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Mitigating risks and maximizing sustainability of treated wastewater reuse for irrigation

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ABSTRACT

Scarcity of freshwater for agriculture has led to increased utilization of treated wastewater (TWW), establishing it as a significant and reliable source of irrigation water. However, years of research indicate that if not managed adequately, TWW may deleteriously affect soil functioning and plant productivity, and pose a hazard to human

Abbreviations: TWW, treated wastewater; TDS, total dissolved solids; EC, electrical conductivity; SAR, sodium adsorption ratio; OM, organic matter; DOM, dissolved organic matter; WWTP, wastewater treatment plant; CEC, contaminants of emerging concern; PPCP, pharmaceuticals and personal care products; PFAS, poly- and perfluoroalkyl substances; MP, microplastics; AMR, antimicrobial resistance; ADI, acceptable daily intake; TTC, threshold of toxicological concern; ARB, antibiotic resistant bacteria; ARG, antimicrobial resistant genes; QMRA, quantitative microbial risk assessment; DBP, disinfection by-products; NDMA, nitrosodimethylamine; NF, Nano filtration; RO, Reverse Osmosis; GHG, Greenhouse gasses.

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and environmental health. This review leverages the experience of researchers, stakeholders, and policymakers from Israel, the United-States, and Europe to present a holistic, multidisciplinary perspective on maximizing the benefits from municipal TWW use for irrigation. We specifically draw on the extensive knowledge gained in Israel, a world leader in agricultural TWW implementation. The first two sections of the work set the foundation for understanding current challenges involved with the use of TWW, detailing known and emerging agronomic and environmental issues (such as salinity and phytotoxicity) and public health risks (such as contaminants of emerging concern and pathogens). The work then presents solutions to address these challenges, including technological and agronomic management-based solutions as well as source control policies. The concluding section presents suggestions for the path forward, emphasizing the importance of improving links between research and policy, and better outreach to the public and agricultural practitioners. We use this platform as a call for action, to form a global harmonized data system that will centralize scientific findings on agronomic, environmental and public health effects of TWW irrigation. Insights from such global collaboration will help to mitigate risks, and facilitate more sustainable use of TWW for food production in the future.

1. Introduction

Agriculture accounts for ~70 % of global freshwater consumption annually, with irrigated crops composing ~40 % of the cultivated lands globally (Pastor et al., 2019). The climate crisis and growing demand for food due to population growth have impacted freshwater availability, motivating the search for alternative water sources for agriculture, especially in arid and semi-arid regions (Assouline et al., 2015; European Commission 2020; Pastor et al., 2019). Reusing wastewater is emerging as a credible alternative to supply irrigation water, however only ~50 % of current wastewater production goes through treatment (Jones et al., 2021). In developing regions of the world, water stress leads to use of crude wastewater (i.e. raw sewage or lightly treated wastewater) for irrigation, resulting in detrimental public health and environmental consequences (Contreras et al., 2017; Qadir et al., 2010). Wastewater treatment circumvents many of these effects, and so irrigation with treated wastewater (TWW) can provide agriculture with multiple economic, environmental, and social advantages (Mannina et al., 2022; Tal, 2006; Thebo et al., 2021).

Currently, only ~20 % of the global treated wastewater produced is reused (Jones et al., 2021), with the rest being discharged into the environment. The long term experience of countries such as Israel, where ~85 % of the generated TWW is reused for agricultural irrigation (Cohen et al., 2020), can promote widespread use of this untapped resource. Despite its advantages, it bears noting that widespread TWW irrigation poses challenges to agricultural production, the environment, and public health that need to be addressed (Levy et al., 2011; Ofori et al., 2021; Tal, 2016). The primary objective of this manuscript is to provide a roadmap for researchers, stakeholders, and policymakers to understand current and emerging challenges associated with agricultural TWW use, drawing upon the vast experience gained in Israel, Europe and the US. By contextualizing present-day research, policy and practical experience, this publication aims to inspire the expansion of agricultural TWW reuse. This work was the product of a four day international symposium (TreWAg 2022), supported by the United States-Israel Binational Agricultural Research and Development Fund, the European Union's Horizon 2020 PRIMA program, and the US EPA Water Reuse Action Plan (WRAP Action 1.6), which brought together a multidisciplinary group of scientists, stakeholders and policymakers.

The first two sections of this work highlight the potential detrimental agronomic and environmental impacts of TWW irrigation (Section 2), as well as potential public health risks arising from the transfer of chemical and microbial contaminants from TWW to irrigated produce (Section 3). Section 4 provides well established technological and management solutions that can help circumvent these hazards. Section 5 discusses policy, outreach, education, and regulatory actions that can promote beneficial reuse of TWW as well as recommendations for future research. By integrating these topics, this paper provides a holistic perspective, which is essential for the sustainable use of TWW, especially in view of the complex interactions among the multiple stakeholders along the TWW use and supply chain.

TWW quality is highly variable because of the different sources contributing to the wastewater (e.g., industrial sources vs municipal) and the types of treatments employed. Here, we focus on municipal TWW, because urban areas are the largest potential source of wastewater for agricultural irrigation (Jones et al., 2021). The majority of studies covered in this work come from Israel, Europe and the US, referring to irrigation with secondary and tertiary TWW. Throughout the manuscript, the term freshwater refers to irrigation water sources that are not primarily composed of wastewater (i.e. groundwater or surface water).

2. Agronomic and environmental challenges of TWW reuse

While the quality of TWW can vary significantly depending on the level of treatment, it is typically characterized by elevated levels of inorganic and organic constituents as compared to freshwater (Table 1), which if not managed adequately may lead to unintended environmental and agronomic outcomes, detailed below.

2.1. Salinization and phytotoxicity

Total dissolved solids (TDS) in municipal sewage are typically 250–850 mg L^{-1} (0.4–1.3 dS m^{-1}) higher than corresponding freshwater supplies (Muttamara, 1996), and may be higher in areas with elevated domestic water use-efficiency (Schwabe et al., 2020). These salts can pose a potential hazard to crops (Ayoub et al., 2016; Bernstein, 2013; Jahany and Rezapour, 2020; Lado et al., 2012) even when irrigation water contains moderate salinity levels (Aragüés et al., 2015). Furthermore, these salts can be transported to groundwater below irrigation sites (Kurtzman et al., 2021; Mohanavelu et al., 2021). In developing contexts, it should be noted that freshwater sources may already be saline (e.g., Da'as and Walraevens, 2010), therefore TWW reuse requires careful planning as it could either compound the problem or provide a less-saline irrigation water source.

