Agricultural wastewater reuse for a sustainable circular economy

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Sections

Abstract

Facing climate change, effective management of water resources is crucial for global food security, sustainable economic development, community well-being, and ecosystem services. This review explores the potential benefits and challenges associated with treated wastewater (TW) reuse for agricultural irrigation, offering strategic solutions to the escalating issues of water demand and scarcity. By implementing adaptable centralized or decentralized reuse schemes tailored to local conditions and supported by robust legal and regulatory frameworks, we can fortify the production of safe agricultural products. Simultaneously, these initiatives can free significant amounts of fresh water for other essential uses. Technological advancements, particularly in treatment, recovery, monitoring, and overall management, can facilitate the transformation of wastewater treatment plants into eco-friendly facilities. These facilities can play a vital role in utilizing wastewater and biosolids to generate safe, fit-for-purpose TW, energy, fertilizers, and valuable by-products within the circular economy framework. To meet the potential, international organizations, governmental authorities, academia, industry, stakeholders, and communities must collectively recognize the transformative capacity of a circular TW management. Consequently, they should invest substantial efforts and resources to facilitate the transition of this critical sector, aligning it with sustainable practices that not only enhance ecological integrity but also effectively address global water challenges.

Key points

- Treated wastewater (TW) reuse has the potential to alleviate water imbalances, especially in water scarce regions, and boost/sustain food production by expanding irrigated agriculture, thus promoting global food and water security.
- Best practices, including the establishment of TW-irrigated agricultural hotspots served by either centralized, decentralized or hybrid TW reuse systems can promote sustainable rural development that is sensitive to the climate-water-energy-food nexus.
- Comprehensive regulatory frameworks are essential to safeguard the smooth functioning and sustainability of TW reuse systems, and vital to ensure environmental and public health, and social acceptance of reuse schemes.
- Wastewater treatment plants (WWTPs) must operate as energy and carbon neutral facilities, with water, nutrients and other materials recovered and reused, thus promoting the circular economy and SDGs.
- Advanced wastewater treatment processes necessitate ongoing research and site-specific evaluations for cost-effective and sustainable reuse practices.
- Modern advancements in wastewater treatment and recovery technologies, materials, and Fourth Industrial Revolution (4IR) tools can transform wastewater treatment, resulting in the production of high-quality fit-for-purpose TW.

Introduction

Water scarcity is emerging as a critical concern for an increasing number of countries. Severe water imbalances are anticipated to intensify spatially and temporarily under climate change scenarios, causing catastrophic losses and substantial economic impacts[1]. According to the UN Environment programme, today, 2.4 billion people live in water-stressed countries, defined as nations that withdraw 25 per cent or more of their renewable freshwater resources to meet water demand. By 2025, 1.8 billion people are likely to face what the Food and Agriculture Organization calls "absolute water scarcity" and two-thirds of the global population is expected to be grappling with water stress. Extreme weather events, such as the recent 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[2, 3], and exemplify that urgent actions need to be undertaken[4, 5]. 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 latest UN Water conference[6]. Due 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[7].

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 due to population growth, urbanization, improved standards of living and industrialization[8]. 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 climate change[8, 9]. Within this context, the need to maintain food security by using non-conventional water resources of adequate quality in the agricultural sector has never been more imperative. Adequately treated wastewater (TW) (also referred to as reclaimed water) is an attractive alternative for the mitigation of irrigation water scarcity, especially where conventional water resources are limited or absent. TW reuse in agriculture is already a common practice in some countries worldwide, and can substantially boost agricultural production and rural development, while promoting circular economy[10].

The quantities of wastewater produced annually at the global level are substantial, as all human activities that consume water inevitably produce wastewater. However, only a small portion of the wastewater generated is currently treated (less than 20% globally, with rates varying across different regions and countries according to their economic status)[11, 12]. High-income countries treat on average about 70% of the wastewater they generate. This ratio drops to 38% in upper middle-income countries and to 28% in lower middle-income countries. In low-income countries, only 8% of wastewater generated undergoes treatment of any kind[12]. Jones et al., (2021) estimate the global wastewater production at 359.4×10^9 m^3 yr^{-1} of which 63 % (225.6×10^9 m^3 yr^{-1}) is estimated to be collected and 52 % (188.1×10^9 m^3 yr^{-1}) treated. They also estimate that 48 % of global wastewater production is released to the environment untreated, which is substantially lower than the previous figures[13, 14]. The release of untreated wastewater to various receiving environments, including agricultural land, surface water bodies and marine environments, poses serious health, environmental and economic impacts[12]. The volumes of TW reused for agricultural irrigation are currently very low, as most TW is reused for other purposes, or discharged to downstream environments, like rivers and lakes[15]. There is thus vast untapped potential for productively reusing TW in agriculture. Increased adoption of TW reuse in agriculture is currently constrained by challenges such as reuse application governance, 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[12, 16]. Hence, the motivation of this review is to provide insights into how this practice can be made more sustainable and expanded, while addressing the contemporary challenges posed by the climate crisis.

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 also highlight the challenges accompanying this practice, mainly evolving from insufficient wastewater treatment and poor governance in some countries, and the presence (even at extremely low concentrations) of problematic pollutants in TW. We show that evolving technologies can promote circularity in the wastewater treatment sector by retrofitting treatment facilities into resource recovery factories where 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, and present relevant future research directions and perspectives.

Droughts and global health

This section seeks to examine the cumulative health effects resulting from droughts and other climate-sensitive factors. Additionally, it aims to underscore the positive outcomes derived from harnessing wastewater as a valuable resource amidst the changing climate. TW reuse in agriculture is expected to be a key component in efforts seeking to promote global health.

Reuse benefits in a changing climate

Climate change and variability[17] influence the frequency, intensity, and seasonality of multiple environmental exposures. The health impacts associated with climate-sensitive exposures are becoming more broadly documented and include both direct and indirect mechanisms[18]. Notably, extreme heat events are among the deadliest climate sensitive extreme weather events globally with the highest impact in terms of attributable number of deaths. For example, over 60,000 heat-related deaths occurred in Europe during the summer of 2022[19]. In parallel, precipitation anomalies have substantial direct and indirect impacts on human health. It has been recently shown that, while anomalously wet conditions increase the risk of infectious diseases among children in some humid, subtropical regions, these health risks were rather exacerbated because of anomalously dry conditions in many other regions including tropical savanna regions[20].

Drought can be decomposed into meteorological (negative precipitation anomaly), hydrological (surface or groundwater water supplies), agricultural (when the amount of soil moisture does not suffice for a particular crop) or socioeconomic (when water shortages begin to affect people and economic activities) categories. The increasing patterns in droughts around the globe are unambiguously related to anthropogenic climate change[21]. Droughts may impact population health through various mechanisms including water-borne diseases, wildfires, dust storms or vector borne diseases[22, 23]. For example, in California (USA), droughts increase the intensity and frequency of wildfires which are now becoming a central source of air pollution in the Western US even eroding decades of air pollution abatement, but also have substantial health impacts[24, 25]. Droughts also exacerbate the occurrence of airborne mineral dust events which can lead to Coccidioidomycosis (aka valley fever)[26].

