Irrigating With Treated Wastewater

Ghida Krisht, Rania Bou Said, Lena Aboujaoude, Tia Hajjar, Farah Kamaleddine, Abdul Rahman Soufi, and Isam Bashour, American University of Beirut, Lebanon
Sandra F Yanni, Agriculture and Agri-Food Canada, Canada
Rabi Mohtar, Texas A&M University, United States and American University of Beirut, Lebanon
Anne Dare, Purdue University (former), United States

 doi:10.1016/B978-0-323-90386-8.00091-7

Abstract

Water scarcity is increasing due to (1) increased water demand resulting from population growth and the global increase in freshwater demand for agriculture, and (2) decreased water availability resulting from climate change and natural calamities (droughts, floods, and mismanagement of water resources). Thus, shifting to non-conventional water resources is now a global goal, under SDG 6.3. In this chapter, we review the reuse of treated wastewater (TWW) for agricultural and domestic purposes and its role in contributing to addressing the water supply gap. We identify the cultural, socio-economic, environmental, monitoring, and public health concerns associated with the quality, risks, and implementation of regulations regarding treated wastewater. Finally, the chapter provides case studies of wastewater reuse and highlights some emerging areas of research, technologies, methodologies, strategies, and tools developed by taxonomists, hydrologists, agronomists, social scientists, policy makers, and AI scientists to enhance the quality of treated wastewater reuse, decrease its environmental and health risks, decrease its cost, and promote its usage.

Key Points

- Assess peoples' perceptions towards treated wastewater and its management, from a cultural, socio-economical and governance perspective.
- Identify the environmental and public health risks of treated wastewater.
- Explore current wastewater governance strategies.
- Identify future trends, policies and role of IoT the future in wastewater treatment sector.

Background

Global Water Gap

Demands of a growing population

As the global population is projected to reach 8.5 and 9.8 billion by the year 2030 and 2050, respectively (United Nations, 2022), the demands on agriculture to produce enough food are increasing. Food demand is projected to increase by 70% by 2050 (UNESCO World water Assessment Program, 2012). Concurrently, there is a consensus that agricultural production should be sustainable with mindful use of natural resources and considerations for use of renewable resources wherever possible. Conservation agriculture, unlike intensive and conventional agriculture, plays an essential role in mitigating the effect of climate change. In China, conservation agriculture plays a role proven to reduce greenhouse gas emissions and ensure food security considering the growing demand and climate change (Zhang *et al.*, 2022). Due to population growth, the growing demand for food is leading to an increase of land, water, and energy demands. Under current conditions and with future climatic projections, there is a shortage of water for food production with varying degrees of severity across geographical regions. The distribution of water is not equal across the globe. To achieve food security, countries may opt to increase agricultural production, which generates additional demands on water resources.

Irrigation currently accounts for 70% of annual freshwater withdrawals globally (UNESCO World Water Assessment Program, 2012) and any new land placed under irrigation will compete with other sectoral water demands. In some of the drier countries, the amount of water used for irrigation exceeds the recharge rate of renewable water resources (Khan and Hanjra, 2009). This is especially important when considering that the length and severity of drought is expected to increase with climate change in the Mediterranean, Southwestern U.S., Western Amazon, South Africa, Russia, India, Australia, and southern Europe (Cook *et al.*, 2018; Mukherjee *et al.*, 2018; Cohen-Shields, 2021). Population growth, urbanization, and climate change will increase competition for water resources (World Bank, Understanding Poverty). Rosa *et al.* (2020) estimated that current global freshwater used for irrigation is 1083 km^3/year. If water was sustainably managed, water use would include non-conventional water resources that can play an essential role in closing the supply-demand gap for agriculture and other sectors. The treatment and reuse of wastewater is one option for meeting irrigation water demands. Wastewater is defined as a amalgamation of one or more of the following: household sewage including blackwater (excrement, urine, and fecal sludge) and greywater (used water from cleaning and bathing); liquid from commercial establishments and institutions, including hospitals; industrial discharges, stormwater, and other runoff from urban areas; as well as agricultural, horticultural, and aquaculture runoff (Raschid-Sally and Jayakody, 2008). The suitability of treated wastewater (TWW) for irrigation depends on the treatment level, crop types, and country/regional polices and regulations. Treated wastewater, provided that the treatment yields sufficient quality, and that supply is consistent, can be used for the expansion of irrigated agriculture. Wastewater reuse in irrigation can potentially provide other benefits (e.g., nutrients) or introduce risks (e.g., environmental contaminants). This chapter will discuss the potential for wastewater reuse in irrigation, benefits and risks, governance and socioeconomic aspects, examples of reuse from different geographic regions, and future trends.

Effects of climate change

The 2022 IPCC report warns of the effects and threats of intensified global warming and extreme weather events on food and water security. It highlights that although science and investment have increased agriculture productivity, that productivity is hindered due to climate change over the past 50 years (IPCC, 2022). It emphasizes the sustainability benefits of circulating materials for reuse and recycle to minimize waste and pollution and maximize renewable energy. Wastewater management and the reuse of TWW in agriculture reflect a high efficiency and circular economy approach to adapt to dwindling freshwater resources for agriculture. An estimate of 830 billion m3 of wastewater/year is produced globally, an amount equal to 15% of agriculture water withdrawal (IPCC, 2022). Furthermore, 13.4% of the global agricultural demand of nitrogen, phosphorus and potassium can be covered from wastewater (Jiménez and Asano, 2008; Fernández-Arévalo *et al*., 2017).

The UN HABITAT and WHO global progress report on wastewater treatment prioritizes encouraging the safe and regulated reuse of TWW and monitoring reuse through SDG 6.3 (UN Habitat and WHO, 2021). One of the targets to achieve by 2030 is the safe reuse of water (SDG 6.3) through improving water quality by reducing pollution and hazardous chemicals, increasing recycling, and ensuring safe reuse globally. A recent study revealed an estimated 11% of the wastewater produced globally is reused (Jones *et al*., 2021). Jones *et al* (2021) developed a global spatial assessment of wastewater produced, collected, treated, and reused. Results show that approximately 63% of wastewater produced is collected, that 52% is treated, and that the share of production, collection, and treatment is proportional with a country's income level. With only about 10% of global population, western Europe and the Middle East and North Africa represent a third of the world's reuse of TWW (Jones *et al*., 2021).

Variability exists within and between geographic regions in per capita wastewater production, collection, and treatment (Jones *et al*., 2021). In North America and Western Europe, wastewater treatment rates are higher than those of South America and Southeast Asia. Regions with low wastewater treatment rates, such as sub-Saharan African and Southeast Asia, also lack adequate access to fresh water and consequently there is often low reuse of TWW (Jones *et al*., 2021). They indicate a strong positive correlation between wastewater treatment rates and a country's income level, reaching 93%, 73%, 60% and 47% in high-, upper-middle-, lower-middle- and low-income countries, respectively. Similarly, wastewater reuse in water scare regions is dependent on the country's income and wastewater treatment. In developing countries, such as the Gulf region, Cayman Islands. In the US Virgin Islands and Malta, TWW reuse reaches 80%, 78% 75% and 67%, respectively, and is higher than that of developed countries such as Scandinavia, where reuse is $< 5\%$ (Jones *et al*., 2021).

Challenges induced by climate change, urbanization, migration, and environmental degradation neglect and further threaten the available water resources most needed and used for agriculture. It is against this backdrop that TWW has gained recognition as an alternative source of fresh water in agriculture (Jiménez and Asano, 2008; United Nations World Water Assessment, 2017). Treated wastewater is reused for human food and non-food crops (animal fodder, commercial plant nurseries) in agriculture based on the level of treatment and the permissible quality thresholds (Englande *et al*., 2015).

The Right to Water and Food

The right to adequate water and sanitation was recognized as a human right at the United Nations General Assembly (Resolution 64/292) in 2010. The United Nations Sustainable Development Goal (SDG) 6 is focused on access to safe water and adequate sanitation, increasing water use efficiency (reducing waste, increasing overall productivity, and promoting reuse), protecting and restoring water-related ecosystem services, and promoting cooperation on water issues. SDG 6 has clear connections to other goals focused on food, energy, and health. The connection between the right to water and the right to food is a synergistic trade-off. Food production relies on clean and sufficient water, while the consumption of food must also consider the conservation of natural resources, including water. According to the United Nations Human Right Association, the right to food is achieved "when every man, woman and child, alone or in a community with others, has physical and economic access at all times to adequate food or means for its procurement" (UNHR, 2010). According to Priyadarshi Shukla, Co-Chair of IPCC Working Group III, the impact of future climate change on food security will become more pronounced. This will manifest as reduced yields, particularly in tropical regions, leading to higher prices, decreased nutritional value, and disruptions in the supply chain. The repercussions will vary across nations, with the most severe consequences expected for economically disadvantaged countries in Africa, Asia, Latin America, and the Caribbean (IPCC, 2019).

Water security connects with both food security and the impact of climate change. As per the FAO, around 3.2 billion inhabitants of agricultural regions experience significant water shortages or scarcity, predominantly in developing nations. This circumstance greatly affects food security. The complications are worsened by climate change, causing droughts and less reliable water availability for agriculture and food production across various global regions. According to the UN, South Asia and Southern Africa are climate pressured regions, this negatively impact the water cycle leading to food insecurity (International Decade for Action 'Water for Life' 2005-2015).

Right to food can be facilitated by advocating for the safe reuse of water. Wastewater presents a potentially cost-effective and sustainable water source, offering nutrients and organic matter beneficial for agricultural production. Embracing this approach can help mitigate the pressures stemming from escalating water demands (UNESCO, 2017). In semi-arid and arid regions, water serves as a reliable resource for irrigation. The increase of TWW availability is significantly correlated to the increase in population, playing a crucial role in addressing the rising demand for water and food resulting from water scarcity and population increase. Once wastewater undergoes proper treatment, it has the potential to effectively address several challenges such as mitigating water scarcity, enabling sustainable nutrient recycling, and minimizing the need for excessive fertilizer usage in agriculture (Al Hamedi *et al*., 2023).

Cultural norms: water and wastewater practices

Water holds cultural, social, political, spiritual, environmental, and economic values that have a powerful impact on water use, accessibility, and pricing. Thus, it is essential to include cultural and spiritual usages of water in the planning and design of water management strategies. Some examples of these varying values and uses follow. In Japan and Hindu regions, water is used to purify oneself from sin as it awakens the mind and body. Padusan and Misogirahai rituals and Islamic principles of water management focus on preserving water resources from damage. In Islam, water is considered of God's ownership, thus it should not be deteriorated and should be equitable to all humans (Yulianti *et al*., 2021; Kedzior, 2015; Loodin and Wolf, 2021). Hindu water patterns significantly change during the Holi (होली) festival of colors or Phalguna, when Hindus celebrate Krishna by spraying or painting one another. The cleaning after the Spring celebration increases water usages. In Judaism, water usage increases on the Sabbath, celebrated with a Friday dinner, a Saturday lunch, and a third meal in late afternoon. In Islam, the usage of water increases in the month of Ramadan, when many Muslims use water to cleanse themselves before each prayer, known as "wuddu" (Smith and Ali, 2006). It is essential to note that while Smith and Ali (2006), have described the increase in water use patterns, the quantity of water used among these groups remain unexplored.

