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Review article

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Sustainable wastewater reuse for agriculture

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Abstract

Effective management of water resources is crucial for global food security and sustainable development. In this Review, we explore the potential benefits and challenges associated with treated wastewater (TW) reuse for irrigation. Currently, 400 $km^3 yr^{-1}$ of wastewater is generated globally, but <20% is treated, and of that TW, only 2–15% is reused for irrigation depending on region. The main limitation of TW for irrigation is the inability of current treatment technologies to completely remove all micropollutants and contaminants of emerging concern, some of which have unknown impacts on crops, environment and health. However, advanced water treatment and reuse schemes, supported by water quality monitoring and regulations, can provide a stable water supply for agricultural production, as demonstrated in regions such as the USA and Israel. Such schemes could potentially serve a net energy source, as the embedded energy in wastewater exceeds treatment needs by 9 to 10 times. Agriculturally useful nutrients such as nitrogen, phosphorus and potassium could be also recovered and reused. TW reuse for irrigation could act as a major contributor to a circular economy and sustainable development, but the first steps will be funding and implementation of advanced and sustainable treatment technologies and social acceptance.

Sections

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Key points

- Over 80% of global wastewater is discharged untreated (over 95% in some of the least developed countries) into groundwater, rivers or lakes. This untreated wastewater is also sometimes used directly or indirectly for the production of potentially contaminated feed or food.
- Advanced water treatment and reuse schemes, supported by water quality monitoring and regulations, can provide a safe and stable water supply for agricultural production, freeing up equal volumes of fresh water for drinking and other uses.
- Treated wastewater (TW) reuse for irrigation has the potential to alleviate irrigation water imbalances, especially in water-scarce regions, and boost or sustain food production by expanding irrigated agriculture, thus promoting global food and water security.
- Advanced wastewater treatment processes necessitate ongoing research and site-specific evaluations for cost-effective and sustainable reuse practices.
- Technological opportunities can transform wastewater treatment plants into water, energy and nutrient recovery facilities, achieving energy–carbon neutrality.
- Comprehensive regulatory frameworks and risk management plans are essential to safeguard the smooth functioning and sustainability of TW reuse systems, and they are vital to ensure environmental and public health, and social acceptance.

Introduction

Water scarcity is emerging as a critical concern for an increasing number of regions, such as the southwestern USA and Mexico, Northern and Eastern Africa, the Arabian Peninsula and the North China Plain[1]. Severe water imbalances are anticipated to intensify spatially and temporarily under climate change scenarios, causing catastrophic losses to human life and infrastructures with substantial economic impacts[2]. Extreme weather events, such as the 2023 extended heatwaves in Europe, Western North America and Asia, and floods in Pakistan, Bangladesh, Australia and Libya, are occurring at increased frequency and severity, causing further disturbances to the hydrological cycle[3,4], and exemplify that urgent actions need to be undertaken[5,6]. The limited progress towards achieving the Sustainable Development Goal 6 (SDG 6) for universal access to safe water and sanitation by 2030 was confirmed at the UN 2023 Water Conference[7]. Owing to the current inadequate rate of progress, it is estimated that by 2030, 1.6 billion people will not have access to safely managed drinking water and 2.8 billion people will not have access to safely managed sanitation[8].

In the context of this intensifying water crisis, the agricultural sector is facing the most severe impacts as it is the major consumer of water globally (using 70% of abstracted water worldwide), while also facing escalating competition from the other water use sectors owing to population growth, urbanization, improved standards of living and industrialization[9]. Water imbalances in the agricultural sector will be further exacerbated by the inevitable need for cultivation expansion to meet the demands of the growing population, and because of further pressures on yield and irrigation needs posed by the impacts of climate change[9,10]. Within this context, the need to maintain food security by using non-conventional water resources of adequate quality in the agricultural sector is imperative. Adequately treated wastewater (TW) (also referred to as reclaimed water) is an attractive alternative for the mitigation of irrigation water scarcity, especially in areas wherein conventional water resources are limited or absent. TW reuse in agriculture is already a common practice in some regions worldwide, such as Israel, Cyprus, California, China and Australia (Box 1), and can substantially boost agricultural production and rural development, while promoting circular economy[11].

Currently, nearly 400 km^3 (359.410^9 m^3 yr^{-1}) of urban wastewater are generated each year globally, with projections of 50% increase by 2050 owing to population growth and urbanization[12]. These volumes of wastewater represent almost 10% of global fresh water use (over 4,000 km^3), sufficient to meet nearly 15% of current irrigation water needs[13,14]. These huge quantities of generated wastewater are a worldwide source of contamination that can cause waterborne disease outbreaks and substantial environmental problems if discharged untreated. Presently, only a small portion of generated wastewater is treated (less than 20% globally, with rates varying between 8% and 70% in low-income and high-income countries, respectively)[15,16]. The volumes of this TW reused for agricultural irrigation are even lower (2–15%; Fig. 1), as most TW is reused for other purposes, used for recharging aquifers, or discharged to downstream environments, such as rivers and lakes[17]. As such, wastewater is an untapped resource of valuable water, in addition to energy and nutrients. Thus, wastewater collection, treatment and reuse offers multiple economic, social and environmental benefits and also contributes to meeting the global SDGs[18]. The exploitation of TW for diverse uses (and irrigation in particular) also appears as a key strategy to minimize the public health burden (including human life losses) associated with the direct and indirect impacts of droughts and heatwaves induced by anthropogenic climate change[19–21]. For example, TW reuse in agriculture has the potential to alleviate human health problems associated with drought-related water resource quality, increased concentrations of pollutants and cascading droughts, highlighting TW as a key component in efforts seeking to promote global health. However, TW reuse in agriculture is currently limited by challenges such as limited social awareness and acceptance, the presence of various microbiological and chemical (micro)contaminants in treated effluents, and the will of governmental and intergovernmental organizations to invest and subsidize this practice[16,22].

In this Review, we summarize the prospects of reusing TW in agriculture to safeguard food security, enhance public health and advance sustainable development at the global level. We explore the challenges posed by insufficient TW reuse, policies and problematic pollutants. We discuss how evolving technologies can promote circularity in the wastewater treatment sector by retrofitting treatment facilities into resource recovery factories wherein energy, nutrients and other valuable by-products (in addition to water) can be recovered and reused. Finally, we propose actions and future directions for promoting long-term, safe wastewater treatment and reuse in agriculture.

Wastewater treatment and reuse

Wastewater has been reused for irrigation since ancient times, though the lack of specific treatment posed several health and environmental risks[23]. Rapid urbanization and increased hygiene and food production needs, alongside scientific and technological progress, subsequently enabled the development of the wastewater treatment and reuse sector. Wastewater reuse for irrigation is mostly applied through

Box 1

Long-standing adoption of TW reuse schemes for agricultural irrigation in various countries

Israel

Israel can be classified as a pioneer in TW reuse for agricultural irrigation, a practice introduced owing to the long-term severe water scarcity that the country has been experiencing. More than 85% of the produced effluents are reused (direct reuse) in agriculture, providing more than half of the total irrigation needs of the agricultural sector. TW that is not reused during the winter months is stored in reservoirs. More than 160,000 ha of agricultural land (~45% of the cultivated land) are irrigated with TW, producing a considerable proportion of agricultural commodities in the country, while also allowing export of produce[187].

The success in increasing the use of TW by the Israeli agricultural sector is attributed to several factors: (1) Centralized water system: water is defined in Israel as a nationalized public good; all water is the property of the state, including fresh water (surface and groundwater), rainwater, wastewater and runoff. (2) Agricultural viability: farmers were allocated with a specific water quota, forcing farmers to shift from fresh water to TW. (3) Financial support: allocation of funds (loans and grants) for construction of the necessary infrastructure (wastewater treatment plants (WWTPs), pipelines, reservoirs, irrigation equipment). (4) Research: funding for research to assess the impact of intensive utilization of TW on crops and soil, including the establishment of a comprehensive national survey that examined the effects over a 10-year period. (5) Regulations: implementation of strict regulations regarding health and agronomic quality of TW.

Cyprus

In the same line, Cyprus, a Mediterranean country with the highest water exploitation index in Europe (124% in 2019)[188], reuses nearly 80% of all tertiary TW produced for direct and indirect agricultural irrigation and considers TW as a substantial component of integrated water resources management plans[189].

Other European countries

TW irrigation is practiced in other European countries as well, though not in an extended level. The irrigation of rice and vegetables fields in Valencia, Barcelona and Murcia in Spain, and in Milan, Italy, are some examples[12].

USA

In the USA, TW reuse schemes in agriculture are based on comprehensive regulations and guidelines[55,141]. In Florida, most of the TW is reused for landscape irrigation even in areas with public access, whereas agricultural irrigation mostly refers to citrus orchard irrigation[56]. In the Monterey County in California, disinfected tertiary TW constitutes an important component of the 'One Water' management scheme[57]. TW is reused both for aquifer recharge aiming at managing seawater intrusion and supplying the indirect potable reuse system, and for the irrigation of thousands of hectares of high-value vegetables, including artichokes, broccoli, cauliflower, celery and lettuce[55].

China

In the south eastern suburb of Beijing, China, TW reuse for irrigation of hundreds of square kilometres of agricultural land has a long history in producing remarkable quantities of food for the city[190].

Australia

In Australia, TW reuse in agriculture is increasingly common as jurisdictions seek to secure 'climate-independent' supplies[191]. TW for multiple uses, including for agricultural irrigation, is now a key component of diverse water supply portfolios for many Australian water authorities[192]. In 2019–2020, Australian agriculture used about 6,500 hm^3 of water, of which 124 hm^3 (1.9%) was reclaimed water obtained from off-farm sources[193]. Outcomes from the Australian experience to date indicate that TW from capital city WWTPs adjacent to suitable vegetable growing land have been the most successful recycling schemes[193].

comprehensive wastewater treatment plants (WWTPs) and reuse a (Fig. 2), and regulated by various legal frameworks.

Centralized urban wastewater treatment

Urban wastewater consists of up to 99% water with the rest being solids, dissolved and particulate matter, and microorganisms, although the exact composition varies depending on the source and the mixture of wastewater (for example, domestic, industrial, stormwater and runoff), as well as the season[15,24].

Centralized WWTPs are large-scale water treatment facilities that include physical pretreatment (screening, sedimentation and skimming), biological and chemical wastewater treatment, and sludge handling (Fig. 2). Typically, centralized treatment of urban wastewater occurs in medium-large WWTPs and includes a secondary biological process (such as activated sludge and membrane biological reactor (MBR)), conventional filtration on granular media (except in the case of MBR being used as secondary treatment), and disinfection with UV lamps or with oxidizing agents (typically chlorine or peracetic acid), as tertiary treatments[25]. However, the energy demands of conventional activated sludge (CAS)-based biological treatment and anaerobic sludge digestion can be as high as 0.6 kWh m^{-3} of wastewater treated, depending on the process configuration and effluent composition, with most of the energy consumed by biological aeration and mechanical pumping[26,27].

A great variety of treatments, including physical, biological and chemical technologies, applied alone or in combination, can effectively remove microbiological and chemical inorganic and organic pollutants from wastewater and produce reclaimed water complying with acceptable quality standards for the intended use (often referred to

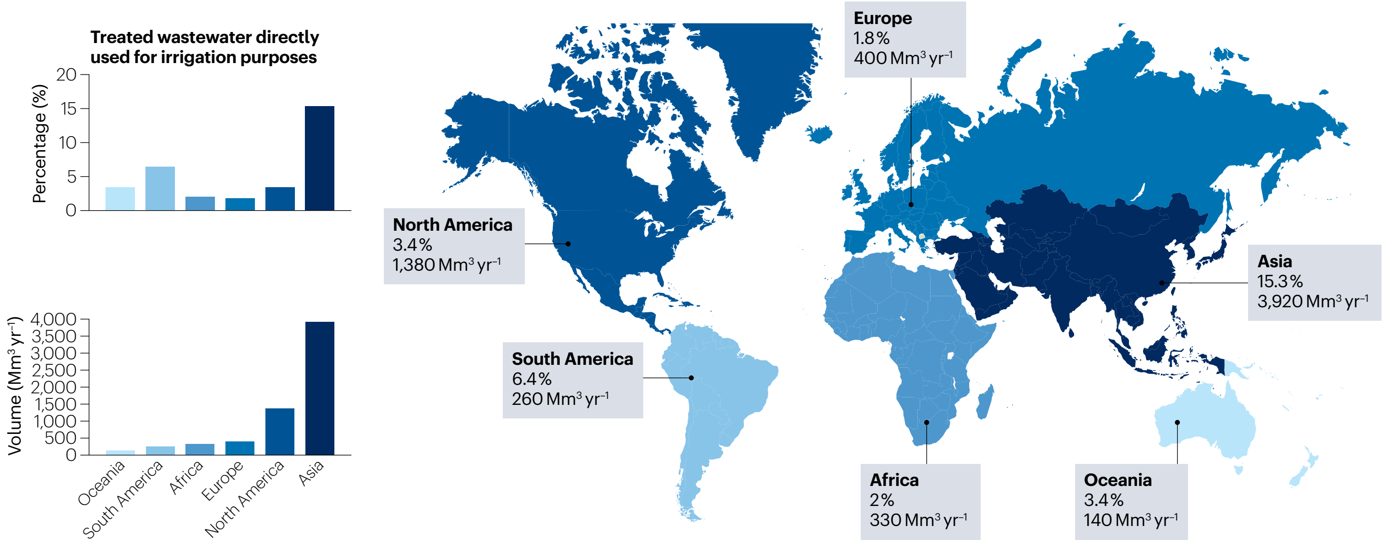

Fig. 1 | Annual volume and percentage of TW reused directly for irrigation. Global direct reuse of TW (with no or little dilution with freshwater) for irrigation varies among continents. Direct application for irrigation is highest in Asia on a continental level, and on regional levels, it is a prevalent practice in countries in Middle East and North Africa, Australia, the Mediterranean region, Mexico, China and the USA. The direct reuse of TW for irrigation is influenced by local water scarcity, availability of treatment infrastructure, presence and enforcement of regulatory measures, and economic motivations. Data for the figure are from refs. 44,46.

as 'fit-for-purpose' TW)[25]. The most suitable treatment approach is usually defined by local regulations and restrictions pertaining to TW quality standards, system operation and maintenance costs, approved reuse purposes, the ecological footprint, social acceptance of TW systems and other considerations[25]. However, current challenges in wastewater treatment, such as the removal of micropollutants and contaminants of emerging concern (MCEC), including the control of antibiotic resistance (AR) and micro(nano)plastics, are expected to change the state-of-the-art in the coming years. In this Review, the term micropollutants refers to substances present in the wastewater at very low concentrations, posing potential risks to ecosystems and human health, some of which are already included in policies and regulations[28]. Contaminants of emerging concern constitute a broader category of chemical contaminants in very low concentrations, as well as biological contaminants such as AR determinants (antibiotic-resistant bacteria (ARB), antibiotic resistance genes (ARGs) and relevant mobile genetic elements[29]), which are not yet fully understood or regulated. Herein, MCEC is used as a concise term to refer to both categories, aiming at enhancing comprehension and facilitating a more nuanced dialogue regarding the diverse nature of contaminants and their implications for environmental and public health. MCEC can also include other classes of chemical compounds, such as biocides, flame retardants, micro(nano)plastics, pesticides, personal care products, pharmaceuticals and both synthetic and natural hormones.