Therefore, in parallel to mitigation efforts that aim at reducing the emissions and concentrations of greenhouse gases which ultimately will reduce climate change and variability in a few decades, it is timely to develop adaptation efforts, especially among most vulnerable communities, to deal with the changes in precipitation regimes and the increasing incidence and severity of droughts. In this context, the exploitation of wastewater for diverse usages appears as a key strategy to minimize the public health burden associated with direct and indirect impacts of droughts induced by anthropogenic climate change. It is thus imperative to, not only advance epidemiological evidence in relation to emerging TW-related contaminants, but also contrast such potential harmful impacts with potential health co-benefits regarding water resources, quality, and cascading droughts.

Current status of wastewater reuse

Wastewater has been reused for irrigation since ancient times, though the lack of specific treatment posed several health and environmental risks[27]. 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 currently regulated by various legal frameworks, and mostly applied through comprehensive wastewater reuse systems.

Urban wastewater

Currently, nearly 400 km^3 ($359.410^9\ \mathrm{m}^3\ \mathrm{yr}^{-1}$) of urban wastewater are generated each year globally, with projections of 50% increase by 2050 due to population growth and urbanization[28]. These volumes of wastewater represent almost 10% of global fresh water use (over 4000 km^3), sufficient to meet nearly 15% of current irrigation water needs[29, 30]. 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. At the same time, wastewater is a valuable source of water, energy, and nutrients. Thus, wastewater collection, treatment and reuse offers multiple economic, social and environmental benefits, and also contributes to meeting the global SDGs[31]. Advancements in wastewater treatment technologies during the last century have been remarkable, enabling the cost-effective production of high-quality TW that can be reused for multiple purposes.

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, runoff) and the season[11, 32]. 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 as 'fit-for-purpose' recycled water)[33]. The most suitable treatment approach is usually defined by local regulations and restrictions pertaining to recycled water quality standards, system operation and maintenance costs, approved reuse purposes, the ecological footprint, social acceptance of TW systems and other considerations[33].

With the objective to enhance comprehension and facilitate a more nuanced dialogue regarding the diverse nature of contaminants and their implications for environmental and public health, we would like to clarify the use of the two following terms in this review. Micropollutants refer 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. Contaminants of emerging concern constitute a broader category of chemical contaminants in very low concentrations, and also antimicrobial resistant bacteria, resistance genes and mobile genetic elements; not yet fully understood or regulated. In this paper, the acronym "MCEC" is used as a concise shorthand to collectively refer to both categories.

TW agricultural reuse

Despite the benefits and the technological progress in wastewater treatment and reuse, the global TW implementation for agricultural irrigation still remains low[11, 12]. 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)[34]. In some areas with extreme water stress, municipal wastewater undergoes advanced treatment to be used for potable purposes[35, 36].

TW reuse for crop irrigation and for the purposes mentioned above can free equal volumes of high quality fresh water for the domestic and other sectors, while can also enhance critical ecosystem services related with environmental flows[12, 37]. 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 system, wastewater treatment plant (WWTP) facilities, hundreds or even thousands of kilometers of pipes, reservoirs and distribution system[38]. Major technical components of a sustainable TW reuse system includes 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, sprinklers), including components adjacent to the point of use (for example, run-off canals and buffer strips)[28] (Fig. 1).

Assessing the global extent of TW use is challenging due 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[14, 39]. Information on TW application in agriculture may account both direct and indirect reuse, the latter indicating TW discharged into surface waters or aquifers through artificial recharge, and subsequently withdrawn for irrigation. Direct use of TW allows for better water quality control since rules and standards applies at the reclamation facility outlet[39, 40] (Fig. 1b). Irrigational water quality lacks similar control measures, unless risks resulting from mixing TW with other sources are identified, hindering the systematic promotion of direct reuse[41]. 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[28] (Fig. 1 a).

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[28, 42]. According to the 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[28, 43].

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 may allow for recontamination of treated effluent, either by algae growth in reservoirs, formation of biofilm in pipes, and/or bacterial regrowth[44]. The fate of micropollutants (including disinfection by-products) during treatment, storage and transportation deserves scrutiny in relation to their persistence and effects after their release into the environment[45]. 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 base of the Precautionary Principle, are also crucial for enhancing end-of-pipe TW quality and therefore reuse acceptance and promotion[46].

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 United States have a long history of reusing TW for irrigation (Box 1). This practice has been most successful in urban and peri-urban areas, where TW is easily available and where there is a nearby market for agricultural products[47]. Box 2 presents the storyline and the important success factors of Israel's journey into harnessing the wastewater potential for agricultural growth.

In conclusion, as we 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 water-rich but are now compelled to embrace sustainable practices for the future[47].

Current wastewater treatment for reuse

The state of the art in the treatment of urban wastewater for reuse in agriculture changes significantly according to the country or geographical area (Table 1) 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. As a matter of fact, the war in Ukraine resulted in drastic increase in European gas (115%) and electricity (237%) prices in 2023[48]. Water utilities experienced a general inflationary pressure (10.6% in October 2022) and, for the coming years, are likely to face electricity costs of 100-300 EUR/MWh as opposed to past multi-year average values of 40-80 EUR/MWh[49]. Therefore, the cost of energy is expected to influence current and future choices of technologies to be implemented for wastewater treatment.

Typically, the state of the art of treatment of urban wastewater for reuse in medium-large WWTPs includes a secondary biological process (activated sludge, membrane biological reactor (MBR) etc.), conventional filtration on granular media (except in the case MBR is used as secondary treatment), and disinfection with UVC lamps or with chemical agents (typically chlorine or peracetic acid), as tertiary treatments[33]. However, current challenges in wastewater treatment such as the removal of MCEC, the control of antibiotic resistance spread and microplastics, are expected to change the state of the art in the coming years.

The availability of alternative water resources and the corresponding costs are also important factors. In California (USA), for example, the cost of urban wastewater reuse projects (1.2 US $\$/m^3$) was found to be higher than that of stormwater capture (0.5 US $\$/m^3$), but lower than seawater desalination (2.3 US $\$/m^3$)[50]. Reuse or irrigation is a widespread practice in the southern USA, particularly in California, Florida, Texas, and Arizona. In several African countries there have been important investments in recent years in wastewater treatment and reuse facilities for the construction and upgrading of large WWTPs, such as in Algeria (€14 million), Egypt (€132.6 million) and Morocco (€40.7 million). Urban wastewater agricultural reuse in China and India is poor and not documented. 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[51, 52]. In India, the total installed capacity for domestic wastewater treatment from urban areas is 44% of total produced wastewater (31.8 million m^3/d vs. 72.4 million m^3/d of generated wastewater) but the actual treatment is only 28% (20.2 million m^3/d). Wastewater reuse is 49% in Chennai, 19% in Delhi and 6% in Hyderabad[53]. The availability of large surface areas at relatively low costs allows to opt for more energetically sustainable solutions, such as in the case of the Western WWTP in Melbourne, where sequential anaerobic and aerobic lagoons have been successfully implemented (Table 1).

