

Innovative Approaches and AI Applications in Agricultural Reuse of Urban Treated Wastewater

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Abstract

There are increasing effects of climate change and growing urbanization on depleting freshwater supplies worldwide, making sustainable water reuse solutions critically necessary. Urban-origin treated wastewater offers a viable alternative source for agricultural irrigation; however, its application must be carefully managed to ensure safety and efficiency. This review explores cutting-edge methods and the integration of artificial intelligence (AI) to enhance the use of urban treated wastewater in farming. It reviews the latest advancements in treatment techniques such as membrane bioreactors, advanced oxidation processes, and eco-engineered systems, coupled with AI-based tools for forecasting water quality, optimizing irrigation schedules, and evaluating potential hazards. Predictive models using machine learning and deep learning have demonstrated considerable potential in anticipating contaminant removal rates, improving treatment operations, and maintaining compliance with irrigation standards. The review also highlights challenges, including limited datasets, model transparency, and regulatory considerations, emphasizing the necessity for cross-disciplinary collaboration. Collectively, applying AI alongside innovative wastewater management strategies can support sustainable water practices and foster climate-resilient agricultural systems.

Keywords: Agricultural irrigation, AI-driven irrigation, Climate change, Water quality, Wastewater reuse

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INTRODUCTION

The increasing scarcity of freshwater resources, driven by population growth, rapid urbanization, and climate change, has positioned treated wastewater (TWW) as a critical alternative water source for irrigation (Qadir et al., 2020). Globally, agriculture accounts for nearly 70% of freshwater withdrawals, and in many arid and semi-arid regions, the reuse of TWW has become a strategic solution to balance water supply and food production (FAO, 2021). Wastewater reuse is underappreciated worldwide, despite its many advantages. Just 11% of wastewater produced worldwide and 2.4% of treated trash in the EU were reused in 2020 (Jones et al., 2021). Some studies attribute this low adoption to various barriers, including social acceptance and trust issues, concerns about political and environmental consequences, costs, and inconsistent regulations regarding water and nutrient reuse. Vinasse, municipal wastewater, olive mill wastewater, and pig and cow wastewater are examples of wastewaters that may be recycled into agricultural goods. Some, like landfill leachate, should be utilized carefully, though, since they may be high in nutrients and organic matter but may also include pollutants like microplastics that can harm soil (Canaj and Mehmeti, 2024).

Technological advances have increased the potential in this area: membrane bioreactors (MBR), advanced oxidation processes (AOP), constructed wetlands, and similar nature-based systems provide significant progress towards improving the quality of treated water and making it suitable for reuse (Saravanan et al., 2022; Biswal and Balasubramanian, 2022). Designing these technologies within a “fit-for-purpose” framework requires ensuring suitability for different water use scenarios such as irrigation, landscaping, and non-landscape use. In addition, the reuse of urban TWW raises significant concerns regarding health risks and environmental impacts, especially contaminants such as microbial pathogens, heavy metals, pesticide residues, antibiotics, and antibiotic resistance genes (Amahmid et al., 2023; Qadir et al. 2007). The effects of toxic metals accumulated in soil on human health through long-term consumption, including crop quality, soil structure

stability, and groundwater contamination, are critical, though less studied, particularly in low- and middle-income countries (Dickin et al., 2016).

Artificial intelligence (AI) and machine learning (ML) techniques can play critical roles in this context: in applications such as water quality prediction, pollutant removal optimization, process control, online monitoring, modeling the behavior of micropollutants remaining after biological treatment, and irrigation scheduling. For example, in the study conducted by Köksal et al. (2025), the suitability of treated water for agricultural use was estimated with high accuracy using Artificial Neural Networks (ANN), Adaptive Neuro-Fuzzy Inference System (ANFIS), and Fuzzy Logic (FLM) combinations; approximately 69-72% availability and 35% irrigation potential of 20,000 hectares of agricultural land were determined. The prevalence of ML applications has increased significantly in recent years: bioreactor control, process optimization, fault diagnosis, and water quality classification, to name a few. Policy and regulatory frameworks are also evolving to support these technological advancements. The European Union's "Minimum Requirements for Water Reuse" regulation (Regulation (EU) 2020/741), which establishes standard quality criteria, monitoring requirements, and risk management plans for the reuse of urban wastewater for agricultural irrigation, entered into force on June 26, 2023. However, practical implementation still faces limitations:

- **Lack of data:** Continuous and reliable monitoring data are not sufficiently available in every region. This scarcity of data, particularly for parameters such as micropollutants, antibiotic resistance genes, and dose-response relationships of pathogens, limits modeling.