Centralized urban wastewater treatment plants generate substantial quantities of TW that are sequentially capable of supporting intensive, mechanized agriculture practiced at the large scale in urban and peri-urban areas (Fig. 2).

Decentralized rural wastewater treatment

Rural domestic sewage, especially in developing countries and low-population-density areas, is one of the foremost obstacles to achieving several global SDGs[30]. Globally, less than 60% of people are connected to sewage collection systems, and sewage treatment stands at a much lower percentage, with the lowest proportion being reported in the Global South[12,31]. Centralized wastewater treatment systems are a common choice in urban areas and megacities, but they are typically infeasible and lacking in poor rural areas owing to the substantial construction, operation and maintenance costs[32]. To this effect, decentralized wastewater treatment systems constitute a flexible, emerging approach for sustainable and economic water reuse at the point of wastewater generation, in rural and suburban areas and scattered developments[33] (Fig. 2).

The application of decentralized wastewater treatment systems is not exclusively independent from the traditional centralized system, as the integration of the two systems could be preferable depending on the local conditions[34]. Decentralized systems include among others constructed wetlands, anaerobic and biofilm reactors, and MBRs[35,36], which might be applied individually or jointly. However, more research is needed into the capacity of decentralized wastewater treatment facilities to efficiently remove MCEC from wastewater intended for reuse, as limited research so far exists regarding the type of decentralized technologies in relation to their efficacy to remove such contaminants[37].

Decentralized WWTPs are designed to support localized, less intensive and more traditional farming by full-time or part-time farmers seeking additional income[38].

Overview of TW reuse for agriculture

Despite the benefits and the technological progress in wastewater treatment and reuse, the global TW implementation for agricultural irrigation still remains low[15,16]. Large quantities of TW are either discharged to downstream aquatic environments or reused for other purposes. These include landscape irrigation, recreation, environmental enhancements, groundwater recharge, or in urban water systems (for example, toilet flushing, street cleaning, dust suppression, and fire protection), and in industrial processes (for example, as process water in the textile and paper industry, steelworks, or for heating and cooling, and in construction)[39]. In some areas with extreme water stress, municipal wastewater undergoes advanced treatment to be used for potable purposes[40,41]. TW reuse for crop irrigation and for the purposes mentioned in the previous section can free equal volumes of high-quality fresh water for domestic use and other sectors, and it can also enhance critical ecosystem services related with environmental flows[16,42]. To this effect, this Review paper aims at promoting TW reuse in agriculture mainly over discharge to aquatic environments.

The long-term sustainable reuse of TW in agriculture requires complex systems, managed all the way from collection to application. This requires infrastructures such as sewage collection systems, WWTP facilities, hundreds or even thousands of kilometres of pipes, reservoirs and distribution systems[43] (Fig. 2). Major technical components of a sustainable TW reuse system include the urban WWTP and/or reclamation facility (which might include further treatments such as disinfection), storage systems (for example, reservoir), pumping stations and distribution pipeline network, treatment facilities for irrigation purposes (for example, filters), and irrigation system components (for example, irrigation hoses, drips and sprinklers), including components adjacent to the point of use (for example, run-off canals and buffer strips)[12] (Fig. 2).

Assessing the global extent of TW reuse is challenging owing to varying data and interpretations of reuse across countries. For example, for some countries, the volumes of reused TW submitted under regulatory reporting requirements are lower than those estimated and reported in the literature[44,45]. Information on TW application in agriculture can account for both direct and indirect reuse, the latter indicating TW was discharged into surface waters or aquifers through artificial recharge, and subsequently withdrawn for irrigation. Direct use of TW allows for better water quality control because rules and standards apply at the reclamation facility outlet[44,46] (Fig. 1). Irrigation water quality lacks similar control measures, unless risks resulting from mixing TW with other

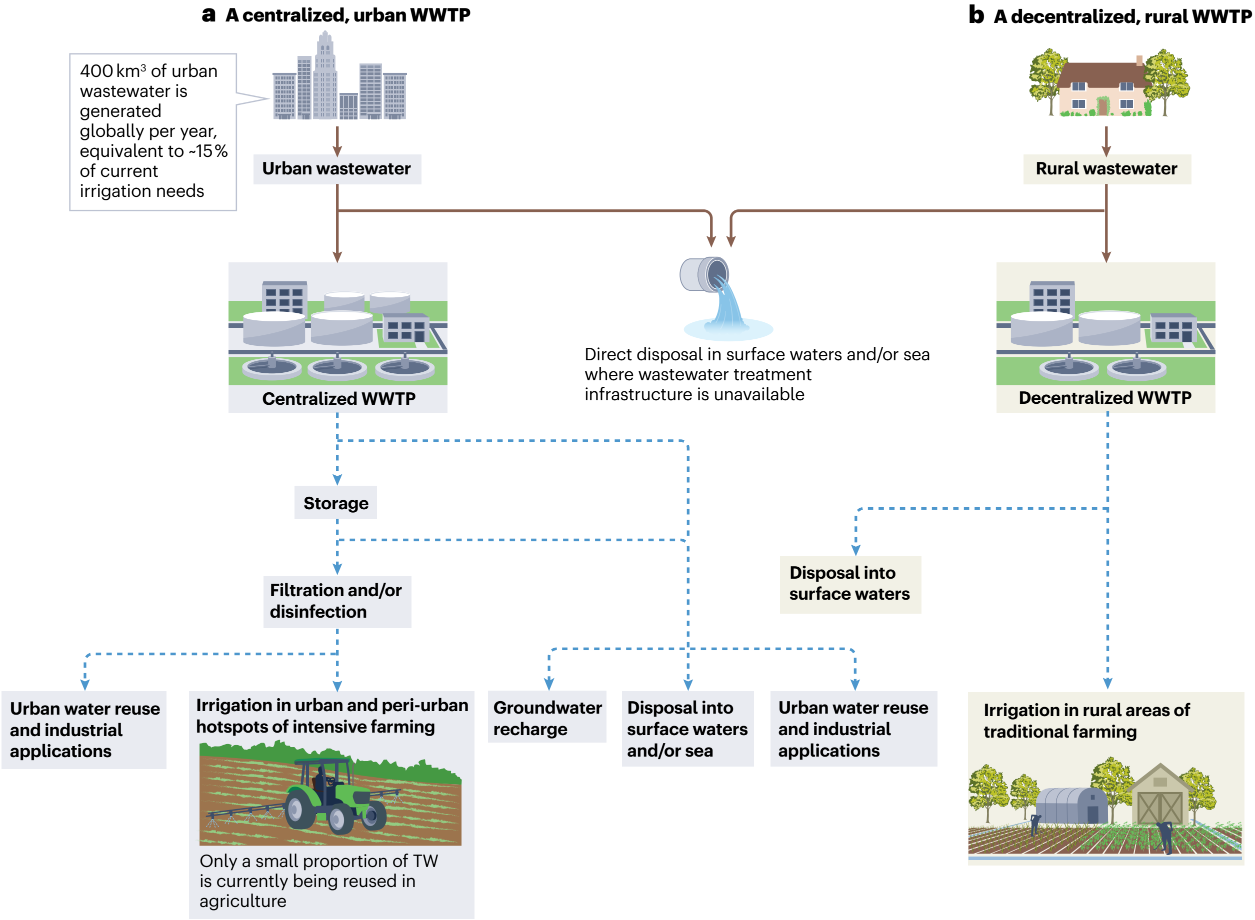

Fig. 2 | Wastewater generation, treatment and reuse. Wastewater produced by anthropogenic activities is collected and conveyed through piping systems to a wastewater treatment plant (WWTP). **a**, Centralized WWTPs process wastewater produced in large urban areas. **b**, Decentralized WWTPs process lower volumes of wastewater in small rural agglomerations, providing reclaimed water of sufficient quality and cost efficiency, as substantial reduction in sewage collection and treatment and maintenance costs can be achieved. Applied treatment technologies purify and decontaminate wastewater, sometimes over multiple cycles of disinfection and/or filtration for the efficient removal of micropollutants and contaminants of emerging concern (MCEC), before achieving the production of reclaimed water of sufficient quality for reuse purposes. On the basis of its quality and the current reuse guidelines, reclaimed water can be reused for the irrigation of various crops (for example, fodder crops, vegetables and fruit trees), thus boosting the economy and ensuring food supply and security.

sources are identified, hindering the systematic promotion of direct reuse[47]. Further consideration should also be given to the TW-irrigated soil and commodities produced from TW-irrigated crops (combining the application of specific water quality of TW with irrigation systems and crop species at the right time and site), as these are crucial factors for protecting environmental and human health[12] (Fig. 2).

Broad acceptance of TW reuse in agriculture as a standardized and safe practice requires comprehensive evaluations of risks and continuous monitoring, including through digitalization of as many components of TW reuse systems as possible, along with appropriate and flexible regulatory and institutional frameworks[12,48]. According to the European Union (EU) Water Reuse Regulation 2020/741, a water reuse system risk management plan should be based on key elements, including system description, identification of all parties involved with roles and responsibilities, environmental and health risk assessment, preventive measures for controlling exposure to hazards, quality control systems, environmental monitoring systems, incident and emergency systems, and coordination mechanisms[12,49].

Apart from appropriate treatments to facilitate the generation of fit-for-purpose TW, special attention should be given to storage and distribution systems, as suboptimal management could allow for recontamination of treated effluent, either by algae growth in reservoirs, formation of biofilm in pipes, and/or bacterial regrowth[50]. The fate of MCEC during treatment, storage and transportation requires scrutiny in relation to their persistence and effects after their release into the environment[51]. The avoidance of pollution through input prevention and source control, the application of realistic regulations and standards, and the promotion of green and sustainable chemistry, on the basis of the precautionary principle, are also crucial for enhancing end-of-pipe TW quality and therefore reuse acceptance and promotion[52].

In conclusion, to confront the challenges of climate change, the systematic establishment and implementation of wastewater reuse schemes are anticipated to gradually expand into regions that were once rich in water but are now compelled to embrace sustainable practices for the future[53].

Successful TW-irrigation schemes

Urban wastewater treatment and reuse in agriculture varies substantially by region because of various factors, including the existence of more or less stringent regulations, the availability of alternative water resources, and the availability and cost of raw materials (including energy), land, and technology. Countries that have historically suffered from water stress and shortages, such as the Mediterranean countries, Middle East and Gulf countries, China, Australia, Mexico and the USA have a long history of reusing TW for irrigation (Box 1).

The initial use of TW in agriculture was pioneered in Israel in the early 1950s, and since then, its use has steadily increased. Initially, TW was utilized only for irrigation of non-edible crops, to expand cultivation in areas where fresh water sources were unavailable and/or could not be supplied constantly. Water shortages in the 1980s and a severe water crisis in the 1990s triggered the government to declare two main measures to overcome water scarcity: increasing production of potable water by desalination and expanding the use of TW for irrigation. According to the Israeli Water Authority, Israel produced an estimated total amount of raw wastewater at 620.5 million m^3, and about ~95.4% (about 592 million m^3) of this total wastewater was treated in WWTPs during 2022 (ref. 54). The reuse of TW for irrigation currently provides 45–50% of the total water use for agricultural irrigation (Box 1). However, although the utilization of TW is high and expected to increase in the future, the capacity of TW utilization is still not maximal owing to lack of infrastructure for transferring TW from surplus production areas (central region of Israel) to areas with high agricultural activities facing water shortage in the south and north parts of the country[54].

Reuse for irrigation is a widespread practice in the southern USA, particularly in California, Florida, Texas and Arizona[55–57]. Several African countries, such as in Algeria, Egypt and Morocco have seen important investments in wastewater treatment and reuse facilities, of €14 million, €132.6 million and €40.7 million, respectively[58]. The total municipal water reuse in China reached 12.6 billion m^3 in 2019, with $88 billion invested in the development of urban wastewater treatment and reuse facilities between 2016 and 2020 (refs. 59,60). In India, despite the relatively low volumes of current wastewater treatment (20.2 million $m^3\ d^{-1}$ or 28% of the generated wastewater volume of 72.4 million $m^3\ d^{-1}$), the large volumes of generated wastewater represent a vast future potential for reuse for crop irrigation[61].

On a more local scale, urban and peri-urban areas generally have more readily available TW and a nearby market for agricultural products[53], leading to the development of TW-irrigated agricultural hotspot areas near either centralized or decentralized WWTPs. These hotspot areas of agricultural production can result in freshwater savings, reduced greenhouse gas (GHG) emissions and energy consumption through alleviating water pumping and water and food transportation needs, while promoting public health by limiting irrigation with untreated wastewater[62].

The example of the North-Western Sahara Aquifer System, which covers large parts of Algeria, Tunisia and Libya (one of the water-scarcest regions in the world), highlights the importance of TW reuse for agricultural irrigation. TW reuse-based agricultural hotspots in this region facilitated the alleviation of groundwater stress by halving the volume of water abstracted from the deep aquifer, reducing the energy costs of pumping by about 15%, and supporting sustainable food production in peri urban areas[63].

