Fig. 3 Country-level balance between treated wastewater (sewers and septic tanks) and untreated wastewater, grouped by income level, with the size of the dots scaled by population size. Based on the data from 140 countries with data available on these parameters

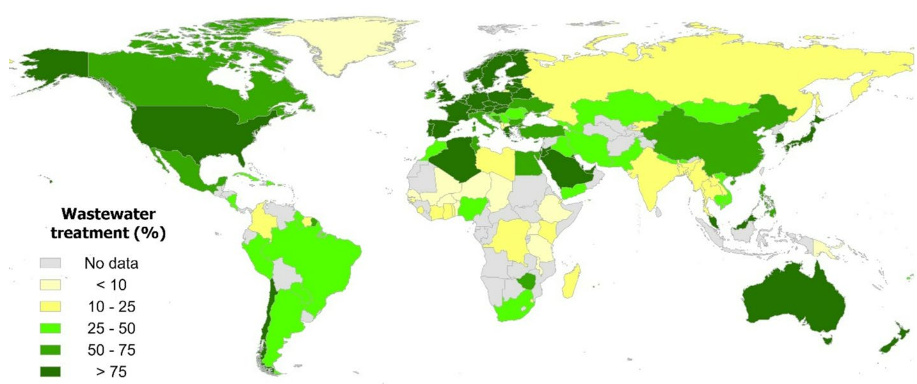

Fig. 4 Proportion of domestic wastewater treatment (%) nationally in a country or a territory. Based on the 2023 country files for SDG 6.3.1 data reported by WHO on the estimates of domestic wastewater treatment for 140 countries with 89% of the population [14]

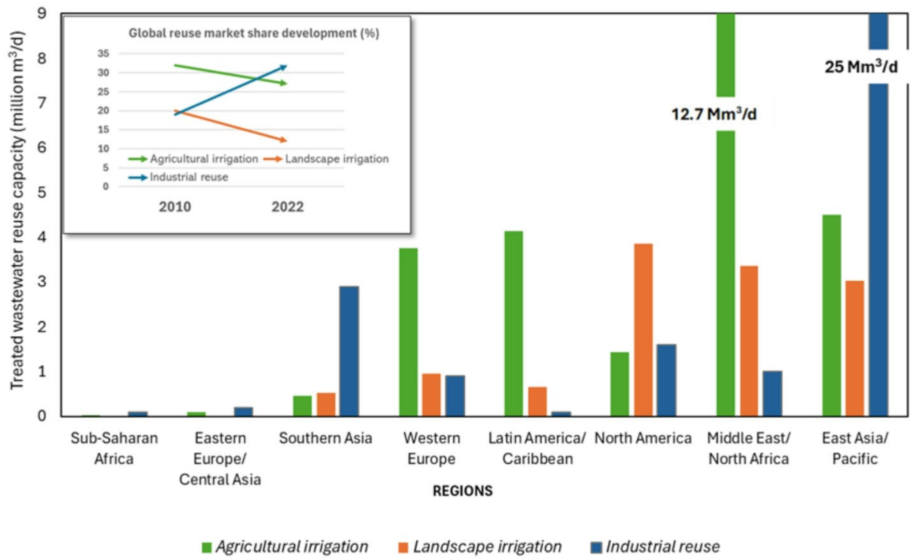

Fig. 5 Installed tertiary reuse capacity (≥ 5000 $m^3\,d^{-1}$) by region between 2012 and 2022, and relative reuse trend (%) between sector using highly (usually tertiary) treated wastewater 2010–2022 [18–20]

report data, with most of the intentional reuse taking place in high- and upper-middle-income countries, which aligns with the availability of treatment capacities [11]. Data from the informal or farmer-led reuse sector of usually unsafe water which is dominant in lower-middle-income and low-income countries [21, 22] is rare, also as wastewater generation is increasing faster than treatment capacities. Here, the mostly untreated wastewater finds its way from rapidly urbanizing areas through natural or artificial water systems into drains, streams and rivers used for irrigation. In this way, about 29 million ha (Mha) of farmland has been estimated to receive mostly diluted, un- or poorly treated wastewater [21]. Given the mix of water sources, it is impossible to differentiate between domestic and industrial wastewater or treated and untreated in such irrigated landscapes where all water enters the same streams and rivers downstream of urban areas where farmers practice irrigation.