- **Model interpretability:** AI/ML models are often perceived as “black boxes,” which can create trust issues for decision-makers.

- **Implementation scalability and cost:** Using advanced technologies for small businesses or in regions with poor infrastructure can require high capital and operating costs.

- **Policy and regulatory compliance:** Water reuse standards, permitting processes, monitoring, and enforcement mechanisms vary across countries, creating challenges for international or regional cooperation and comparability.

The aim of this article is to present the current status in depth and systematically present future research gaps and recommendations by considering innovative engineering approaches, AI/ML-based applications, health and environmental risks, and regulatory-policy frameworks for agricultural reuse of urban treated wastewater.

Significance of Treated Wastewater in Irrigation

Treated wastewater offers two advantages: it helps recycle nutrients and offers a consistent supply of water. For instance, total nitrogen 5.84–12.00 mg L⁻¹, total phosphorus 0.03–0.35 mg L⁻¹, and chloride 144–1770 mg L⁻¹ are all present in high proportions in treated wastewater (Li et al., 2025). In a previous study that evaluated treated wastewater, the levels of TDS, chlorine, total nitrogen, and total phosphorus were 1062 mg L⁻¹, 250 mg L⁻¹, 20 mg L⁻¹, and 2.3 mg L⁻¹, respectively (Ansari et al., 2018). There are also other studies that exemplify the positive effects of using treated wastewater for agricultural irrigation on yield and fertilization (Uzen et al., 2016; Adalı and Kılıç, 2020). Through the use of treated wastewater, farmers may cut their production costs by using these nutrients, which are essential for crop development, instead of expensive chemical fertilizers. Studies have shown that the use of secondary or tertiary TWW in irrigation can enhance soil fertility, improve crop yields, and support sustainable agricultural practices without compromising food safety when managed properly (Carpanez et al., 2024). From an environmental perspective, wastewater reuse contributes to circular water economy principles, reducing the discharge of effluents into natural water bodies and mitigating eutrophication risks (Jones et al., 2021). Moreover, by reducing freshwater extraction from rivers and aquifers, it helps preserve ecological balance and groundwater sustainability (Cordeiro et al., 2023). In regions like the Mediterranean Basin, the Middle East, and North Africa, the practice of wastewater reuse in agriculture has become a cornerstone of national water strategies, providing resilience against droughts and seasonal variability (Frasconi et al., 2018). However, the benefits of TWW reuse can only be realized under adequate treatment and monitoring regimes. Inadequately TWW poses risks of salinity build-up, heavy metal accumulation, and pathogen contamination, which may affect both crops and human health (Toze, 2006). Therefore, effective treatment processes such as MBRs, AOPs, and constructed wetlands are essential to meet irrigation water quality standards (Yılmaz et al., 2020). Beyond technical aspects, social acceptance and regulatory frameworks play crucial roles in promoting wastewater reuse for irrigation. Public perception often associates wastewater with health hazards, emphasizing the need for awareness campaigns, farmer training, and clear safety regulations (Alzahrani et al., 2023). The integration of smart technologies, including AI and the Internet of Things (IoT), can further enhance monitoring, control, and adaptive management of TWW systems, ensuring safe and efficient irrigation practices (Alprol et al., 2024). Overall, reusing TWW for irrigation represents a transition to sustainable, resource-efficient, and climate-resilient agriculture. This not only addresses water scarcity but also contributes to many Sustainable Development Goals (Khan et al., 2022).

Reduction of Environmental Pollution

The growing use of TWW for irrigation is strongly influenced by a set of environmental drivers that stem from the global challenges of water scarcity, climate change, and ecosystem degradation. These pressures are prompting a shift from traditional linear water management toward circular and adaptive reuse strategies (Fernandes and Cunha, 2023). Discharging untreated or partially treated wastewater into natural water bodies contributes to eutrophication, microbial contamination, and the degradation of aquatic ecosystems (Jiménez and Asano, 2015). Reusing wastewater in agriculture instead of direct disposal helps reduce pollutant loading into rivers and lakes, thereby improving downstream water quality and protecting aquatic biodiversity (FAO, 2021). Moreover, the reuse of wastewater can contribute to reducing greenhouse gas (GHG) emissions from conventional wastewater treatment by lowering energy demand for nutrient removal (Falk et al., 2013). By decreasing freshwater withdrawals from rivers and aquifers, wastewater reuse alleviates stress on aquatic ecosystems and groundwater-dependent habitats (Luthy et al., 2015). It contributes to maintaining environmental flows, which are essential

for preserving biodiversity and ecosystem services. In water-scarce regions, integrating TWW reuse into agricultural systems supports both human water security and ecosystem resilience (Al-Hazmi et al., 2023).