Assessment of secondary treatment processes

Members of the international scientific network, i.e. NEREUS COST Action ES1403[54] titled "New and emerging challenges and opportunities in wastewater reuse, chaired by the corresponding author, undertook a thorough analysis of full-scale and pilot-scale secondary biological technologies for a group of target MCEC relevant for wastewater reuse. 33 chemical MCEC were selected according to their relevance for potential uptake by crops, public health issues and/or environmental safety implications. Additionally, ARB and ARGs were included because of their critical relevance to public health and, above all, their recognized persistence and self-replication potential in environmental compartments. The analysis focused on the performance of Conventional Activated Sludge (CAS), Membrane Bioreactors (MBR), and Moving Bed Bioreactors (MBBR), and Constructed Wetlands (CW)[54, 55]. This analysis, (Table 2), which is still valid today, showed the potential of four secondary biological treatment technologies for the removal of selected MCEC and the need to reach effluent quality suitable for irrigation purposes[55]. This in turn, allowed defining the research needs for the analyzed technologies in respect to the removal of MCEC.

The CAS process has been extensively studied for mitigating the presence of MCEC. However, the traditional aerobic layout proves ineffective, and enhanced performance is achievable with elevated solid retention times or sequential anoxic-aerobic phases for specific MCEC. Therefore, it is imperative to focus research efforts on optimizing process performance through the adjustment of operational parameters and exploring synergies with advanced technologies for tertiary treatment[55]. While MBR technology is well-researched for MCEC removal, a comprehensive understanding of mechanisms, such as fouling layer interactions and the role of membrane surface deposits, is still lacking. Additionally, the identification of bacterial species or enzymes responsible for chemical MCEC removal, determination of optimal operating conditions, and elucidation of (bio)transformation products during MBR treatment are essential. Integrated MBR systems with cost-effective, synergistic effects warrant further development, emphasizing system optimization, scalability, and full-scale validation[55]. CWs represent a novel research area for MCEC removal, yet current CWs exhibit limitations in effectively eliminating MCEC. Further research is needed to assess the feasibility of full-scale applications, with process efficiency contingent on operational mode, design, substrate type, and the presence of specific plants. Considering the unique prerequisites of CWs, including large area requirements and potential temperature dependencies, site-specific application considerations are crucial[55]. A limited number of studies have explored the fate of MCEC in full-scale MBBR processes. Comprehensive research projects should delve into MCEC removal pathways, including biofilm diffusion and hydrodynamic conditions, while investigating the regulation of bacterial communities through biofilm thickness. While the active biomass in MBBR biofilms holds potential for recalcitrant organic MCEC removal, the thin biofilm often lacks sufficient biomass for realistic degradation in typical contact times. Increasing available biomass in MBBR treatment trains is a crucial focus, and MBBR is a noteworthy, advanced treatment technology for recalcitrant MCEC removal.

Despite the technology employed, the removal of MCEC relies on treatment conditions and physicochemical properties of individual compounds. The complex and variable factors influencing their fate underscore the unique microbial ecosystems of each plant. As a result, assessing the impact of MCEC on wastewater receiving environments and enhancing MCEC removal necessitate ongoing research. This emphasizes the importance of biological processes in maximizing MCEC removal while ensuring the effective removal of conventional parameters for the safe reuse of reclaimed water.

Assessment of advanced treatment processes

The review paper by Rizzo et al.[56], again within the framework of the NEREUS COST Action ES1403[54], critically examined well-established techniques such as ozonation, activated carbon (AC), and membranes, along with emerging methods like Advanced Oxidation Processes (AOPs). The evaluation focused on several key aspects: (i) the efficacy of these methods in removing MCEC from wastewater, (ii) their respective advantages and limitations, (iii) potential challenges hindering the widespread adoption of homogeneous AOPs, (iv) technological constraints and future perspectives for heterogeneous processes in the mid to long term, and (v) a thorough technical and economic comparison among diverse processes and technologies. The review outlined the main gaps in the understanding and implementation of advanced wastewater treatment, which persist still today (Table 3).

Advanced methods for urban wastewater treatment, including activated carbon (AC), adsorption (utilizing both powdered AC and granular AC), ozonation, and nanofiltration or reverse osmosis membrane filtration, demonstrate effectiveness in removing MCEC[56]. Notably, economically viable full-scale implementations of AC adsorption and ozonation have recently been established in Germany and Switzerland. While filtration with tight membranes, such as in nanofiltration or reverse osmosis, is found to be more cost-intensive, full-scale applications of reverse osmosis membranes in potable reuse projects have been successful in the United States, Singapore, and Australia, offering additional benefits in salinity and metal reduction. However, the treatment of concentrated waste streams in membrane filtration processes warrants further evaluation.

In regions with high annual solar irradiation (between latitude 40°N and 40°S), solar-driven AOPs emerge as competitive alternatives for MCEC removal. However, these technologies are currently at a lower technology readiness level, posing challenges for direct comparisons. Similarly, many innovative processes and novel combinations of existing processes, often studied only at small scale or under non-realistic source water conditions, require further development and evaluation[56].

The removal of MCEC from wastewater through AOPs is influenced by operating parameters, water matrix composition, and abatement mechanisms unique to each treatment technology. Ozonation and AOPs may generate oxidation transformation products with potential biological effects, necessitating eco-toxicological studies. Post-treatments such as sand filters or biological activated carbon have proven effective in addressing this concern after ozonation but come with increased treatment costs[56].

The significant local wastewater variability in MCEC and water matrix characteristics underscores the need for optimization tailored to each application, encompassing choices in adsorbents and/or flocculants, membrane selection, dosing procedures, system configurations, mixing conditions, and more. Systematizing knowledge and developing tools for predicting MCEC behavior in wastewater treatment is crucial.

The lack of comparative investigations between established methods (AC adsorption and ozonation) and emerging processes (novel AOPs) complicates the conclusive evaluation of the most suitable and cost-effective solutions for advanced urban wastewater treatment. Site-specific limitations, such as space availability and solar energy accessibility, may lead to different conclusions for different locations. Importantly, these comparative investigations should consider various relevant endpoints for safe effluent discharge or reuse, including MCEC removal, effluent toxicity, bacteria inactivation, by-products minimization or removal, antibiotic resistance control, and treatment cost.

Decentralized wastewater treatment

Rural domestic sewage, especially in developing countries and low density population areas is one of the foremost obstacles to achieving several global SDGs[57]. Globally, less than 60% of people are connected to sewage collection systems, however sewage treatment stands at a much lower percentage, with the lowest proportion being reported in the Global South[12, 58]. Centralized wastewater treatment systems are a common choice in urban areas and megacities, but typically infeasible and lacking in poor rural areas due to the significant construction, operation and maintenance costs[59]. 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[60].

The application of decentralized wastewater treatment systems is not exclusively independent from the traditional centralized system, as the integration of the two systems may be preferable depending on the local conditions[61]. Several technologies have been reported in decentralized systems, including among others constructed wetlands, anaerobic and biofilm reactors, and membrane bioreactors (MBR),[62, 63] 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 a wide range of pathogens and MCEC[64].

Centralized urban wastewater treatment and reuse schemes are capable of supporting intensive, mechanized agriculture practiced at the large scale, whereas decentralized ones can support localized, less intensive and more traditional farming by full-time or part-time farmers seeking additional income[65] (Fig. 2).

