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EDITED BY
Arindam Malakar,
University of Nebraska-Lincoln, United States

REVIEWED BY
Cristina Couto,
Cooperativa de Ensino Superior Politécnico e Universitário, Portugal
Helder Gomes,
Polytechnic Institute of Bragança (IPB), Portugal
Marzhan Kalmakhanova,
M. Kh Dulati Taraz State University, Kazakhstan

*CORRESPONDENCE
Monica Brienza,
monica.brienza@unibas.it

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Risks associated with wastewater reuse in agriculture: investigating the effects of contaminants in soil, plants, and insects

Vincenzo Trotta[1], Oussama Baaloudj[2] and Monica Brienza[2]*

[1]School of Agricultural Forestry, Food and Environmental Sciences (SAFE), University of Basilicata, Potenza, Italy, [2]Department of Science, University of Basilicata, Potenza, Italy

Rapid urbanization has heightened the urgency of the necessity for sustainable water management in agriculture. This review focuses on the impacts of using reused wastewater in agricultural practices, specifically highlighting the nutrient benefits and consequences of pollutants on important environmental elements. It investigates the impact of contaminants on agricultural ecosystems by assessing the soil composition and nutrient equilibrium. This research also examines the impact of pollution exposure on plants and insects, elucidating the behavioural adaptations and their broader ecological consequences in agricultural environments. Eventually, a comprehensive analysis was conducted to consolidate these findings, emphasizing the challenges and significance of implementing sustainable practices. This study highlights the necessity of addressing the health and environmental concerns associated with the agricultural reuse of wastewater, while also giving valuable information to guide future regulations.

KEYWORDS

wastewater reuse, contaminants, environmental risks, ecological consequences, sustainable agriculture

Introduction

Soil health and water scarcity affect various human activities, including agricultural irrigation, food and energy production, manufacturing, drinking water supply, and ecosystem preservation (Shahriar et al., 2021). It has been estimated that 20% of the Mediterranean population experiences chronic water stress, with over 50% of that number being impacted by water stress during the summer (EEA, 2021) and agriculture remains the activity that consumes 70% of fresh water (Meffe et al., 2021; Shannag et al., 2021). Globally, it has been estimated that over 20 million hectares of land are irrigated with non-conventional water resources (Rusănescu et al., 2022). The concept of using recycled wastewater for irrigation is not new; in fact, it dates back to about 3000 B.C., and although there are no precise global estimates of wastewater reuse, it is assumed that at least 7% of irrigated land uses wastewater (WHO, 2013). However, wastewater reuse in agriculture may be associated with environmental and human health risks due to the presence of salts, heavy metals, and organic contaminants that can lead to the contamination of soil, crops, and groundwater (Verma et al., 2023). Another negative effect associated with wastewater reuse is the potential spread of antibiotic-resistant bacteria, which can survive the inhibitory effects of common antibiotics (Bougnom and Piddock, 2017).

It is clear that the need to reuse unconventional water is leading the scientific community to improve its quality, and many research papers have been published on adsorption (Kamińska et al., 2022), photocatalysis (Foti et al., 2022), electrochemistry (Brienza and Garcia-Segura, 2022), etc. At the same time, research activities on wastewater reuse for agriculture started, but due to the fact that there is no clear regulation and it is often considered a forbidden practice in many countries, the research is developed at laboratory scale, greenhouse scale and really few at field scale. For this reason, the scientific literature on municipal wastewater treatment has grown exponentially over the past 10 years, and the amount of published research on agricultural water reuse has intensified, although the absolute number of publications on the latter argument is generally two orders of magnitude less than the former (Figure 1).

The chemical and physical properties of wastewater effluent are contingent upon its source and exhibit variations influenced by factors such as climate, socio-economic conditions, and the behavioural patterns of the local population (Gatta et al., 2021). Wastewater is a complex matrix of a wide variety of microorganisms, organic and inorganic compounds. Organic compounds range from carbohydrates, lignin, fats, proteins, household cleaning products, industrial products, pharmaceuticals, and personal care products. Inorganic substances include a variety of compounds, some of which have hazardous properties and contain heavy metals (Bawa, 2023). Microorganisms consist of various species, including pathogenic genera such as *Trichuris*, *Ascaris*, and *Giardia* (Zeleke et al., 2021).