When it comes to re-use of wastewater that has undergone tertiary treatment processes, industrial end-users remain the leading source of demand, and data availability increases. These end-users accounted for 31.4 million $m^3\,d^{-1}$ of new capacity over the past decade, a third of all new reuse capacity [12, 20]. The key regions are East Asia and the Pacific (Fig. 5), followed by MENA where agricultural reuse for desert reclamation dominates. The big driver of industrial reuse has been China. Over the past decade China has increased its water reuse capacity nearly fivefold and maintains now 44% of the world's treatment capacity for the reuse of advanced treated wastewater. As a result, the globally contracted water treatment capacity for reuse in 2023 exceeded the one of desalinated water (which remains most predominant in the Gulf region) by a factor of 2.5 [20].

Regulatory pressures have been critical to the uptake of reuse as an alternative source of water for industry, with new requirements and guidelines set to drive volumes still higher in future. Agricultural irrigation is now the second-largest source of demand for highly (usually tertiary) treated wastewater reuse, with 27 million $m^3\,d^{-1}$ of new capacity awarded globally since 2012 [18], nearly doubling the estimated reuse capacity in 2008

[23]. Egypt is the leading market for new irrigation projects, alone accounting for 31% of the global ten-year total, including two record-size mega-projects which have been awarded in recent years (Bahr al-Baqar in 2019 (5.6 million m^3 d^{-1}) treating a mix of domestic, agricultural and industrial wastewater, and the El Hamam plant in 2021 (7.5 million m^3 d^{-1}) of mostly agricultural wastewater. As Egypt's reuse is largely agricultural drainage water (treated and blended with freshwater), the market size can be inflated compared to other countries which do not count this source.

The use of treated wastewater is the lowest while the use of untreated wastewater is often the highest in specific regions of the world characterized by low treatment capacities, such as Sub-Saharan Africa and South Asia. In general, the use of wastewater is not common in regions with ample rainfall or with adequate levels of freshwater provided by conventional water sources, such as Scandinavia and Eastern Europe [11].

A review of current data on treated wastewater use for irrigated farming showed stagnation in some key countries and remarkable progress in certain countries, such as China, Mexico and India, and regions like the Middle East and North Africa. Although Europe is experiencing increasing water scarcity, and the volume of treated wastewater for reuse has increased continuously [25], it still shows a small percentage of global reuse applications, lagging behind the Americas, MENA and Asia in the implementation of these solutions [26].

China Given substantial investments, China has made notable advancements to implement safely managed wastewater systems. By 2019, the country had established facilities to reuse 12.6 billion m^3 of treated municipal wastewater. Major part of this volume (> 80%) was used for ecological, environmental and industrial purposes. The remaining volume was used to support crop production systems and various urban applications [27]. Based on the quality of treated wastewater, its reuse followed the concepts of 'fit for purpose' and 'fit for case'. The terms 'fit for purpose' and 'fit for case' are unique while considering their implementation as 'fit for purpose' refers to treating wastewater to achieve a specific water quality level compatible with its intended reuse, a common practice observed in many high-income countries. In contrast, the term 'fit for case' emphasizes tailoring wastewater treatment approaches based on specific local contexts and conditions while considering the characteristics and requirements of the wastewater reuse site [27, 28]. Due to significant use of untreated wastewater for irrigation in the past, China continues to implement the use of treated wastewater for crop production systems with caution. For example, in 2015, only 0.05 and 4.13% of the treated wastewater was used in Beijing and the Jiangsu province, respectively, for farming, forestry or pasture irrigation [26]. Estimates based on the annual treatment data point at around 0.1 to 0.2 Mha of farmland irrigated with treated wastewater across China [27, 29]. AQUASTAT, on the other hand, reports since 2015 the same volume of 3.45 Mm^3 d^{-1} for the direct use of treated municipal wastewater for irrigation [30] reflecting challenges in data access.