TW-irrigated agricultural hotspots

The climate-water-energy-food nexus, along with health benefits, can thrive in TW-irrigated hotspots of agricultural production in urban and peri-urban areas. This involves producing food within environmentally safe systems, ensuring an adequate and healthy supply for consumption in local markets, simultaneously, implementing and promoting relevant SDGs[66]. In this context, such agricultural hotspot areas could be developed near either centralized or decentralized WWTPs. Such an approach could 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[67].

The example of the North-Western Sahara Aquifer System covering 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[68]. 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[69]. 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%. The production of high quality crops will generate more revenue and the recovery of nutrients will reduce input costs, as well[70]. 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[71]. Constructed wetlands provide decentralized wastewater treatment in rural communities in India, thus allowing the production of TW-irrigated food in small agricultural hotspots with reduced disease burden and decreased environmental pollution[72].

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 treated wastewater reused for agriculture remains low. Comprehensive systems, from treatment plants to irrigation, are essential for sustainability. Decentralized wastewater treatment can address rural challenges. TW-irrigated agricultural hotspots, exemplified in water-scarce regions, showcase significant water savings, reduced energy consumption, and improved food production sustainability.

TW reuse for irrigation: pros and cons

The use of TW for irrigation offers several benefits, but careful consideration of the 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 been 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.

Implication of TW for crop irrigation can offer nutrient enrichment of the agro environment which stands out as a significant agronomic advantage. TW carries essential macro nutrients such as nitrogen, potassium, and phosphorus, functioning the water as a fertilizer for crops. By integrating TW into irrigation practice, farmers can reduce their reliance on commercial fertilizers, thereby cutting costs and minimizing the environmental footprint associated with fertilizer application. This practice must therefore be associated with routine monitoring and appropriate training of the farmers. Otherwise, access of nutrients will be provided causing pollution rather than environmental and agronomical benefits. A potentially notable disadvantage of TW as a sole irrigation source is related to the potential for soil salinity. TW often contains elevated levels of salts, which can accumulate in the receiving soils and more importantly impede crop growth crops[73]. Furthermore, TW irrigation can contaminate groundwater situated below irrigation sites[74]. To reduce the potential risk, routine monitoring of TW as well as region/state-level water management must be implemented to reduce salt input into the sewage system. In various occasions, TW can be characterized by high sodium adsorption ratio. This can deteriorate soil structure by clay swelling and dispersion leading to unfavourable soil physical and hydraulic properties[75]. Long-term TW irrigation can therefore reduce water and oxygen availability to plants, ultimately harming crop performance.

The addition of dissolved and particulate organic matter originating from TW to soils can change their physicochemical properties. One of the physical effects resulting from TW application is water repellence. In a water-repellent soil, soil wettability is lower promoting flow instabilities that lead to the formation of preferential flow paths[76]. Also, careful attention should be placed to boron (B) which is abounded in detergents and known to induce plant toxicity at low concentration. Like sodium, boron level should be controlled at the source since it is not removed during wastewater treatment. Furthermore, if TW is not adequately treated, the water may carry pathogens that can harm farmers and infect crops and pose risks to human health through the food chain. Thus, strict adherence to water quality standards and robust monitoring systems are imperative to address this concern.

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.

MCEC-related challenges

Along with advantages, TW reuse in agriculture comes with limitations and considerations, mainly driven by the inability of currently applied treatment technologies to completely remove MCEC. Their environmental fate, as well as their potential impacts on living organisms pose several challenges and therefore constitute an important research topic in the field of TW reuse in agriculture.

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[77, 78]. MCEC can include biocides, flame retardants, micro(nano)plastics, pesticides, personal care products, pharmaceuticals, synthetic and natural hormones, and antimicrobial resistance (AR) determinants, such as antibiotic resistant bacteria (ARB), resistance genes (ARGs) and relevant mobile genetic elements[79] (Fig. 3).

Biological treatment technologies such as conventional activated sludge (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[80, 81]. At the same time, these combinations of technologies and widely used disinfection technologies including chemical oxidation agents like chlorine and physical agents such as ultraviolet irradiation[82], as well as emerging disinfection processes using peracetic acid[83] and performic acid[84] bear limitations in addressing holistically MCEC. Limitations include the fact that even though some technologies are successful in removing parent compounds of micropollutants and chemical contaminants of emerging concern, they do so while generating transformation products (often more harmful than their parent compounds), toxicity, mutagenicity, and endocrine disruption effects for example[85], the selection of potentially pathogenic bacteria (repair and/or regrowth) and alteration of wastewater microbial community structures[86].

Furthermore, it is crucial to consider the impact of external contamination on treated wastewater (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 antimicrobial-resistant bacteria (ARB), should be thoroughly examined in the context of reuse systems[87, 88]. 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[89, 90].

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[91]. Consequently, hundreds of micropollutants and chemical contaminants of emerging concern are routinely detected and quantified in environmental matrices receiving TW downstream of WWTPs, including TW-irrigated soils, surface and groundwater systems, parks, even drinking water[79, 89, 92]. Many of them are simultaneously released via treated effluents, forming cocktails which vary in concentration and composition in receiving environments, both spatially and temporally[93]. Various micropollutants and chemical contaminants of emerging concern have been shown to accumulate in TW-irrigated agricultural soils following transportation and transformation (by both biotic and abiotic factors), to be taken up by wild and cultivated crop plants and accumulated within their tissues[89, 94]. Upon their entrance into the food web, a number of them displaying favorable physicochemical properties can potentially bioaccumulate in other organisms and in humans[95, 96], potentially provoking toxicity effects[97].

Studies performed under controlled conditions have uncovered mechanisms involved in their uptake by plants, as well as their accumulation in different plant tissues, including edible ones[98]. In addition, it was shown that upon their uptake by plants, they can induce transcriptomic and metabolomic rearrangements that impact normal plant physiology and morphology, indicating stress responses[99, 100]. Micropollutants and chemical contaminants of emerging concern 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’[99, 101]. Real-world field experiments (primarily on pharmaceutical compounds) and field surveys also revealed their uptake and accumulation in the edible parts of crop plants under 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[102-104]. Moreover, control trials verified the presence of carbamazepine and its metabolites in the urine of people that consumed vegetables collected from TW-irrigated fields for a prolonged period, compared with control samples[95] (Fig. 3).

Accumulating evidence shows that WWTPs release significant quantities of micro(nano)plastics into the environment as, despite the high removal efficiencies (up to 98%) reported for currently applied secondary and tertiary treatment technologies, TW is continuously released to the environment in huge volumes[105, 106]. Due to their surface properties, micro(nano)plastics can be colonized by wastewater microorganisms resulting in the formation of dynamic biofilms, known as plastispheres[107], which interact with other co-existing contaminants in WWTPs, including MCEC[108]. Wastewater plastispheres can enhance the persistence of AR elements and bacterial pathogens by favoring their microenvironment and horizontal gene transfer[108, 109] and limiting their inactivation by disinfection processes[110], thus accelerating their toxicological impacts in the downstream environments[109].