When exposed to saline conditions, crops may experience both rapid (hours to days) osmotic stress, and slower (days to weeks) phytotoxic damage. Osmotic stress hinders plant water uptake, which harms seed germination and plant development, potentially resulting in yield loss and lower produce quality (Hopmans et al., 2021). The osmotic sensitivity of plants significantly differs between species (Hanin et al., 2016; Zörb et al., 2019), with sensitive crops (such as beans, turnips, carrots, and strawberries) exhibiting yield losses at EC values of irrigation water exceeding 1.0 dS m^{-1} (Maas, 1987).

Particular TWW-derived elements, can accumulate in soils and plants, eventually leading to phytotoxic damage (Ayoub et al., 2016; Bedbabis et al., 2015; Bernstein, 2019; Kalavrouziotis et al., 2008; Pedrero and Alarcón, 2009; Raveh and Ben-Gal, 2016; Ravindran et al., 2016). The primary elements of concern are Na and Cl, whose concentrations in treated effluents are typically 40 - 70 mg L^{-1}, and 20 - 50 mg L^{-1}, respectively higher in TWW than in local freshwater supplies (Feigin et al., 1991), but can be almost twice as high (Muttamara, 1996).

Other elements of concern include B, Cu, Zn, Cd, Pb, Ni, and Co. Phytotoxic damage occurs primarily in woody perennials, such as trees and vines (Maas et al., 1982). Typical symptoms include growth inhibition and necrosis, with frequent reduction in yield and produce quality (Grattan et al., 2015; Kisekka et al., 2023; Maas, 1987; Poustie et al., 2020; Xu et al., 1999). Mechanistically, phytotoxic elements either directly interfere with essential physiological processes or indirectly affect plant-nutrient homeostasis through mechanisms such as competition between Na and K uptake (Arif et al., 2020; Kronzucker et al., 2013). Although most phytotoxic damage is observed in plant leaves, there is evidence that accumulation of Na in trunk and root tissues can also have detrimental effects (Netzer et al., 2014; Yalin et al., 2017).

Soil conditions, including oxygen availability, pH, redox potential, and organic matter (OM) content can drastically affect the potential for phytotoxicity (Barbieri, 2016; Barrett-Lennard and Shabala, 2013; Rai et al., 2019). For instance, Yermiyahu et al. (2001) reported that compost amendments reduced availability and uptake of B in bell pepper, due to adsorption to soil OM. Another study reported that enhanced soil aeration decreased citrus root Na concentrations, presumably due to improved root resistance to Na induced by elevated oxygen availability (Paudel et al., 2019).

2.2. Deterioration of soil physical and hydraulic properties

The presence of typically elevated sodium adsorption ratio (SAR) coupled with distinct forms of dissolved organic matter (DOM) in TWW, can deteriorate soil structure. Clay swelling and dispersion are the main cause of damage (Levy and Nachshon, 2022), but pore clogging (Vinten et al., 1983) and water repellency (Leuther et al., 2018) have also been reported following irrigation with TWW. These effects lead to unfavorable soil physical and hydraulic properties (Assouline and Narkis, 2011), reducing water and oxygen availability to plants, and ultimately harming crop performance.

Degradation of soil structure is mainly driven by elevated SAR. However, the SAR threshold, above which degradation occurs, is also dictated by the soil ionic strength, texture, mineralogy, and DOM content (Assouline and Narkis, 2013; Lado and Ben-Hur, 2009). The effect of TWW-borne DOM on subsurface water flow has been estimated to be equivalent to an increase in SAR of two to three units (Assouline et al., 2016; Suarez and Gonzalez-Rubio, 2017). Pore clogging can result from suspended solids in TWW (Vinten et al., 1983), increased microbial growth due to the presence of labile organic carbon (Vandevivere et al., 1995), and accumulation of dispersed clay material (Shainberg and Letey, 1984). Alteration of the soil wetting properties and subsequent development of hydrophobicity has been associated with the coating of soil particles with TWW-derived DOM, which impedes hydraulic conductivity and can lead to preferential flow (Adabembe et al., 2022; Liu et al., 2019).

Despite decades of widespread TWW use in agriculture, only a few field studies have examined the long-term effects of irrigation with TWW on soil physical properties. These have revealed reduced soil infiltrability and aeration (Assouline and Narkis, 2013; Erel et al., 2019; Yalin et al., 2021), and non-uniform wetting of the soil at the field scale (Rahav et al., 2017). The capacity to remediate hydraulic properties of damaged soil at the field scale has only begun to be investigated (Assouline et al., 2020; Kramer et al., 2022; Ogunmokun and Wallach, 2021).

2.3. Nutrient availability

Municipal effluents typically contain significant concentrations of essential inorganic plant nutrients (Elgallal et al., 2016; Shtull-Trauring et al., 2020). Treatment regulations in many countries require removal of a large portion of N (nitrogen) and P (phosphorus) from the effluents (e.g., Inbar, 2007), to prevent these elements from reaching ground and surface waters, where they can have detrimental environmental and public health ramifications (Shoushtarian and Negahban-Azar, 2020). Conversely, if considered and managed according to crop requirements, the presence of these elements in TWW can reduce fertilizer application rates, reducing the costs and environmental impacts of fertilizer production. Recent research in Israel has shown that in most of the examined cases, TWW could provide at least 50 % of the required N, and all of the required P and K for low-demand crops such as citrus and avocado (Shtull-Trauring et al., 2022). The authors proposed that in watersheds with low eco-hydrological sensitivity, less stringent wastewater treatment processes can be promoted to supply more of the crop N requirements.

The phyto-availability of nutrients from TWW is generally equivalent to common mineral and organic fertilizers (Bar-Tal et al., 2010). However, supplying nutrients with TWW is challenging because TWW irrigation loads and scheduling regimes are principally dictated by crop water requirements rather than nutrient requirements. This may result in temporal imbalances between nutrient supply and plant requirements (Fig. 1), which can fluctuate between excess nutrient supply and deficiency (necessitating fertilizer supplementation).