In the rapidly developing city of Hyderabad, India, TW reuse in agriculture resulted in food production with minimized pathogen contamination compared to untreated wastewater irrigation, 33% reduction in GHG emissions, and direct groundwater savings[64]. In rural communities in India, constructed wetlands also provide decentralized wastewater treatment, thus allowing the production of TW-irrigated food in small agricultural hotspots with reduced disease burden and decreased environmental pollution[65].

The implementation of an integrated peri-urban wastewater treatment and reuse system in Milan, Italy, is predicted to result in energy savings of up to 7.1% and a reduction of GHG emissions by up to 2.7%. In addition, the production of high-quality crops will generate more revenue and the recovery of nutrients will reduce input costs[66]. In Jordan, a country facing increasing water scarcity, the decentralization of treatment plants to rural and urban settlements and the reuse of TW for irrigation is considered as an important component for the sustainable management of available water resources[67].

In summary, reuse for irrigation has evolved with advancements in treatment technologies, providing a valuable water source for agriculture. Reclaimed water, treated to meet quality standards, offers economic, social and environmental benefits. However, despite progress, the percentage of global TW reused for agriculture remains low. TW-irrigated agricultural hotspots, exemplified in water-scarce regions, showcase examples of substantial water savings, reduced energy consumption and improved sustainable food production (Fig. 2).

Key benefits and challenges

The reuse of TW for irrigation offers several benefits, but careful consideration of the agroenvironment and reclaimed water quality is required to mitigate associated drawbacks. In this section, we aim to highlight the agronomic advantages and drawbacks of reusing TW in agriculture, as well as the challenges related to the presence of MCEC in TW applied for irrigation.

Effects on the agroenvironment

In water-scarce regions, TW irrigation offers farms with year-around stable and low-cost water source. However, the agronomic implication of TW for crop irrigation is far from a simple change in water resources. This practice offers a spectrum of advantages and disadvantages that can impact the overall sustainability and productivity of agricultural systems.

TW carries essential macro-nutrients such as nitrogen, potassium and phosphorus, and the potential to recover these nutrients stands out as a substantial agronomic advantage by reducing reliance on commercial fertilizers. However, this practice must be associated with routine monitoring and appropriate training; otherwise, the introduction of nutrients to the environment through TW irrigation could cause pollution rather than environmental and agronomical benefits.

A potentially notable disadvantage of TW as the sole irrigation source is related to the potential for it to increase soil salinity. TW often contains elevated levels of salts, which can accumulate in the receiving soils and more importantly impede crop growth[68]. Severe cases of salts accumulation and/or addition of dissolved and particulate organic matter originating from TW in soil can result in soil structure deterioration, leading to unfavourable soil physical and hydraulic properties[69,70], reducing water and oxygen availability to plants, ultimately harming crop performance. Furthermore, TW irrigation can contaminate groundwater situated below irrigation sites[71]. To reduce the potential risk, overall water management at the regional or state level can reduce salt input into the sewage system and routine monitoring of generated TW must be implemented.

Also, careful attention should be placed to boron which can be found in detergents and therefore can transfer to sewage and TW, and can induce phytotoxicity at low concentrations[72]. Therefore, boron levels should be controlled at the source because it is not removed during wastewater treatment. Furthermore, if TW is not adequately treated, the TW could carry pathogens that can harm farmers and infect crops and pose risks to human health through the food chain[73]. Thus, strict adherence to water quality standards and robust monitoring systems are imperative to address these concerns.

The agronomic advantages of using TW for crop irrigation come with challenges. Balancing these factors is essential for realizing the potential benefits of TW in agriculture while mitigating the associated risks.

Contaminant-related challenges

The inability of currently applied treatment technologies to completely remove MCEC is a primary challenge of widespread wastewater reuse for agricultural purposes. The environmental fate of MCEC and their potential impacts on living organisms pose several challenges and therefore constitute an important research topic in the field of TW reuse in agriculture (Fig. 3).

Although the reuse of TW for agricultural irrigation has gained acceptance as a viable practice to service crop nutrient needs and water requirements, and major advances have been made that support the production of TW that is safe for reuse, TW can still contain MCEC that can induce negative environmental and health impacts[28,74]. Biological treatment technologies, such as CAS and MBR, and combinations with membrane filtration methods (nanofiltration and reverse osmosis), ozonation, advanced oxidation processes, and adsorption processes can achieve from sufficient to very high removals of MCEC[75,76]. At the same time, these combinations of technologies and widely used disinfection technologies including oxidizing agents such as chlorine and physical agents such as ultraviolet irradiation[77], as well as emerging disinfection processes using peracetic acid[78] and performic acid[79], bear limitations in addressing holistically MCEC. Limitations include the fact that even though some technologies are successful in removing parent compounds of MCEC, they do so while generating transformation products (often more harmful than their parent compounds), toxicity, mutagenicity and endocrine disruption effects[80], while also selecting potentially pathogenic bacteria (repair and/or regrowth) and altering the microbial community structures of wastewater influent and of TW[81].

Furthermore, it is crucial to consider the impact of external contamination on TW storage, particularly given that storage facilities are often uncovered. Additionally, the influence of transportation piping, primarily attributed to biofilm formation (including also the pipes material and roughness), on the potential for post-treatment repair and regrowth of harmful microorganisms, including pathogens and ARB, should be thoroughly examined in the context of reuse systems[82,83]. Currently, several important questions concerning the presence of MCEC in TW reuse systems and their subsequent release into the environment through TW irrigation remain, preventing potentially a wider application of the practice of reuse[84,85].

Environmental fate of MCEC

Advances in analytical techniques and instruments have enabled the acquisition of both qualitative and quantitative information on organic pollutants in very low concentrations[86]. Consequently, hundreds of MCEC are routinely detected and quantified in environmental matrices receiving TW downstream of WWTPs, including TW-irrigated soils, surface and groundwater systems, parks and even drinking water[29,84,87]. Many of them are simultaneously released via treated effluents, forming cocktails which vary in concentration and composition in receiving environments, both spatially and temporally[88]. Various MCEC have been shown to accumulate in TW-irrigated agricultural soils following transportation and transformation (by both biotic and abiotic factors), and to be taken up by wild and cultivated crop plants and accumulated within their tissues[84,89]. Upon their entrance into the food web, a number of them displaying favourable physicochemical properties can potentially bioaccumulate in other organisms and in humans[90,91], potentially provoking toxicity effects[92].

Mechanisms involved in MCEC uptake by plants, as well as their accumulation in different plant tissues, including edible ones, have been studied under controlled conditions[93]. In addition, it was shown that upon MCEC uptake by plants, the pollutants can induce transcriptomic and metabolomic rearrangements that impact normal plant physiology and morphology, indicating stress responses[94,95]. MCEC can be metabolized and detoxified in plant cells by a versatile system that has strong similarities to those used by humans and animals, thus termed the 'green liver'[94,96].

Real-world field experiments (primarily on pharmaceutical compounds) and field surveys also revealed the uptake and accumulation of MCEC in the edible parts of crop plants cultivated under real

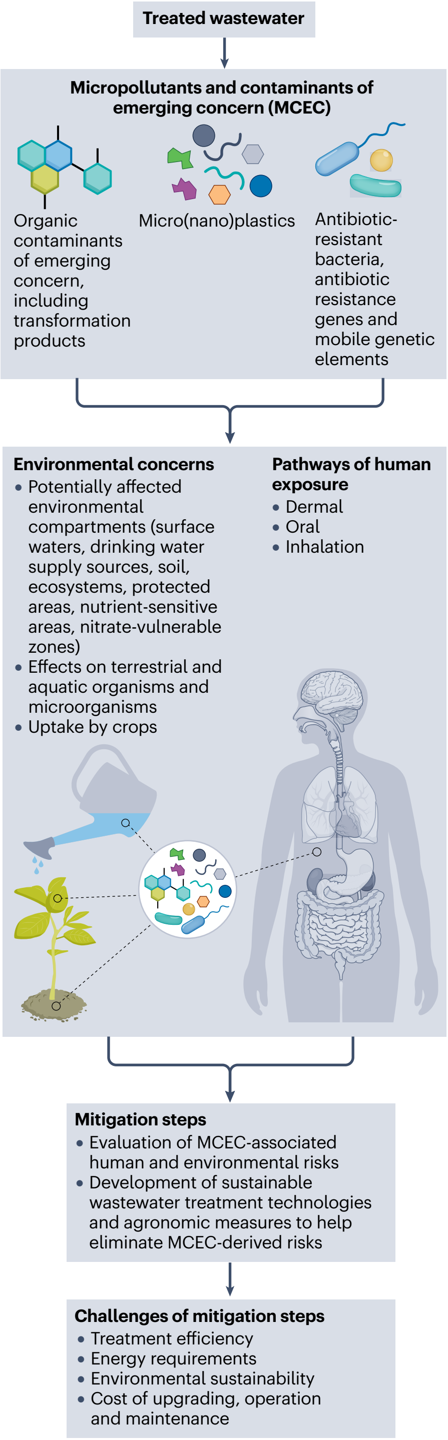

Fig. 3 | Challenges and limitations in treated water (TW) reuse. Applied treatment processes fail to completely remove all micropollutants and contaminants of emerging concern (MCEC) from treated effluents, resulting in their release to the environment through reuse applications. MCEC introduced into the agroecosystem can interact with plants and other organisms with potentially negative impacts. For example, the dissemination of antibiotic resistance (AR) determinants through TW irrigation could cause their potential transfer to bacteria of clinical relevance, which could then enter the food web upon uptake by crop plants. Micro(nano)plastics co-released with other contaminants could also enhance AR dissemination and thus result in enhanced toxicological impacts. Associated challenges and risks of TW irrigation to human and environmental health should be addressed. The upgrade of WWTPs to include advanced treatment steps and the implementation of risk management plans covering the entire TW reuse system can effectively mitigate TW reuse-associated challenges.

agricultural conditions (the uptake potential is mostly affected by the plant species, the soil physicochemical properties and environmental conditions governing evapotranspiration, among others), as well as the potential associated human health risks[97–99]. Moreover, control trials verified the presence of carbamazepine and its metabolites in the urine of people that consumed vegetables collected from fields irrigated with TW for a prolonged period, compared with control samples[90] (Fig. 3).

Accumulating evidence also shows that WWTPs release substantial quantities of micro(nano)plastics into the environment, despite the high removal efficiencies (up to 98%) reported for currently applied secondary and tertiary treatment technologies, as TW is continuously released into the environment[100,101]. Owing to their surface properties, micro(nano)plastics can be colonized by wastewater microorganisms resulting in the formation of dynamic biofilms, known as plastispheres[102], which interact with other co-existing contaminants in WWTPs, including MCEC[103]. Wastewater plastispheres can enhance the persistence of AR elements and bacterial pathogens by favouring their microenvironment and horizontal gene transfer[103,104] and limiting their inactivation by disinfection processes[105], thus accelerating their toxicological impacts in the downstream environments[104].

In addition, micro(nano)plastics can accumulate in soil fauna, wildlife and plants and exert negative impacts[106,107]. The uptake and accumulation of micro(nano)plastics in cultivated plants, alongside other co-contaminants in TW and/or irrigated soil, can induce phytotoxic effects with negative impacts on plant growth and development[108]. Moreover, the accumulation of micro(nano)plastics in the edible parts of crop plants can further contribute to their biomagnification in the food chain, with potential human health risks[109]. Thus, measures to efficiently control and minimize the impact of micro(nano) plastics at the WWTP level should be considered[110].

The transformation products of MCEC often have similar molecular structure to their parent compound. They still contain the toxicophore-like moiety, whereas some other derivatives incorporate almost the complete parent compound structure and might thus show similar environmental behaviour and bioactivity[111]. Research has suggested that some transformation products might pose a similar or greater risk than their active parent compound exhibiting similar or higher ecotoxicological effects[112]. Transformation products along with their parent compounds have been detected in the soil–crop continuum in TW-irrigated agroecosystems[113,114].

Regarding the current concerns about AR, the need to investigate the residual antibacterial potential of antibiotic transformation products is profound. Although the relationship between the parent antibiotic compounds and AR is well documented, the impacts of their transformation products on AR development (through enhanced selective pressure on resistant bacteria) and on TW-receiving environments are not well understood. Risk assessment studies on human and environmental health should encompass not only parent compounds but also transformation products as well as other non-pharmaceutical selection pressures[115,116] (Fig. 3).

AR determinants in TW reuse schemes

Irrigation with TW will entrain sub-minimum inhibitory concentrations of antibiotics, ARB, ARGs and mobile genetic elements such as *intI1* into soil[117,118]. The enrichment of ARG concentrations in TW-irrigated public park soil[87], as well as the increase in the concentration of antibiotic-resistant *Escherichia coli* on the leaf surface of romaine lettuce following TW irrigation[119], highlight the potential for human exposure to AR determinants as a result of TW irrigation. However, no correlation of various investigated ARG concentrations between TW and irrigated soils has been verified, despite the strong correlation of TW *intI1* concentrations to those found in sandy soil fields, with a factor in this suggested to be limitations of the quantification methods utilized[120].

Changes in the microbial community structure within soil–crop systems cannot be ignored when considering potential AR determinant spread events in the agricultural environment, as the abundance of putative antibiotic-resistant pathogens (often bearing clinically relevant ARGs) might be impacted by TW irrigation, leading to selective pressures acting on the resistome, especially in the presence of residual antibiotic concentrations[121,122]. Advances in molecular and data analysis techniques, such as omics technologies and bioinformatics methods, have offered increased resolution of genetic constituents of the microbial community within various environmental matrices[123]. The precise role of agricultural practices on the dissemination of AR determinants in the agroecosystem and of their subsequent entrance to the food web remains uncertain, largely owing to very little data obtained under real-world field-scale conditions. The impacts on AR propagation posed by the climatic conditions prevailing in a certain agricultural site, the applied soil amendment practices, the type of irrigation system used, the cropping system and the type of crop cultivated, remain largely unexplored[118,124,125].