Micro(nano)plastics can accumulate in soil fauna, wildlife and plants and exert negative impacts[111, 112]. 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[113]. 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[114]. Thus, measures to efficiently control and minimize the impact of micro(nano)plastics at the WWTP level should be considered[115].

Transformation products of micropollutants and chemical contaminants of emerging concern often have similar molecular structure to their parent compound. They still contain the toxicophore-like moiety, while some other derivatives incorporate almost the complete parent compound structure and might thus show similar environmental behavior and bioactivity[116]. Research has suggested that some TPs might pose a similar or greater risk than their active parent compound exhibiting similar or higher ecotoxicological effects[117]. TPs along with their parent compounds have been detected in the soil-crop continuum in TW-irrigated agroecosystems[118, 119].

Regarding the current concerns about AR, the need to investigate the residual antibacterial potential of antibiotic TPs is profound. While the relationship between the parent antimicrobial compounds and AR is well documented, the impacts of their TPs on AR development (through alternative or 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 TPs as well as other non-pharmaceutical selection pressures[120, 121] (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[122, 123]. The enrichment of ARG concentrations in TW-irrigated public park soil[92], as well as the increase in the concentration of antibiotic-resistant *E. coli* on the leaf surface of romaine lettuce following TW irrigation[124], highlight the potential for human exposure to antibiotic resistant 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[125].

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[126, 127]. 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[128]. 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 due 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[123, 129, 130].

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 significantly higher ($x10^3$ - $x10^4$) compared to those in the edible crop tissue[131], with the ARGs *bla_{TEM}* and *sul1* being of highest abundance within the soil-crop system in the available studies[132]. On the other hand, 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[131]. 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[131].

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, as stated previously[133, 134]. In line with this, soil bacteria have been shown to 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[134, 135].

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 TPs in TW and reuse environments[121, 136]. 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[137]. 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)[138].

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 TPs) 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[139-141]. 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[139]. 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. While acknowledging the importance of concentration data per unit volume, it's also worthwhile to consider that other units may offer valuable insights in different scenarios[142]. It is also imperative to provide sample metadata, encompassing a comprehensive explanation of the treatment technologies employed 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[136, 143].

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, water repellence, and the presence of micropollutants, including pharmaceuticals and antimicrobial resistance determinants. Current treatment technologies have limitations in completely removing these contaminants, posing environmental and health risks. 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. Comprehensive regulations often include a permit system for the production and use of TW for various applications. 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[28, 43]. 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[28]. For example, the Australian Guidelines for water recycling[144] and the US EPA Guidelines for Water Reuse[145] 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 International Organization for Standardization (ISO) and the World Health Organization (WHO) 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[146, 147, 148]. In the EU, the Water Reuse (EU) Regulation 2020/741 aims at gaining benefits of wastewater as a resource and alleviate the increasing water scarcity under the effects of climate change[43]. In addition to providing EU uniform minimum water quality and monitoring criteria, this regulation requires a mandatory risk management plan (Fig. 4) applied to water reuse schema in all the EU Member States (except those that have decided to make use of a regulatory opt-out clause). To this effect, the Joint Research Centre (JRC) of the European Commission developed an array of technical guidelines that can be applied for assessing and managing health and environmental risks associated with water reuse systems[28]. Other countries in which TW reuse in agriculture is well-established have also developed their own regulatory framework, including the Israeli water reuse law[149] and the Chinese water reuse guidelines[150]. As of January 2023, a national-level framework on the safe reuse of treated water that provides guidelines on preparing reuse policies was launched in India[151]. Despite the establishment of regulatory frameworks and guidelines, governance strategies for water reuse need to address various challenges due 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[152]. The main regulatory frameworks currently applied around the world are described in Box 3.

Risk management frameworks

The assessment and management of health and environmental risks associated with the reuse of reclaimed water in agricultural irrigation, are addressed by several international guidelines, and standards. Examples are the EU Water Reuse Regulation 2020/741[42], the ISO 20426:2018 - Guidelines for Non-Potable Water Reuse[146], the ISO 16075:2020 - Use of Treated Wastewater for Irrigation Projects[147], the WHO Guidelines for the Safe Use of Wastewater[148] and Quantitative Microbial Risk Assessment[153], the WHO Sanitation Safety Planning Manual[154], the Australian Guidelines for Water Recycling[144] and the US EPA Guidelines for Water Reuse[145].

The WHO[148] and the Australian Guidelines[144], have influenced the structure of the risk management plan (Fig. 4) proposed by the Technical Guidance on the Water Reuse Risk Management for Agricultural Irrigation Schemes in Europe[28]. 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[146], the ISO 16075:2020[147], and the Australian Guidelines[144]. The risks to be addressed can be grouped into 2 categories: a) health risks to humans exposed to reclaimed water (workers, bystanders, and residents in nearby communities), and b) risks to 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[28] is to guarantee that a water reuse system operates while ensuring the protection of the health of workers, farmers, and consumers, and 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 plan must be based on 11 key elements of the risk management plan (KRMs) representing the basis to ensure that the reclaimed water is used and managed safely to protect the human and animal health and the environment[28] (Fig. 4, Box 4).

Sustainability of wastewater reuse

Wastewater treatment contributes significantly to anthropogenic GHG emissions and global warming. However, technological innovations can mitigate energy consumption and enhance circularity by recovering valuable resources, such as nutrients and other by-products. Below, we discuss the current drawbacks in conventional treatment technologies and the potential provided by technological advancements for energy and resource recovery.

Major challenges and solutions

Conventional wastewater treatment as currently applied in WWTPs is energy demanding and a serious GHG emitter, thus contributing to global climate change[155]. 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[156, 157]. The energy demands of 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[158, 159]. Besides their high energy demand and large environmental footprint, WWTPs are currently also characterized by low resource recovery and cost effectiveness, as they were primarily designed to reduce effluent nutrients, suspended solids and pathogenic microbial loads in order to protect downstream users and environments[160].

Climate change effects on water availability, energy and the resources crisis, all call for a paradigm shift in the water-energy-sanitation-food-carbon nexus in a circular economy framework, with sewage as the core backbone. Thus, the concept of ‘sewage collection, treatment and disposal’ is redefined to ‘reuse, recycle, and energy and resource recovery’[161, 162]. Wastewater is a massive untapped resource of water, energy, nutrients and other products[12, 155, 159], which can potentially change WWTPs into energy and resource recovery facilities in which wastewater and sludge will be used as raw material sources, promoting associated SDGs and net-zero carbon schemes[163] (Fig. 5).

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 is primarily due to technical immaturity and/or non-technical bottlenecks such as costs, resource quantity and quality, operational distractions, acceptance, and policy[160]. 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[164, 165]. However, the upgrade of technology readiness level, economic performance and environmental benefits of these green technologies is expected to promote their wider adoption in the coming years[163].

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[166, 167]. 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[11].

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[159, 168]. The energy that can be recovered from the total volume of wastewater produced globally through the conversion of biogas released by anaerobic digestion can be enough to provide electricity to 158 million households or to up to 632 million people, with projections for steady increase due to the increasing volumes of produced wastewater[169]. 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[163, 170].