The use of wastewater for irrigation has both advantages and disadvantages for agricultural applications. However, its main problem is that the addition of nutrients, any contaminants or residues in the wastewater can accumulate in the soil during irrigation and could be dangerous due to their uptake by crops (Margenat et al., 2019; Trotta et al., 2024). For this reason, proper risk assessment is required when considering the use of treated effluent for irrigation. The European Parliament and Council published the minimum requirements for agricultural irrigation (EUR-Lex, 2020). For examples, in food and root crops consumed raw where the edible part is in direct contact with reclaimed water, the number of *E. coli*/100 mL should be ≤10, BOD_5 (mg/L) ≤ 10, TSS (mg/L) ≤ 10, turbidity (NTU) ≤ 5, *Legionella* spp.: <1,000 cfu/L, intestinal nematodes (helminth eggs): ≤1 egg/L. The presence of pollutants in wastewater makes it necessary to study their effects on soil, plants, pests, and human health, but at the same time to improve conventional wastewater treatment by adding low-cost tertiary treatment to improve the quality of the effluent.

This review aims to provide an overview of the benefits and environmental risks associated with the use of wastewater in agricultural irrigation and to assess the ecological consequences.

Harvesting opportunities: benefits of using wastewater in agriculture

The use of wastewater presents both challenges and opportunities. Its use can lead to positive outcomes for farmers, society, and municipalities, as its nutrient content can be effectively used in agricultural and other productive activities (Belhaj et al., 2016; Hettiarachchi et al., 2018). Wastewater has a substantial effect on crop production by enhancing yields (Ofori et al., 2021), improving soil performance, increasing soil microbial activity, and enhancing its physical structure (Zhang and Shen, 2019). From an economic perspective, this practice has the potential to reduce fertilizer use and freshwater consumption for irrigation, with benefits to the local economy (Avadí et al., 2022). The European Parliament and Council are reinforcing the use of wastewater to preserve water resources and promote a circular economy, protecting human health and ensuring the adequate collection, treatment, and discharge of urban and industrial waste waters (EUR-Lex, 2020). It is well known that wastewater sludge is a source of nutrients, but it can also be turned into biogas for profitable use (Elalami et al., 2019). Mavhungu et al. (2020) reported an interesting pilot-scale study in which it was demonstrated through a zero liquid discharge that 3.5 m^3 of municipal wastewater it was possible to simultaneously recover struvite (52.5 kg) useful for the agricultural industry and 3.4 m^3 of drinking water. In addition, wastewater can be a source of rare earth elements, as demonstrated by Al Momani et al. (2023).

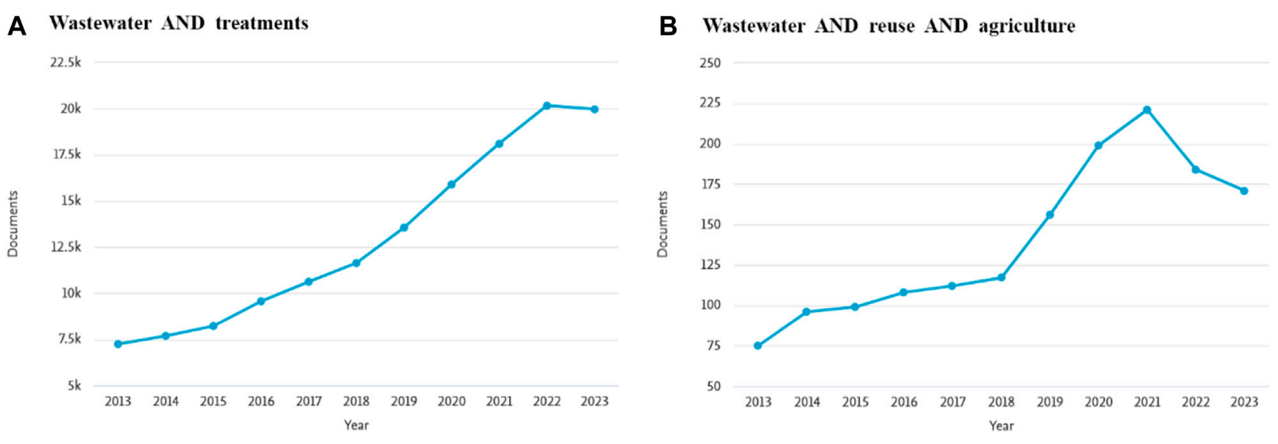

FIGURE 1
Distribution over time of publications extracted from Scopus (Elsevier) from 2013 to December 2023. Only publications containing the words "wastewater" AND "treatments" (A) and wastewater" AND "treatments" AND "agriculture" (B) in the title, abstract or keywords were included.