2.4. Impact on soil microbial community structure and activity

The physiochemical changes in the soil environment (i.e., soil pH, salinity, humidity, and carbon- and nutrient- availability) and introduction of exogenous microbiota, may alter the soil microbiome (Becerra-Castro et al., 2015; Dang et al., 2019; Zolti et al., 2019). This facilitates complex interactions that affect soil microbial activity, diversity, and biomass, which can be crudely divided into positive

Table 1

Characteristics of treated municipal wastewater (TWW) used for irrigation in Israel. Range and median values of TWW quality includes reported data from 56 wastewater treatment plants (WWTP), and the Dan region, "Shafdan" WWTP. Data is for the years 2017–2018 and includes only WWTP producing more than 10^6 m^3 effluent yr^{-1} (overall with the Shafdan covering 97 % of the TWW produced in those years in Israel). "Range" describes the 2.5 - 97.5 percentiles. Data retrieved from Cohen et al. (2020).

Parameter		Supply volume	BOD_5*	pH	N**	P	K	Na	Ca	Mg	Cl	SAR***	EC****
Units		10^6 x m^3 yr^{-1}	mg L^{-1}		mg L^{-1}							meq $L^{-0.5}$	dS m^{-1}
WWTP excluding Shafdan	Range	1.2 – 31.4	1 – 78	6.1 – 8.0	2 - 79	1 - 17	10 - 83	70 - 200	37 - 103	5 - 58	111 - 364	1.9 - 5.4	0.6 - 1.6
	Median (n)	3.1 (56)	8 (56)	7.5 (30)	19 (45)	4 (52)	32 (41)	112 (55)	62 (56)	16 (56)	168 (55)	3.5 (55)	0.9 (56)
Shafdan WWTP	–	145	5	7.4	6	1	22	146	58	20	205	4.2	1.1

* - Biological oxygen demand after 5 days incubation at 20 °C.
** - Kjeldahl total nitrogen.
*** - Sodium adsorption ratio.
**** - Calculated from the sum of major cations according to: EC [dS m^{-1}] x 10 = sum of cations [meq L^{-1}].

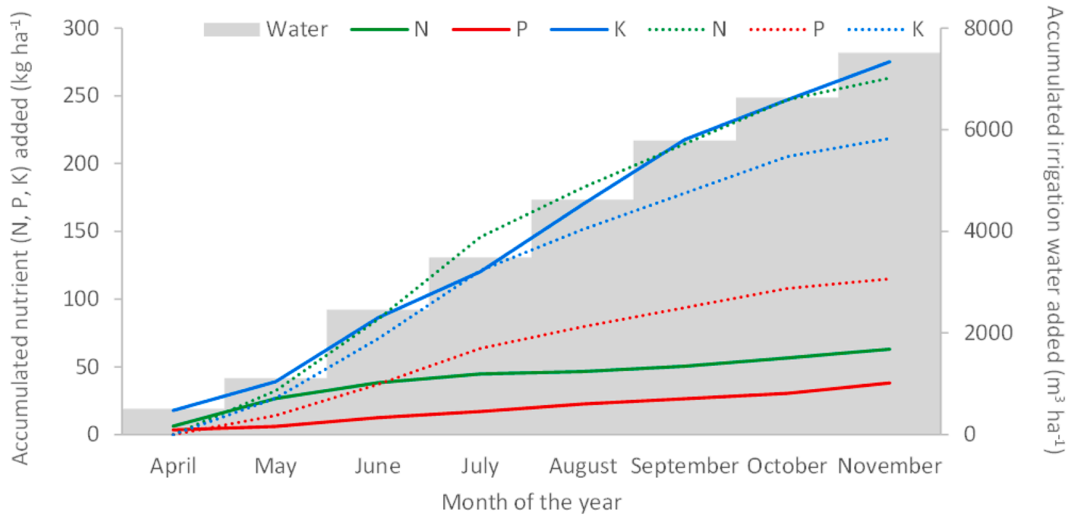

Fig. 1. Cumulative amount of nutrients and water in a TWW-irrigated orchard, showing irrigation water volume (grey bars). Actual nutrients supplied with TWW (solid line), as compared to the agronomic recommended nutrient requirements (broken lines). Study site: Avocado orchard in Acre, Israel. Data from the 2013 irrigation season (courtesy of Anat Lowengart-Aycicegi).

(Bastida et al., 2017; Garcia and Hernandez, 1996); neutral (Frenk et al., 2014; Ibekwe et al., 2018; Li et al., 2019), and mixed (Cui et al., 2018; García-Orenes et al., 2015; Guo et al., 2017) effects. Unraveling these complex interactions has begun recently through studies examining changes in specific microbial groups.

Collectively, research has indicated that irrigating with TWW: (a) increases bacterial diversity and reduces fungal diversity in soil (Dang et al., 2019); (b) lowers the relative abundance of *Actinomycetota* (formerly *Actinobacteria*) and increases the relative abundance of *Gammaproteobacteria* and *Bacteroidota* (formerly *Bacteroidetes*) in root bacterial communities (Frenk et al., 2014; Wafula et al., 2015; Zolti et al., 2019); (c) increases relative abundance of *Gemmatimonadota (*formely *Gemmatimonadetes), Bacteroidota* (formerly *Bacteroidetes)*, and *Pseudomonadota* (formerly *Proteobacteria*) (Guo et al., 2018; Obayomi et al., 2020); (d) facilitates shifts in the composition of ammonia-oxidizing bacteria, with *Nitrosomonas* detected in TWW-irrigated soils, but not in freshwater-irrigated soils (Frenk et al., 2014; Oved et al., 2001); and (e) increases *Cyanobacteriota* (formerly *Cyanobacteria*) abundance (Liu et al., 2018). These changes potentially have weighty implications on the ecology of microbial communities, for example, due to cyanobacteria's ability to fix atmospheric nitrogen (Martins et al., 2011). Notably, some studies suggest that observed shifts in TWW-irrigated microbial communities are transient, with soil bacterial populations of TWW-irrigated soils indistinguishable from those under freshwater irrigation within one growing season following the rainy season when irrigation is not applied (Frenk et al., 2014). The revelation that TWW irrigation significantly stimulated root-associated bacterial genes associated with salinity, pH, and oxygen stress, suggests that the root-associated microbiome can serve as a "barometer" for plant stress (Zolti et al., 2019). If further developed, the microbiome analysis could be utilized as a proxy in future research on TWW.