A decreasing gradient of AR determinants has been observed in the soil–crop continuum, as the ARG loads in soil and rhizosphere were found to be substantially higher ($x10^3$ - $x10^4$) compared to those in the edible crop tissue[126], with the ARGs bla_{TEM} and *sul1* being of highest abundance within the soil–crop system[127]. By contrast, the prevalence of *intI1* and of bla_{TEM} and *sul1*, was shown to be higher in *Lactuca sativa* compared to *Lycopersicon esculentum* and *Vicia faba* L. crops, indicating the impact of crop species selection on ARGs loads[126]. The prevalence gradient of AR determinant loads from TW-irrigated soil to the above ground plant tissues showcases the impact that TW irrigation might have on the soil microbiome, whereas AR determinants might in turn be taken up and/or accumulate in crop tissue, though to a much lesser extent[126].

Thus, plant rhizospheric and endophytic microbiome can be impacted by TW reuse through the horizontal gene transfer of AR determinants in the soil and their transfer to rhizospheric and plant bacteria[128,129]. Similarly, soil bacteria have the capacity to capture plasmids and mobile genetic elements from other proximal bacteria and then migrate into the endophytic surface or internal tissue, thus spreading these elements within the plant tissue microbiome along with nutrient plant uptake[129,130].

MCEC-mediated impacts on human health

Limited research, together with technical risk assessment challenges currently hinder the assessment of human health risks arising from exposure to AR determinants, sub-MIC antibiotic concentrations and their associated transformation products in TW and reuse environments[116,131]. However, the associated potential risks driven by the environmental development and transfer of AR to humans in the wastewater reuse settings should be evaluated having in mind the international aspect of AR challenge, the precautionary principle, and the One Health concept which recognizes the interconnectedness of humans, animals and the environment[132]. To this effect, AR hotspots and associated risks from reuse schemes should be counted and managed alongside with risks derived from pharmaceutical manufacturing sites, food and animal production (use of antibiotics in livestock, plant protection and aquaculture) and clinical settings (hospitals)[133].

Currently, there are open discussions regarding the potential risks posed by the presence of sub-lethal antibiotic levels (present in cocktails of parent compounds and transformation products) and of resistant endophytic bacteria in human gut as a result of the consumption of TW-irrigated agricultural produce, and the potential of altering human microbiome and promoting adaptive resistance selection[134–136]. Risks assessment of AR should be grounded in the state of the science and vetted by academic experts, and based on real-world research data on AR determinants found in TW, soil and edible crops[134]. The scientific community should address relevant questions such as which are the relevant endpoints, risks thresholds and/or safe exposure levels for ARGs when assessing AR risks. To enhance our understanding and to be able to develop risk assessments for ARB and ARG in reclaimed water, it is imperative that future data collection efforts adopt a standardized approach in reporting. Although the importance of concentration data per unit volume is acknowledged, it is also worthwhile to consider that other units may offer valuable insights in different scenarios[137]. It is also imperative to provide sample metadata, encompassing a comprehensive explanation of the treatment technologies used and a delineation of the intended reuse purposes, methods for conveyance to the point of use, and available physicochemical water quality data. Additional research is needed aimed at identifying recommended ARB and ARG monitoring targets and for developing approaches to incorporate metagenomic data into risk assessment[131,138].

In summary, the use of TW for crop irrigation has both advantages and challenges. On the positive side, TW serves as a cost-effective and stable water source, enriching crops with essential nutrients and reducing reliance on commercial fertilizers. However, challenges arise from potential soil salinity and the presence of MCEC, including pharmaceuticals and AR determinants. Adequate monitoring, adherence to water quality standards and further research on the fate of contaminants are crucial for balancing the agronomic benefits and challenges of TW irrigation.

Wastewater reuse governance

The global promotion of sustainable and safe reuse of TW in agricultural irrigation has led international organizations and countries to develop regulatory frameworks and guidelines. These policies ensure that TW meets quality standards to protect the environment and human and animal health, while also promoting social acceptance and facilitating the international trade of food.

Regulations and permits

Comprehensive regulations often include a permit system for the production and use of TW for various applications (Box 2). This system is based on respecting a set of microbial and chemical quality standards which depend on the technical specifications of wastewater treatment, such as secondary, tertiary, or advanced treatment, nutrient reduction, and disinfection. Regulations also detail the types of crops that can be irrigated with TW, the components of the irrigation system, and rules on restricted entry and harvesting intervals after irrigation. They may also establish physical barriers, such as buffer zones, and regulate the proximity of TW application to sensitive or protected ecosystems[12,49].

Despite the establishment of regulatory frameworks and guidelines, governance strategies for water reuse need to address various challenges owing to fragmented knowledge and expertise, diverse institutions, a mix of stakeholders involved, and the willingness to implement policies. These strategies should consider the interdisciplinary scientific evidence, acting on the science–policy–practice interface for the coproduction of accepted governance solutions[139]. The main regulatory frameworks currently applied around the world are described in Box 2.

Risk management frameworks

In addition to established criteria for water quality, some policies suggest or impose the use of a risk management approach to identify and manage health and environmental risks in all components of the TW reuse systems, under both regular conditions and emergencies[12]. For example, the Australian Guidelines for Water Recycling[140] and the US EPA Guidelines for Water Reuse[141] require a risk management framework that could be voluntarily applied to water reuse systems in their territories, allowing for the regional adaptation of rules. The ISO (the ISO 20426:2018 — Guidelines for Non-Potable Water Reuse[142] and the ISO 16075:2020 — Use of Treated Wastewater for Irrigation Projects[143]), the World Health Organization (WHO)[144] also developed risk management-based guidelines for the safe reuse of TW that could be applied worldwide, particularly in less developed countries where local legal frameworks are missing.

The WHO[144] and the Australian Guidelines[140] have influenced the structure of the risk management plan of the European Union Water Reuse Regulation 2020/741 (ref. 49) (Fig. 4) proposed by the Technical Guidance on the Water Reuse Risk Management for Agricultural Irrigation Schemes in Europe[12]. Some of its technical components, including identification of health hazards, health risk management framework, environmental risk assessment on freshwater resources and the effects of reclaimed water on soil and crops were developed based on relevant parts of the ISO 20426:2018 (ref. 142), the ISO 16075:2020 (ref. 143) and the Australian Guidelines[140]. The risks to be addressed can be grouped into those concerning health risks to humans exposed to reclaimed water (workers, bystanders and residents in nearby communities) and those concerning the local environment (surface waters and groundwater, soil and relevant ecosystems).

Considering that a water reuse system complies with the minimum requirements for water quality of the Annex I of the Water Reuse European Regulation, the overall objective of a risk management plan[12] is to guarantee that a water reuse system operates while ensuring the protection of the health of workers, farmers, and consumers, and

Box 2

Legal and regulatory frameworks covering TW reuse for irrigation

The International Organization for Standardization (ISO) guidelines

The ISO 16075:2020 (ref. 143) covers guidelines for the use of TW in irrigation projects. It suggests standards for *Escherichia coli*, biological oxygen demand (BOD$_5$), total suspended solids (TSS) and turbidity for different water quality category depending on treatment levels. It also includes suggested levels for agronomic parameters (for example, nutrients, salinity and heavy metals) for the protection of soil and crops irrigated with TW. The ISO 20426:2018 (ref. 142) provides an approach for health risk assessment and management of TW used in non-potable applications. The WHO has also provided guidelines for the safe use of wastewater[144] which contains a methodology to ensure safe reuse of TW around the world.

European Union Water Reuse Regulation

The European Union (EU) Regulation 2020/741 (ref. 49) sets out harmonized minimum water quality and monitoring requirements for *E. coli*, BOD$_5$, TSS, and turbidity for water quality classes A, B, C and D depending on crop types and irrigation methods. The regulation imposes the mandatory development of a risk management plan for water reuse systems, for which guidelines have been established[12]. Additional requirements on water quality and monitoring, which may include non-regulated micropollutants, could be added based on the outcome of the risk assessment on the specific water reuse system. The competent authority designated at EU member states level issues the permit(s) for the production and supply of TW by setting out any obligations and conditions for the permitted uses.

US regulatory framework

In the USA, standards for the use of TW in irrigation have not been established at federal level. The 28 states of the USA have own regulations for the reuse of TW for irrigation of food and non-food crops. Quality requirements varies greatly among the states depending on crop types, irrigation methods and wastewater treatment levels. For example, the Title 22 of California sets out strict criteria on total coliform bacteria, turbidity, F-specific bacteriophages MS-2 or poliovirus for the irrigation of edible food crops with the water quality class corresponding to disinfected and filtered TW (disinfected tertiary TWr)[194]. Additional to state laws, the US EPA Guidelines for Water Reuse[141] provides a non-mandatory national guidance for planning and regulating water reuse across the states following a risk management framework approach.

Israeli water reuse law

The Israeli water reuse law approved by the Ministry of Health (2010) regulates the unrestricted use of TW for agricultural irrigation[195]. It established rules for granting permits for irrigation with TW ensuring the protection of public health and the environment.

Australian Guidelines

The Australian Guidelines for Water Recycling[140] issued in 2006 aims at providing a guidance for safe use of TW. The document does not set out mandatory standards but provides indications on how to identify and set levels for the quality of water used in irrigation based on a health and environmental risk management approach.

safeguarding the environment. The risk management plan is considered as a tool of paramount importance to ensure the integration of site-specific particularities and requirements into a larger regional, national and even European framework, usually defined by ordinances, laws and the EU Water Acquis. The risk management plan ensures that the reclaimed water is used and managed safely to protect the human and animal health and the environment[12] (Fig. 4).

Sustainability of wastewater reuse

Modern wastewater collection and treatment processes account for ~3% of global electricity consumption and total GHG emissions, despite the substantial improvements achieved in the sector to date[145,146]. However, further technological innovations can mitigate energy consumption and enhance circularity by recovering valuable resources, such as nutrients and other by-products. Increasing water scarcity, and the energy and resources crises, call for a paradigm shift in the water–energy–sanitation–food–carbon nexus in a circular economy framework, with wastewater and sludge redefined as sources of energy, nutrients and other products[16,27,147–149] (Fig. 5). In the following section, we discuss the potential provided by technological advancements for energy and resource recovery and steps to achieving circular wastewater treatment.

Technological advancements

Although numerous technologies for the recovery of water, energy, fertilizer, and other products from wastewater have been explored in the academic and industrial arenas, few of them have ever been applied on a large scale. This lack of widespread application is primarily owing to technical immaturity and/or non-technical bottlenecks such as costs, resource quantity and quality, operational distractions, acceptance and policy[150]. Consequently, the implementation of full-scale circular economy-oriented technologies in the wastewater sector is still very limited, with most wastewater management utilities focusing on wastewater collection, treatment and disposal rather than resource recovery[151,152]. However, the upgrade of technology readiness level, economic performance and environmental benefits of these green technologies are expected to promote their wider adoption in the coming years[153] (Fig. 5).

Upgrades in WWTP treatment lines aiming to produce quality reclaimed water complying with the stringent regulations of minimum discharge standards typically include unit processes such as ozonation, activated carbon adsorption, chemical disinfection with chlorine or peracetic acid, ultraviolet irradiation, advanced oxidation processes and membrane filtration and separation processes such as ultra-filtration or nano-filtration and reverse osmosis[25]. Advanced treatment and disinfection technologies in treatment trains should be selected to suit the intended water reuse, meet discharge standards, mitigate health risks, service economic and environmental requirements (limit energy use and GHG emissions), and be based on life cycle assessment and decision support tools[154].

Nanotechnology and advanced materials are set to be an important aspect of the future of the wastewater sector, as some materials offer unique benefits such as superior efficiency and selectivity, high natural abundance, good recyclability, low production cost and sufficient stability to favour their use in wastewater treatment[155]. Nanomaterial-based membranes, including nanofiber-based, nanoparticle-based, nanotube-based, nanocrystal-based, nanowire-based and nanosheet-based membranes, can substantially enhance MBR performance and reduce fouling, operation and maintenance costs[156]. Carbonaceous (for example, activated carbon, carbon nanotubes, carbon quantum dots, graphene or graphene oxide) or metal and metal oxide nanomaterials can be utilized as nano-motors and micro-motors to enhance adsorption, mixing, photocatalysis and advanced oxidation processes during wastewater treatment[157].

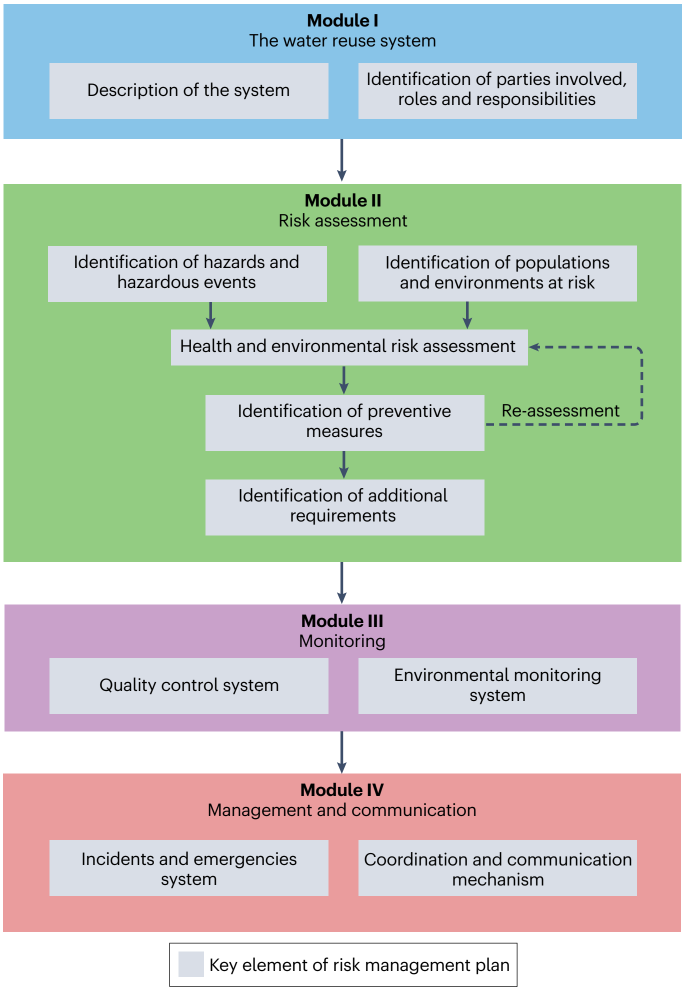

Fig. 4 | Effective wastewater reuse management and risk planning. The risk management plan includes activities such as a detailed description of the entire water reuse system, with its extensions and limitations, and the identification of the roles and responsibilities of the involved actors. Health and environmental risk assessments involve identification of preventive measures and parameters, with reassessment when required. Monitoring activities include identification of procedures and protocols for the quality control of the system and for the environmental monitoring system. Effective management requires emergency and communication protocols and coordination. Figure adapted from ref. 12, under a Creative Commons licence CC BY 4.0.