Mexico For the past 80 years, most of the wastewater produced in the metropolitan area of Mexico City has been sent untreated to the Tula Valley (also known as Mezquital Valley) without treatment for use by ~ 60,000 smallholders to irrigate more than 70,000 ha. The Atotonilco wastewater treatment plant started operations in 2015, serving the same area while treating 60% of the wastewater from Mexico City using two fit-for-purpose treatment processes, one supporting environmental flows, and the other making the water suitable for irrigation. An important objective was to preserve most of the nutrients to provide added value to the farmers, who were unsure about the benefits of treated wastewater [31, 32]. The Atotonilco success story adds approximately 70,000 ha to the share of treated wastewater use while decreasing the same area from the hectarage of untreated wastewater irrigation. There is no similar progress across other parts of Latin America and the Caribbean region, where irrigation with untreated wastewater (or a mix of treated and untreated) still dominates despite good progress, e.g., in Colombia [33].

India The Indian water and wastewater treatment market, i.e., the number of new plants constructed [19], is on a dynamic trajectory and is projected to rise by a compelling annual growth rate of 9.7%. However, this has yet to transform into increased treated wastewater reuse. On the contrary, India remains one of the countries with the largest informal wastewater irrigation sector, with an estimated 8.9 Mha irrigated with mostly diluted wastewater [21]. About one-third of the generated wastewater is treated, and only 3% is productively reused nationwide for different purposes, like irrigation [34]. A survey of 118 Indian cities showed that usually a mix of treated, partly treated, or untreated wastewater from domestic and industrial sources is directly or indirectly disposed of in local water bodies. About 20% of these often-mixed water types are discharged on agricultural lands [35]. The area under safely treated wastewater remains insignificant compared to other countries. The same outlook applies to Pakistan due to very low wastewater treatment levels [36].

Middle East and North Africa The number of water reuse (wastewater use) projects in the region has approximately doubled every decade since the 1990s, reaching 409 projects in 2020. Agriculture is the dominant user of treated wastewater (Fig. 5). Despite the rapid growth of water reuse projects, municipal wastewater treatment for designated direct reuse remains low at around 11% of the total wastewater generated. In comparison, about 35% of the treated wastewater is indirectly reused, mostly along rivers for groundwater recharge or agriculture. About 54% of the treated wastewater is lost unproductively [37]. Positive exceptions are Israel, which has a 99% reuse rate of treated wastewater, followed by Jordan, which has increased its reuse of treated wastewater from 76% in 2014 [38] to more than 90% in 2023 [39], mostly for irrigation, creating valuable water supplies. Data on treated and untreated wastewater irrigation is in general scarce partly due to the informal character of the farmer-led practice as well as the use of mixed water sources (indirect reuse) or deliberate data suppression to avoid food trade problems [40]. An exception is Egypt (see below).

Egypt The country plays a particular role in water reuse as also mentioned above. The country produces 35% of the total wastewater generated across the MENA region, accounting for up to 60% of the total indirect reuse. The datasets on wastewater irrigation are now changing because of significant investments in treatment capacity. Egypt aims to increase its agricultural land by 20% while creating the largest treated wastewater-irrigated area globally. Three record-breaking wastewater treatment plants (Bahr al-Baqar: 0.15 Mha; El Hamam or New Delta: 0.42–0.62 Mha; and Al Mahsama: 30,000 ha) are treating municipal and agricultural wastewater to irrigate together about 0.8 Mha in

North and Middle Sinai, and the western desert, supported by deep groundwater extraction and accompanied by new settlements. The wastewater treatment plants are operational, while some infrastructure, like the 114 km artificial canal supplying the El Haman plant with agricultural wastewater, will soon be finished. To reclaim up to 4.0 million feddan (1.68 Mha), there will be additional land reclamation areas solely supported by groundwater (ca. 88%) and surface water (ca.12%). Like in similar endeavors, a challenge will be managing the already existing soil salinity [41–43] despite high-end wastewater treatment.