As for wastewater reuse, while public perception may suggest that it is religiously antithetical (Faruqui *et al*., 2001; Garcia and Pargament, 2015), religious scholars have issued statements indicating that the use of TWW is suitable. The Council of Leading Islamic Scholars (CLIS) states that the usage of "[treated] wastewater does not cause any harm", thus, it is not *haram or forbidden*. Furthermore, they declared that TWW can be used for drinking and is deemed safe for other Islamic practices, such as "wudu" (CLIS, 1978). Similarly, the Baptist Church declared that the use of TWW is not a spiritual issue, however they are concerned about its practicality and safety (Wilson and Pfaff, 2008). In summary, it may also be critical to understand the perspective of local religious authorities in determining the feasibility of TWW reuse. No reliable data is available on other religions.

Irrigation With Treated Wastewater

Economics

In the field of wastewater treatment, technological advancements have been widely reported, but technologies are still associated with high costs, in terms of technological assets, operations, and maintenance of the plant. Fit-for-purpose solutions may be a way to reduce these costs (Morris *et al*., 2021). However, disposal, delivery and monitoring of treated waste might be costly, specifically in areas with poor infrastructure (Zhang and Shen, 2019). For example, areas where the wastewater treatment plants and farms are distant from each other, the cost of pipelines and energy needed for pumping is high (Lee *et al*., 2018). Farmers are generally unwilling to pay the higher price (Massoud *et al*., 2019). The higher cost of TWW, combined with the lack of confidence in its quality, decreases farmer willingness to pay and adapt the reuse of TWW, especially where conventional water is inexpensive or even free (Saliba *et al*., 2018).

Water pricing and tariffs

Water pricing and traffic are hard to achieve due to cultural norms and trust concerns. Indigenous and peasant groups consider water resources to be part of their territory and refuse to accept the "payment for environmental services" principles, as it drives them to poverty, hinders their participation in decision making, and weakens community reciprocity relations (Boelens *et al*., 2014). Others argue that water tariffs do not enhance the condition of water resources, but rather feed into the pockets of services planners and ignore the role of these planners to study, plan, address, and assign the value, and protect available water (Sullivan, 2009). Unfortunately, without adequate water pricing, water resources are not well managed, and are misallocated and deteriorated. Farmers, the main opponents of water pricing reforms, have no incentive to efficiently use free or undervalued water (de Azevedo and Baltar, 2005). However, farmers are not the only people with blame for water deterioration: water policy makers are also responsible. In Europe, though water policies aim to ensure efficient use of water resources, those policies are not supported by strong hydrologic evidence. For example, groundwater taxations are the fees of well license and are paid only once, expect in Italy, where groundwater tariffs are paid at regular intervals. In contrast, Spain exempts groundwater tariffs and Germany and the Netherlands exempt irrigation water users from water taxation (Berbel *et al*., 2019). Thus, given the current situation of low to null water tariffs and the absence of current and future water availability in water pricing and tariffs, farmers are likely to continue exploiting freshwater and to find the use of TWW to be expensive.

Willingness to pay

The acceptance or refusal of farmers to reuse TWW is one of the most critical factors to be considered while planning such projects. Specific economic and technical factors, such as costs associated with all available sources of irrigation water, irrigation techniques, and cropping patterns, differ from region to region, influence farmer decisions, and must also be considered (Deh-Haghi *et al*., 2020). The costs associated with a TWW irrigation scheme may prove to be more than irrigating with fresh water due to the cost of installing and operating the irrigation network (energy and infrastructure costs are dependent on distance and topography between the wastewater treatment plant and agricultural lands), and costs associated with wastewater treatment, including capital costs, operation and maintenance, energy consumption, and handling of by-products. The perception of farmers is often that TWW is a less valuable and less desirable water resource, when, there are much higher costs involved in treating and conveying a cubic meter of wastewater than pumping from more traditional freshwater sources (Dare and Mohtar, 2018).

Quantifying environmental impacts and services

Environmental efficiency has grown in popularity and importance in the field of sustainability, as the concept focuses on diagnosing the efficiency of an economic activity related to nature's goods and services. Most newer research directions focus on using environmental efficiency analysis by integrating environmental and economic aspects. Integration of economic and environmental aspects can be achieved using the life cycle assessment (LCA) and life cycle cost estimation (LCC), giving impetus to the sustainability performance of TWW reuse projects (Canaj *et al.*, 2021). The ecological footprint method can be used to assess the environmental impact through multiple indicators, including internal economic impact indicators (production cost), farm revenue, the total value added (TVA) due to water and approved management practices.

Economic feasibility of water reuse

An analysis of economic feasibility is critical to justify the investments in infrastructure required to shift to a wastewater reuse strategy, or justify the costs associated with the water itself. As in any project, TWW reuse projects can adopt a method of cost-benefit analysis on a large scale that shows the profitability of the project from the perspective of the wastewater company or utility, the farmer, or the investor. Several studies have shown that when external benefits are correctly identified and incorporated into economic analyses, projects are more sustainable and the number of water reuse projects increases (Asano, 1998; Molinos-Senante *et al.*, 2011; Condom *et al.*, 2012).

Studies on TWW reuse reveal a range of challenges including social acceptability and public perception, weak regulatory and policy environment, and achieving cost-effectiveness that enables the plant to cover its operation and maintenance costs. Water reuse projects must consider public opinion, risk analysis, evaluation of monetary benefits, willingness to pay, and the environmental impacts of irrigating with reclaimed water A case study of TWW reuse from a circular economy approach in Valencia, Spain, reported benefits from both farmers and wastewater treatment plant operators. Farmers expressed positive attitudes about using TWW for irrigation due to the good quality effluent and performance of the Wastewater treatment plants (WWTPs), despite concerns about salinity and pathogens, and so long as it is provided free of charge (including pumping costs). Findings in this study pointed to a need for increased interaction and collaboration between farmers, wastewater treatment operators, and relevant national officials (Hagenvoort *et al.*, 2019).

Ongoing debates on TWW economic feasibility

Source treatment

Reducing wastewater generation at the source is the most sustainable way to reduce water pollution and cost of treatment: it is less expensive than wastewater collection and treatment. Special innovations are needed for this purpose. Industries can benefit from certain technologies to reduce wastewater discharge in their operations and maintenance activities as well as their costs. For example, the usage of the microbial cells (MCF) to covert waste into energy through microbial activity, such as the bacteria present in sludge is a promising technology to reuse treatment costs and greenhouse gas emissions, ensuring clean power and waste reduction (Sanusi *et al.*, 2023). Another example is the use of moving bed biofilm reactors (MBBR) to reduce BOD/COD and excel in the nitrification and denitrification processes. In Norway, this method has proved to achieve high denitrification rates using the combined denitrification MBBR process, even at low temperatures. This is an effective solution as its efficient due to its compactness, saving costs by using existing settling tanks (Ødegaard, 2006). In India, the zero liquid discharge (ZLD) system was adopted in their textile industries in Tirupur (Grönwall and Jonsson, 2017). Industrial symbiosis is another opportunity for managing industrial wastewater by locating industries adjacent to each other, thus reducing the treatment costs, and benefiting from reclaimed water and by-products (WWDR, 2017).

Environmental economics

The economic state of a WWTP is affected by external factors. Although the identification of internal economic influences can be easily translated into monetary units, external effects may be difficult to measure because the market fails to consider factors, such as urbanization, agriculture, climate, and hydrology. Alongside the real cost, environmental benefits are not quantified in the economic feasibility of TWW plants since they do not have a market value (Molinos-Senante *et al.*, 2010). This makes evaluation of economic feasibility more complex, which makes the economic feasibility of TWW reuse projects insufficiently studied (Molinos-Senante *et al.*, 2011). Thus, the real or total costs and benefits of many projects have not been adequately evaluated (Segui, 2004).

Environmental and Public Health Concerns

An additional benefit of wastewater reuse is the nutritive supply, which may act as a fertilizer input, if it complies with local regulations. However, with reuse in irrigation, there are environmental and public health concerns of both known, regulated contaminants, and emerging, unregulated contaminants (Carter *et al.*, 2019), which concentrate in soil, ground, and surface water, and are taken up by crops (Colon and Toor, 2016). Thus, if proper technologies are not implemented, seasonal variations in the effluent's composition could limit its use. High salinity, heavy metals, and contaminants of emerging concern, such as pharmaceuticals and antimicrobial-resistant bacteria, could accumulate in soils and crops or contaminate the environment microbiologically entering the food chain (Morris *et al.*, 2021). According to the World Health Organization (WHO Factsheet, November 21, 2023) antimicrobial-resistant bacteria can lead to negative effects such as the increase of fatal illness and duration of epidemics (i.e., more challenging to cure).

Chemical contaminants

Wastewater treatment plants both reduce disease-causing bacteria and pollutants and kill harmful organisms. However, the presence of heavy metals in TWW remains a concern. Heavy metals from TWW accumulate in soil and are transferred to plants, and consequently, to food systems (Kiziloglu *et al.*, 2007). Nitrogen (N) and Phosphorous (P) content are higher in plots irrigated with TWW compared to plots irrigated with freshwater (Mañas *et al.*, 2009). High N and P content leads to an increase in farmer losses and eutrophication of surface water bodies, making them unhealthy for human contact (Peng *et al.*, 2011; Liu and Qiu, 2007). High P levels lead to an increase in undesirable algae (Sharpley *et al.*, 1993), where algal blooms produce toxins leading to dead zones in water. High nitrogen TWW is unsuitable for humans as its direct use leads to methemoglobinemia in infants (Fan *et al.*, 1987).

Biological contaminants

Poorly TWW discharge contains pathogens, which are transmitted to the environment when such TWW is used for irrigation, further increasing environmental and human health risks (Symonds *et al.*, 2014). Studies have shown that high levels of bacteria and enteric viruses were indicated in poorly TWW plants (Osuolale and Okoh, 2017). Some studies demonstrated that viruses are commonly resistant to conventional wastewater treatment and disinfection (Samie *et al.*, 2009; Horan *et al.*, 2004). The Mpumalanga Wastewater study in south Africa showed that the use of TWW in irrigation resulted in the presence of pathogenic bacteria in different plants, including Vibrio spp., Campylobacter, Enterococcus and Salmonella. Shigella spp. The high presence of Vibrio spp. increases the spread of cholera in the region (Samie *et al.*, 2009).