3. Chemical and microbial hazards

TWW may contain potentially harmful pathogens, chemical contaminants, and related issues of concern (e.g., antimicrobial resistance genes), with concentrations dependent on numerous factors, including upstream industrial waste discharges and treatment types employed by individual wastewater treatment plants. These contaminants can accumulate in soils and edible crops, and be transferred to groundwater and surface water following irrigation (Christou et al., 2017; Fatta-Kassinos et al., 2011a). However, there is limited data regarding their presence, concentrations, plant uptake, and viability (microbes) in both the soil and crops irrigated with TWW, which is essential for risk assessment and recommended mitigation measures. Research is ongoing to assess risks of these contaminants.

3.1. *Contaminants of emerging concern*

Contaminants of emerging concern (CECs) are a constantly evolving category of anthropogenically derived constituents that includes amongst others, a diverse range of pharmaceutical compounds, personal care products, flame-retardants, microplastics (MP), and disinfectants (Sauvé and Desrosiers, 2014).

Many studies have evaluated pharmaceuticals in TWW (Alygizakis et al., 2020; Beretsou et al., 2022; Moslah et al., 2018; Panthi et al., 2019; Rapp-Wright et al., 2023; Rordriguez-Mozaz et al., 2020;); including those noting that TWW has higher prevalence and concentration of antimicrobials than other irrigation water sources (Panthi et al., 2019). The uptake of pharmaceuticals and other CECs by plants results from passive diffusion through the cell membrane. The magnitude of this process, and the distribution of accumulated pharmaceuticals within the plant depends on the soil properties and root lipid content (Ben Mordechay et al., 2022a; Filipović et al., 2020), the lipophilicity and charge of the molecule (Briggs et al., 1982; Trapp, 2000), the transpiration rate and in-plant metabolism (Malchi et al., 2022; Miller et al., 2015). When considering irrigation with TWW, it is vital to identify and target the most recalcitrant CECs that can potentially persist in soil and accumulate in crops. Frequently, accumulation occurs in roots and leaves, which are the edible portion of many crops (Ben Mordechay et. al. 2022b; Garcia et. al. 2018).

Highly recalcitrant CECs of interest in TWW include carbamazepine (anticonvulsant), diclofenac (non-steroidal anti-inflammatory drug) (Fatta-Kassinos et al., 2011b; Zhang et al., 2008), poly-and perfluoroalkyl substances (PFAS; Lenka et al., 2021), and microplastics (MPs) (Hu et al., 2022). In Israel, carbamazepine has been found more frequently and in higher concentrations in the urine of consumers of produce irrigated with secondary TWW, relative to consumers of freshwater-irrigated produce (Paltiel et al., 2016; Schapira et al., 2020). Ben Mordechay et al. (2022b) estimated that in extreme cases, human exposure to carbamazepine and epoxide-carbamazepine via consumption of TWW irrigated produce in Israel may exceed the acceptable daily intake (ADI) for adults. MPs have been shown to accumulate in some edible plants, such as lettuce, wheat, rice, and carrots (Jiang et al., 2019;

Naziri et al., 2023). However, the effects of consuming MP-containing produce on human health are currently unknown and require further research (De-la-Torre, 2020; Smith et al., 2018) utilizing standardized methods to comprehensively understand the effect of plastic waste (Campanale et al., 2020). PFAS includes thousands of highly persistent, bio-accumulative, and potentially toxic substances (Cousins et al., 2020). PFAS concentrations in TWW vary by location, and data on their levels in irrigated soils and crops are limited and conflicting (Mroczko et al., 2022; Shigei et al., 2020; Table 2), highlighting the need for further research and comprehensive evaluation on local scales.

3.2. Pathogens in TWW

Contamination of produce by pathogens in the TWW is a public health concern (Gurtler and Gibson, 2022); however, data are inconsistent. Predominantly, public health regulations rely on the enumeration of standardized indicator microbes such as fecal coliforms, thermotolerant coliforms, or *Escherichia coli* (Blumenthal et al., 2000). However, numerous studies have established that *E. coli* levels are not consistently associated with the presence of other pathogen groups (Weller et al., 2020), particularly enteric parasites and viruses. Furthermore, pathogen levels are highly dependent on the level of wastewater treatment and the pathogen concentrations in the influent (Table 2). Thus, additional surveillance targets are required to establish health risks (Ofori et al., 2021).

Table 2
A selection of literature regarding the presence, concentration, and/or persistence of chemical contaminants of emerging concern (CECs) and pathogenic contaminants in treated municipal wastewater (TWW) intended for irrigation.

Contaminant	Country	Did the contaminant persist in soil/crops after irrigation OR were levels higher in TWW than other sources?	Reference
Chemical contaminants			
PFAS *	USA	Yes - Persistence after irrigation	Mroczko et al., 2022
PFAS	Jordan	No - No persistence	Shigei et al., 2020
Carbamazepine, other epilepsy drugs	Israel	Yes - Persistence after irrigation	Ben Mordechay et al., 2022a; Paltiel et al., 2016; Schapira et al., 2020
Antimicrobials	USA	Yes - TWW higher than other irrigation sources, with exception of ciprofloxacin	Panthi et al., 2019
Antimicrobials	Germany	Yes - Persistence after irrigation	Kampouris et al., 2022
Bacterial and viral contaminants			
Enteric viruses	Spain	Yes - TWW higher than other irrigation sources	López-Gálvez et al., 2016
E. coli	Palestine	TWW not consistently different than other irrigation water sources	Craddock et al., 2020
Vibrio spp.	USA	TWW not consistently higher than other irrigation water sources	Malayil et al., 2021
Salmonella enterica and *Listeria monocytogenes*	USA	No - Surface water had higher levels than TWW	Acheamfour et al., 2021
ARGs **	USA	Yes - TWW higher than other irrigation sources	Malayil et al., 2022
Resistant *Enterococcus*	USA	No - TWW had no impact on ARB in sludge	McLain and Williams, 2014
ARGs	Israel	No - TWW had no impact on food surface	Seyoum et al., 2022
ARBs *** /ARGs	Israel	Mixed effects, dependent on soil factors, enrichment capability	Marano et al., 2021, 2019

* - poly-and perfluoroalkyl substances.
** - Antimicrobial Resistance Genes.
*** - Antibiotic Resistant Bacteria.