Artificial intelligence-driven data analytics can support WWTPs process design, operation and control. Its adoption can potentially reduce operating costs, improve system reliability, predict maintenance requirements and conduct troubleshooting, thus increasing water quality and process optimization[158]. Artificial intelligence models have efficiently managed biological[159] and MBR[160] wastewater treatment processes in full-scale WWTPs by predicting the performance, real-time

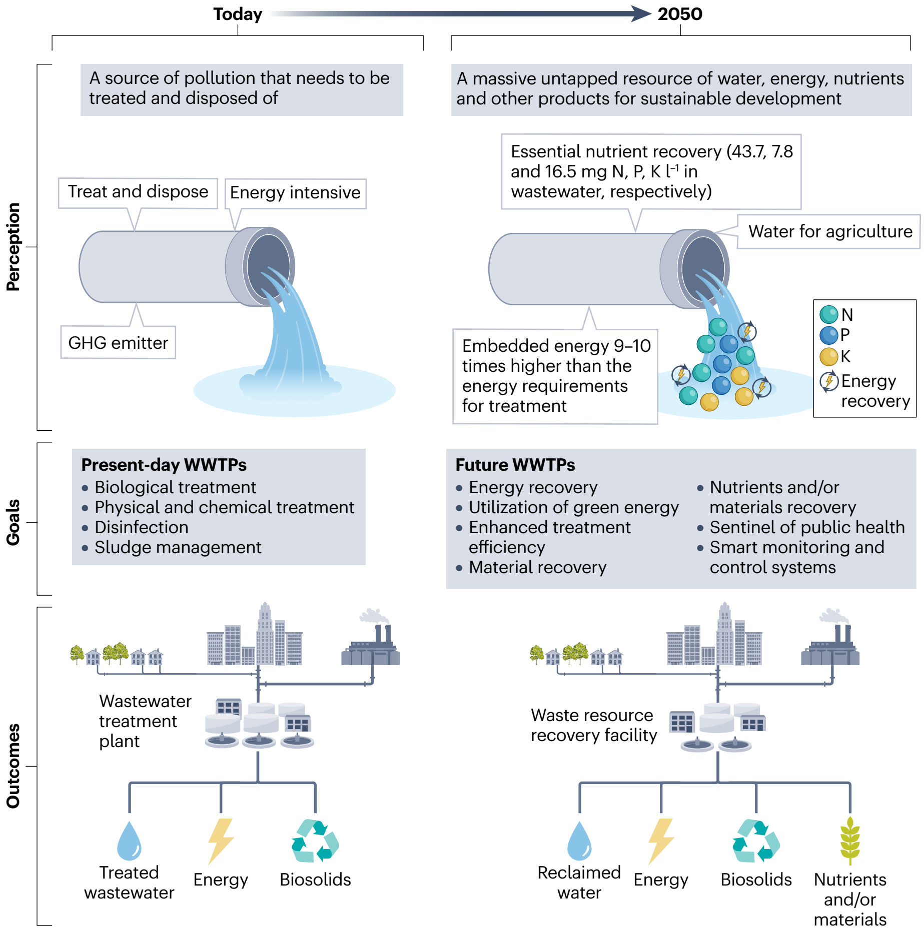

Fig. 5 | Emerging technologies that have the potential to transform the wastewater treatment sector into a circular economy framework. A comparison of current and future perceptions, goals and outcomes for the wastewater treatment sector. Often, current perception is that wastewater is a source of pollution that needs energy-intensive treatment and then disposal, in a process that involves serious greenhouse gas (GHG) emissions. The goals and outcomes are limited only to treatment, disinfection, sludge management and disposal. New technologies are capable of retrofitting and upgrading all the functions of wastewater treatment plants (WWTPs) towards a more circular model, transforming perceptions of wastewater to see it as an untapped resource of reclaimed water, energy, nutrient and other products for sustainable development. The goals and outcomes of future WWTPs will be to become energy-neutral and carbon-neutral facilities, wherein nutrients and other added-value materials are recovered and reused. To this effect, the wastewater treatment sector can become part of a circular economy and contribute to achieving the Sustainable Development Goals (SDGs) in the forthcoming decades.

problems and treated effluent quality. The reduction of costs and of management and maintenance challenges, as well as the elevated training of personnel, will further facilitate the adoption of artificial intelligence in the wastewater treatment sector[161]. Moreover, data-driven methods[162], as well as advancements in analytical chemistry tools, bioinformatics and multi-omics data, can achieve fault detection, variable prediction and advanced control of WWTPs[163].

In summary, the future of wastewater treatment involves upgrading existing technologies, with advanced tertiary treatment technologies. Nanotechnology and advanced materials, particularly nanomaterial-based membranes, are set to revolutionize wastewater treatment, with artificial intelligence-driven data analytics having a crucial role in optimizing processes and ensuring water quality. These advancements promise improved efficiency, energy cost savings and environmental sustainability.

Energy and carbon neutrality

Although wastewater collection and treatment require substantial amount of energy, WWTPs can be transformed to energy neutral or net positive facilities through the recovery of energy contained in wastewater itself. Indicatively, the thermal energy released through the oxidation of the organic compounds contained in wastewater is approximately 9–10 times greater than the energy requirements of a typical WWTP (0.6 kWh m^{-3}); thus, recovering the chemical energy contained in sewage is economically profitable[164,165]. The embedded thermal (~80%), chemical (~20%) and hydraulic (<1%) energy contained in wastewater can be recovered in the form of heating or cooling, biogas and electricity generation through either new or hybrid technologies, or by modifying the existing ones[15].

The anaerobic digestion process that has been applied for decades in WWTPs to stabilize sludge produces biogas that can be utilized for combined heat and power, and can potentially satisfy more than half of the energy needs of a typical conventional aerobic treatment plant[27,166]. The energy that can be recovered from the total volume of wastewater produced globally through the conversion of biogas released by anaerobic digestion could be enough to provide electricity to 158 million households or to up to 632 million people, with projections for steady increase owing to the increasing volumes of produced wastewater[167]. Co-digestion of sewage sludge with municipal waste can further result in improved biogas production rates in the anaerobic digestion process leading to self-sufficient and energy-positive WWTPs, while also reducing the amount of sludge for incineration or landfill[153,168].

Other anaerobic processes, such as anaerobic membrane bioreactor and upflow anaerobic sludge blanket reactor, are finding their way to the market, offering advantages such as improved effluent quality, low sludge production, compact size and high biogas production, which in turn promote their energy neutrality[169,170]. In this line, the anaerobic ammonium oxidation process, either used as side stream or mainstream treatment for nitrogen removal (up to 87%), can result in lower aeration demands and substantial energy savings (more than half of influent chemical oxygen demand can be converted to methane gas and at least 75% reduction in sludge can be achieved)[171]. However, the process still transforms ammonium to dinitrogen gas (N_2), as the underlying principle of all biological nitrogen removal processes remains unchanged (conversion of ammonium to nitrogen gas), failing to recover nitrogen[172].

Salinity gradient energy treatment processes, including pressure-retarded osmosis, reverse electrodialysis and single-pore osmotic generators, can be characterized as mature breakthrough technologies with power density comparable to intermittent solar and wind energy[153]. Moreover, bioelectrochemical systems, particularly microbial fuel cells, photocatalytic fuel cells and microbial electrolysis cells, display numerous benefits in wastewater treatment and energy recovery when applied individually or in treatment trains, although optimization of their architecture and durability and lower installation costs are still required[173,174]. The ability of microbial fuel cells to produce green hydrogen of very high purity can potentially reduce the overall cost of this technology, while also promoting decarbonization and the green energy transition[175] (Fig. 5).

Nutrient recovery

Besides potentially providing a safe alternative source of freshwater, wastewater could also become a valued source of fertilizer nutrients and mitigate existing shortages in nutrients supplies in agriculture[176,177]. On the basis of 53 wastewater quality datasets from across the world, the average concentrations of major nutrients in wastewater were estimated to be 43.7, 7.8 and 16.5 mg l^{-1} for nitrogen (N), phosphorus (P) as P_2O_5 and potassium (K) as K_2O, respectively. These nutrient concentrations are close to those reported in medium strength wastewater[178]. These nutrient concentrations and the global volumes of wastewater generated were used to estimate that the nutrients potentially embedded in wastewater could be up to 16.6, 3.0 and 6.3 Tg (10^9 kg) of N, P and K, respectively, representing 14.4, 6.8 and 18.6% of the respective global fertilizer nutrient demands, or US $13.6 billion of potential total revenue[167]. Nutrient recovery from wastewater could thus constitute a major step towards circular economy as it can promote reuse and recycling and effectively alleviate the need of applying energy-demanding and environment-polluting processes for nutrient resource extraction and fertilizer manufacturing[152].

Several nutrient recovery processes have been developed and applied either to the mainstream wastewater treatment technologies or to the 'side streams' associated with sludge handling. These processes include biological, electrochemical, ion exchange, crystallization or membrane systems[152,179]. However, system combinations and plant-wide configurations are necessary, as none of these methods alone can provide complete recovery of all major nutrients[152,164].

Struvite or vivianite crystallization is one of the most promising technologies for recovering P (over 60%, depending on the physicochemical properties of wastewater) and to lesser extent N (20–30%) and Mg in WWTPs. It can be used either for the main stream water line or side streams (for example, anaerobic membrane bioreactor effluent or water from sludge dewatering systems) and is currently at technology readiness level 7 or higher[180]. Integration of membrane-based technologies such as osmotic MBR, electrodialysis and bioelectrochemical systems can result in high N and/or P recovery even at the full-scale[152,181]. Moreover, microalgae or autotrophic hydrogen-oxidizing bacteria grown in photobioreactors or open systems treating wastewater can display high nutrient recovery rates (50–70%) in the produced biomass, which can subsequently be transformed into several end products, such as fertilizers or animal feedstock rich in amino acids[182,183].

Sewer mining for valuable products

The paradigm shift of changing WWTPs from wastewater treatment and disposal facilities to resource recovery facilities can be further reinforced through the recovery of value-added by-products. High monetary value by-products can be recovered in side streams, including sludge handling, mainly by fermentation processes, bioelectrochemical systems and microalgae treatment. Mining wastewater for hydrogen by microbial fuel cells to produce green energy can provide important revenues which in turn lower treatment cost[175]. Valuable trace elements such as gold, silver, nickel, platinum and other can be also recovered through various electrochemical extraction processes[184]. Macroalgae-based integrated biorefinery, applied in microbial fuel cells, photobioreactors or open systems, can remediate wastewater with the simultaneous production of bioelectricity and value-added products because the harvested microalgae biomass contains valuable biomolecules (for example, biopolymers, cellulose, single-cell protein, polyhydroxyalkanoates and volatile fatty acids), which in turn can facilitate the production of biofuels, bioplastics, biochemicals, nutrition supplements for animal feedstock, antioxidants and nanoparticles[185,186].

In summary, wastewater treatment can transition to a sustainable model through technological innovations promoting energy and resource recovery. Shifting towards a circular economy, wherein sewage is a resource, can transform wastewater facilities into energy-neutral or energy-positive entities. Technologies such as anaerobic digestion, salinity gradient energy processes and microbial fuel cells offer promising avenues for energy recovery. Additionally, nutrient recovery from wastewater can address global fertilizer demands, fostering a circular economy. Sewer mining for valuable by-products further strengthens the paradigm shift towards resource recovery in wastewater management.

Summary and future perspectives

Water management schemes around the world should be designed and implemented within a context of diminishing water availability posed by continuously growing demands and increasing stress to water resources driven by over-abstraction, pollution and climate change. Within this setting, improved wastewater management stands as a major catalyst for sustainable development, simultaneously protecting human health and the environment, and promoting circular economy, rural development and natural resource management. Applied wastewater treatment technologies can produce TW of sufficient quality to be fit-for-purpose for safe reuse in a variety of different applications. The total volume of TW produced globally could satisfy nearly ~15% of all irrigation water needs[13,14], thus supporting the expansion or maintenance of irrigated agriculture and promoting food security, while also releasing equal quantities of freshwater for other uses. Decentralized and hybrid wastewater treatment approaches can provide flexible and resilient solutions fitted to local conditions, further facilitating the sustainable and safe production of food for local markets.

Currently, over 80% of global wastewater is discharged untreated (over 95% in some of the least developed countries)[15,16], with serious environmental and human health risks. The perception of wastewater as an inconvenient waste product that needs to be disposed of must change. The energy-intensive linear approach currently applied in most wastewater treatment systems can potentially evolve to become fully resource efficient and circular, by shifting to the 'reuse, recycle and resource recovery' paradigm. Within this circular approach, technological opportunities can transform WWTPs into water, energy and nutrient recovery facilities, achieving energy–carbon neutrality (Fig. 5). Cost mitigation through decentralization, energy and nutrients recovery, and proper pricing of both freshwater and wastewater can efficiently promote wastewater reuse practices.

Upstream measures focusing on water pollution prevention at source through restrictions and development of greener alternatives should be also given priority over traditional end-of-pipe treatment measures[16]. Moreover, the upgrade of treatment by incorporating advanced technologies, the implementation of control and preventing measures in the whole TW reuse systems and the adoption of best agricultural practices (advanced irrigation systems, use of sorbent materials, crops selection) can also contribute to the mitigation of TW reuse risks associated with MCEC, including AR determinants and transformation products[28].