Soil salinization and structure

Treated wastewater has a high nutritive value, which increases yields and soil fertility and, thus, decreases the need for application of fertilizers (Kiziloglu *et al.*, 2007). Although TWW increases organic content in topsoil, it also has some negative outcomes (Mohammad and Mazahreh, 2003). Studies show that TWW increases the soils ammonium accumulation, salt content, electrical conductivity, as nitrogen, phosphorus, iron, manganese, potassium, calcium, magnesium concentrations. (Mohammad and Mazahreh, 2003; Kiziloglu *et al.*, 2007; Angin *et al.*, 2005). The high content of ammonium in TWW, a source of hydrogen ions, decrease soil pH (Mohammad and Mazahreh, 2003). On another note, increased soil salinity affects seed germination, soil productivity, soil microorganisms and soil productivity (Mohammad and Mazahreh, 2003) as well as increasing soil hydrophobicity (Tarchitzky *et al.*, 2007; Graber *et al.*, 2006), reducing infiltration and water retention, causing increased water runoff and decreased plant available water. Thus, TWW should be properly managed to prevent accumulation of soil nutrients and heavy metals, and enhance soil organic matter, fertility, and productivity.

Governance

The literature shows that the lack of government implementation and control of wastewater practices and inadequate or absent regulatory frameworks are recurring legal and governance barriers. Both factors demonstrate an inconsistent approach to water resource management at various levels and scales. Indeed, inconsistent legislation and regulation can obstruct progress toward a broader application of water reuse practices (Morris *et al.*, 2021). Furthermore, due to a lack of political will or capacity to control and enforce regulations, untreated or poorly TWW may be used in restricted practices (Khalid *et al.*, 2018).

Regulations

Wastewater discharge and TWW quantities are not typically reported in developing countries. Irregular monitoring and data reporting about wastewater production, collection, treatment, and reuse was cited as a major challenge in a study by Dare *et al.* (2017) that explored the opportunities and challenges of wastewater treatment in the West Bank, Tunisia, and Qatar. Without meaningful evidence generated from regularly collected data, it is extremely difficult to gain any traction with policy (Dare *et al.*, 2017). In addition, the absence of legislation disempowers institutions from implementing monitoring mechanisms, making it harder to explore TWW reuse in agriculture. Regulations for reuse vary across regions and countries; mandates undergo continuous updating to include emerging contaminants (Carter *et al.*, 2019). Updated versions of the guidelines issued by the United States Environmental Protection Agency (US-EPA) and the United States Agency for International Development (USAID) include international cases of TWW reuse, best practices in management, emerging technologies, and advanced testing instruments in water treatment (Shoushtarian and Negahban-Azar, 2020).

Genesis of modern treated wastewater reuse regulations

In a detailed review of international standards and regulations for TWW reuse in agriculture, Shoushtarian and Negahban-Azar (2020) identified several guidelines that serve as reference regulations. These include the World Health Organization, US Environmental Protection Agency, Food and Agriculture Organization, International Organization for Standardization, European commission, and the oldest in the world, California's Department of Homeland Security. The FAO guidelines, and more specifically its physio-chemical parameters, serve as the leading reference for regulations and criteria adopted by several countries, agencies, and organizations (Shoushtarian and Negahban-Azar, 2020).

Genesis of various regulations

The establishment of wastewater regulations vary from one region to another. In arid or semi-arid countries water scarcity necessitates government implementation of regulations for TWW reuse in agriculture (Shoushtarian and Negahban-Azar, 2020). Some regions of the world use untreated municipal wastewater directly in irrigation (Thebo *et al.*, 2014). Generally, high-income countries have the resources to implement and meet the safe TWW guidelines, thus, regulations on TWW reuse tend to be more strict in high-income countries (Shoushtarian and Negahban-Azar, 2020).

Key debates related to development of regulation

There is a vast category of unregulated potential water contaminants that lacks regulation and represents an evolving knowledge gap. Technological advances have enabled the measurement of a substantial list of traces of wide-ranging products, including pharmaceutical, household, and personal care products. Traditional wastewater treatment systems are not designed to either remove or monitor these contaminants of emerging concern (CEC). The literature warns of the public health risks posed by CECs including increased animal and human resistance to antibiotics, disruptions in reproductive systems, and normal development. Despite this, effluent guidelines do not include CECs that could be in the treated water. There is a vast class of these compounds found ubiquitously in modern life and this complicates their assessment. There is substantial progress to be made in narrowing the regulatory gaps related to CECs (Shoushtarian and Negahban-Azar, 2020).

Perception

Public trust in wastewater management authorities

The lack of government implementation and control of wastewater practices and the inadequate or absent regulatory framework are recurring legal and governance barriers in the literature. Both factors demonstrate an inconsistent approach to water resource management at various levels and scales. Indeed, inconsistent legislation and regulations can obstruct progress toward a broader application of water reuse practices (Morris *et al.*, 2021). Furthermore, the lack of political will or capacity to control and enforce regulations for untreated or poorly TWW can be used in restricted practices (Khalid *et al.*, 2018). This creates mistrust of local water and sanitation authorities to effectively monitor and manage wastewater treatment plants and deliver safe effluent for irrigation (Dare and Mohtar, 2018). This mistrust negatively affects the approval of water reuse by most of the population, especially in countries with limited transparency (Massoud *et al.*, 2018). When this barrier is combined with a lack of information on wastewater quality and procedures, the implementers develop a prejudiced view of the source's value (Saliba *et al.*, 2018). Farmers' insufficient knowledge of the benefits and characteristics of wastewater and its treatment methods has been observed to lead to a lower acceptance of its use on their farms (Morris *et al.*, 2021). When food consumers are also properly informed about and familiar with the potential benefits and risks, their acceptance seems to increase (Savchenko *et al.*, 2018). Thus, effective stakeholder collaboration allows for an open and transparent flow of information and exchange of concerns (Morris *et al.*, 2021).

Attitudes of farmers

Farmers are the owners of their agricultural land; their decision to irrigate with TWW defines the success or failure of TWW reuse projects. According to Michetti *et al.* (2019), farmers are more likely to use TWW irrigation on crops, such as alfalfa, not intended for human consumption (Michetti *et al.*, 2019). However, in some areas, where water scarcity hinders crop production, TWW is used for irrigation, even when farmers reject the wastewater reuse concept, perceiving it of high environmental and health risks (Antwi-Agyei *et al.*, 2016). Thus, regardless of perception on TWW reuse, farmers use TWW out of necessity to overcome water scarcity and food insecurity. In Jordan, farmers support wastewater reuse as a concept, however its application in irrigation is low mainly due to the economic risk factors related to TWW irrigation, such as limited access to markets or reduction of produce prices linked to sociocultural norms (Carr *et al.*, 2011). Therefore, water availability, economic benefits, economic risks, and food security play essential roles in shaping farmer attitudes toward TWW.

Attitudes of consumers

The 'yuck' factor and the perceived health risks associated with TWW heavily influence public acceptance (Saliba *et al.*, 2018). Savchenko *et al.* (2019), argue that gender is significantly correlated with costumer willingness, finding that women are less likely to accept TWW irrigated foods. Also, willingness to accept is associated with neophobia (fear of trying new and potentially risky foods), safety concerns, real or exaggerated perceived risks, and the disgust factor (Savchenko *et al.*, 2019). Leong adds that acceptance is linked to subjective norms (influence of people around one), knowledge or information about the water scheme, trust in water control authority (Ching, 2010; Ching, 2016). To increase willingness to accept, it is essential to overcome intuitive, contagion-based thinking through promoting wastewater regulation combined in educational activities, "because the more wastewater reuse becomes a norm, the less problematic it will be" (Rozin *et al.*, 2015; Ricart *et al.*, 2019). Thus, social scientists and community psychologist have a key role in identifying actors related to public rejection to TWW reuse, and in designing strategies and approaches to enhance public acceptance, as well as in conducting monitoring and evaluation assessments.

Table 1 Examples of wastewater treatment practices from different geographical regions

Region	*Country*	*Quantity of treated wastewater, annual*	*Area irrigated (or equipped for irrigation) with wastewater*	*Irrigated types of crops*	*Notes*
MENA	Tunisia	159–260 Mm^3 • ∼ 5–6% of renewable water resources[a,b] • 87% of generated wastewater[b]	8065 ha[b]	Agriculture, golf courses, landscape, and artificial groundwater recharge.[a]	About 5% of TWW is reused in irrigation[b]. Plans for expansion of irrigation projects and infrastructure to deliver TWW from Tunisia to other regions in the country
	Jordan	180–174 Mm^3 • ∼15–18% of renewable water resources[c,b] • 81% of generated wastewater[b]		Agriculture, groundwater recharge	About 90% of reclaimed wastewater is reused, most in agriculture
	Egypt	4282 Mm^3 • ∼ 7.5% of renewable water resources[b] • 60.5% of generated wastewater[b] and 74.4% of collected wastewater[d]	35,500 ha[b]	Agriculture (non-food crops) and greenbelt. Some use for food crops is practiced unofficially, (i.e. forest production, field crops, fruit trees)[d]	About 7% of the treated wastewater is reused in irrigation
	Palestine	83 Mm^3 • 10% of renewable water resources[b] • 95.5 (West Bank) & 80 (Gaza Strip) Mm^3 (2016)[e]	_	Some small scale use on fodder crops, fruit trees, and field crops[f]	_
	Qatar	274 Mm^3 • > 100% of renewable water resources[b]	828 ha[b]	Fodder and landscape irrigation[g]	About 28% of TWW reused in irrigation[b]
SSA	Senegal	11 Mm^3 • 0.03% of renewable water resources[b]	_		About 18% of TWW reused in irrigation[b] A 2022 World Bank study reports a circular economy approach could help develop TWW reuse for aquifer recharge and irrigation
	Kenya	42 Mm^3 • 0.14% of renewable water resources	_	_	_
	South Africa	2200 Mm^3 • 4.3% of renewable water resources[b]	_	Fruit trees, vegetable crops, grains, landscape. Legislation exists with reuse guidelines.[h]	About 0.3% of the treated wastewater is reused in irrigation[b]

Table 1 Continued

Region	Country	Quantity of treated wastewater, annual	Area irrigated (or equipped for irrigation) with wastewater	Irrigated types of crops	Notes
South Asia	India	4416 Mm^3 • 0.23% of renewable water resources[b] • ~28% of generated wastewater[b,i,j]	1321 ha[b]	Some formal water reuse schemes exist for agriculture and horticulture[k]	Only a few states have effective governance structures[5] Use of untreated and partially treated wastewater for irrigation is widespread[k,i] creating major health concerns
East Asia	Japan	11,560 Mm^3 • About 2.69% of renewable water resources[b] • 68.3% of generated wastewater[b]	_	Landscape irrigation primarily[L]	About 0.1%[b,L] of the TWW used in irrigation; Lacks sufficiently comprehensive quality standards for wastewater and low economic competitiveness with conventional water are cited as barriers to use[L]
South Pacific	Australia	2000 Mm^3 • 0.41% of renewable water resources[b] • 95.5% of generated wastewater[b]	_	Public open spaces are common in Western Australia. Nurseries and floriculture, mushrooms and vegetables, fruits and nut trees, other crops;[m] growing interest managed aquifer recharge (MAR) for later use to irrigate open public spaces[n]	About 7% of the TWW used in irrigation. Of 8100 Mm^3 of irrigation water used in 2020–21, about 135 Mm^3 (9%) was from recycled or reused water Interest in wastewater reuse is growing as drought increases[m]