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[171, 172]. 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 COD can be converted to methane gas and at least 75% reduction in sludge can be achieved)[173]. 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[174].

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[163]. 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[175, 176]. 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[177] (Fig. 5).

From wastewater to resource

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[178, 179]. Based on 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[180]. These nutrients concentrations and the global volumes of wastewater were used to estimate that the nutrients potentially embedded in wastewater may contain up to 16.6, 3.0 and 6.3 Tg (10^9 kg) of N, P, and P, respectively, representing 14.4, 6.8 and 18.6 % of the respective global fertilizer nutrient demands, or 13.6 billion $ of potential total revenue[169]. 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 environmental polluting processes for nutrient resource extraction and fertilizer manufacturing[165].

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[165, 181]. However, system combinations and plant-wide configurations are necessary, as none of these methods alone can provide complete recovery of all major nutrients[165, 166].

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[182]. 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[165, 183]. Moreover, microalgae or autotrophic hydrogen oxidizing bacteria grown in photobioreactors or open systems treating wastewater can display high nutrient recovery rates (50 to 70%) in the produced biomass, which can subsequently be transformed into several end products, such as fertilizers or animal feedstock reach in amino acids[184, 185].

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[177]. Valuable trace elements such as gold, silver, nickel, platinum and other can be also recovered through various electrochemical extraction processes[186]. 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, as the harvested microalgae biomass contains valuable biomolecules (for example, biopolymers, cellulose, single-cell protein, polyhydroxyalkanoates, volatile fatty acids), which in turn can facilitate the production of biofuels, bioplastics, biochemicals, nutrition supplements for animal feedstock, antioxidants and nanoparticles[187, 188].

In summary, wastewater treatment can transition to a sustainable model through technological innovations promoting energy and resource recovery. Shifting towards a circular economy, where sewage is a resource, can transform wastewater facilities into energy-neutral or positive entities. Technologies like 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.

Future wastewater treatment systems

Future technology development will underpin the sustainability and safety of TW reuse and support expansion of this important sector. Further efforts by industry and academia are needed to ensure that TW continues to meet the quality standards required under comprehensive regulatory frameworks that are also in a state of development and essential for sustainable and safe TW reuse.

Upgrades in existing technologies

Biological oxidation of organic and of nitrogenous compounds through CAS treatment following the primary mechanical pre-treatment has been at the core of municipal wastewater treatment since its introduction over a century ago. Large scale available advances to CAS treatment include the MBR process and related modifications (which are still an integration of CAS process and membrane filtration to separate treated water from biomass), as well as granular sludge systems and anaerobic digestion[189, 190]. However, the increasing complexity of wastewater streams, stringent regulations on minimum discharge standards, and the myriad of MCEC that can pose threats to environmental and human health are increasingly leading to the introduction of advanced tertiary treatment technologies into treatment trains, post CAS or MBR treatment.

Upgrades in WWTP treatment lines 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- or nano-filtration and reverse osmosis[33]. 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 based on life cycle assessment and decision support tools[191].

Advancements applied at a large scale

Bacterial and algal-bacterial aerobic granular sludge treatment has been implemented both at the pilot and full scale levels with very good efficiency in terms of both effluent quality and energy cost savings[189]. The aerobic granular sludge systems commercialized worldwide under the Nereda® technology tradename offer compact structure, lower energy requirement (35-70%) and land footprint (40-50%), higher flexibility in emergency events (high loads), excellent nutrient and organic pollutants removal, and also enable the recovery of valuable products such as P, crude protein and biopolymers[192]. In addition, microbial electrochemical technologies, specifically microbial fuel cells, electrolysis cells and recycling cells have been successfully applied at the large scale for the treatment of industrial effluent, however several challenges, mainly concerning high capital cost and low energy output, currently restrict their scalability and hinder their full-scale application in municipal WWTPs[193].

Innovations in wastewater treatment

Nanotechnology and advanced materials are set to revolutionize 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 favor their use in wastewater treatment[194]. Nanomaterial-based membranes, including nanofibers-, nanoparticles-, nanotubes-, nanocrystals-, nanowires- and nanosheet-based membranes can substantially enhance MBR performance and reduce fouling, operation and maintenance costs[195]. 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- and micro-motors to enhance adsorption, mixing, photocatalysis and advanced oxidation processes during wastewater treatment[196].

Technologies of the Fourth Industrial Revolution (4IR) constitute a technological catalyst for all fields of human endeavor, and therefore could also be harnessed to support the climate-water-energy-food nexus, facilitating the achievement of SDGs[197]. For instance, computing, digital transformation, digital twin, artificial intelligence, big data analytics and Internet of Things (IoT) can facilitate online model-data optimization in wastewater treatment processes and in reuse schemes (for example, smart farming), through sensors, high-resolution remote sensing and communication technologies, and human-machine interaction for achieving environmental and economic sustainability[198].

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[198]. Artificial intelligence models have efficiently managed biological[199] and MBR[200] wastewater treatment processes in full scale WWTPs, by predicting the performance, real-time 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[201]. Moreover, data-driven methods[202], as well as advancements in analytical chemistry tools, bioinformatics, and multi-omics data, can achieve fault detection, variable prediction and advanced control of WWTPs[203] (Fig. 6).

In summary, the future of wastewater treatment involves upgrading existing technologies, with advanced tertiary treatment technologies. Nanotechnology and advanced materials, particularly nanomaterial-based membranes, and the integration of 4IR technologies, are set to revolutionize wastewater treatment. These advancements promise improved efficiency, energy cost savings, and environmental sustainability, with artificial intelligence-driven data analytics playing a crucial role in optimizing processes and ensuring water quality.

Summary and future directions

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. It is estimated that the total volume of TW produced globally can satisfy nearly 15% of all irrigation water needs, thus supporting the expansion/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.

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. To this end, 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. To progress efforts in this area, governmental and intergovernmental organizations should devote effort and resources to promote and fund wastewater treatment and reuse in agriculture in developing counties. This is especially important because over 80% of global wastewater is discharged untreated (over 95% in some of the least developed countries). This untreated wastewater can be used directly or indirectly for the production of potentially contaminated feed or food that can potentially be consumed anywhere in the world as a result of international trade[204].

Overcoming TW reuse governance challenges stands as a fundamental step for the expansion of reuse practices globally, simultaneously ensuring TW quality and public and environmental health. 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 possibility of regulating the presence of MCEC in treated effluent should now be considered[143], given that this will be based on real-world research data concerning toxicological impacts to humans and the environment, the real magnitude of pollution burden in the end of the reuse systems, the impending cost, and the effectiveness of currently applied technologies.

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[12]. 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 introduction to the agroecosystems and the food web, including AR determinants and TPs78.

The diverse challenges faced by CAS, MBR, MBBR, and CW 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. While solar-driven AOPs exhibit promise, yet 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.

Cost mitigation through decentralization, energy and nutrients recovery, and proper pricing of both freshwater and wastewater can efficiently promote wastewater reuse practices. Wastewater reuse systems should consider local data and information on wastewater volumes and quality, TW intended reuse applications and appropriate and affordable treatment technologies. Importantly, social acceptance through awareness raising and education aiming to overcome social, cultural and farmers and consumers barriers constitutes a prerequisite for a successful reuse scheme[205].