The diverse challenges faced by CAS, MBR and constructed wetlands technologies, necessitate further research on operational adjustments and mechanistic understanding. The pivotal role of biological processes in achieving safe water reuse, urges continuous innovation and investigation for sustainable wastewater treatment practices. The efficacy of advanced wastewater treatment methods, including ozonation, activated carbon, and membranes, in removing MCEC is demonstrated through economically viable implementations in various countries. Although solar-driven advanced oxidation processes exhibit promise, they face technological readiness challenges. Considering site-specific factors and diverse endpoints for evaluating the most suitable and cost-effective solutions for advanced urban wastewater treatment is important. The need for ongoing research, system optimization and eco-toxicological studies is emphasized to address gaps in understanding and implementation of such processes.

Effective management practices enforced by appropriate governance and regulatory frameworks and technological innovation can offer further opportunities towards transforming wastewater reuse at the global level, especially in developing countries. Suitable legal and regulatory frameworks, adapted and implemented either at the local or national level, should be empowered by sufficient implementation tools. This empowerment requires political, institutional and financial support. Furthermore, these frameworks should be characterized by transparency and citizen involvement and engagement. In addition, regulations should incentivize wastewater management circularity by enabling recovered resources such as nutrient fertilizers and other by-products to enter the markets. The regulation of MCEC in treated effluent should now be considered[138], given that any new policies will be based on real-world research data on the toxicological impacts to humans and the environment, the real magnitude of pollution burden in the end of the reuse systems, the associated costs and the effectiveness of currently applied technologies. The risk levels of reuse practices can be also monitored and reduced through the implementation of comprehensive risk management plans that include toxicological endpoints for all involved environmental matrices (for example, water resources, soil, plants, wildlife and humans).

Sustainable wastewater management incorporating TW reuse for irrigation can act as a major catalyst for circular economy and sustainable development. The social acceptance and adoption of this perspective by several international organizations and national authorities is the first step towards the capitalization of all derived opportunities arising from this practice. To progress to this objective, the active involvement and good services of all involved parties, including public authorities, relevant stakeholders, industry, academia, farmers and the public (consumers), is necessary.

References

1. Huggins, X. et al. Hotspots for social and ecological impacts from freshwater stress and storage loss. *Nat. Commun.* **13**, 439 (2022).
2. Schewe, J. et al. State-of-the-art global models underestimate impacts from climate extremes. *Nat. Commun.* **10**, 1005 (2019).
3. Schumacher, D. L. et al. Amplification of mega-heatwaves through heat torrents fuelled by upwind drought. *Nat. Geosci.* **12**, 712–717 (2019).
4. Rahman, M. F. et al. As the UN meets, make water central to climate action. *Nature* **615**, 582–585 (2023).
5. Naddaf, M. The world faces a water crisis — 4 powerful charts show how. *Nature* **615**, 774–775 (2023).
6. Mueller, J. T. & Gasteyer, S. The widespread and unjust drinking water and clean water crisis in the United States. *Nat. Commun.* **12**, 3544 (2021).
7. Ovink, H., Rahimzoda, S., Cullman, J. & Imperiale, A. J. The UN 2023 Water Conference and pathways towards sustainability transformation for a water-secure world. *Nat. Water* **1**, 212–215 (2023).
8. UN DESA. The sustainable development goals report 2022 (UN DESA, 2022).
9. Flörke, M., Schneider, C. & McDonald, R. I. Water competition between cities and agriculture driven by climate change and urban growth. *Nat. Sustain.* **1**, 51–58 (2018).
10. Zhu, P. et al. Warming reduces global agricultural production by decreasing cropping frequency and yields. *Nat. Clim. Change* **12**, 1016–1023 (2022).
11. Fito, J. & Van Hulle, S. W. Wastewater reclamation and reuse potentials in agriculture: towards environmental sustainability. *Environ. Dev. Sustain.* **23**, 2949–2972 (2021).
12. Maffettone, R. & Gawlik, B. *Technical Guidance Water Reuse Risk Management for Agricultural Irrigation Schemes in Europe.* JRC129596 (Publications Office of the European Union, 2022).
13. FAO. Water for sustainable food and agriculture, Rome, 2017 (FAO, 2017).
14. FAO. *The State of the World's Land and Water Resources for Food and Agriculture — Systems at Breaking Point.* Synthesis report 2021 (Food and Agriculture Organization of the United Nations, 2021).
15. European Investment Bank (EIB). *Wastewater as a resource* (European Investment Bank, 2022).
16. WWAP (United Nations World Water Assessment Programme). *The United Nations World Water Development Report 2017. Wastewater: the Untapped Resource* (UNESCO on behalf of UN-Water, 2017).
17. Salgot, M. & Folch, M. Wastewater treatment and water reuse. *Curr. Opin. Environ. Sci. Health* **2**, 64–74 (2018).
18. Tortajada, C. Contributions of recycled wastewater to clean water and sanitation Sustainable Development Goals. *NPJ Clean Water* **3**, 22 (2020).
19. van Daalen, K. R. et al. The 2022 Europe report of the Lancet Countdown on health and climate change: towards a climate resilient future. *Lancet Public Health* **7**, e942–e965 (2022).
20. Ballester, J. et al. Heat-related mortality in Europe during the summer of 2022. *Nat. Med.* **29**, 1857–1866 (2023).
21. Dimitrova, A., McElroy, S., Levy, M., Gershunov, A. & Benmarhnia, T. Precipitation variability and risk of infectious disease in children under 5 years for 32 countries: a global analysis using Demographic and Health Survey data. *Lancet Planet. Health* **6**, e147–e155 (2022).
22. Cipolletta, G. et al. Policy and legislative barriers to close water-related loops in innovative small water and wastewater systems in Europe: a critical analysis. *J. Clean. Prod.* **288**, 125604 (2021).
23. Angelakis, A. N., Asano, T., Bahri, A., Jimenez, B. E. & Tchobanoglous, G. Water reuse: from ancient to modern times and the future. *Front. Environ. Sci.* https://doi.org/10.3389/fenvs.2018.00026 (2018).
24. Singh, V. & Suthar, S. Occurrence, seasonal variation, mass loading and fate of pharmaceuticals and personal care products (PPCPs) in sewage treatment plants in cities of upper Ganges bank, India. *J. Water Process Eng.* **44**, 102399 (2021).
25. Rizzo, L. et al. Best available technologies and treatment trains to address current challenges in urban wastewater reuse for irrigation of crops in EU countries. *Sci. Total Environ.* **710**, 136312 (2020).
26. Daw, J., Hallett, K., DeWolfe, J. & Venner, I. Energy efficiency strategies for municipal wastewater treatment facilities (NREL, 2012).
27. McCarty, P. L., Bae, J. & Kim, J. Domestic wastewater treatment as a net energy producer — can this be achieved? *Environ. Sci. Technol.* **45**, 7100–7106 (2011).
28. Yalin, D. et al. Mitigating risks and maximizing sustainability of treated wastewater reuse for irrigation. *Water Res. X* **21**, 100203 (2023).
29. Alygizakis, N. A. et al. Evaluation of chemical and biological contaminants of emerging concern in treated wastewater intended for agricultural reuse. *Environ. Intern.* **138**, 105597 (2020).

30. Zhong, L. et al. Bibliometric overview of research progress, challenges, and prospects of rural domestic sewage: treatment techniques, resource recovery, and ecological risk. *J. Water Process Eng.* **51**, 103389 (2023).
31. Torre, A., Vázquez-Rowe, I., Parodi, E. & Kahhat, R. Wastewater treatment decentralization: is this the right direction for megacities in the Global South? *Sci. Total Environ.* **778**, 146227 (2021).
32. Jung, Y. T., Narayanan, N. & Cheng, Y.-L. Cost comparison of centralized and decentralized wastewater management systems using optimization model. *J. Environ. Manag.* **213**, 90–97 (2018).
33. Massoud, M. A., Tarhini, A. & Nasr, J. A. Decentralized approaches to wastewater treatment and management: applicability in developing countries. *J. Environ. Manag.* **90**, 652–659 (2009).
34. Chen, P. et al. Research progress on integrated treatment technologies of rural domestic sewage: a review. *Water* **14**, 2439 (2022).
35. Arias, A., Feijoo, G. & Moreira, M. T. in *Current Developments in Biotechnology and Bioengineering* (eds Mannina, G. et al.) 259–287 (Elsevier, 2020).
36. Yang, F. et al. Performance analysis and evaluation of the 146 rural decentralized wastewater treatment facilities surrounding the Erhai Lake. *J. Clean. Prod.* **315**, 128159 (2021).
37. Hube, S. & Wu, B. Mitigation of emerging pollutants and pathogens in decentralized wastewater treatment processes: a review. *Sci. Total Environ.* **779**, 146545 (2021).
38. Datta, A., Singh, H. O., Raja, S. K. & Dixit, S. Constructed wetland for improved wastewater management and increased water use efficiency in resource scarce SAT villages: a case study from Kothapally village, in India. *Int. J. Phytorem.* **23**, 1067–1076 (2021).
39. Bixio, D. et al. Wastewater reuse in Europe. *Desalination* **187**, 89–101 (2006).
40. Lau, S. S. et al. Toxicological assessment of potable reuse and conventional drinking waters. *Nat. Sustain.* **6**, 39–46 (2023).
41. Liu, L. et al. The importance of system configuration for distributed direct potable water reuse. *Nat. Sustain.* **3**, 548–555 (2020).
42. Zawadzka, J., Gallagher, E., Smith, H. & Corstanje, R. Ecosystem services from combined natural and engineered water and wastewater treatment systems: going beyond water quality enhancement. *Ecol. Eng.* **142**, 100006 (2019).
43. Padrón-Páez, J. I., Almaraz, S. D.-L. & Román-Martínez, A. Sustainable wastewater treatment plants design through multiobjective optimization. *Comput. Chem. Eng.* **140**, 106850 (2020).
44. European Environmental Agency. WISE Freshwater database. https://water.europa.eu/freshwater/countries/uwwt/european-union (2020).
45. Jones, E. R., Van Vliet, M. T., Qadir, M. & Bierkens, M. F. Country-level and gridded estimates of wastewater production, collection, treatment and reuse. *Earth Syst. Sci. Data* **13**, 237–254 (2021).
46. Food and Agricultural Organization of the United Nations. AQUASTAT Database. www.fao.org/nr/water/aquastat/main/index.stm (2020).
47. Alcalde-Sanz, L. & Gawlik, B. Science for policy report: minimum quality requirements for water reuse in agricultural irrigation and aquifer recharge. Towards a legal instrument on water reuse at EU level (Publications Office of the European Union, 2017).
48. Radini, S., González-Camejo, J., Andreola, C., Eusebi, A. & Fatone, F. Risk management and digitalisation to overcome barriers for safe reuse of urban wastewater for irrigation — a review based on European practice. *J. Water Process Eng.* **53**, 103690 (2023).
49. European Union. Regulation (EU) 2020/741 of the European Parliament and of the Council of 25 May 2020 on minimum requirements for water reuse. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32020R0741 (2020).
50. Cui, Q. et al. Bacterial removal performance and community changes during advanced treatment process: a case study at a full-scale water reclamation plant. *Sci. Total Environ.* **705**, 135811 (2020).
51. Xiao, R. et al. Disinfection by-products as environmental contaminants of emerging concern: a review on their occurrence, fate and removal in the urban water cycle. *Crit. Rev. Environ. Sci. Technol.* **53**, 19–46 (2023).
52. Kümmerer, K., Dionysiou, D. D., Olsson, O. & Fatta-Kassinos, D. Reducing aquatic micropollutants — increasing the focus on input prevention and integrated emission management. *Sci. Total Environ.* **652**, 836–850 (2019).
53. Ungureanu, N., Vlăduț, V. & Voicu, G. Water scarcity and wastewater reuse in crop irrigation. *Sustainability* **12**, 9055 (2020).
54. Israel Water Authority. Master plan for the sewage system 2030–2050 https://www.gov.il/he/departments/policies/master_plan_for_the_sewage_system (2023).
55. Ritter, W. State regulations and guidelines for wastewater reuse for irrigation in the US. *Water* **13**, 2818 (2021).
56. Parsons, L. R. Agricultural use of reclaimed water in Florida: food for thought. *J. Contemp. Water Res. Educat.* **165**, 20–27 (2018).
57. Gile, B. C., Sciuto, P. A., Ashoori, N. & Luthy, R. G. Integrated water management at the peri-urban interface: a case study of Monterey. *California Water* **12**, 3585 (2020).
58. Nikiema, J. et al. Wastewater treatment practices in Africa — experiences from seven countries. *Ratio* **658**, 26–34 (2010).
59. Hu, H.-Y., Chen, Z., Hao, S. & Wu, Y. Towards the new era of water reuse in China. *The Source* (*IWA*) https://thesourcemagazine.org/towards-the-new-era-of-water-reuse-in-china/ (2021).
60. Kitano, N., Qu, F. & Bennon, M. Building Gaobeidian: developing the environmental infrastructure of modern Beijing. *Asian Development Bank Institute* https://www.adb.org/sites/default/files/publication/898301/adbi-building-gaobeidian-developing-environmental-infrastructure-modern-beijing.pdf (2023).
61. Bassi, N., Gupta, S. & Chaturvedi, K. Reuse of treated wastewater in India. Market potential and recommendations for strengthening governance. *The Council on Energy, Environment and Water* (*CEEW*) https://www.ceew.in/sites/default/files/scaling-wastewater-reuse-treatment-and-management-india.pdf#page=4.10 (2023).
62. Estévez, S., González-García, S., Feijoo, G. & Moreira, M. T. How decentralized treatment can contribute to the symbiosis between environmental protection and resource recovery. *Sci. Total Environ.* **812**, 151485 (2022).
63. Ramirez, C., Almulla, Y. & Nerini, F. F. Reusing wastewater for agricultural irrigation: a water-energy-food nexus assessment in the North Western Sahara Aquifer System. *Environ. Res. Let.* **16**, 044052 (2021).
64. Miller-Robbie, L., Ramaswami, A. & Amerasinghe, P. Wastewater treatment and reuse in urban agriculture: exploring the food, energy, water, and health nexus in Hyderabad, India. *Environ. Res. Lett.* **12**, 075005 (2017).
65. Friedrichsen, C. N., Monroe, M. C., Daroub, S. H. & Wani, S. P. Yuck! Plural valuation of constructed wetland maintenance for decentralized wastewater treatment in rural India. *Front. Sustain. Food Syst.* **4**, 564539 (2021).
66. Marinelli, E. et al. Water-energy-food-climate nexus in an integrated peri-urban wastewater treatment and reuse system: from theory to practice. *Sustainability* **13**, 10952 (2021).
67. Alfarra, A., Kemp-Benedict, E., Hötzl, H., Sader, N. & Sonneveld, B. A framework for wastewater reuse in Jordan: utilizing a modified wastewater reuse index. *Water Res. Manag.* **25**, 1153–1167 (2011).
68. Aragüés, R. et al. Soil salinization as a threat to the sustainability of deficit irrigation under present and expected climate change scenarios. *Irrig. Sci.* **33**, 67–79 (2015).
69. Nadav, I., Tarchitzky, J. & Chen, Y. Soil cultivation for enhanced wastewater infiltration in soil aquifer treatment (SAT). *J. Hydrol.* **470–471**, 75–81 (2012).
70. Leuther, F., Weller, U., Wallach, R. & Vogel, H.-J. Quantitative analysis of wetting front instabilities in soil caused by treated waste water irrigation. *Geoderma* **319**, 132–141 (2018).
71. Kurtzman, D., Kanner, B., Levy, Y., Nitsan, I. & Bar-Tal, A. Maintaining intensive agriculture overlying aquifers using the threshold nitrate root-uptake phenomenon. *J. Environ. Qual.* **50**, 979–989 (2021).
72. Zhao, Q., Zhang, R., Wang, L., Sun, H. & Liu, C. Boron accumulation in soil, sediment, and plant of wastewater-irrigated areas in Tianjin, China. *Environ. Monitor. Assess.* **195**, 110 (2023).
73. Becerra-Castro, C. et al. Wastewater reuse in irrigation: a microbiological perspective on implications in soil fertility and human and environmental health. *Environ. Int.* **75**, 117–135 (2015).
74. Ofori, S., Puškáčová, A., Růžičková, I. & Wanner, J. Treated wastewater reuse for irrigation: pros and cons. *Sci. Total Environ.* **760**, 144026 (2021).
75. Fennell, B. D., Mezyk, S. P. & McKay, G. Critical review of UV-advanced reduction processes for the treatment of chemical contaminants in water. *ACS Environ. Au* **2**, 178–205 (2022).
76. Zhang, Y. et al. Characterization of UV/chlorine process for micropollutant abatement by probe compound-based kinetic models. *Water Res.* **237**, 119985 (2023).
77. Zhang, Z. et al. Effects of UV disinfection on phenotypes and genotypes of antibiotic-resistant bacteria in secondary effluent from a municipal wastewater treatment plant. *Water Res.* **157**, 546–554 (2019).
78. Balachandran, S. et al. Simultaneous inactivation of multidrug-resistant *Escherichia coli* and enterococci by peracetic acid in urban wastewater: exposure-based kinetics and comparison with chlorine. *Water Res.* **202**, 117403 (2021).
79. Maffettone, R. et al. Performic acid disinfection of municipal secondary effluent wastewater: inactivation of murine norovirus, fecal coliforms, and enterococci. *Environ. Sci. Technol.* **54**, 12761–12770 (2020).
80. Shu, Z. et al. Pilot-scale UV/H_2O_2 advanced oxidation process for municipal reuse water: assessing micropollutant degradation and estrogenic impacts on goldfish (*Carassius auratus* L.). *Water Res.* **101**, 157–166 (2016).
81. Hembach, N., Alexander, J., Hiller, C., Wieland, A. & Schwartz, T. Dissemination prevention of antibiotic resistant and facultative pathogenic bacteria by ultrafiltration and ozone treatment at an urban wastewater treatment plant. *Sci. Rep.* **9**, 12843 (2019).
82. Drigo, B. et al. Inactivation, removal, and regrowth potential of opportunistic pathogens and antimicrobial resistance genes in recycled water systems. *Water Res.* **201**, 117324 (2021).
83. Brienza, M. et al. Reclaimed wastewater reuse in irrigation: role of biofilms in the fate of antibiotics and spread of antimicrobial resistance. *Water Res.* **221**, 118830 (2022).
84. Christou, A. et al. The potential implications of reclaimed wastewater reuse for irrigation on the agricultural environment: the knowns and unknowns of the fate of antibiotics and antibiotic resistant bacteria and resistance genes — a review. *Water Res.* **123**, 448–467 (2017).
85. Piña, B. et al. On the contribution of reclaimed wastewater irrigation to the potential exposure of humans to antibiotics, antibiotic resistant bacteria and antibiotic resistance genes — NEREUS COST Action ES1403 position paper. *J. Environ. Chem. Eng.* https://doi.org/10.1016/j.jece.2018.01.011 (2018).
86. Beretsou, V. G. et al. Multiclass target analysis of contaminants of emerging concern including transformation products, soil bioavailability assessment and retrospective screening as tools to evaluate risks associated with reclaimed water reuse. *Sci. Total Environ.* **852**, 158391 (2022).
87. Wang, F.-H. et al. Impact of reclaimed water irrigation on antibiotic resistance in public parks, Beijing, China. *Environ. Pol.* **184**, 247–253 (2014).
88. Shah, A. I. et al. Prospectives and challenges of wastewater treatment technologies to combat contaminants of emerging concerns. *Ecol. Eng.* **152**, 105882 (2020).