[a]Water Reuse in the Arab World: From Principle to Practice. Expert Consultation Wastewater management in the Arab World, May 22–24, 2011, Dubai-UAE
[b]FAO. AQUASTAT Database, 2018–2022. AQUASTAT Website accessed on [24/04/2022].
[c]Abu-Awwad, A.M. 2021. Wastewater Treatment and Reuse of Wastewater in Jordan. Jordan Journal of Agricultural Sciences, 17: Supplement 2021.
[d]Elbana *et al.*, 2017. Reuse of Treated Wastewater in Egypt: Challenges and Opportunities. In: Negm, A. (eds) Unconventional Water Resources and Agriculture in Egypt. The Handbook of Environmental Chemistry, vol 75. Springer, Cham. https://doi.org/10.1007/698_2017_46
[e]World Bank. 2018. Securing Water for Development in West Bank and Gaza. Water Global Practice of the World Bank Group. Washington, DC.
[f]ARIJ (Applied Research Institute –Jerusalem). 2015. Status of the Environment in the State of Palestine 2015. ARIJ, Bethlehem, Palestine.
[g]Manawi *et al.*, 2017. Evaluation of the current state and perspective of wastewater treatment and reuse in Qatar. Desalination and Water Treatment, 71, 1–11.
[h]Treated Effluent By-law, 2017, Published in Gauteng Provincial Gazette no. 102 on 26 April 2017.
[i]Minhas *et al.*, 2022. Wastewater irrigation in India: Current status, impacts and response options. Science of The Total Environment, 808, 152001.
[j]CPCB, Central Pollution Control Board (www.cpcb.nic.in/status-of-stps/).
[k]Breitenmoser, L., Cuadrado Quesada, G., Anshuman N., *et al.*, 2022. Perceived drivers and barriers in the governance of wastewater treatment and reuse in India: Insights from a two-round Delphi study. Resources, Conservation and Recycling, 182, 106285.
[L]Takeuchi, H., Tanaka, H., 2020. Water reuse and recycling in Japan – History, current situation, and future perspectives. Water Cycle, 1:1–12.
[m]Seshadri, B., Bolan, N., Kunhikrishnan, A. *et al.*, 2015. Recycled Water Irrigation in Australia. In: Environmental Sustainability. 10.1007/978–81–322–2056–5_2.
[n]Government of Western Australia, Department of Water and Environmental Regulation. Managed aquifer recharge in Western Australia (2021). www.dwer.wa.gov.au
[o](https://www.abs.gov.au/statistics/industry/agriculture/water-use-australian-farms/2020–21).
[p]Senegal - Challenges and Recommendations for Water Security in Senegal at National Level and in the Dakar-Mbour-Thiès Triangle (English). Washington, D.C. : World Bank Group http://documents.worldbank.org/curated/en/099625003082251396/P1722330bb79db04d0993305b34176c0341.

Approaches to influence perception

Workshops, demonstration plots, and technical trainings, which ensure the spread of awareness, engagement, and knowledge sharing are crucial to promote and adopt safe water reuse practices. For example, the project "DEMOWARE," which is financially supported by the European Union, recently organized a workshop centered around the governance of water reuse. The primary aim was to kick-start a technical dialog regarding the essential standards for water reuse in agricultural irrigation and aquifer recharge. This encompassed various pertinent factors such as water quality, crop types, application conditions, and monitoring practices. The overarching focus was on safeguarding both health and the environment, thereby instilling public trust in the practice of water reuse (EU, 2016). Another example to promote the adaptation of water reuse is the demonstration plots near water treatment facilities in the north-west of Borj Toul, Tunisia, to show that water reuse is safe for growing plants (World Bank, 2022). The lack of technical expertize also has great impact on water reuse potential. This is particularly true in low-income countries, where the link between universities and industries is weak, resulting in a disconnect between education and its application in society (Khalid *et al.*, 2018). As a result, technical training is required to ensure the acquisition of the necessary skills by the personnel for the appropriate operation of wastewater projects (Morris *et al.*, 2021).

Biosolids

During wastewater treatment, solids are digested into stable organic matter: sewage sludge or biosolids that have high nitrogen and phosphorous contents. Biosolids can be treated through dewatering, heat drying, lime stabilization or composting. In Canada, regulated biosolids are eligible for use as crop fertilizers (Apedaile, 2001). Along with its forage quality, the use of biosolids as a nutrient has increased yields in barley and wheat (Pampana *et al.*, 2021; Lu *et al.*, 2012). Moreover, the decomposition of biosolids in soil reduces the bioavailability of pharmaceuticals and personal care products, as it enhances the soil's adsorptive properties (2018).

Examples of Wastewater Generation and Reuse From Varying Geographic Regions

Overview

The UN World Water Development Report (WWDR, 2017) noted the significant unevenness between low- and high-income countries and that greater economies of scale can sustain a tighter operational environment through centralized wastewater treatment facilities. In contrast, lower-income countries with reduced economies of scale and centralized water treatment plants may not be as comprehensive in their coverage, treatment efficiency, and effluent quality assurance. Decentralized treatment facilities can present an opportunity to close community access gaps in lower income developing countries (United Nations World Water Assessment, 2017).

Table (1) provides some examples of different regions and countries with varying levels of wastewater treatment and reuse, whether formal or informal. In the Middle East and North Africa (MENA) the extent of wastewater treatment averages 43% (Frascari *et al.*, 2018), but variability between countries is dramatic with relatively affluent countries such as Israel, Qatar, and the United Arab Emirates having very high rates of wastewater collection and treatment, and less affluent and conflict-affected countries such as the West Bank, Gaza, Iraq, and Libya having very low rates. In Sub-Saharan Africa (SSA), very little of the generated wastewater is treated ($<5\%$), and untreated or partially treated or blended wastewater is used in agriculture extensively (Niquice Janeiro *et al.*, 2020). Data in the literature is less available about wastewater treatment in many SSA countries, as evident from the FAO Aquastat dataset and online internet literature resource. The reviewed literature mostly reiterates the need for wastewater treatment and reuse at larger scale and for a variety of uses, some of which are presented in **Table (1)** and depend on many factors including cultural, climatic, and socioeconomic which dictate the acceptability of use. The need stems from climate change and variability in precipitation, population increase, migration, and increasing sectoral demand for water that puts pressure on freshwater resources.

Future Trends

Shifting to Treated Wastewater (TWW)

TWW has been used for decades in cities like London, Berlin, Milan, and Paris. There has been an increase in wastewater reuse in water-scarce countries; vegetables are irrigated with TWW, by 26% and 80% in Pakistan and Vietnam (Mousavi *et al.*, 2015). In Jordan, the reconstruction and upgrade of As Samra wastewater treatment plant has decreased groundwater dependence by 20% as farmers shift to TWW for irrigation (Almanaseer *et al.*, 2020). To increase wastewater reuse, the EPA has announced a $12 Million grant to support small, rural, and tribal wastewater systems (US-EPA News Release, 2021). Congress authorized grants for wastewater treatment facilities under Title II of P.L. 92–500, to be administered by EPA. It has provided $104 billion to wastewater treatment plants since 1972, and EPA estimates that $271 billion are needed in the next 20 years to meet the Clean Water Act objectives (Ramseur, 2018).

Emerging Areas of Research and Remaining Needs

Research conducted on TWW varies between techniques and methods used, impact on hydrological systems, the effect of TWW on soils, yields and public health, and public willingness to use TWW. Treated wastewater plants hold a high environmental value, if they shift from their single functionality of treating water to a multifunctional role of water-resource-energy recovery of a carbon neutral character that aims to maximize environmental wellbeing and ensure economic sustainability (Zhang *et al.*, 2021). Emerging research aims to enhance the level of TWW and further assess the benefits of TWW in CO_2 reduction, epidemiology, and the energy sector. Alexander *et al.* (2015), state that microbiome-based carbon sequestration minimizes carbon release while maintaining treatment quality. However, further studies are needed to investigate capture and utilization of CO_2 in TWW plants for lower carbon footprints and assess the role of microbiota in CO_2 emission (Zhu *et al.*, 2022). Technologies to generate bioelectricity from sludge using bacteria, aerobic granular sludge technology, anaerobic ammonium oxidation (ANAMMOX), and biomass manipulation, are under development. There are also opportunities for combined energy and nutrient recovery: recovered energy can be used to meet energy and heat demands of the treatment plant itself (WWDR, 2017). Peter *et al.* (2022) highlight the use of microalgae, cultivated in wastewater by transformed nutrients, as a promising renewable energy source - biofuel (2022). This biofuel has great potential that needs to be explored. NASA's Offshore Membrane Enclosures for Growing Algae (OMEGA) project is exploring the feasibility of producing aviation fuels from farming microalgae in floating offshore pods 'fed' by wastewater from cities (Trent, 2012). In Japan, the 'algae industry' is rapidly growing and being tested to produce high-value products such as transportation biofuels, bioplastics, bio-chemicals, nutrition supplements for humans and animals, antioxidants, and cosmetic ingredients (WWDR, 2017).

Aside from the wastewater-energy-environment nexus, the environmental-human health nexus is emerging, wherein scientists believe wastewater epidemiology to be a tool to track pharmaceutical use and assess population health (Boogaerts *et al.*, 2021). Further research needs to be conducted on the effect of climate change on wastewater management (GWP, 2014).

The Internet of Things (IoT) and Treated Wastewater Plants

A problem cannot be defined and resolved if it is not measured. Therefore, monitoring is of substantial importance in wastewater management. Monitoring technologies include techniques based on new sensors, computerized telemetry devices, and innovative data analysis tools. IoT plays an essential role in providing real-time information, tracking logistics operations, and delivering performance insight. In smart cities, IoT collects and analyzes data to detect threats, malfunctions, and potential opportunities to improve infrastructure, and public utilities and services. Remote monitoring systems, including mobile applications, are frequently introduced to operate the Supervisory Control and Data Acquisition (SCADA). Quantitative, science-based approaches such as Life Cycle Assessments (LCA) are also relevant to avoid policies that favor the 'exportation' of the most polluting industries to reduce wastewater-related problems domestically (UNEP, 2012). Periodic monitoring of wastewater quality under the Global Enhanced Monitoring Initiative (GEMI), initiated as part of the UN-WATER framework, will allow for global comparisons and national guidance. The formation of Pollutant Release and Transfer Registries (PRTR) can also be used in wastewater monitoring. The main role of PRTRs is to identify sources of pollution, thus enhancing decision-making and upgrading treatment facilities. Other monitoring efforts include environmental impact assessments and cost-benefit analyses of wastewater production and reuse. However, their application is generally limited to project and company levels (WWDR, 2017).