The first environmental matrix to benefit from wastewater irrigation is the soil. In addition to its nutrient content to reduce fertilizer dosage in agricultural activities, wastewater is free from climate impacts, low-cost and could positively influence soil performance since contains dissolved organic matter, improves soil physical structure, and increases soil microbial activity (Dang et al., 2019). The levels of nutrients introduced by wastewater increase soil fertility and can be safe for short cultivation crops such as lettuce (Urbano et al., 2017) or eggplant and tomato (Cirelli et al., 2012). Lettuce irrigated with treated wastewater had higher leaf macronutrients (N, P, K, Ca, Mg, and S), higher fresh weight (+50% in the first cycle and +100% in the second), and greater root surface area than lettuce irrigated with drinking water (Urbano et al., 2017). In addition, tomato plants irrigated with treated municipal wastewater produced higher yields (about 20%) than plants irrigated with fresh water and increased the number of marketable fruits (Cirelli et al., 2012). Another relevant positive aspect of these studies was the safety of lettuce from the presence of *Escherichia coli* on the leaves or in the soil, and the high microbiological quality of eggplant and tomato. After the soil, plants are the first level of the trophic chain that includes herbivorous insects, predators, and pollinators, and the use of reclaimed wastewater for crop irrigation raises the attention to the interaction between plants and insect pests. Contaminated wastewater can negatively shape the population dynamics of insect pests in an agroecosystem by affecting plant growth and physiology through bottom-up effects involving uptake and translocation of contaminants or increased salinity stress (Dong et al., 2020; Ghodoum Parizipour et al., 2021). Wastewater irrigation can also increase the chemical defenses of plants, reducing their nutritional quality for herbivorous insects, and thus contributing positively to pest management programs (Güntner et al., 1997; Han et al., 2016). In addition, contaminated wastewater can adversely affect the fitness of pest insects through direct ingestion of chemicals accumulated in non-edible plant parts (Culliney et al., 1986).

Highlighting challenges: risks in wastewater use in agriculture

While water reuse offers many benefits, the scientific community has identified several human health and environmental concerns and challenges (Helmecke et al., 2020). The higher nutrient levels in wastewater may have positive effects on plant growth but also on herbivorous insect performance, and it is not obvious that the more vigorous plants are able to mitigate the negative consequence of higher pest infestation (Price, 1991; Shannag et al., 2021). Under this scenario, pesticide use would increase.

Urban wastewater treatment plants typically discharge effluents containing a wide range of organic chemicals, toxic metals, and microbial pathogens (Salgot et al., 2006). These effluents present a number of potential hazards related to the presence of contaminants in the soil. In this sense, there are considerable concerns about the potential risks to human wellbeing, including the contamination of potable water and the accumulation of harmful substances in consumable agricultural products (Shuval et al., 1997).

Another serious problem associated with the weakness of wastewater treatment systems is bacterial contamination. In fact, the presence of elevated levels of pathogens and microbial hazards also raises concerns about their impact on human welfare (Deb, 2018). The potential risks may result in adverse health effects, including (but not limited to) diarrhea and parasitic infections, microbial outbreaks, skin disorders, and systemic infections (Stec et al., 2022). Besides health consequences, nitrosamines are carcinogenic to multiple organs in at least 40 animal species (Bogovski and Bogovski, 1981). The ubiquitously occurrence of N- nitrosamine in different environmental compartments including surface and ground waters (Ma et al., 2012), sludge (Venkatesan et al., 2014), and soil (Chiron and Duwig, 2016) has been reported. Research on N-nitrosamines has been mainly limited to those compounds included in the US EPA Contaminant Candidate List 3, namely, N-nitroso-diethylamine (NDEA), NDMA, N-nitroso-di-n-propylamine (NDPA), N-nitroso-diphenylamine (NDPhA), N-nitroso-pyrrolidine (NPYR). However, all secondary and tertiary amines can theoretically undergo nitrosation reactions and there is no clear rationale for only targeting those particular compounds. So, it has demonstrated that these compounds can be generated during wastewater treatmen, as reported by Brienza et al. (2020), on the case of the fate of Ciprofloxacin under denitrification sludge treatment. In addition, these substances are among the most common chemical pollutants identified in groundwater aquifers worldwide (Zhang et al., 2020). The presence of phosphorus has a substantial influence on surface water, the reaction between nitrogen (N) and phosphorus (P) compounds in water presents significant hazards to both the environment and human health (Nieder et al., 2018). The absence of NO might have detrimental consequences since it can potentially cause the death of denitrification microorganisms (Brienza et al., 2017). The presence of these bacteria is essential to maintaining the overall health of the ecosystem, and their ability to survive is extremely important. In addition, the presence of N-nitroso compounds as impurities can potentially harm these microorganisms, exacerbating environmental problems (Ahamad et al., 2020). The presence of antibiotics in wastewater can also contribute to amplifying the risk of antibiotic resistance by exerting selective pressure, promoting gene transfer, and sustaining resistant bacterial populations (Guo and Kong, 2019).