89. Mordechay, E. B., Mordehay, V., Tarchitzky, J. & Chefetz, B. Fate of contaminants of emerging concern in the reclaimed wastewater-soil-plant continuum. *Sci. Total Environ.* **822**, 153574 (2022).
90. Paltiel, O. et al. Human exposure to wastewater-derived pharmaceuticals in fresh produce: a randomized controlled trial focusing on carbamazepine. *Environ. Sci. Technol.* **50**, 4476–4482 (2016).
91. Schapira, M. et al. Involuntary human exposure to carbamazepine: a cross-sectional study of correlates across the lifespan and dietary spectrum. *Environ. Int.* **143**, 105951 (2020).
92. Zhang, C., Barron, L. & Sturzenbaum, S. The transportation, transformation and (bio) accumulation of pharmaceuticals in the terrestrial ecosystem. *Sci. Total Environ.* **781**, 146684 (2021).
93. Tian, R. et al. Uptake and metabolism of clarithromycin and sulfadiazine in lettuce. *Environ. Pollut.* **247**, 1134–1142 (2019).
94. Christou, A. et al. Stress-related phenomena and detoxification mechanisms induced by common pharmaceuticals in alfalfa (*Medicago sativa* L.) plants. *Sci. Total Environ.* **557–558**, 652–664 (2016).
95. Christou, A., Michael, C., Fatta-Kassinos, D. & Fotopoulos, V. Can the pharmaceutically active compounds released in agroecosystems be considered as emerging plant stressors? *Environ. Int.* **114**, 360–364 (2018).
96. Mansilla, S. et al. Compounds of emerging concern as new plant stressors linked to water reuse and biosolid application in agriculture. *J. Environ. Chem. Eng.* **9**, 105198 (2021).
97. Christou, A., Karaolia, P., Hapeshi, E., Michael, C. & Fatta-Kassinos, D. Long-term wastewater irrigation of vegetables in real agricultural systems: concentration of pharmaceuticals in soil, uptake and bioaccumulation in tomato fruits and human health risk assessment. *Water Res.* **109**, 24–34 (2017).
98. Christou, A. et al. Ranking of crop plants according to their potential to uptake and accumulate contaminants of emerging concern. *Environ. Res.* **170**, 422–432 (2019).
99. Mordechay, E. et al. Wastewater-derived organic contaminants in fresh produce: dietary exposure and human health concerns. *Water Res.* **223**, 118986 (2022).
100. Ali, I. et al. Micro- and nanoplastics in wastewater treatment plants: occurrence, removal, fate, impacts and remediation technologies — a critical review. *Chem. Eng. J.* **423**, 130205 (2021).
101. Carr, S. A., Liu, J. & Tesoro, A. G. Transport and fate of microplastic particles in wastewater treatment plants. *Water Res.* **91**, 174–182 (2016).
102. Xia, Y. et al. Plastic materials and water sources actively select and shape wastewater plastispheres over time. *Front. Environ. Sci. Eng.* **16**, 145 (2022).
103. Liu, P. et al. Sources of micro(nano)plastics and interaction with co-existing pollutants in wastewater treatment plants. *Crit. Rev. Environ. Sci. Technol.* **53**, 865–885 (2023).
104. Junaid, M. et al. Wastewater plastisphere enhances antibiotic resistant elements, bacterial pathogens, and toxicological impacts in the environment. *Sci. Total Environ.* **841**, 156805 (2022).
105. Manoli, K. et al. Investigation of the effect of microplastics on the UV inactivation of antibiotic-resistant bacteria in water. *Water Res.* **222**, 118906 (2022).
106. Cui, Q., Wang, F., Wang, X., Chen, T. & Guo, X. Environmental toxicity and ecological effects of micro(nano)plastics: a huge challenge posed by biodegradability. *TrAC Trends Anal. Chem.* **164**, 117092 (2023).
107. Wang, F. et al. Micro(nano)plastics and terrestrial plants: up-to-date knowledge on uptake, translocation, and phytotoxicity. *Resour. Conserv. Recycl.* **185**, 106503 (2022).
108. Naziri, A. et al. Looking into the effects of co-contamination by micro(nano)plastics in the presence of other pollutants on irrigated edible plants. *Sci. Total Environ.* **892**, 164618 (2023).
109. Liu, Y. et al. Uptake, transport and accumulation of micro- and nano-plastics in terrestrial plants and health risk associated with their transfer to food chain — a mini review. *Sci. Total Environ.* **902**, 166045 (2023).
110. Rout, P. R. et al. Micro- and nanoplastics removal mechanisms in wastewater treatment plants: a review. *J. Hazard. Mat. Adv.* **6**, 100070 (2022).
111. Maculewicz, J. et al. Transformation products of pharmaceuticals in the environment: their fate, (eco)toxicity and bioaccumulation potential. *Sci. Total Environ.* **802**, 149916 (2022).
112. Yin, L. et al. Pay special attention to the transformation products of PPCPs in environment. *Emerg. Contam.* **3**, 69–75 (2017).
113. Murrell, K. A., Teehan, P. D. & Dorman, F. L. Determination of contaminants of emerging concern and their transformation products in treated-wastewater irrigated soil and corn. *Chemosphere* **281**, 130735 (2021).
114. Madmon, M. et al. Pharmacokinetics of the recalcitrant drug lamotrigine: identification and distribution of metabolites in cucumber plants. *Environ. Sci. Technol.* **57**, 20228–20237 (2023).
115. Löffler, P., Escher, B. I., Baduel, C., Virta, M. P. & Lai, F. Y. Antimicrobial transformation products in the aquatic environment: global occurrence, ecotoxicological risks, and potential of antibiotic resistance. *Environ. Sci. Technol.* **57**, 9474–9494 (2023).
116. Ashbolt, N. J. et al. Human health risk assessment (HHRA) for environmental development and transfer of antibiotic resistance. *Environ. Health Perspect.* **121**, 993–1001 (2013).
117. Han, X.-M. et al. Impacts of reclaimed water irrigation on soil antibiotic resistome in urban parks of Victoria, Australia. *Environ. Pollut.* **211**, 48–57 (2016).
118. Zammit, I., Marano, R. B., Vaiano, V., Cytryn, E. & Rizzo, L. Changes in antibiotic resistance gene levels in soil after irrigation with treated wastewater: a comparison between heterogeneous photocatalysis and chlorination. *Environ. Sci. Technol.* **54**, 7677–7686 (2020).
119. Summerlin III, H. N. et al. Prevalence of *Escherichia coli* and antibiotic-resistant bacteria during fresh produce production (romaine lettuce) using municipal wastewater effluents. *Front. Microbiol.* **12**, 660047 (2021).
120. Marano, R. B., Zolti, A., Jurkevitch, E. & Cytryn, E. Antibiotic resistance and class 1 integron gene dynamics along effluent, reclaimed wastewater irrigated soil, crop continua: elucidating potential risks and ecological constraints. *Water Res.* **164**, 114906 (2019).
121. Marano, R. B., Gupta, C. L., Cozer, T., Jurkevitch, E. & Cytryn, E. Hidden resistome: enrichment reveals the presence of clinically relevant antibiotic resistance determinants in treated wastewater-irrigated soils. *Environ. Sci. Technol.* **55**, 6814–6827 (2021).
122. Kampouris, I. D. et al. Antibiotic resistance gene load and irrigation intensity determine the impact of wastewater irrigation on antimicrobial resistance in the soil microbiome. *Water Res.* **193**, 116818 (2021).
123. Zhuang, M. et al. Distribution of antibiotic resistance genes in the environment. *Environ. Pollut.* **285**, 117402 (2021).
124. Seyoum, M. M., Lichtenberg, R., Orlofsky, E., Bernstein, N. & Gillor, O. Antibiotic resistance in soil and tomato crop irrigated with freshwater and two types of treated wastewater. *Environ. Res.* **211**, 113021 (2022).
125. Liu, Y. et al. Cropping system exerts stronger influence on antibiotic resistance gene assemblages in greenhouse soils than reclaimed wastewater irrigation. *J. Hazard. Mat.* **425**, 128046 (2022).
126. Cerqueira, F. et al. Antibiotic resistance gene distribution in agricultural fields and crops. A soil-to-food analysis. *Environ. Res.* **177**, 108608 (2019).
127. Leiva, A. M., Piña, B. & Vidal, G. Antibiotic resistance dissemination in wastewater treatment plants: a challenge for the reuse of treated wastewater in agriculture. *Rev. Environ. Sci. Biotechnol.* **20**, 1043–1072 (2021).
128. Guo, Y. et al. Diversity and abundance of antibiotic resistance genes in rhizosphere soil and endophytes of leafy vegetables: focusing on the effect of the vegetable species. *J. Hazard. Mat.* **415**, 125595 (2021).
129. Xu, H. et al. Antibiotic resistance gene-carrying plasmid spreads into the plant endophytic bacteria using soil bacteria as carriers. *Environ. Sci. Technol.* **55**, 10462–10470 (2021).
130. Xiao, R. et al. Antibiotic resistance in soil-plant systems: a review of the source, dissemination, influence factors, and potential exposure risks. *Sci. Total Environ.* **869**, 161855 (2023).
131. Garner, E. et al. Towards risk assessment for antibiotic resistant pathogens in recycled water: a systematic review and summary of research needs. *Environ. Microbiol.* **23**, 7355–7372 (2021).
132. Djordjevic, S. P. et al. Genomic surveillance for antimicrobial resistance — a One Health perspective. *Nat. Rev. Genet.* https://doi.org/10.1038/s41576-023-00649-y (2023).
133. Berendonk, T. U. et al. Tackling antibiotic resistance: the environmental framework. *Nat. Rev. Microbiol.* **13**, 310–317 (2015).
134. Ben, Y. et al. Human health risk assessment of antibiotic resistance associated with antibiotic residues in the environment: a review. *Environ. Res.* **169**, 483–493 (2019).
135. Gudda, F. O. et al. Antibiotic-contaminated wastewater irrigated vegetables pose resistance selection risks to the gut microbiome. *Environ. Pollut.* **264**, 114752 (2020).
136. Scaccia, N., Vaz-Moreira, I. & Manaia, C. M. The risk of transmitting antibiotic resistance through endophytic bacteria. *Trends Plant. Sci.* **26**, 1213–1226 (2021).
137. Yin, X. et al. Toward a universal unit for quantification of antibiotic resistance genes in environmental samples. *Environ. Sci. Technol.* **57**, 9713–9721 (2023).
138. Manaia, C. M. Framework for establishing regulatory guidelines to control antibiotic resistance in treated effluents. *Crit. Rev. Environ. Sci. Technol.* **53**, 754–779 (2023).
139. Breitenmoser, L. et al. Perceived drivers and barriers in the governance of wastewater treatment and reuse in India: insights from a two-round Delphi study. *Resour. Conserv. Recyc.* **182**, 106285 (2022).
140. NRMMC, EPHC & AHMC. Australian Guidelines for Water Recycling: managing health and environmental risks (phase 1) https://www.waterquality.gov.au/sites/default/files/documents/water-recycling-guidelines-full-21.pdf (2006).
141. US Environmental Protection Agency. Guidelines for water reuse (EPA, 2012).
142. ISO. ISO 20426:2018 — guidelines for non-potable water reuse (ISO, 2018).
143. ISO. ISO 16075:2020 — guidelines for treated wastewater use for irrigation projects — parts 1 to 4 (ISO, 2020).
144. WHO. Guidelines for the safe use of wastewater, excreta and greywater in agriculture and aquaculture (WHO, 2006).
145. Walton, M. The energy sector should care about wastewater. *International Energy Agency* https://www.iea.org/commentaries/the-energy-sector-should-care-about-wastewater (2018).
146. Lu, L. et al. Wastewater treatment for carbon capture and utilization. *Nat. Sustain.* **1**, 750–758 (2018).
147. Zhang, X. & Liu, Y. Resource recovery from municipal wastewater: a critical paradigm shift in the post era of activated sludge. *Biores. Technol.* **363**, 127932 (2022).
148. Tian, X., Richardson, R. E., Tester, J. W., Lozano, J. L. & You, F. Retrofitting municipal wastewater treatment facilities toward a greener and circular economy by virtue of resource recovery: techno-economic analysis and life cycle assessment. *ACS Sustain. Chem. Eng.* **8**, 13823–13837 (2020).