The role of science in solving the world's emerging water problems is well reviewed[206]. Academia and industry should cooperate in developing fit-for-purpose, science-based solutions through advancement in technology that will enable the affordable production of quality TW (minimization of MCEC in treated effluent) within a circular economy framework. Moreover, the incorporation of 4IR technologies in the entire TW reuse system is essential for advancing treatment, monitoring, and troubleshooting. Additionally, these technologies play a crucial role in promoting smart and precision agriculture through advanced irrigation and farming practices. This integration will further ensure the safe reuse of TW in agriculture (Fig. 6). The sustainability of reuse practices can be also enforced by the implementation of comprehensive risk management plans which will include among other toxicological endpoints regarding all involved environmental matrices (for example*,* water resources, soil, plants, wildlife, 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 this objective, the active involvement, and good services of all involved parties, including public authorities, relevant stakeholders, industry, academia, farmers, and the public (consumers), are necessary.

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Author Contributions

AC and DFK led the conceptualization and writing of the Review. VB, II, and PK contributed to data collection and analysis. VB, II, PK, CM, TB, BC, ED, YL, TTL, LL and ET discussed and amended the content of the Review. All authors reviewed and edited the manuscript before submission.

Competing interests

The authors declare no competing interests.

Figure Captions

Fig. 1 a | TW reuse system. Urban wastewater produced by anthropogenic activities is collected (from houses, offices, factories, etc.) within a settlement via a labyrinth-like piping system and conveyed to a WWTP through a final mainstream pipe. Applied treatment technologies in WWTPs can purify and decontaminate wastewater, finally achieving the production of reclaimed water of sufficient quality for reuse purposes. TW might undergo further treatment such as disinfection or filtration for the efficient removal of MCEC prior to its storage and further distribution for reuse practices, mainly agricultural irrigation. Based on its quality and the current reuse guidelines, reclaimed water can be reused for the irrigation of various crops (for example, fodder crops, vegetables, fruit trees), thus boosting the economy and ensuring food supply and security.

Fig. 1 b | Annual volume and percentage of TW used for direct irrigation. Global direct reuse of TW (with no or little dilution with freshwater) for irrigation varies among continents. Direct application for irrigation is a prevalent practice in Middle Eastern and North African countries, Australia, the Mediterranean region, Mexico, China, and the USA, influenced by local water scarcity, availability of treatment infrastructure, presence and enforcement of regulatory measures, and economic motivations. Data source[39, 40].

Fig. 2 | Centralized or decentralized wastewater treatment systems can facilitate the establishment of agricultural hotspots. Wastewater treatment systems that are best suited to local conditions can effectively promote circular economy and SDGs. Wastewater treatment options can vary based on the volumes of wastewater to be treated and its quality, economic welfare, reuse purposes, available technologies, local regulatory frameworks, and social acceptance, among others. Centralized wastewater treatments can serve for the treatment of wastewater produced in big urban areas, generating large volumes of reclaimed water for reuse purposes. On the other hand, decentralized WWTPs can serve for the treatment of lower volumes of wastewater in small rural agglomerations, providing reclaimed water of sufficient quality and cost effectively, as substantial reduction in sewage collection and treatment and maintenance costs can be achieved. The reuse of reclaimed water for crop irrigation can promote the establishment of agricultural sites where intensive agricultural activities are practiced (for example, agricultural hotspots), with their size being in line with the reclaimed water produced (smaller and less intensive hotspots in decentralized systems). The production of food for the local communities can boost the local economy and promote the climate-water-energy-food nexus.

Fig. 3 | Challenges and limitations in TW reuse. Applied treatment processes fail to completely remove MCEC from treated effluents, resulting in their continuous release to the environment through reuse applications. MCEC introduced into the agroecosystem can interact with other organisms with potentially negative impacts, promote the dissemination of AR determinants and their potential transfer to bacteria of clinical relevance, while entering the food web upon their uptake by crop plants. Micro(nano)plastics co-released with other contaminants may enhance AR dissemination and thus result in enhanced toxicological impacts. Associated challenges and risks posed to human and environmental health should be addressed taking into consideration that MCEC entering the agroecosystem and the food web are present in mixtures varying spatially and temporarily in composition, considering the Precautionary Principle. 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.

Fig. 4 | Key Risk Management Elements (KRMs, Box 4) and four modules for effective risk planning according to the Technical Guidance Water Reuse Risk Management for Agricultural Irrigation Schemes in Europe[28]. Module I consists of preparatory activities necessary to set up the risk management plan 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. Module II entails the health and environmental risk assessments. Module III includes all the monitoring activities planned for the water reuse system: identification of procedures and protocols for the Quality Control of the system and for the Environmental Monitoring System (EMS). Operational and environmental monitoring programmes to provide assurances to workers, the public and authorities, of adequate system performance. Module IV includes management, emergencies and communication protocols and coordination.

Fig. 5 | Emerging technologies have the potential to retrofit the wastewater treatment sector in a circular global economy. New technologies capable of retrofitting and upgrading all the functions of WWTPs towards a more circular model are in the pipeline for their commercialization in the forthcoming years (given that their technology readiness level is improved to an adequate level), while some of them are already applied at full scale. Future WWTPs are expected to display enhanced treatment efficiency through the incorporation of advanced technologies, thus acting as sentinel of public and environmental health. Moreover, the 'reuse, recycle and resource recovery' concept can turn WWTPs into energy and carbon neutral facilities, where nutrients and other added-value materials are recovered and reused. To this effect, the wastewater treatment sector can pave the pathway towards circular economy and SDGs in the forthcoming decades.

Fig. 6 | Advancements in knowledge and technologies can transform the wastewater treatment sector, by enhancing efficiency and promoting circularity. The incorporation of advanced materials and nanotechnology in wastewater treatment technologies can retrofit WWTPs, resulting in the production of high-quality reclaimed water within a circular economy model. Upgrades in advanced treatment and the use of nanomaterials in membrane filtration and separation processes, as well as the introduction of microbial electrochemical technologies (for example, microbial fuel cells, electrolysis cells) constitute important elements towards the operation of greener WWTPs. In addition, the incorporation of 4IR technologies (for example, artificial intelligence, autonomous systems, big data analytics, digital transformation, and internet of things), along with advancements in analytical chemical tools and the integration of omics and bioinformatics can improve wastewater systems through the optimization of operation and on-line monitoring and troubleshooting, thus improving their economic, energy and carbon footprint. The incorporation of 4IR technologies in TW-irrigated agroecosystems (smart farming) is expected to promote public health and environmental safety in TW reuse applications, while also can expand irrigated areas and therefore increase agricultural production.

BOXES

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 due 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[207].

Cyprus

In the same line, Cyprus, a Mediterranean country with the highest water exploitation index in Europe (124% in 2019)[208], reuses more than 70% of all tertiary treated effluent produced for agricultural irrigation, and considers TW as a substantial component of integrated water resources management plans[209].

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[28].