Kumar and Hong (2022) calculate TWW plant effectiveness and explore the potential of Surveillance-based Sewage Wastewater Monitoring System (SSWMS) with IoT to monitor wastewater treatment plant performance and improve water quality by ensuring that chemical releases are below permissible concentrations . In Bangladesh, the smart wastewater monitoring system, constituted of a microcontroller, deploys temperature, pH, turbidity, total dissolved solid (TDS), and broke up Dissolved Oxygen sensors (Hasan *et al.*, 2020). Karn *et al.* (2021), propose a smart system that consists of the five sensors mentioned earlier and a flow sensor to detect velocity, a photosensor to detect blockage, a gas sensor to detect poisonous gases, a chlorine sensor at the final stage to notify in case of excessive chlorine, and a coli sensor to detect the count of E. coli or fecal coliforms. Thus, IoT can play an essential role in ensuring the enforcement of TWW policies, regulations, and safety guidelines.

Future of Policy

Overview

With the global demands for freshwater continuously growing, compounded by limited water resources, increasing water pollution, and alarming climate change, considering nonconventional water resources becomes vital. Although wastewater treatment has crossed far distances, particularly in developed countries, over 80% of global wastewater is still discharged without treatment into water bodies (WWDR, 2017). Thus, there is room to achieve progress in wastewater collection, treatment, and reuse. Improved wastewater treatment directly relates to reduced water pollution, removal of contaminants from wastewater, safe reuse of TWW, and recovery of useful byproducts (WWDR, 2017).

Substantial improvements in wastewater treatment technologies have occurred since the 1920s, when aerated systems such as activated sludge (which uses microorganisms to remove organic matter from sewage) were invented. During the oil crisis of the 1970' s, anaerobic digestion became the preferred method and in the 1980's and 1990's, natural treatment systems for nutrient removal, mainly nitrogen (N) and phosphorus (P), started to gain interest in developed and developing countries to overcome eutrophication and detrimental environmental impacts of wastewater (WWDR, 2017). The technological processes for wastewater treatment are continuously advancing to comply with the strict water quality regulations and effluent standards.

The role of treated wastewater in circular economy

There is a growing trend toward considering wastewater as a resource and part of a circular economy rather than simply a waste product to be disposed of and a burden on the economy. Indeed, wastewater is a resource to produce energy, nutrients, metals, and other by-products using innovative installations. There is evidence that resource recovery from wastewater is viable, sustainable, and a profit-producing business model from the revenues of by-products such as fertilizers (Wichelns *et al.*, 2015). Significant advances have been made in nutrient recovery technologies from sewage or sewage sludge. Many countries are successful in nutrient recovery, including, but not limited to, Bangladesh, Ghana, India, and South Africa. All use different methods, such as septage sludge dewatering, safe co-composting, and palletization (Nikiema *et al.*, 2014). Phosphorous recovery from on-site treatment facilities such as septic tanks and latrines can become technically and financially feasible, transforming septage into organic or organic-mineral fertilizer. Extractable P mineral resources are expected to become scarce or exhausted in the next 50–100 years (Van Vuuren *et al.*, 2010). Thus, P recovery from wastewater is an increasingly viable and realistic alternative. An estimated 22% of global P demand could be satisfied by recycling human urine and feces worldwide (Mihelcic *et al.*, 2011). The problem lies in the low nutrient content of biosolids, particularly N, which prohibits market sales. Only 5–15% of available N in the wastewater can be recovered, compared to 45–90% of the P in wastewater (Drechsel *et al.*, 2015a). Finally, the 'Fit-for-purpose' concept for water reuse is constantly rising. It is treating the water to a level suitable for the intended use. However, this concept needs to be supported by regulatory frameworks to alleviate barriers (WWDR, 2017).

Decentralization of treated wastewater plants

Wastewater management is expensive and capital-intensive (estimated annual expenditure is between US$100 billion and US $104 billion) (Heymann *et al.*, 2010), particularly large centralized systems, which may no longer be a viable option in many countries. Therefore, a growing global trend favoring decentralized wastewater treatment systems has appeared. It is estimated that investment costs for these treatment facilities represent only 20–50% of the costs for conventional treatment plants despite even lower operation and maintenance costs (Wichelns *et al.*, 2015). A combination of centralized and decentralized wastewater treatment facilities is being tested. It is characterized by its customizability to local conditions (Cairns-Smith *et al.*, 2014). Similarly, the 'distributed wastewater systems' concept is a larger scale, optimal application of the combined centralized and decentralized systems. However, numerous challenges can interrupt its implementation (OECD, 2015b). Decentralized storm water drainage can help reduce the chance of polluting water at the source. One common example is green roofs that capture rainwater before it runs onto polluted pavements and streets (WWDR, 2017). The new trends in wastewater management include the low-cost sewerage (smaller diameter pipes, shallower depth) particularly beneficial for developing countries where conventional sewerages are very expensive. They can be connected to centralized systems and have proven successful in refugee settings (Van de Helm *et al.*, 2015).

Technologies and Innovations

New technologies allow for separation of wastewater components such as ammonia, carbon dioxide, and clean minerals. Microbial re-synthesis is used at a later stage to harvest nitrogen as microbial protein for use for animal feed or food purposes (Matassa *et al.*, 2015). Another approach addresses the use of fish in wastewater to uptake a large portion of its organics and inorganics (Crab *et al.*, 2012), and fish biomass can be used as feed or food. The water remaining after these two procedures can be used for irrigation or discharged. Although wastewater has been used historically in aquaculture, its use is declining globally due to health risks. The alternative is using wastewater to produce fish feed, such as duckweed.

Other innovations in wastewater treatment and research include:

- Membrane filtration technologies, including reverse osmosis, microfiltration, ultrafiltration, and others, are mostly used for tertiary or advanced treatments and can be used to secure potable water.
- Membrane bioreactors (MBRs) technology, an emerging, intensified technology that can be incorporated with the activated sludge process (Van Loosdrecht and Brdjanovic, 2014). This technology is flexible and can be operated via remote control.
- Microbial fuel cells are yet another innovation that uses anaerobic digestion to mimic bacterial interactions in nature and produce energy in the form of an electrical current. However, scaling up is not practical and it needs further improvements.
- Nanotechnology is a growing field with potentially promising applications in water purification, wastewater treatment, and wastewater monitoring (Qu *et al.*, 2013). This technology is still in the maturation phase.
- Natural treatment systems (constructed wetland systems) are becoming more attractive as innovative natural solution to complement existing technological limitations, with research increasingly focusing on natural processes.
- Modeling is becoming an increasingly important aspect of wastewater management and is helpful in translating scientific knowledge to practical applications, as well as facilitating communication between scientists and engineers (Brdjanovic, 2015).

Although the technologies are available, their widespread application is hindered by limited market opportunities and other barriers related to economies of scale. Moreover, the use of wastewater can encounter strong public resistance due to lack of awareness and mistrust regarding the human health risks. Other factors include different cultural and religious perceptions about water in general and/or using TWW. Esthetic aspects of reclaimed water, such as color, odor, and taste, also play an important role in public acceptance.

Future research and wastewater treatment technologies are predicted to focus on resource recovery. Moreover, the future will witness an increasing call for technologies that can operate with limited external energy needs and low operational and management costs, particularly in developing countries (Libhaber and Orozco-Jaramillo, 2012). Technologies and collected data need to be transferred from developed to developing countries, supported by knowledge transfer and capacity-building. Transformative and holistic educational material and training programs on wastewater treatment and reuse need to be developed and addressed to all community members. Infrastructure and data availability, alongside social and public acceptance of wastewater reuse, are central issues that improvement in wastewater treatment and management should address.

Conclusion

The agriculture sector is the most vulnerable to water scarcity mainly due to the growing population and pressures from climate change. Climate change is affecting both water supply and water demand, with an increase in crop water requirement and a decrease in water availability from streams and aquifers. New agricultural land is going under irrigation in areas that were previously rainfed to overcome the effects of climate change. Treated wastewater plays crucial to bridge the water demand – water supply gap in irrigation, conserve blue water, and decrease farmers' vulnerability to water scarcity. With blue water being a finite source, wastewater resource-based planning needs to be followed to achieve SDGs 2, 3, 6, 11, 13, 14 and 15. It is a process that will put the TWW resources base at the forefront, and develop an agricultural, food security, environmental health and socio-economic development recommendations, accordingly.

Although the wastewater treatment has been established in the early 1900s, it is still considered an emerging sector with on-going experiments on its potentialities, risks and opportunities for development. Further experiments need to be conducted to identify the eligibility of crops that could be irrigated with TWW. After assessing the cultural, socio-economic, environmental, and monitoring and public health concerns of wastewater usage in irrigation, and identifying the on-going innovations and research opportunities, it is evident that bringing all stakeholders together is fundamental to disseminate scientific knowledge, technical concerns, economic profitability, socio-cultural perceptions, and innovative solutions in the wastewater sector. Also, synergies and interlinkages need to be identified, to design an efficient, sustainable and clear developmental strategy and regulations, and enhance the quality, quantity, and utilization of treated wastewater. Moreover, IoT and technologies have made it easier to track trends and impact indicators, while monitoring and evaluating strategic plan, performance and policy implication. Finally, funding sustainable water reuse projects in developing areas is vital for addressing water scarcity and securing clean water access. These projects must tackle unique challenges, integrating innovative technologies and building lasting local capacity. Clear implementation guidelines and strong quality monitoring are crucial for project success, ensuring efficient resource use and community well-being even after external funding ends.

Acknowledgments

This work was supported by the PRIMA programme of the European Union, under grant agreement number PRIMA 2020 Section 1 Water IA 2022 MAGO.

References

Abu-Awwad, A.M., 2021. Wastewater treatment and reuse of wastewater in Jordan. Jordan Journal of Agricultural Sciences 17 (Suppl. 2021),

Al Hamedi, F.H., Kandhan, K., Liu, Y., *et al*., 2023. Wastewater irrigation: A promising way for future sustainable agriculture and food security in the United Arab Emirates. Water 15 (12), 2284. https://doi.org/10.3390/w15122284. (MDPI AG. Retrieved from).

Alexander, J., Karaolia, P., Fatta-Kassinos, D., Schwartz, T., 2015. Impacts of advanced oxidation processes on microbiomes during wastewater treatment. In: Fatta-Kassinos, D., Dionysiou, D., Kümmerer, K. (Eds.), Advanced Treatment Technologies for Urban Wastewater Reuse. The Handbook of Environmental Chemistry, vol 45. Cham: Springer. https://doi.org/10.1007/698_2015_359.