149. Zhang, X. & Liu, Y. Circular economy is game-changing municipal wastewater treatment technology towards energy and carbon neutrality. *J. Chem. Eng.* **429**, 132114 (2022).
150. Kehrein, P. et al. A critical review of resource recovery from municipal wastewater treatment plants — market supply potentials, technologies and bottlenecks. *Environ. Sci. Water Res. Technol.* **6**, 877–910 (2020).
151. Furness, M., Bello-Mendoza, R., Dassonvalle, J. & Chamy-Maggi, R. Building the 'bio-factory': a bibliometric analysis of circular economies and life cycle sustainability assessment in wastewater treatment. *J. Clean. Prod.* **323**, 129127 (2021).
152. Robles, Á. et al. New frontiers from removal to recycling of nitrogen and phosphorus from wastewater in the circular economy. *Bioresour. Technol.* **300**, 122673 (2020).
153. Rani, A., Snyder, S. W., Kim, H., Lei, Z. & Pan, S.-Y. Pathways to a net-zero-carbon water sector through energy-extracting wastewater technologies. *npj Clean Water* **5**, 49 (2022).
154. Chhipi-Shrestha, G., Hewage, K. & Sadiq, R. Fit-for-purpose wastewater treatment: conceptualization to development of decision support tool (I). *Sci. Total Environ.* **607–608**, 600–612 (2017).
155. Raza, A., Altaf, S., Ali, S., Ikram, M. & Li, G. Recent advances in carbonaceous sustainable nanomaterials for wastewater treatments. *Sustain. Mat. Technol.* **32**, e00406 (2022).
156. Pervez, M. N. et al. A critical review on nanomaterials membrane bioreactor (NMs-MBR) for wastewater treatment. *npj Clean Water* **3**, 43 (2020).
157. Hodges, B. C., Cates, E. L. & Kim, J.-H. Challenges and prospects of advanced oxidation water treatment processes using catalytic nanomaterials. *Nat. Nanotechnol.* **13**, 642–650 (2018).
158. Matheri, A. N., Mohamed, B., Ntuli, F., Nabadda, E. & Ngila, J. C. Sustainable circularity and intelligent data-driven operations and control of the wastewater treatment plant. *Phys. Chem. Earth A/B/C* **126**, 103152 (2022).
159. Matheri, A. N., Ntuli, F., Ngila, J. C., Seodigeng, T. & Zvinowanda, C. Performance prediction of trace metals and cod in wastewater treatment using artificial neural network. *Comput. Chem. Eng.* **149**, 107308 (2021).
160. Kamali, M., Appels, L., Yu, X., Aminabhavi, T. M. & Dewil, R. Artificial intelligence as a sustainable tool in wastewater treatment using membrane bioreactors. *Chem. Eng. J.* **417**, 128070 (2021).
161. Zhao, L. et al. Application of artificial intelligence to wastewater treatment: a bibliometric analysis and systematic review of technology, economy, management, and wastewater reuse. *Process Saf. Environ. Prot.* **133**, 169–182 (2020).
162. Newhart, K. B., Holloway, R. W., Hering, A. S. & Cath, T. Y. Data-driven performance analyses of wastewater treatment plants: a review. *Water Res.* **157**, 498–513 (2019).
163. Kuo, E. Y. et al. Multiomics approaches and genetic engineering of metabolism for improved biorefinery and wastewater treatment in microalgae. *Biotechnol. J.* **17**, 2100603 (2022).
164. Fernández-Arévalo, T. et al. Quantitative assessment of energy and resource recovery in wastewater treatment plants based on plant-wide simulations. *Water Res.* **118**, 272–288 (2017).
165. Li, L. et al. Carbon neutrality of wastewater treatment — a systematic concept beyond the plant boundary. *Environ. Sci. Ecotech.* **11**, 100180 (2022).
166. Abdel Wahaab, R., Mahmoud, M. & van Lier, J. B. Toward achieving sustainable management of municipal wastewater sludge in Egypt: the current status and future prospective. *Renew. Sustain. Energy Rev.* **127**, 109880 (2020).
167. Qadir, M. et al. Global and regional potential of wastewater as a water, nutrient and energy source. *Nat. Resour. Forum* **44**, 40–51 (2020).
168. Iqbal, A. et al. Potential for co-disposal and treatment of food waste with sewage: a plant-wide steady-state model evaluation. *Water Res.* **184**, 116175 (2020).
169. Arthur, P. M. A. et al. Performance evaluation of a full-scale upflow anaerobic sludge blanket reactor coupled with trickling filters for municipal wastewater treatment in a developing country. *Heliyon* **8**, e10129 (2022).
170. Kong, Z. et al. Insights into the carbon neutrality for the treatment process engineering of municipal wastewater by anaerobic membrane bioreactor integrated with partial nitritation-anammox: CO_2 reduction and energy recovery. *J. Water Process Eng.* **49**, 102996 (2022).
171. Gu, J., Yang, Q. & Liu, Y. Mainstream anammox in a novel A-2B process for energy-efficient municipal wastewater treatment with minimized sludge production. *Water Res.* **138**, 1–6 (2018).
172. Cruz, H. et al. Mainstream ammonium recovery to advance sustainable urban wastewater management. *Environ. Sci. Technol.* **53**, 11066–11079 (2019).
173. Ardakani, M. N. & Gholikandi, G. B. Microbial fuel cells (MFCs) in integration with anaerobic treatment processes (AnTPs) and membrane bioreactors (MBRs) for simultaneous efficient wastewater/sludge treatment and energy recovery — a state-of-the-art review. *Biomass Bioenergy* **141**, 105726 (2020).
174. Pandey, P. et al. Recent advances in the use of different substrates in microbial fuel cells toward wastewater treatment and simultaneous energy recovery. *Appl. Energy* **168**, 706–723 (2016).
175. Chen, Y. Mining wastewater for hydrogen. *Nat. Rev. Earth Environ.* **3**, 551 (2022).
176. Barbieri, P., MacDonald, G. K., Bernard de Raymond, A. & Nesme, T. Food system resilience to phosphorus shortages on a telecoupled planet. *Nat. Sustain.* **5**, 114–122 (2022).
177. Sniatala, B., Kurniawan, T. A., Sobotka, D., Makinia, J. & Othman, M. H. D. Macro-nutrients recovery from liquid waste as a sustainable resource for production of recovered mineral fertilizer: uncovering alternative options to sustain global food security cost-effectively. *Sci. Total Environ.* **856**, 159283 (2023).
178. Tchobanoglous, G., Burton, F. L. & Stensel, H. D. *Wastewater Engineering — Treatment and Reuse* (McGraw-Hill, 2003).
179. Ye, Y. et al. Nutrient recovery from wastewater: from technology to economy. *Bioresour. Technol. Rep.* **11**, 100425 (2020).
180. Zhang, C., Guisasola, A. & Baeza, J. A. A review on the integration of mainstream P-recovery strategies with enhanced biological phosphorus removal. *Water Res.* **212**, 118102 (2022).
181. Vecino, X., Reig, M., Gibert, O., Valderrama, C. & Cortina, J. L. Integration of liquid-liquid membrane contactors and electrodialysis for ammonium recovery and concentration as a liquid fertilizer. *Chemosphere* **245**, 125606 (2020).
182. Díaz, V. et al. Microalgae bioreactor for nutrient removal and resource recovery from wastewater in the paradigm of circular economy. *Bioresour. Technol.* **363**, 127968 (2022).
183. Chen, Y.-Z. et al. Sustainable treatment of nitrate-containing wastewater by an autotrophic hydrogen-oxidizing bacterium. *Environ. Sci. Ecotech.* **9**, 100146 (2022).
184. Zhang, F., Li, J. & He, Z. A new method for nutrients removal and recovery from wastewater using a bioelectrochemical system. *Bioresour. Technol.* **166**, 630–634 (2014).
185. Arun, S., Sinharoy, A., Pakshirajan, K. & Lens, P. N. L. Algae based microbial fuel cells for wastewater treatment and recovery of value-added products. *Renewab. Sustain. Energy Rev.* **132**, 110041 (2020).
186. Goswami, R. K., Mehariya, S., Verma, P., Lavecchia, R. & Zuorro, A. Microalgae-based biorefineries for sustainable resource recovery from wastewater. *J. Water Process Eng.* **40**, 101747 (2021).
187. Tal, A. Rethinking the sustainability of Israel's irrigation practices in the drylands. *Water Res.* **90**, 387–394 (2016).
188. European Environment Agency. Water scarcity conditions in Europe (water exploitation index plus) (8th EAP). *European Environment Agency* https://www.eea.europa.eu/ims/use-of-freshwater-resources-in-europe-1 (2023).
189. Christou, A., Eliadou, E., Michael, C., Hapeshi, E. & Fatta-Kassinos, D. Assessment of long-term wastewater irrigation impacts on the soil geochemical properties and the bioaccumulation of heavy metals to the agricultural products. *Environ. Monit. Assess.* **186**, 4857–4870 (2014).
190. Liu, X., Liang, C., Liu, X., Zhao, F. & Han, C. Occurrence and human health risk assessment of pharmaceuticals and personal care products in real agricultural systems with long-term reclaimed wastewater irrigation in Beijing, China. *Ecotoxicol. Environ. Saf.* **190**, 110022 (2020).
191. Radcliffe, J. C. Water recycling in Australia — during and after the drought. *Environ. Sci. Water Res. Technol.* **1**, 554–562 (2015).
192. Radcliffe, J. C. & Page, D. Water reuse and recycling in Australia — history, current situation and future perspectives. *Water Cycle* **1**, 19–40 (2020).
193. Radcliffe, J. C. Current status of recycled water for agricultural irrigation in Australia, potential opportunities and areas of emerging concern. *Sci. Total Environ.* **807**, 151676 (2022).
194. US Environmental Protection Agency. Regulations and end-use specifications explorer (REUSExplorer). *US Environmental Protection Agency* https://www.epa.gov/waterreuse/regulations-and-end-use-specifications-explorer-reusexplorer (2023).
195. Inbar, Y. in *Wastewater Reuse — Risk Assessment, Decision-Making and Environmental Security* (ed. Zaidi, M. K.) 291–296 (Springer, 2007).

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Competing interests

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