3.3. Antimicrobial resistance

Antimicrobial resistance (AMR) poses a specific challenge when relating to microbial contamination. For routine monitoring of effluents and receiving environments, it is crucial to select antibiotic resistant gene (ARG) markers that are clinically relevant, common in TWW, occur in association with mobile genetic elements, are persistent in receiving environments, and for which testing equipment is market available (Manaia, 2023). Recent reviews have proposed ARG and antibiotic resistant bacterial (ARB) indicators that can be targeted for monitoring and regulation (Liguori et al., 2022; Manaia, 2023); however, benchmark levels for these indicators have not yet been established. The recent proposal for a directive of the European Union (EU) Parliament and Council concerning urban wastewater treatment (COM/2022/541 final) dictates that by 2025 large WWTPs need to periodically monitor AMR indicators. It is therefore conceivable that future criteria for irrigation with TWW could require monitoring for target levels of specific AMR indicators in the EU and beyond. However, there are currently no standardized methods or regulatory guidelines for AMR in TWW or irrigated produce.

3.4. Risk assessment

Risk assessment is applied to quantify human health risks for both hazardous chemicals and pathogens in situations where effect sizes are small and logistically challenging to measure using epidemiological studies (Ofori et al., 2021). It utilizes a range of assessments, modeling, and statistical analyses to make inferences regarding risk (Haas et al., 2014; WHO, 2016; National Research Council (US) Committee on the Institutional Means for Assessment of Risks to Public Health, 1983).

Chemical risk assessment can potentially rely on sentinel chemicals (Revitt et al., 2021). However, CEC persistence, as well as accumulation in edible portions, is highly variable, requiring routine monitoring (Ben Mordechay et al., 2022B; Delli Compagni et al., 2020; Shi et al., 2022). Some notable challenges in chemical risk assessments are the breadth of chemicals (studies often range from dozens to hundreds of chemical targets), plant-specific risks, the occurrence of metabolites (which can potentially be more hazardous than parent materials), the impact of mixtures, and the impact of long-term sub-clinical exposure (Egli et al., 2021; Goldstein et al., 2018; Malchi et al., 2014; Paz et al., 2016).

Quantitative microbial risk assessment (QMRA) of TWW has typically focused on risk-based monitoring targets, specific risk benchmarks that have been defined through multiple research studies (e.g., 36 gastrointestinal illnesses per 1000 recreators for swimming), and ranking risks and associated tradeoffs (Foster et al., 2021; Hamilton et al., 2019; Hultquist, 2016; NRMMC et al., 2006; Petterson et al., 2021; SWRCB, 2016; USEPA, 2012; WHO, 2013; Zhang et al., 2019). Numerous QMRA models have focused on TWW for irrigation, often using lettuce as an index crop due to its uptake and raw consumption practices (Beaudequin et al., 2016; Amha et al., 2015; Kouamé et al., 2017; Silverman et al., 2013; Hamadieh et al., 2021; Mara et al., 2007). While historically QMRA has focused on fecal-associated pathogens, monitoring approaches are expanding to incorporate opportunistic respiratory pathogens (i.e., *Legionella pneumophila*), ARBs, and ARGs (Schoen et al., 2021; Hamilton et al., 2018). However, this expansion is limited by a relative lack of research providing direct comparisons of TWW with freshwater and other irrigation water sources. Holistic QMRA that includes CECs is critical for decision-making for TWW reuse, as it can inform regulations and guidance (Rock et al., 2019), the utility of "barrier criteria" interventions (Ofori et al., 2021), or inform which crops are irrigated with TWW. Looking forward, expansion of the QMRA paradigm to integrate findings more holistically with chemical risk assessments and to expand pathogens of focus will be beneficial for informing decision-making around TWW use for irrigation purposes.

4. Technological and management solutions for safe and sustainable irrigation with treated wastewater

Sections 2 and 3 underline the need to eliminate organic and inorganic constituents, and specifically recalcitrant chemical and microbial pollutants when considering the reuse of municipal wastewater for irrigation. Designing processes and policies to improve water quality for irrigation can be complicated by local regulatory disparities, differences in exposure pathways between crops (e.g., use as animal feed, peeling or cooking before eating), and public acceptance. Furthermore, concerns about emerging (i.e., CECs and ARGs) and yet-to-be-discovered contaminants of health concern necessitate flexible technological and regulatory solutions.

4.1. Source control

Two strategies can be employed by stakeholders and policymakers to reduce the transfer of undesired constituents from TWW to soil and crops: (1) regulatory policies that restrict the use of specific materials, or (2) implementation of more stringent treatment processes when industrial or high-risk (e.g., hospital) effluents are released to the sewer shed (Harris-Lovett and Sedlak, 2020).

4.1.1. Policy-based source control

Most, but not all, CECs enter municipal wastewater facilities through consumer use. The majority of these compounds degrade during secondary and advanced wastewater treatment, but as described in Section 3, certain CECs are highly recalcitrant and can potentially accumulate in TWW-irrigated produce. Stewardship programs aimed at reducing the use and disposal of these CECs are impetrative (Daughton, 2003), especially in cases where alternatives that do not pose risks to the food supply are available. Additionally, biodegradability and cytotoxicity should be considered during the registration and introduction of new products (Kümmerer et al., 2018). For example, the risk of boron phytotoxicity (see Section 2.1) can be evaded by replacing boron based detergents with appropriate substitutes (Tal, 2006). Likewise, policies that discourage the use of Na-based ion exchange water softening devices can lower salinity in TWW.

4.1.2. Industrial/commercial source control

Water reuse schemes that implement risk-averse strategies to monitor contaminants may target specific compounds relevant to agricultural wastewater reuse. Because the illegal discharge of pollutants is unpredictable, "real-time" monitoring approaches that apply remote sensing or on-line monitoring of indicator parameters such as electrical conductivity (EC), pH, redox potential, organic matter (OM), temperature, and turbidity, enable the detection of anomalies caused by key pollutants such as salts, acids, and selected nutrients. In contrast, analysis for hazardous pollutants such as heavy metals, persistent organic compounds, and pharmaceutical contaminants currently require analytical laboratories (Bertanza et al., 2022). Integrating continuous data acquisition platforms from sewage collection systems with accurate and reliable data management and predictive analytics can ensure high-quality TWW for irrigation, significantly reducing post-treatment costs. These networks can be enhanced with application of novel online-monitoring technologies, including sensors that detect and quantify hazardous metals, CECs, bacterial pathogens, and ARGs (Manny, 2023). Fluorescence spectroscopy is one technology currently used to detect OM in different water sources (Yu et al., al.,2015; Carstea et al., 2019), or organic contaminants in irrigation water (Sinitsa et al., al.,2022). Such spectroscopic methods are increasingly supported by machine learning tools to enhance on-line monitoring platforms for detection of various organic contaminants (Khamis et al., 2015, Hansen et al., 2020, Sinitsa et al., at.,2023).