Almanaseer, N., Hindiyeh, M., Assaf, R., *et al*., 2020. Hydrological and environmental impact of wastewater treatment and reuse on Zarqa River Basin in Jordan. Environments 7 (2), 14.

Angin, I., Yaganoglu, A.V., Turan, M., 2005. Effects of long-term wastewater irrigation on soil properties. Journal of Sustainable Agriculture 26, 31–42.

Antwi-Agyei, P., Peasey, A., Biran, A., Bruce, J., Ensink, J., 2016. Risk perceptions of wastewater use for urban agriculture in Accra, Ghana. PLOS One 11 (3), e0150603.

Apedaile, E., 2001. A perspective on biosolids management. Canadian Journal of Infectious Diseases and Medical Microbiology vol. 12, 3. https://doi.org/10.1155/2001/801432. Article ID 801432.

ARIJ (Applied Research Institute –Jerusalem). 2015. Status of the Environment in the State of Palestine 2015. ARIJ, Bethlehem, Palestine.

Asano, T., 1998. Wastewater Reclamation and Reuse. Singapore: Technomic Publishing Co.

Australian Bureau of Statistics, Water Use on Australian Farms 2020–2021 (https://www.abs.gov.au/statistics/industry/agriculture/water-use-australian-farms/2020–21)

Berbel, J., Borrego-Marin, M.Mar, Exposito, A., *et al*., 2019. Analysis of irrigation water tariffs and taxes in Europe. Water Policy 21 (4), 806–825. https://doi.org/10.2166/wp.2019.197.

Boelens, R., Hoogesteger, J., Rodriguez de Francisco, J.C., 2014. Commoditizing water territories: The clash between Andean water rights cultures and payment for environmental services policies. Capitalism Nature Socialism 25 (3), 84–102.
Boogaerts, T., Ahmed, F., Choi, P.M., *et al*., 2021. Current and future perspectives for wastewater-based epidemiology as a monitoring tool for pharmaceutical use. Science of the Total Environment 789, 148047.
Brdjanovic, D., 2015. Innovations for Water and Development. Delft, The Netherlands: UNESCOIHE, (www.unesco-ihe.org/sites/default/files/unesco-ihe_innovations_e_vs05).
Breitenmoser, L., Cuadrado Quesada, G., Anshuman, N., *et al*., 2022. Perceived drivers and barriers in the governance of wastewater treatment and reuse in India: Insights from a two-round Delphi study. Resources, Conservation and Recycling 182, 106285.
Cairns-Smith, S., Hill, H., Nazarenko, E., 2014. Urban Sanitation: Why a Portfolio of Solutions is Needed. Working Paper. The Boston Consulting Group. www.bcg.com/documents/file178928.pdf
Canaj, K., Morrone, D., Roma, R., *et al*., 2021. Reclaimed water for vineyard irrigation in a mediterranean context: Life cycle environmental impacts, life cycle costs, and eco-efficiency. Water 13 (16), 2242.
Carr, G., Potter, R.B., Nortcliff, S., 2011. Water reuse for irrigation in Jordan: Perceptions of water quality among farmers. Agricultural Water Management 98, 847–854.
Carter, L.J., Chefetz, B., Abdeen, Z., Boxall, A.B.A., 2019. Emerging investigator series: towards a framework for establishing the impacts of pharmaceuticals in wastewater irrigation systems on agro-ecosystems and human health. Environmental Science: Processes and Impacts, DOI: 10.1039/c9em00020h
Ching, L., 2010. Eliminating "yuck": A simple exposition of media and social change in water reuse policies. International Journal of Water Resources Development 26 (1), 111–124. https://doi.org/10.1080/07900620903392174.
Ching, L., 2016. A lived-experience investigation of narratives: Recycled drinking water. International Journal of Water Resources Development 32 (4), 637–649. https://doi.org/10.1080/07900627.2015.1126235.
CLIS (Council of Leading Islamic Scholars), 1978. Judgement regarding purifying wastewater: Judgement no. 64 on 25 Shawwal, 1398 AH, thirteenth meeting of the council of leading islamic scholars (CLIS) during the second half of the Arabic month of Shawwal, 1398 AH (1978)," Taif, Saudi Arabia. Journal of Islamic Research 17, 40–41.
Cohen-Shields, N. (2021, July 5). How climate change is worsening drought. Climate 411. Retrieved from https://blogs.edf.org/climate411/2021/04/30/how-climate-change-is-worsening-drought/
Colon, B., Toor, G.S., 2016. A review of uptake and translocation of pharmaceuticals and personal care products by food crops irrigated with treated wastewater. Advances in Agronomy 140, 75–100.
Condom, N., Lefebvre, M., Vandome, L., 2012. Treated wastewater reuse in the Mediterranean: Lessons learned and tools for project development. Blue Plan Papers. Valbonne, France: Plan Bleu, p. 11.
Cook, B.I., Mankin, J.S., Anchukaitis, K.J., 2018. Climate change and drought: From past to future. Current Climate Change Reports 4, 164–179. https://doi.org/10.1007/s40641-018-0093-2.
CPCB, Central Pollution Control Board (www.cpcb.nic.in/status-of-stps/)
Crab, R., Defoirdt, T., Bossier, P., Verstraete, W., 2012. Biofloc technology in aquaculture: Beneficial effects and future challenges. Aquaculture 356–357, 351–356.
Dare, A., Mohtar, R.H., 2018. Farmer perceptions regarding irrigation with treated wastewater in the West Bank, Tunisia, and Qatar. Water International 43 (3), 460–471. https://doi.org/10.1080/02508060.2018.1453012.
Dare, A.E., Mohtar, R.H., Jafvert, C.T., *et al*., 2017. Opportunities and challenges for treated wastewater reuse in the West Bank, Tunisia, and Qatar. Transactions of the ASABE 60 (5), 1563–1574. https://doi.org/10.13031/trans.12109.
de Azevedo, Luiz Gabriel T., Baltar, A.M., 2005. Water pricing reforms: Issues and challenges of implementation. International Journal of Water Resources Development 21 (1), 19–29. https://doi.org/10.1080/0790062042000316794.
Deh-Haghi, Z., Bagheri, A., Fotourehchi, Z., Damalas, C.A., 2020. Farmers' acceptance and willingness to pay for using treated wastewater in crop irrigation: A survey in western Iran. Agricultural Water Management 239, 106262.
Drechsel, P., Qadir, M., Wichelns, D. (Eds.), 2015a. Wastewater: Economic Asset in an Urbanizing World. Springer Netherlands.
Elbana, T.A., Bakr, N., Elbana, M., 2017. Reuse of treated wastewater in Egypt: Challenges and opportunities. In: Negm, A. (Ed.), Unconventional Water Resources and Agriculture in Egypt. The Handbook of Environmental Chemistry, vol. 75. Cham: Springer.https://doi.org/10.1007/698_2017_46.
Englande Jr., A.J., Krenkel, P., Shamas, J., 2015. Wastewater treatment & water reclamation. Reference Module in Earth Systems and Environmental Sciences. Elsevier. https://doi.org/10.1016/b978-0-12-409548-9.09508-7.
EU, 2016. Deliverable D7.3 policy-makers dissemination report - CTM. DEMOWARE. http://demoware.ctm.com.es/en/results/deliverables/deliverable-d7–3-policy-makers-dissemination-report.pdf
Fan, A.M., Willhite, C.C., Book, S.A., 1987. Evaluation of the nitrate drinking water standard with reference to infant methemoglobinemia and potential reproductive toxicity. Regulatory Toxicology and Pharmacology 7 (2), 135–148.
FAO. AQUASTAT Database 2018–2022. AQUASTAT Website accessed on [24/04/2022].
Faruqui, N., Biswas, A.K., Bino, M.J., 2001. Water Management in Islam. Tokyo: United Nations University.
Fernández-Arévalo, T., *et al*., 2017. Quantitative assessment of energy and resource recovery in wastewater treatment plants based on plant-wide simulations. Water Research 118, 272–288. https://doi.org/10.1016/j.watres.2017.04.001.
Frascari, D., Zanaroli, G., Abdel Motaleb, M., *et al*., 2018. Integrated technological and management solutions for wastewater treatment and efficient agricultural reuse in Egypt, Morocco, and Tunisia. Integrated Environmental Assessment and Management 14, 447–462.
Garcia, X., Pargament, D., 2015. Reusing wastewater to cope with water scarcity: Economic, social, and environmental considerations for decision-making. Resources, Conservation and Recycling 101, 154–166.
Government of Western Australia, Department of Water and Environmental Regulation. Managed aquifer recharge in Western Australia, www.dwer.wa.gov.au.
Graber, E., Ben-Arie, O., Wallach, R., 2006. Effect of simple disturbance on soil water repellency determination in sandy soils. Geoderma 136, 11–19.
GWP (Global Water Partnership), 2014. Impacts of Climate on Wastewater Management. Discussion Brief No. 5. Global Water Partnership. Stockholm, GWP.
Grönwall, J., Jonsson, A.C., 2017. The impact of 'zero' coming into fashion: ZLD uptake and sociotechnical transitions in Tirupur. Water Alternatives 10 (2), 602–624.
Hagenvoort, J., Ortega-Reig, M., Botella, S., *et al*., 2019. Reusing treated wastewater from a circular economy perspective — The case of the real acequia de moncada in Valencia (Spain). Water 11 (9), 1830. https://doi.org/10.3390/w11091830.
Hasan M.S., Khandaker S., Iqbal M.S., Monirul Kabir M. 2020 A real-time smart wastewater monitoring system using IoT: Perspective of Bangladesh. In: Proceedings of the 2020 2nd International Conference on Sustainable Technologies Ind. 4.0, STI 2020 0 19–20
Heymann, E., Lizio, D., Siehlow, M. 2010. World water markets: High investment requirements mixed with institutional risks. Deutsche Bank Research Frankfurt am Main, Germany.
Horan, N.J., Fletcher, L., Betmal, S.M., Wilks, S.A., Keevil, C.W., 2004. Die-off of enteric bacterial pathogens during mesophilic anaerobic digestion. Water Research 38 (5), 1113–1120.
International Decade for Action 'Water for Life' 2005-2015. https://www.un.org/waterforlifedecade/food_security.shtml, Accessed on [December 23, 2023]
IPCC, 2019: P.R., Shukla, J., Skea, E., Calvo Buendia, *et al.* (eds.). Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. In press.
IPCC, 2022. In: Pörtner, D.C., Roberts, M., Tignor, E.S., *et al.* (Eds.), Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA: Cambridge University Press, p. 3056. https://doi.org/10.1017/9781009325844