Currently, there is little knowledge of the effects of antibiotics at environmental concentrations on terrestrial insects (both beneficial and pest) or their microbial community composition. For example, most common pharmaceutical (including antibiotics) and personal care products found in reclaimed water negatively affect the life history traits of the agricultural pest *Trichoplusia ni* (Lepidoptera: Noctuidae) thought an influence on its microbial communities (Pennington et al., 2017). Also, pharmaceuticals and personal care products at environmentally concentrations can negatively influence the development of *Culex* mosquitoes (Pennington et al., 2016). However, although the use of wastewater in integrated pest management programs seems promising (pesticide rates would be reduced or pests would become more susceptible), it is possible that these chemicals could be transferred to consumed crops, and we do not yet know their potential effects on human health.

The widespread presence of urban pest control insecticides, such as fipronil and imidacloprid, and their principal transformation products, has been consistently observed in wastewater analyses (Sadaria et al., 2017). In the context of ecological implications, it is noteworthy that insects, particularly pollinators, exhibit heightened sensitivity to these chemical agents compared to aquatic organisms.

10.3389/fenvs.2024.1358842

The utilization of wastewater contaminated with these insecticides for irrigation introduces a concerning dimension, as it may have discernible negative effects on the life history traits of insect pollinators. This concern is particularly relevant due to the potential for pollinators to experience chronic exposure to these pesticides through various routes throughout the foraging season (Krupke et al., 2012; Sadaria et al., 2017; Carter et al., 2020).

Strategies for safer and productive wastewater reuse in agriculture

Efforts to minimize the risks of agricultural wastewater reuse include the development of a comprehensive risk management strategy, the advancement of sophisticated methods to eliminate hazardous chemicals, and the adoption of guidelines to ensure the protection of human health during agricultural wastewater reuse (Al-Hazmi et al., 2023). The challenges that come with using wastewater for irrigation are well documented and include several dimensions, namely, economic, environmental, social, and health challenges (Singh et al., 2018). In many countries, extensive wastewater collection and treatment is seen as a long-term strategy for the future due to the scarcity of financial and technological resources (Bdour et al., 2009). To achieve this goal, it is also important to reduce chemical and biological oxygen demand, total suspended solids, and total bacteria counts (Iqbal et al., 2022). A multitude of conventional wastewater treatment facilities have employed a combination of physical, chemical, and biological processes to mitigate the concentrations of solids as well as diverse organic and inorganic compounds (Hai et al., 2007). A variety of techniques, such as adsorption, photocatalysis, electrochemistry, filtration, sedimentation, and flotation, are employed to efficiently eradicate both inorganic and organic particulate matter. In order to maximize the benefits derived from wastewater, it is insufficient to solely assess the associated risks. Careful consideration of the amount of crop nutrients added to the soil by wastewater in irrigation is essential.

The implementation of suitable irrigation systems in agriculture is also crucial for more sustainable wastewater reuse. Different irrigation methods, such as subsurface irrigation, drip irrigation, furrow irrigation, and sprinkler systems offer varying advantages (Eisenhauer et al., 2021). An example is drip irrigation, which delivers water directly to the root zone of plants, minimizing the interaction between wastewater and plant leaves, thereby reducing the risk of pathogen transfer and soil contamination (Ungureanu et al., 2020). In addition, the use of modern irrigation technology allows for better regulation of water application rates and timing, maximizing water use efficiency and minimizing the risk of excessive irrigation (Valipour and Singh, 2016).

Inoculation with endophytic plant growth-promoting fungi is also considered a valid strategy to mitigate the negative effects of stress caused by wastewater reuse in agriculture (OECD, 2023). These organisms are able to promote plant resistance and mitigate the effects of biotic and abiotic stresses by producing phytohormones and antioxidants (Studholme et al., 2013).