3.3 Progress in water reuse monitoring for SDG 6.3

The volumetric and irrigation area specific data compiled by [23], with about 15.4 Mm^3 d^{-1} used for wastewater irrigation and 0.54 Mha worldwide irrigated with treated wastewater could serve as a pre-SDG baseline. A comparable volume of 14.8 Mm^3 d^{-1} of treated municipal wastewater used directly for irrigation was estimated by FAO for pre-SDG 2015 which increased to 18.6 Mm^3 d^{-1} in their latest (2021) estimate, which does not yet account for the changes reported above. If the work in Egypt continues at the current speed, an extra 0.42 to 0.62 Mha will be under planned reuse very soon. Egypt alone would then, with up to 1.5 Mha, nearly triple the area under treated reuse compiled by Jimenez and Asano [23] from around the year 2000, which should be valued as a success for the reuse component of SDG 6.3 in view of its target to "substantially increase water recycling and safe reuse globally". In addition, Jimenez and Asano [23] estimated roughly 1.8 Mha under cultivation with mostly untreated wastewater. However, in 2017, about 29 Mha of farmland were estimated to be receiving largely untreated wastewater [21], either directly or indirectly (i.e., through dilution). This area is posing health risk for 880 million urban consumers as estimated by [21] and the global efforts to address this challenge through safe water reuse guidelines and best practices show so far, a very low success rate [44].

If this challenge could be addressed at a rate of 10% per year, all the areas currently under unsafe (informal) reuse could be brought under safe reuse by 2034. However, with a rate of only a 5% increase in acreage, it might take 20 years. Such safe reuse could be achieved through conventional or on-farm treatment combined with safety practices from farm-to-fork. While wastewater treatment is slowly increasing in lower-middle-income and low-income countries, the main challenge appears the adoption of additional risk reduction practices due to low-risk awareness and missing incentives for behavior change [45]. The situation can be very different in high-income and upper-middle-income countries where risk awareness and regulatory standards are usually high and water reuse challenged by negative perceptions [8, 26].

4 Discussion

4.1 Wastewater generation and treatment

There are apparent and expected differences across countries from geographic regions and income groups, in every aspect of the safely treated wastewater assessments, indicating that progress remains uneven across the globe, as previously reported [11, 14].

While the estimates of domestic wastewater generation at the national level are available from 231 countries and territories, the proportions of safely treated wastewater are reported for 140 countries and territories. Many low-income and lower-middle-income countries are among those 91 countries and territories with insufficient data on wastewater treatment or have decided against reporting their data. These limitations mask the accurate assessment of safely treated wastewater at the national level due to: (1) underperformance of many wastewater treatment plants as they have to run at capacities below or far above their design capacity; (2) several wastewater treatment facilities may remain non-operational after installation due to inadequate funding to support their operation and maintenance; (3) some wastewater treatment sites may still be in planning stage or under construction while the corresponding volumes of wastewater to be treated on these sites are already reported by the countries as treated wastewater; (4) the volumes of treated wastewater may encompass any form of treatment, even basic methods such as simple filtration and sedimentation; (5) certain wastewater treatment facilities can face challenges if they are not adequately planned and established to treat wastewater to required standards, for example, the treatment plants designed to treat household wastewater may struggle to handle large volumes of a mix of industrial wastewater and domestic wastewater; and (6) limited or inaccurate water and wastewater flow measurements leading to incorrect reporting of wastewater treatment status.

However, the situation is not static. Where income levels change, the implementation of a wastewater levy can provide incentives to fund wastewater treatment infrastructure, especially in lower-income regions where such infrastructure might be lacking. Increasing investments are also happening within export-dependent industries in need of their wastewater to comply with international standards. Overall, the interplay between income, financial mechanisms and incentives can strongly influence infrastructure development towards achieving the goals of SDG 6.3.1. Related market trends are discussed e.g. by [19].