Jiménez, B., Asano, T., 2008. Water Reuse: An International Survey of Current Practice, Issues and Needs. IWA Publishing. http://doi.org/10.2166/9781780401881.
Jones, E.R., van Vliet, M.T.H., Qadir, M., Bierkens, M.F.P., 2021. Country-level and gridded estimates of wastewater production, collection, treatment and reuse. Earth System Science Data 13 (2), 237–254. https://doi.org/10.5194/essd-13-237-2021. (Copernicus GmbH).
Karn, A.L., Pandya, S., Mehbodniya, A., *et al.*, 2021. An integrated approach for sustainable development of wastewater treatment and management system using IoT in smart cities. Soft Computing. doi:10.1007/s00500-021-06244-9.
Kedzior, S.B., 2015. Pollution and the renegotiation of river goddess worship and water use practices among the hindu devotees of India's ganges/ganga river. In: Brunn, S. (Ed.), The Changing World Religion Map. Dordrecht: Springer. https://doi-org.ezproxy.aub.edu.lb/10.1007/978-94-017-9376-6_28.
Khalid, S., Shahid, M., Bibi, I., *et al.*, 2018. A review of environmental contamination and health risk assessment of wastewater use for crop irrigation with a focus on low and high-income countries. International Journal of Environmental Research and Public Health 15 (5), 895. https://doi.org/10.3390/ijerph15050895. (Retrieved from).
Khan, S., Hanjra, M.A., 2009. Footprint of water and energy inputs in food production – Global perspectives. Food Policy 34, 130–140.
Kiziloglu, M., Turan, F., Sahin, M., *et al.*, 2007. Effects of wastewater irrigation on soil and cabbage-plant (brassica olerecea var. capitate cv. yalova-1) chemical properties. Journal of Plant Nutrition and Soil Science 170 (1), 166–172.
Kumar, P.M., Hong, C.S., 2022. Internet of things for secure surveillance for sewage wastewater treatment systems. Environmental Research 203, 111899.
Lee, E.J., Criddle, C.S., Geza, M., Cath, T.Y., Freyberg, D.L., 2018. Decision support toolkit for integrated analysis and design of reclaimed water infrastructure. Water Research 134, 234–252. ISSN 0043-1354. https://doi.org/10.1016/j.watres.2018.01.037. (Retrieved from).
Libhaber, M., Orozco-Jaramillo, Á., 2012. Sustainable treatment and reuse of municipal wastewater. For Decision Makers and Practicing Engineers. London: IWA Publishing.
Liu, W., Qiu, R.L., 2007. Mini-review water eutrophication in China and the combating strategies. Journal of Chemical Technology & Biotechnology 82, 781–786.
Loodin, N., Wolf, A., 2021. Comparison and contrast of Islamic water management principles with international water law principles: A case study of helmand River Basin.
Lu, Q., He, Z.L., Stoffella, P.J., 2012. Land application of biosolids in the USA: a review. Applied and Environmental Soil Science. 2012, 201462.
Mañas, P., Castro, E., Heras, J.I., 2009. Irrigation with treated wastewater: Effects on soil, lettuce (Lactuca sativa L.) crop and dynamics of microorganisms. Journal of Environmental Science and Health, Part A 44 (12), 1261–1273. https://doi.org/10.1080/10934520903140033.
Manawi, Y., Fard, A.K., Hussein, M.A., Benamor, A., Kochkodan, V., 2017. Evaluation of the current state and perspective of wastewater treatment and reuse in Qatar. Desalination and Water Treatment 71, 1–11.
Massoud, M.A., Terkawi, M., Nakkash, R., 2019. Water reuse as an incentive to promote sustainable agriculture in Lebanon: Stakeholders' perspectives. Integrated Environmental Assessment and Management 15 (3), 412–421. https://doi.org/10.1002/ieam.4131. (Retrieved from).
Massoud, M.A., Kazarian, A., Alameddine, I., Al-Hindi, M., 2018. Factors influencing the reuse of reclaimed water as a management option to augment water supplies. Environmental monitoring and assessment 190 (9), 1–11. (Retrieved from). https://link.springer.com/article/10.1007/s10661-018-6905-y#Abs1.
Matassa, S., Batstone, D.J., Hülsen, T., Schnoor, J., Verstraete, W., 2015. Can direct conversion of used nitrogen to new feed and protein help feed the world? Environmental Science and Technology 49 (No. 9), 5247–5254. https://doi.org/10.1021/es505432w.
Michetti, M., Raggi, M., Guerra, E., Viaggi, D., 2019. Interpreting farmers' perceptions of risks and benefits concerning wastewater reuse for irrigation: A case study in Emilia-Romagna (Italy). Water 11 (1), 108. https://doi.org/10.3390/w11010108.
Mihelcic, J.R., Fry, L.M., Shaw, R., 2011. Global potential of phosphorus recovery from human urine and feces. Chemosphere 84 (6), 832–839. doi.org/10.1016/j.chemosphere.2011.02.046.
Minhas, P.S., Kumar, S.J., Dotaniya, M.L., Abhijit, S., Madhumonti, S., 2022. Wastewater irrigation in India: Current status, impacts and response options. Science of the Total Environment 808, 152001.
Mohammad, M.J., Mazahreh, N., 2003. Changes in soil fertility parameters in response to irrigation of forage crops with secondary treated wastewater. Communications in Soil Science and Plant Analysis 34 (9–10), 1281–1294.
Molinos-Senante, M., Hernández-Sancho, F., Sala-Garrido, R., 2010. Economic feasibility study for wastewater treatment: A cost–benefit analysis. Science of the Total Environment 408 (20), 4396–4402.
Molinos-Senante, M., Hernandez-Sancho, F., Sala-Garrido, R., 2011. Cost–benefit analysis of water-reuse projects for environmental purposes: A case study for Spanish wastewater treatment plants. Journal of Environmental Management 92, 3091–3097.
Morris, J., Georgiou, I., Guenther, E., Caucci, S., 2021. Barriers in implementation of wastewater reuse: Identifying the way forward in closing the loop. Circular Economy and Sustainability 1 (1), 413–433. (Retrieved from). https://link.springer.com/article/10.1007/s43615-021-00018-z#Sec10.
Mousavi, S.R., Tavakoli, M.T., Dadgar, M., *et al.*, 2015. Reuse of treated wastewater for agricultural irrigation with its quality approach. Biological Forum 7 (1), 814. (Research Trend).
Mukherjee, S., Mishra, A., Trenberth, K.E., 2018. Climate change and drought: A perspective on drought indices. Climate Change Reports 4, 145–163. https://doi.org/10.1007/s40641-018-0098-x.
Nikiema, J., Cofie, O., Impraim, R., 2014. Technological options for safe resource recovery from fecal sludge. Colombo, International Water Management Institute (IWMI) CGIAR Research Program on Water, Land and Ecosystems (WLE). www.iwmi.cgiar.org/Publications/wle/rrr/resource_recovery_and_reuse-series_2.pdf
Niquice Janeiro, C.A., Marques Arsénio, A., Brito, R.M.C.L., van Lier, J.B., 2020. Use of (partially) treated municipal wastewater in irrigated agriculture; potentials and constraints for sub-Saharan Africa. Physics and Chemistry of the Earth, Parts A/B/C 118–119, 102906.
Ødegaard, H., 2006. Innovations in wastewater treatment: -The moving bed biofilm process. Water Science and Technology 53 (9), 17–33. https://doi.org/10.2166/wst.2006.284.
OECD (Organisation for Economic Co-operation and Development). 2015b. Water and Cities. Ensuring Sustainable Futures. Paris, OECD Publishing. www.oecd.org/fr/regional/water-and-cities-9789264230149-en.htm
Osuolale, O., Okoh, A., 2017. Human enteric bacteria and viruses in five wastewater treatment plants in the Eastern Cape, South Africa. Journal of Infection and Public Health 10 (5), 541–547. (Retrieved from). https://www.sciencedirect.com/science/article/pii/S1876034117300242.
Pampana, S., Rossi, A., Arduini, I., 2021. Biosolids benefit yield and nitrogen uptake in winter cereals without excess risk of N Leaching. Agronomy 11 (8), 1482.
Peng, S.Z., Yang, S.H., Xu, J.Z., *et al.*, 2011. Nitrogen and phosphorus leaching losses from paddy fields with different water and nitrogen managements. Paddy and Water Environment 9, 333–342. https://doi.org/10.1007/s10333-010-0246-y.
Peter, A.P., Koyande, A.K., Chew, K.W., *et al.*, 2022. Continuous cultivation of microalgae in photobioreactors as a source of renewable energy: Current status and future challenges. Renewable and Sustainable Energy Reviews 154, 111852.
Qu, X., Alvarez, P.J.J., Li, Q., 2013. Applications of nanotechnology in water and wastewater treatment. Water Research 47 (12), 3931–3946. dx.doi.org/10.1016/j.watres.2012.09.058.
Ramseur, J.L., 2018. Wastewater Infrastructure: Overview, Funding, and Legislative Developments. Congress
Raschid-Sally, L., Jayakody, P., 2008. Drivers and characteristics of wastewater agriculture in developing countries: Results from a global assessment, Colombo, Sri Lanka. IWMI Research Report 127, International Water Management Institute, Colombo.
Ricart, S., Rico, A.M., Ribas, A., 2019. Risk-yuck factor nexus in reclaimed wastewater for irrigation: Comparing farmers' attitudes and public perception. Water 11 (2), 187. https://doi.org/10.3390/w11020187.
Rosa, L., Chiarelli, D.D., Rulli, M.C., Dell'Angelo, J., D'Odorico, P., 2020. Global agricultural economic water scarcity. Science Advances 6, 6031. https://doi.org/10.1126/sciadv.aaz6031.
Rozin, P., Haddad, B., Nemeroff, C., Slovi, P., 2015. Psychological aspects of the rejection of recycled water: Contamination, purification and disgust. Judgment and Decision Making 10, 50–63.