Discussion

As highlighted in the review, the benefits of wastewater reuse, including its nutrient composition and potential economic benefits, are very clear. However, it is important to promptly address the inherent hazards caused by contaminants and pathogens found in untreated or inadequately treated wastewater. The possibility of sustainable wastewater reuse in agriculture depends on the implementation of interdisciplinary approaches (Wichelns et al., 2015). Collaboration among environmental scientists, agronomists, engineers, public health experts, policymakers and other relevant stakeholders is essential. Interdisciplinary research initiatives have the potential to provide comprehensive and holistic perspectives on the complex dynamics associated with the reuse of wastewater. Such initiatives facilitate the formulation of comprehensive strategies that address multiple dimensions, including environmental, agricultural, and public health considerations (Santos et al., 2023). It is important to note that current wastewater treatment systems have certain limitations in their ability to completely remove specific emerging contaminants (Younas et al., 2021). It is important to develop treatment methods that are both innovative and advanced in their ability to effectively remove a wider range of contaminants, such as persistent organic pollutants and pathogens (Gaur et al., 2018; Guerra-Rodríguez et al., 2023). The incorporation of emerging technologies, such as nanotechnology, membrane filtration, and advanced oxidation processes, has the potential to significantly improve the overall quality of treated wastewater (Baaloudj et al., 2022). Implementing more sustainable practices in the use of wastewater is particularly important in arid and semi-arid regions, where the focus should be on building dedicated plants specifically designed for agricultural and landscape irrigation purposes (Rusănescu et al., 2022). Table 1 summarizes, based on the literature, various risks of reusing wastewater in agriculture, including their potential impacts and possible mitigation strategies.

Perspectives

The complexity of using wastewater for agricultural irrigation requires a comprehensive, multi-faceted strategy. Long-term studies to achieve sustainable food production are of great importance, especially when it comes to evaluating the rates at which carbon, nitrogen and phosphorus are converted (Powlson et al., 2011). Global monitoring of organic persistent emerging contaminants and pathogens in irrigated soils has the potential to provide effective strategies for pollution reduction. Understanding the environmental fate of emerging contaminants and identifying harmful by-products of wastewater in soils is essential for conducting a thorough risk assessment. In parallel, understanding the impact of biologically active, pseudopersistent pharmaceuticals in reclaimed water on agricultural ecosystems and the implications for integrated pest management practices must be a research priority. In addition, developing cost-effective wastewater treatment systems and improving water quality at the source are critical to promoting sustainable wastewater reuse in agricultural practices, thereby protecting environmental integrity and human health (Obaideen et al., 2022). It is appropriate to use innovative and advanced tertiary wastewater treatment based on disinfection and decontamination in accordance with the guidelines of the Clean Water Act or of the Water Framework Directive of the European Parliament and Council, which aims to combat water pollution.

TABLE 1 Risks of using wastewater in agriculture and current mitigation strategies.

Risk factor	Description	Potential impact	Mitigation strategies	Reference
Pathogens and microbes	Contamination of crops with enteric viruses, fecal coliforms, bacterial pathogens, and parasites	Diarrheal, intestinal parasitic, and skin infections	Use a tertiary treatment based chlorine and peracetic acid	Collivignarelli et al. (2017)
			The use of membrane bioreactor	Friedler et al. (2006)
			Cessation of irrigation before harvesting	Keraita et al. (2007)
Pesticide residues	Migration and distribution of pesticides in different parts of the crops (soil, fruit, and leaves)	Human exposure to pesticides	Diversifying biocontrol strategies, include functional biodiversity	Jacquet et al. (2022)
Organic contaminants	Presence of organic contaminants in crops grown	Spread of contaminants of emerging concern	Use of constructed wetlands	Santos et al. (2019)
			Use of advanced oxidation techniques such as ozonation, adsorption, and filtration	Shakir et al. (2017)
Heavy metals	Accumulation of heavy metals in soil and crops	Potential carcinogenic risks to humans and crop toxicity	Use of effective wastewater treatment	Aslam et al. (2023)
			Apply appropriate permanent monitoring, periodical water analysis and pollution control	Othman et al. (2021)
			Monitor the wastewater irrigation system	Khan et al. (2023)
			Soil remediation and control its quality	Khan et al. (2008)
High salinity	Soil salinization which significantly affects crop yields	Soil degradation, decreased area of cultivated land and reduced crop productivity	Improved irrigation practices and installation of artificial drainage system	Chen et al. (2013)
			Use of Brackish-Reclaimed Water (RBCI treatment)	Liu et al. (2023)
			Understanding and managing the impact of salinity in reclaimed water	Cheng et al. (2021)

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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