4.2 Wastewater reuse in irrigation

The wastewater reuse component of SDG 6.3. remains both ambiguous ("substantially" increasing recycling and safe reuse globally) and elusive (considering the known challenges of data reporting [30]). With the exception of some developed countries and regions, like Europe, or high-end industrial reuse, data remains scarce and difficult to compare [26, 44].

The share of countries reporting the use of treated wastewater in irrigated agriculture remains relatively small, with just 37 countries, mainly from high-income and upper-middle-income countries, reflecting differences in the availability of treatment capacities [11]. Other reuse data and information are available in scientific literature, but there is a significant variation in terminologies.

1. The definition of 'safe' reuse is traditionally based on water quality thresholds achieved through wastewater treatment. Datasets from planned reuse are captured by governmental entities or private sector-based market intelligence platforms (usually in volumes treated). This is not without challenges, e.g., due to heterogenous terminologies and definitions of treated, reclaimed or safe water, as also steered by public perceptions but can result in a mix of terms between different institutions even in the same country [28]. Related to terminology, data challenges are even more significant. This concerns treated but even more untreated (informal) reuse, particularly in agriculture. The reasons include the absence of quantitative data due to the often illegal and ignored nature of the praxis but also lacking water quality data

and agreements on what to count, e.g., along the transition from diluted wastewater to polluted freshwater. The scientific community is usually of little help by calling any reuse, if treated or untreated, raw or diluted, 'wastewater irrigation'. However, the difference between (polluted) freshwater and diluted wastewater can be small and 'invisible' from the farmer's perspective. Depending on the available technology and reuse purpose, the same ambiguity in water quality and related terminology can occur between treated and untreated wastewater. As a result, what still counts as 'untreated wastewater' in one region could be of better quality than so-called 'treated' wastewater in another. In contrast to direct industrial reuse, the dilution factor is vital in agricultural reuse. In most cases, the treated or untreated wastewater is indirectly used from a receiving water body, which can be lakes, streams or rivers. As dilution can vary in wide margins, often without affecting the risk from pathogenic infections, the standard unit of wastewater volumes used to assess progress on wastewater collection and treatment is often replaced by hectare under agricultural use.

2. Data accounting from source to reuse: While records of drinking water supply and wastewater generation, collection and treatment are common in volumetric units, this is only possible for direct reuse where treatment plants release treated wastewater directly into irrigation schemes. However, while such designed reuse schemes are common in the Global North, they are seldom elsewhere. The by far more common situation in the Global South is that mostly untreated as well as treated wastewater finds its way to other water bodies and somewhere downstream farmers abstract this more or less diluted wastewater for irrigation. In this situation, volumetric reuse data do hardly exist and also make limited sense given the mix of volumes of different water sources and increasing dilution or river self-purification with growing distance from the wastewater source. The consequence is that reuse data for the Global South are usually provided in irrigated areas, and not volumetric units, flow diagrams or balance sheets. The irrigation schemes under indirect reuse are usually farmer-led or informal, and the wastewater quality is unsafe [12, 21, 23, 46]. Another challenge for data balancing is that the country level data used for SDG 6 monitoring focus on domestic wastewater, not the much larger volume of agricultural wastewater, such as drainage water. An exception at scale is Egypt where several of the new record-breaking treatment plants will receive more agricultural than domestic wastewater which will make the cross-country accounting and comparison of treated and reused wastewater volumes more challenging.
3. From the public health perspective, neither wastewater volumes nor hectares are a reasonable approximate for safety. Given the emphasis on health-based targets and the risk of on-farm and post-harvest contamination, extending safe reuse indicators along the food value chain appears more relevant, especially for crops potentially posing a health hazard, like raw eaten salad greens.
4. Given the wide ratio between reusing treated versus untreated wastewater, it should be more critical from a public health perspective to focus on turning existing unsafe reuse into safe reuse for the benefit of millions of urban consumers [20] than [only] to count new reuse projects. Combinations of conventional wastewater treatment and/or other safety practices along the farm-to-fork food chain are recommended to increase safe reuse [46] and can combine reliability and cost-effectiveness [47], but related recommendations remain till today often paper tigers [48].