4.2. Engineered treatment processes

Two primary non-potable wastewater reuse models exist: centralized systems that transport treated effluents from municipal wastewater treatment plants to agricultural hubs for irrigation, and decentralized systems, where effluents are treated and applied locally for irrigation (Angelakis and Snyder, 2015). Decentralized systems substantially reduce storage and transport infrastructure costs and are considered more environmentally sustainable, but operating and monitoring these systems to meet regulatory criteria can be logistically challenging. Implementation of advanced treatment and specific technologies, beyond traditional secondary treatment, strongly depends on the local infrastructure, regulatory requirements, irrigation method, available resources, the TWW quality and the type of crops (i.e., edible/non-edible). We summarize the capabilities and limitations of such technologies in Table 3.

Disinfection processes are frequently applied following secondary wastewater treatment to remove microbial pathogens (viruses, bacteria, and protozoa). Chlorination, the most prevalent disinfection process, involves adding chlorine gas or hypochlorite to TWW, and normally results in the formation of combined chlorine in the water. However, chlorination can produce disinfection by-products (DBPs) such as trihalomethanes that are potentially carcinogenic (Mezzanotte et al.,

Table 3
Capacity of technologies for removing salts, pathogens and contaminants of emerging concern (CECs) from secondary wastewater effluents intended for irrigation.

Treatment type	Removal capacity			Comments
	Salinity	Pathogens	CECs	
Nanofiltration [1]	+	+++++	+++	[1] Requires solutions for treating brine; [2] Energetically expensive; [3] Needs draw solution & correlation between irrigation volume and fertilization quantity
Reverse osmosis [1, 2]	+++++	+++++	+++++	
Forward osmosis [1, 3]	+++++	+++++	+++++	
Chlorination	No	++++	No	Relatively cheap; potentially creates toxic byproducts
Peracetic Acid	No	+++	No	No disinfection products; more expensive/less available than chlorine
UV-C radiation	No	++++	No	No byproducts; relatively easily implemented; requires pre-treatment
Ozonation	No	+++++	+++++	Can be expensive to implement and operate; potentially forms toxic byproducts and therefore requires post-treatment
Homogeneous solar-based	No	++++	++++	Technology not fully mature; more suitable for small-scale systems
UV-C/H_2O_2	No	+++++	+++	Energetically expensive
Activated carbon (AC)	No	No	+++	
Effluent stabilization reservoirs	No	+++	No	Very low operational costs; enables better effluent management

2007). If supported by risk assessment outcomes, DBPs might be restricted according to the EU regulation (EU, 2020), and therefore chlorination is increasingly replaced by alternative disinfection processes such as UV-C radiation and Peracetic Acid (PAA, Rizzo, 2022). While slightly less effective than chlorination, PAA does not generate DBPs when low doses are used (<5–10 mg L^{-1}). It therefore may be advantageous in decentralized systems (Freitas et al., 2021; Mezzanotte et al., 2007), as previously shown (Bell and Wylie, 2016; Di Cesare et al., 2016; Formisano et al., 2016; Manoli et al., 2019; Santoro et al., 2007; Stewart et al., 2018). UV-C radiation has been shown to be more efficient in removal of viruses, protozoa, and bacterial pathogens than chlorination, ozonation and PAA treatment (Mezzanotte et al., 2007), producing effluents suitable for unrestricted irrigation of food crops (Nasser et al., 2006). Since turbidity and suspended solids drastically reduce inactivation efficiency, conventional activated sludge effluents used for irrigation typically require pre-treatment using sand filtration to enable effective UV disinfection (Ghernaout and Elboughdiri, 2020). Additionally, UV disinfection can be energy intensive (Bailey et al., 2020). Ozonation has been widely applied for TWW disinfection and, more recently, for quaternary treatment because unlike other disinfection processes (e.g., chlorination) it also effectively degrades CECs (von Gunten, 2018; Rizzo et al., 2020). Moreover, ozonation is efficient against a broad array of pathogens including chlorine-resistant *Cryptosporidium parvum* oocysts and *Giardia* cysts (Morrison et al., 2022; Rizzo et al., 2020). A pitfall of ozonation is the potential formation of toxic DBPs such as bromate and NDMA (Lim et al., 2016), which can accumulate in irrigated crops (Calderón-Preciado et al., 2011). These can be removed by post-treatments such as biofiltration and activated carbon (Rizzo et al., 2020). Specific ozone doses in the range of 0.4–0.6 g O_3 g_{DOC}^{-1} (DOC, dissolved organic carbon) can ensure high-quality TWW for irrigation (Rizzo et al., 2020).

Activated carbon (AC) adsorbs a broad spectrum of organics due to its large surface area and high degree of surface interactions. Consequently, powdered and granular activated carbon (PAC and GAC, respectively) are applied to remove recalcitrant CECs in WWTP effluents (Mestre et al., 2022). PAC is generally more efficient than GAC, because its smaller size enables dosing it (10–20 mg L^{-1}) into biological treatment processes (Gutiérrez et al., 2021). However, post-treatment is required for separation of residual PAC (Kosek et al., 2020). The low cost and wide availability of materials required for AC treatment (e.g., Steigerwald and Ray, 2021) mark it as a possible solution for low-resource environments.

Photo Homogeneous Advanced Oxidation Processes (AOPs, e.g., UVC/H_2O_2, photo-Fenton) are increasingly investigated for the simultaneous removal of CECs and microbial contaminants in TWW (Rizzo, 2022). UVC/H_2O_2 is a consolidated technology with a cost dependent on the UV lamp intensity and replacement frequency, but the recent development of UV-LED lamps shows promise (Soro et al., 2023). The application of this technology is especially of interest as a tail-end technology for TWW (applying 5–10 mg H_2O_2 L^{-1}). Photo-Fenton is a promising process in view of its technological readiness (Rodriguez-Mozaz et al., 2020), especially when applied at neutral pH thanks to the use of iron complexing agents for maintaining iron in solution, as well as the possibility of being powered by solar irradiation (Zhan and Zhou, 2019). Amortization costs of photoreactors can be high, but these can be significantly reduced when using raceway pond open solar photoreactors that are simple to manufacture (Malato et al., 2020).