Saliba, R., Callieris, R., D'Agostino, D., Roma, R., Scardigno, A., 2018. Stakeholders' attitude towards the reuse of treated wastewater for irrigation in Mediterranean agriculture. Agricultural Water Management 204, 60–68. https://doi.org/10.1016/j.agwat.2018.03.036.
Samie, A., Obi, C.L., Igumbor, J.O., Momba, M.N.B., 2009. Focus on 14 sewage treatment plants in the Mpumalanga Province, South Africa in order to gauge the efficiency of wastewater treatment. African Journal of Biotechnology 8, 14.
Sanusi, S., Makhtar, M.M.Z., Ghazali, A.W., 2023. Microbial fuel cell (MFC) innovation in Wastewater treatment plant: From economic perspective. *In:* Makhtar, M.M.Z., Shukor, H., Yaser, A.Z. (eds) Microbial Fuel Cell (MFC) Applications for Sludge Valorization. Green Energy and Technology. Springer. https://doi.org/10.1007/978-981-99-1083-0_11.
Savchenko, O.M., Kecinski, M., Li, T., Messer, K.D., 2019. Reclaimed water and food production: Cautionary tales from consumer research. Environmental Research 170, 320–331. ISSN 0013-9351. https://doi.org/10.1016/j.envres.2018.12.051.
Savchenko, O.M., Kecinski, M., Li, T., Messer, K.D., Xu, H., 2018. Fresh foods irrigated with recycled water: A framed field experiment on consumer responses. Food Policy 80, 103–112. https://doi.org/10.1016/j.foodpol.2018.09.005. (Retrieved from).
Segui, L., 2004. Reclamation and Reuse System Wastewater. Methodology for Technical-Economic Analysis and Cases. (Doctoral thesis). Barcelona, Spain: Polytechnic University of Catalonia.
Seshadri, B., Bolan, N., Kunhikrishnan, A., *et al.*, 2015. Recycled Water Irrigation in Australia. In: Environmental Sustainability. 10.1007/978–81-322–2056-5_2.
Sharpley, A.N., Daniel, T.C., Edwards, D.R., 1993. Phosphorus movement in the landscape. Journal of Production Agriculture 6 (4), 492–500.
Shoushtarian, F., Negahban-Azar, M., 2020. Worldwide regulations and guidelines for agricultural water reuse: A critical review. Water 12 (4), 971. https://doi.org/10.3390/w12040971. (MDPI AG).
Smith, A., Ali, M., 2006. Understanding the impact of cultural and religious water use. Water and Environment Journal 20 (4), 203–209.
Sullivan, S., 2009. Green capitalism, and the cultural poverty of constructing nature as service-provider. Radical Anthropology 3, 18–27.
Symonds, E., Verbyla, M., Lukasik, J., *et al.*, 2014. A case study of enteric virus removal and insights into the associated risk of water reuse for two wastewater treatment pond systems in Bolivia. Water Research 65, 257–270. https://doi.org/10.1016/j.watres.2014.07.032. (Retrieved from).
Takeuchi, H., Tanaka, H., 2020. Water reuse and recycling in Japan – History, current situation, and future perspectives. Water Cycle 1, 1–12.
Tarchitzky, J., Lerner, O., Shani, U., *et al.*, 2007. Water distribution pattern in treated wastewater irrigated soils: Hydrophobicity effect. European Journal of Soil Science 58, 573–588.
Thebo, A.L., Drechsel, P., Lambin, E.F., 2014. Global assessment of urban and peri-urban agriculture: Irrigated and rainfed croplands. Environmental Research Letters 9, 114002.
Treated Effluent By-law, 2017, Published in Gauteng Provincial Gazette no. 102 on 26 April 2017.
Trent, J. 2012. Offshore Membrane Enclosures for Growing Algae (OMEGA) – A feasibility study for wastewater to biofuels. NASA Ames Research Center project report for the California Energy Commission. www.energy.ca.gov/2013publications/CEC-500–2013-143/CEC-500–2013-143.pdf
UN human rights office, 2010. The right to adequate food . OHCHR. https://www.ohchr.org/sites/default/files/Documents/Publications/FactSheet34en.pdf
UNEP (United Nations Environment Programme), 2012b. Measuring water use in a green economy. A report of the working group on water efficiency to the international resource panel. Nairobi, UNEP. www.unep.org/resourcepanel-old/Portals/24102/Measuring_Water.pdf
UNESCO World water Assessment Programme, Facts and figures; from the United Nations world water development report 4: managing water under uncertainty and risk. https://unesdoc.unesco.org/ark:/48223/pf0000215492.
United Nations Habitat and WHO, 2021. Progress on wastewater treatment – Global status and acceleration needs for SDG indicator 6.3.1. United Nations Human Settlements Programme (UN-Habitat) and World Health Organization (WHO), Geneva.
United Nations, 2022. Department of Economic and Social Affairs. World Population Prospects 2022: Summary of Results. UN DESA/POP/2022/TR/NO. 3.
Van de Helm, A.W.C., Bhai, A., Coloni F., Koning, W.J. G., De Bakker, P.T., 2015. Developing water and sanitation services in refugee settings from emergency to sustainability – The Case of Zaatari Camp in Jordan. In: Proceeding of the IWA Water Development Congress and Exhibition 2015, Jordan, 18–22 October 2015. London, International Water Association (IWA). repository.tudelft.nl/islandora/ object/uuid:7953d49d-194a-4ecb-81d8–63afcb3f6f60?collection=research
Van Loosdrecht, M.C.M., Brdjanovic, D., 2014. Anticipating the next century of wastewater treatment. Science 344 (6191), 1452–1453. http://doi.org/10.1126/science.1255183.
Van Vuuren, D.P., Bouwman, A.F., Beusen, A.H.W., 2010. Phosphorus demand for the 1970–2100 period: A scenario analysis of resource depletion. Global Environmental Change 20 (3), 428–439. doi.org/10.1016/j.gloenvcha.2010.04.004.
Water Reuse in the Arab World: From Principle to Practice. Expert Consultation Wastewater management in the Arab World, May 22–24, 2011, Dubai-UAE
Wichelns, D., Drechsel, P., Qadir, M., 2015. Wastewater: Economic asset in an urbanizing world. In: Dreschel, P., Qadir, M., Wichelns, D. (Eds.), Wastewater – Economic Asset in an Urbanizing World. Springer Netherlands.
Wilson, Z., Pfaff, B., 2008. Religious, philosophical and environmentalist perspectives on potable wastewater reuse in Durban, South Africa. Desalination 228 (1–3), 1–9.
World Bank. 2018. Securing water for development in West Bank and Gaza. Water global practice of the world bank group. Washington, DC.
World Bank. 2022. Senegal - Challenges and Recommendations for Water Security in Senegal at National Level and in the Dakar-Mbour-Thiès Triangle (English). Washington, D.C. : World Bank Group http://documents.worldbank.org/curated/en/099625003082251396/P1722330bb79db04d0993305b34176c0341
WWAP (United Nations World Water Assessment Programme). (2017). The United Nations world water development report 2017: Wastewater, The Untapped Resource. Paris, UNESCO. ISBN :978-92-3-100201-4
WWDR (2017). "The United Nations world water development report 2017. Wastewater: The untapped resource." The United Nations World Water Development Report (2017).
Yulianti, D.R., Trahutami, S.I., Wiyatasari, R., 2021. The meaning of water in Javanese Padusan and Japanese Misogi-Harai Rituals. In E3S Web of Conferences (Vol. 317, p. 02023). EDP Sciences.
Zhang, H., Hobbie, E.A., Feng, P., Niu, L., Hu, K., 2022. Can conservation agriculture mitigate climate change and reduce environmental impacts for intensive cropping systems in North China Plain? Science of The Total Environment 806 (3), 151194.
Zhang, M., Ji, B., Liu, Y., 2021. Microalgal-bacterial granular sludge process: A game changer of future municipal wastewater treatment? Science of The Total Environment 752, 141957.
Zhang, Y., Shen, Y., 2019. Wastewater irrigation: Past, present, and future. Wiley Interdisciplinary Reviews: Water 6 (3), e1234. https://doi.org/10.1002/wat2.1234.(Retrieved from).
Zhu, X., Lei, C., Qi, J., *et al.*, 2022. The role of microbiome in carbon sequestration and environment security during wastewater treatment. Science of The Total Environment 837, 155793.
WHO Factsheet, November 21, 2023. Antimicrobial Resistance, Antimicrobial resistance (who.int), Accessed December 23, 2023
US-EPA News Release, September 20 2021. https://www.epa.gov/newsreleases/epa-announces-recipients-12-million-grant-funding-support-small-rural-and-tribal. Accessed December 23, 2023

Further Reading

Cotruvo, J. 2018. Water technology. Agricultural water reuse and guidelines.
Elliott, S. 2021. Agricultural Research Service Office of Communications in Research and Science
Environmental Protection Agency, 2020. EPA. Retrieved from https://www.epa.gov/newsreleases/epa-announces-recipients-12-million-grant-funding-support-small-rural-and-tribal

FAO, 2021. Home | Food and Agriculture Organization of the United Nations. https://www.fao.org/3/cb4476en/cb4476en.pdf
IPCC, 2018, August. Land is a critical resource, IPCC report says. Land is a critical resource. https://www.ipcc.ch/2019/08/08/land-is-a-critical-resource_srccl/
IRENA, Renewable Energy in the Water, Energy & Food Nexus. 2015. International Renewable Energy Agency.
Li, H., Liang, X.Q., Chen, Y.X., Tian, G.M., Zhang, Z.J., 2008. Ammonia volatilization from urea in rice fields with zero-drainage water management. Agric Water Manage 95, 887–894.
UNESCAP/UN-Habitat/AIT (United Nations Economic and Social Commission for Asia and the Pacific/ United Nations Human Settlements Programme/Asian Institute of Technology). 2015. Policy Guidance Manual on Wastewater Management with a Special Emphasis on Decentralised Wastewater Treatment Systems (DEWATS). United Nations/AIT. www.unescap.org/resources/policy-guidancemanual-wastewater-management
UNESCO (United Nations Educational, Scientific and Cultural Organization). 2015. UNESCO Project on Emerging Pollutants in Wastewater Reuse in Developing Countries. Brochure. Paris, UNESCO. unesdoc.unesco.org/images/0023/002352/235241E.pdfUnited Nations, Department of Economic and Social Affairs, Population Division (2015). Population 2030: Demographic challenges and opportunities for sustainable development planning (ST/ESA/SER.A/389).
UN Water, 2017. Wastewater: The untapped Resource. https://unesdoc.unesco.org/ark:/48223/pf0000247153/PDF/247153eng.pdf.multi
Venkatachalam, L., 2004. The contingent valuation method: A review. Environmental Impact Assessment Review 24 (1), 89–124.
World Bank Group. 2023, August 7. Water security diagnostic initiative. World Bank. https://www.worldbank.org/en/topic/water/publication/water-security-diagnostic-initiative
World Bank. 2020. Rodriguez, D.J., Serrano, H.A., Delgado, A., Nolasco, D., Saltiel, G., From Waste to Resource: Shifting Paradigms for Smarter Wastewater Interventions in Latin America and the Caribbean. World Bank, Washington, DC. © World Bank. https://openknowledge.worldbank.org/handle/10986/33436 License: CC BY 3.0 IGO."
World Bank, 2020. Understanding poverty, topics, water in agriculture. Online https://www.worldbank.org/en/topic/water-in-agriculture#1, Accessed on [August 16, 2022].
World Bank. 2007. Modi, V., McDade, S., Lallement, D., Saghir, J. Energy services for the millennium development goals. Energy Sector Management Assistance Programme, United Nations Development Programme, UN Millennium Project, and World Bank, New York.
World Bank Group, 2022, September 2. Tunisia: Recycled wastewater cleans up the sea, provides water for farming. World Bank. https://www.worldbank.org/en/news/feature/2022/08/30/tunisia-recycled-wastewater-cleans-up-the-sea-provides-water-for-farming