Two of the reasons for limited progress in turning existing unsafe reuse into safe reuse are that, especially in low and lower-middle income countries : (1) investments in wastewater management are often outpaced by population growth and wastewater generation; and (2) we continue to struggle with our understanding of which incentives or institutional support are needed for facilitating and implementing behavior change for the adoption of safety practices among stakeholders with limited risk awareness. Related answers only slowly emerging [49–51] and often remain location specific.

With an eye to 2030, it appears that behavior change could be implemented faster than constructing within the remaining 5 years the large number of required wastewater treatment plants. However, the common assumption that conventional treatment capacities are only slowly growing in many low-income and lower-middle-income countries can no longer be generalized. As the example of China shows, wastewater management was almost neglectable until 40 years ago, but today, the country possesses the world's most significant municipal wastewater infrastructure [52]. Another example of the power of political commitment is the construction of the currently largest wastewater treatment plants in the world, Bahr Al Baqar and El Hamam in Egypt, which took just two years [53].

5 Conclusions and outlook

While countries across the globe are aiming at achieving SDG 6 in times of population growth, expansion of urban areas, and climate change, large volumes of domestic wastewater – about half of the world's total – remain untreated, and progress on the SDG targets remains uneven across the world. Water quality deterioration from releasing untreated wastewater into the environment negatively impacts human and environmental health [13]. The trade-offs of wastewater management systems suggest that the economic gains through the protection of human health and the environment, as well as the recovery of valuable resources in regions with effective and sustainable wastewater systems, dwarf the costs associated with developing such wastewater systems [54, 55].

The study highlights the critical role of safely treated domestic wastewater in sustainable development, particularly in achieving SDG 6.3.1. It presents a comprehensive synthesis of global data, showing that while significant progress has been made in wastewater collection and treatment, challenges remain in achieving equitable treatment and reuse across regions and income levels. The study underscores the potential of treated wastewater for irrigation, emphasizing the need for improved monitoring, terminology clarity and data reporting to enhance the effectiveness of water reuse strategies. Addressing these challenges is essential for achieving sustainable water management and water-related SDGs, also in view of climate change adaptation.

However, three global drivers might strongly influence progress on the targets set by SDG 6 (including water reuse) till and beyond 2030: (1) the increasing push for a more circular economy based on resource recovery and reuse [56], (2) the alarming signs of increasing water scarcity and water quality deterioration [57, 58], and (3) the need for industries to comply with international green growth standards, like the UN Global Compact, which are pushing Corporate Social Responsibility to a new level of environmental sustainability [59, 60]). Countries and businesses respond according to their possibilities from investments in treatment infrastructure to water saving and reuse across all sectors, in particular in urban areas with high water demands. China exemplifies this situation, and so are Egypt and Mexico for accelerating large scale irrigation projects. More attention is, however, needed for the transformation of the significant sector of unsafe reuse due to missing treatment capacities to protect farmers and consumers, especially in Africa and South Asia where the related risk awareness is limited [44].

Supplementary Information

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Supplementary Material 1

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Author contributions
M.Q. Initial conceptualization, wastewater data, methodology, writing; P.D. Conceptualization refinement, methodology, writing, reviewing, graphics, and editing; E.R.J. Wastewater data analysis, methodology, writing, graphics. All authors reviewed the manuscript.

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Availability of data and materials
The authors declare that the supporting data on the findings of this study are available from different publicly available sources listed below: Datasets on the estimates of domestic wastewater generation and treatment: https://www.who.int/teams/environment-climate-change-and-health/water-sanitation-and-health/monitoring-and-evidence/wash-monitoring/2023-country-files-for-sdg-6.3.1Datasets on population at the national level: https://population.un.org/wpp/Datasets on the classification of countries into four income categories: https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups.Dataset on treated wastewater use in irrigation: https://data.apps.fao.org/aquastat/?lang=en.

Declarations

Ethics approval and consent to participate
Not applicable.

Competing interests
The authors declare no competing interests.

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