Membrane processes that remove organic contaminants, pathogens and salts are increasingly applied in different wastewater treatment scenarios (Ezugbe and Rathilal, 2020). Nanofiltration (NF; membrane pore size of 0.01–0.001 μm) removes organics, a selection of inorganic ions, and most pathogens. In contrast, under optimal transmembrane pressure, reverse osmosis (RO, pore size of 0.001–0.0001 μm) removes almost all constituents except water molecules (Naimah et al., 2021). Currently, the high-energy consumption and the susceptibility of membranes to fouling make RO unsuitable for treatment of irrigation water. An obstacle for the use of membrane technologies is the need to find a solution for the concentrate or brine produced (Capocelli et al., 2019), which can be a significant issue in inland systems. Additionally, membrane processes are more energy intensive than conventional wastewater treatment (Bailey et al., 2020).

Effluent storage reservoirs (alternatively known as stabilization reservoirs) modulate between relatively constant sewage production and generally irregular (seasonal) irrigation water demand. They are unique relative to sewage stabilization ponds in their non-steady-state hydraulic regimes, and higher depth (up to 20 m) and volume (Juanicó and Dor, 2011). Retention times of at least three months, coupled with disinfection, ensures water quality that meets Israeli microbial standards for unlimited TWW reuse (Inbar, 2007) and decreases certain metals and recalcitrant organic compounds (Juanicó and Dor, 2011; Marano et al., 2019; Friedler et al., 2003; Kfir et al., 2012). Dual reservoir configurations (where one basin is constantly being filled and the other emptied) enable balancing between influent and effluent flows while maintaining the required retention times. The capacity of stabilization reservoirs is attributed to their robust biota, which along with abiotic processes facilitates "ecosystem functioning" (Shuval and Fattal, 1999). However, these microorganisms (especially photosynthetic microorganisms) produce extra-polymeric substances that can clog distribution and irrigation pipes (Katz et al., 2014).

4.3. Agronomic management mitigation and remediation strategies

Preventing the buildup of salinity in the root-zone soil can be achieved by leaching practices (Ben-Gal et al., 2008; Minhas et al., 2020), which need to consider crop sensitivity to salt, soil properties, chemical composition and salinity of irrigation water, climate, and evapotranspiration (Dudley et al., 2008; Letey et al., 2011; Shani et al., 2007). Decision support systems (e.g., https://app.agri.gov.il/AnswerApp/) can aid in developing irrigation-leaching strategies, crop selection, and evaluating the sensitivity of various parameters that affect the water-soil-crop system (Kaner et al., 2019). To divert salts and nitrates leached from the root-zone from reaching groundwater, drainage solutions such as tile drains and capillary barriers may be employed (Russo, 2017; Singh, 2019).

Various agro-technical measures have been suggested to mitigate and remediate TWW-induced damage to soil hydraulic properties, including: alternating between TWW and fresh-water, diluting TWW with freshwater (Assouline et al., 2020; Nemera et al., 2020), applying gypsum (Ghafoor et al., 2012; Mamedov et al., 2009), and using surfactants (Ogunmokun and Wallach, 2021). However, these treatments have not yet been tested on a commercial scale and there is uncertainty as to whether full remediation is possible (Kramer et al., 2022).

Optimizing plant nutrient utilization, while reducing the risk of groundwater contamination from TWW-borne nitrogen and phosphorus, can be achieved by defining site-specific treatment regulations (Shtull-Trauring et al., 2022) that allow for more lenient removal levels in basins with low eco-hydrological risk. As a result, TWW nutrient use efficiency can be optimized through continuous monitoring systems that inform farmers of real-time nutrient conditions, allowing them to supplement TWW with fertilizers only when needed (Erel et al., 2019; Vazquez-Montiel et al., 1996; Vivaldi et al., 2022).

5. Looking to the future

5.1. From policy to practice

Recurring drought in Israel during the 1980s facilitated administration of major freshwater restrictions for agriculture. This was a major driver for farmers to transition to TWW, which was unrestricted and relatively cheap (Marin et al., 2017). The wide adoption of TWW irrigation in Israel is further attributed to comprehensive research, coupled to feedback networks between farmers, scientists, regulators, and centralized water suppliers that translate insights into practice and policy. These feedback networks need to be dynamic to adapt to emerging challenges and changing conditions. For example, Israeli regions supplied with relatively saline TWW generally refrain from growing crops sensitive to salinity stress, especially in clay soils where oxygen limitation makes plants more prone to salt damage.

Expanding agricultural water shortages in the US, especially in regions supplied by the Colorado River, present the need for wider integration of TWW in agriculture. U.S. farmers have expressed interest in supplementing traditional irrigation water (typically freshwater) sources with TWW for on-farm water applications (Dery et al., 2019). However, only two percent of farms report using TWW, representing an opportunity to expand TWW for agricultural purposes (USDA NASS, 2019; Sheikh, B. 2019). The twenty-eight U.S. states that have regulations for the reuse of TWW in agriculture (food crops) generally have stricter treatment requirements than those required by Israel (US EPA REUSExplorer, 2023; US Food and Drug Administration, 2023), however these regulations generally do not address agronomic, environmental and emerging public health parameters discussed in this review.

Within the EU, about one billion cubic meters of TWW are reused annually for irrigation and there is an estimated potential to expand reuse by six times (European Comission, 2023). In 2020, the EU adopted Regulation (EU) 2020/741 on minimum requirements for water reuse, implemented in June 2023, which harmonized minimum water quality, monitoring, and permitting requirements for the reuse of TWW in agricultural irrigation within all EU Member States (EU, 2020). Prior to this, TWW was reused for agricultural irrigation in several EU Member States (e.g., Cyprus, Italy and Spain), following different water quality criteria set in national legislations that complied with Regulation (EC) 852/2004 on hygiene of foodstuffs (EU, 2004). The new regulation stipulates a water reuse risk management plan to ensure protection of human and animal health and the environment (EU, 2020). In the future, minimum water quality and monitoring requirements may be expanded to include DBPs, CECs, MPs and AMR, depending on the outcome of site-specific risk assessment related to the use of TWW (EU, 2020). Technical guidance on developing risk management plans for wastewater reuse, including methodologies for evaluating environmental and emerging public health parameters, was recently published to support the implementation of the regulation (Maffettone and Gawlik, 2022). The guidance's approach on risk management has been developed on globally established recommendations and criteria (ISO, 2018; ISO, 2020; NRMMC-EPHC-AHMC, 2006; WHO, 2015). Although the EU uses a wider risk management framework for water reuse in agriculture, landscape irrigation and other application, it does not possess an analogue setting on general requirements regarding irrigation water quality. This constitutes a significant obstacle to promote a systematic direct reuse approach.