United States

In the United States, TW reuse schemes in agriculture are based on comprehensive regulations and guidelines[145, 210]. In Florida, most of the TW is reused for landscape irrigation even in areas with public access, while agricultural irrigation mostly refers to citrus orchards irrigation[211]. In the Monterey County in California, disinfected tertiary TW constitutes an important component of the 'One Water' management scheme[212]. 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[210].

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[213].

Australia

In Australia, TW reuse in agriculture is increasingly common as jurisdictions seek to secure ‘climate-independent’ supplies[214]. Recycled water for multiple uses, including for agricultural irrigation, is now a key component of diverse water supply portfolios for many Australian water authorities[215]. In 2019-20, Australian agriculture used about 6500 hm^3 of water, of which 124 hm^3 (1.9%) was recycled water obtained from off-farm sources[216]. Outcomes from the Australian experience to date indicate that TW recycled from capital city WWTPs adjacent to suitable vegetable growing land have been the most successful recycling schemes[216].

Box 2 | Learning from the Past, Cultivating the Future: Israel's transformative journey in utilising wastewater for agricultural growth

The story

The initial use of TW in agricultural in Israel began 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. Then, orchards and plantations were also added as areas where TW could have been incorporated. During the 1980s, water shortages became more frequent, and in the early 1990s, Israel faced a severe water crisis. In response, the government declared two main measures to overcome water scarcity: Increasing production of potable water by desalination and expanding the use of TW for irrigation. The TW use grew significantly, reaching currently 45-50% of the total water use for agricultural irrigation.

The facts

Recent data (2022) about sewage treatment and TW reuse referring to wastewater generation from a population of about 9 million, (i.e., 98.6% of Israel's population) indicate an estimated total amount of raw wastewater at 620.5 million m^3, of which 616.4 million m^3 is domestic and industrial wastewater and about 4.05 million m^3 is cowshed wastewater. About 95.4% (about 592 million m^3) of total wastewater is treated in WWTPs. The wastewater to TW reclamation ratio is 84.7%[217].

The success factors

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. Water planning, marketing and distribution are highly centralized. Centralized system like that enables fast transfer of water resources ensuring public and environmental safety.

(2) Agricultural viability: Farmers were allocated with a specific water quota. This forced the farmers to shift from fresh water to TW, otherwise they would face underutilized production due to insufficient water.

(3) Financial support: Allocation of funds (loans and grants) for construction the necessary infrastructure (WWTPs, pipelines, reservoirs, irrigation equipment, etc.).

(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 ten-year period. The Israeli Ministries of Agriculture and Environmental protection took the lead to establish long-term national monitoring system including setup of specific experimental plots. This system enabled fast response to problems raised by farmers and a close feed-back between farmers, regulators, academia, and the water industry.

(5) Regulations: Implementation of strict regulations regarding health and agronomic quality of TW. Understanding that TW is a key factor for agricultural and environmental health (soil and crop) let to massive upgrading of WWTPs to provide high-quality (tertiary) TW for unlimited irrigation use (TW that can be used to irrigate all types of crops using all type of irrigation techniques). Supplementary regulations were issued for the industry to minimize industrial impact on the quality of TW, including reducing pollutants at the source. A good example is related to banning the use of Boron-containing detergents to reduce the level of B in TW below 0.4 mg/L.

Current challenges

Although the utilization of TW is high and expected to increase soon, the maximum capacity of TW utilization is still not maximal due 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. After fully exploiting the current potential, future dependence on TW is expected to increase with population growth, leading to more water usage and higher demand for TW by both the agricultural as well as the urban sectors. Additionally, further upgrading of WWPTs is needed to address the concern regarding the presence of contaminants of emerging concern that have been shown to be introduced to the food chain and even monitored in biological samples of Israelis consuming produce irrigated with TW.

Box 3 | Legal and regulatory frameworks applied in different regions or countries to ensure public and environmental health during TW reuse for irrigation

Frameworks by international organizations

The International Organization for Standardization (ISO) issued guidelines for the use of TW in agriculture. The ISO 16075:2020[147] covers guidelines for the use of TW in irrigation projects. It suggests standards for *E. coli*, BOD, TSS, 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[146] 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[148] which contains a methodology to ensure safe reuse of TW around the world.

European Union Water Reuse Regulation

The EU Regulation (EU) 2020/74[42] sets out harmonized minimum water quality and monitoring requirements for *E. coli*, BOD_5, TSS, and turbidity for water quality classes A, B, C, 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[28]. 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.

U.S. regulatory framework

In the U.S., standards for the use of TW in irrigation have not been established at federal level. The Twenty-eight states of the U.S. 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 recycled water)[218]. Additional to state-laws, the US EPA Guidelines for Water Reuse[145] provides a non-mandatory national guidance for planning and regulating water reuse across the states following a risk management framework approach.

Israel

The Israeli water reuse law[149] approved by the Ministry of Health (2010) regulates the unrestricted use of TW for agricultural irrigation. It established rules for granting permits for irrigation with TW ensuring the protection of public health and the environment.

The Australian Guidelines

The Australian Guidelines for water recycling[144] 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.

Box 4 | Key Elements of the Risk Management Plan of the European Regulation on Water Reuse[28]

System description (KRM1): description of the entire water reuse system from the entry point to the urban wastewater treatment plant to the point of use.

Parties, roles, and responsibilities (KRM2): identification of all the parties involved in the water reuse system along with their roles and responsibilities.

Hazards identification (KRM3): identification of potential hazards (pathogens and pollutants) and hazardous events (e.g., treatment failures) associated to the water reuse system.

Populations and environments at risk and exposure routes (KRM4): identification of populations and environments potentially exposed to each identified hazard.

Environmental and health risk assessment (KRM5): identification of risks associated with each hazard for receptors (people, animals, crops, terrestrial biota, aquatic biota, soils, and the environment) across exposure routes. Use qualitative and semi-quantitative methods due to data constraints, adhering to regulatory and legislative obligations outlined in the specified Regulation and relevant national or local laws.

Additional requirements (KRM6): the risk assessment may lead to the identification of heightened water quality and monitoring needs, potentially surpassing those outlined in the Regulation. Any additional parameters or limits should stem from the assessment outcomes and be substantiated by scientific evidence, ensuring their connection to the water reuse system rather than external sources. These added parameters may encompass heavy metals, pesticides, disinfection by-products, pharmaceuticals, micropollutants, microplastics and antimicrobial resistance determinants.

Preventive measures (KRM7): identification of preventive measures or barriers, additional or already in place, to be applied to parts of the water reuse system, for example access control methods, additional water treatments or specific irrigation technologies or barriers to limit or mitigate any identified risk.

Quality control systems (KRM8): determination of quality control measures, including protocols for monitoring the reclaimed water for the relevant parameters and maintenance programs for the equipment, to ensure the effectiveness of the treatment chain and of the preventive measures adopted.

Environmental monitoring system (KRM9): set up of an environmental monitoring system to assess the release of the identified pollutants in the exposed environmental receptors (e.g., freshwater, groundwater, soil).

Incidents and emergency systems (KRM10): set up of protocols to manage incidents and emergencies.

Coordination mechanisms (KRM11): definition of coordination and communication mechanisms amongst the different actors involved in the water reuse system.

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