5.2. Outreach and education

Though it is clear that the utilization of TWW for crop irrigation is growing worldwide, the potential for opposition remains. This is not necessarily due to issues with technology; instead, the principal barriers can be farmer hesitancy, which can stem from concerns with safety and quality (Dare and Mohtar, 2018; Dery et al., 2019; Ghanem et al., 2010), concerns regarding lack of public acceptance and perception that crops could be considered unsafe or inferior in quality (Craddock et al., 2021), or concerns regarding cost of implementation (Deh-Haghi et al., 2020).

Farmers' individual characteristics such as production types, motivations and trust levels impact their behaviors, and therefore different strategies and policy interventions for promoting TWW irrigation may appeal to different farmer types (Upadhaya et al., 2021). While optimal outreach strategies for farmers must account for this considerable diversity, information and dedicated workshops addressing environmental and public health concerns are generally key to farmer outreach (Gerdes et al., 2020; Suri et al., 2019). Participatory research frameworks involving extensive bi-directional communication between researchers and farmers are another important tool, which can uncover regionally-specific quality issues, challenges with TWW use, and farmer concerns and knowledge gaps (Konradsen et al., 2009). Establishing and developing trust from the source of information as well as the data is critical to adoption. Recent studies have reflected the importance of presenting the consumers of recycled water with more information rather than less, stating that detailed and credible information is capable of changing perceptions (Tennyson et al., 2015) and informed, accepting consumers allay the fears and concerns of many farmers globally (Dare and Mohtar, 2018; Gerdes et al., 2020). In the EU, Member States are required to develop information and awareness-raising campaigns (EU, 2020), to encourage TWW reuse and ensure that stakeholders and the public are aware of the benefits of such practices. Surprisingly, studies in Israel have found low levels of support and awareness regarding TWW-irrigated agriculture, despite this practice being in regular use for decades (Craddock et al., 2021; Friedler et al., 2006). Overall, when designing consumer and farmer outreach, an understanding of what a community knows and thinks about TWW and which factors are influencing acceptance is critical for its success and utilization (Hartley, 2006; Miller and Buys, 2008; Morgan and Grant-Smith, 2015; Rozin et al., 2015).

5.3. Knowledge gaps

Approximately 50 % of globally produced wastewater is untreated (Jones et al., 2021), and there is an urgent need for development and implementation of cheap, simple, and attainable collection and treatment solutions (e.g., Brix et al., 2007) to increase safe water availability for irrigation in diverse circumstance (i.e., decentralized agriculture, low capacity regions). In developed regions, despite cumulative scientific understanding there are still several knowledge gaps that need to be addressed to ensure long-term sustainability of TWW-irrigation. Agronomic research should transition from studying the impact of specific TWW constituents to investigating the complex interactions between different constituents (such as the effects of joint effect of DOM and SAR on hydraulic properties), and focus more on developing mitigation and remediation approaches for agriculturally-sustainable TWW irrigation (Assouline et al., 2020; Kramer et al., 2022; Nemera et al., 2020; Ogunmokun and Wallach, 2021). Furthermore, it is essential to establish long-term research and monitoring programs because detrimental agronomic and environmental effects often manifest after several years of consecutive TWW irrigation (Assouline et al., 2015; Tal, 2016). The influence of TWW on public health is still not consolidated, with many gaps in knowledge, including the fate of CECs and ARGs along the soil-plant-consumer continuum, and their possible effects on public health. To assess and understand public health risks, standardized methods of detecting and quantifying monitoring targets (i.e. ARGs, CECs) in water, soil, and crops need to be agreed upon within the scientific community.

There is a great need to address the current challenges of TWW irrigation on a global level, and subsequently, we propose to establish a harmonized data sharing system that will promote integration of findings from global research on known and emerging contaminants. This data management platform can be accompanied by more accurate risk assessment models to estimate short- and long-term public health, environmental and agronomic effects, as well as synergistic impacts, which can be translated into regulatory criteria. Another topic of priority is the development of real-time monitoring systems in effluents used for irrigation that can provide stakeholders with on-line notification of risk factors (i.e. pathogens), and potentially be combined with treatment systems to improve water quality (i.e. dilution to reduce salinity below critical levels). Finally, it is important to consistently and broadly evaluate indirect environmental impacts, such as greenhouse gas (GHG) emissions from WWTP and TWW irrigation (Gómez-Llanos et al., 2020), as well as the indirect leaching of contaminants from

TWW-irrigated lands into natural habitats such as estuaries (e.g., Topaz et al., 2020). By addressing these research areas in a unified manner, we can enhance our understanding of TWW irrigation and facilitate the development of effective strategies and policies for its sustainable use.

5.4. Key messages

- As freshwater availability for agriculture decreases globally, TWW has emerged as a significant and reliable source of irrigation water, particularly when water stressed agricultural areas are adjacent to urban areas producing an abundant and consistent TWW supply.
- While numerous organic and inorganic constituents in wastewater are degraded or excluded during treatment, some remain in the TWW used for irrigation. Such materials may deleteriously affect soil health and plant productivity and pose a hazard to human health, if not addressed appropriately by further treatment or agronomic solutions.
- TWW salinity should be monitored and reported due to its effect on soil health and structure as well as phytotoxic effect on growth.
- Irrigation with TWW contributes nutrients that can reduce fertilizer requirements; however, nutrient concentrations are not controlled by farmers and may not be adequate for plant needs.
- Public health risk assessment can be especially challenging for CECs. Standardized methods, broader monitoring of CECs, and expanding QMRA methodologies to include CECs (especially ARGs) can help to improve our understanding of the relative risk of these contaminants.
- Decentralized wastewater treatment systems can provide water locally or onsite for irrigation. Still, the choice of these systems and specific tertiary configurations (i.e., selection of disinfection platforms) depend on local requirements and regulations and the cost of implementation.
- New monitoring technologies, including on-line sensors that detect and quantify hazardous metals, CECs, bacterial pathogens, and ARGs show great promise and can also optimize TWW nutrient use efficiency by informing farmers of real-time nutrient conditions, allowing them to supplement TWW with fertilizers only when needed.
- Research, education and feedback networks need to be dynamic and holistic to adapt to emerging challenges and changing conditions and to allow the translation of research into practice, and of practice into policy.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Hila Korach-Rechtman reports a relationship with Kando Environmental Services LTD that includes: employment.

Data Availability

Data will be made available on request

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