In the reuse of treated wastewater for agricultural irrigation, color removal is a critical parameter for both environmental safety and water quality. Membrane technologies, such as nanofiltration and reverse osmosis, effectively remove coloring compounds and significantly improve water quality; recent studies report that nanofiltration membranes modified with metal oxide nanocomposites can remove dyes up to 98% (Elfiky et al., 2024). Electrocoagulation is also highlighted as an efficient method for treating wastewater, with removal efficiency depending on electrode type, current density, and operational time (Rakhmania et al., 2022). Chemically, AOPs effectively degrade resistant chromophoric compounds through hydroxyl radicals, achieving high decolorization efficiencies (Wypart-Pawul et al., 2023). Moreover, hybrid strategies combining electrocoagulation with photocatalytic oxidation, especially when paired with advanced catalysts have shown synergistic improvements in both color and total organic carbon (TOC) removal (Rakhmania et al., 2022). Overall, combining these methods in a fit-for-purpose strategy allows optimization according to water quality targets and economic constraints.

In summary, the environmental drivers of TWW use in irrigation are multidimensional and interconnected. They encompass climate adaptation, resource recovery, pollution control, and ecosystem conservation, all central pillars of sustainable development. The reuse of TWW not only mitigates environmental degradation but also contributes to long-term climate resilience and agroecological sustainability.

Health Risks

Although the reuse of treated wastewater for agricultural irrigation offers significant advantages in protecting water resources, the literature highlights the potential for various adverse health effects. First, it has been shown that microbial pathogens (*Escherichia coli* (*E. coli*), *Salmonella* spp., enteric viruses, and helminth eggs) can be transmitted to crops or soil via irrigation water due to inadequate treatment or fluctuations in treatment efficiency (Amahmid et al., 2023). The transfer of these pathogens, particularly to raw vegetables, significantly increases the risk of infection. Furthermore, it has been reported that heavy metals (Cd, Pb, Cr, and Ni) can be transported to soil via treated wastewater and accumulate in plants, potentially leading to serious health consequences such as neurotoxicity, kidney damage, and carcinogenic effects with long-term consumption (Dickin et al., 2016). Furthermore, pharmaceutical residues, pesticide metabolites, personal care products, and other micropollutants, which are increasingly detected in wastewater, significantly exceed biological treatment, suggesting that these substances can cause endocrine-disrupting or genotoxic effects even at low doses (Latosińska and Grdulska, 2025). Another important risk is that the presence of antibiotics and antibiotic resistance genes (ARGs) in treated wastewater can increase resistance transmission in soil and plant microbiomes, thus contributing to the critical problem of antimicrobial resistance in public health (Amahmid et al., 2023; Qadir et al., 2025). The literature also indicates that long-term irrigation with waters, particularly those high in conductivity and sodium, can lead to ion accumulation in plant tissues, creating mineral imbalances for human consumption (Li et al., 2025). The combination of these risks demonstrates that appropriate treatment technology selection, continuous quality monitoring, product-based risk management, and consumer safety measures are vital in the reuse of treated wastewater.

Economic Benefits

Using treated water for agricultural irrigation provides financial benefits to producers, communities, and regional development (Dotaniya et al., 2023). Agricultural production is increased by the nutrients and organic matter present in treated wastewater, which enhance soil fertility (Musazura et al., 2019). The amount of nutrients in the treated wastewater used for irrigation and the type of crops grown directly affect the yield obtained (Hashem and Qi, 2021). For instance, when treated wastewater was used instead of groundwater for irrigation, the yields of eggplant, cucumber, tomato, and kidney beans increased by 61%, 24%, 15%, and 7%, respectively (Wu et al., 2010). Another study found that irrigation with treated wastewater increased biomass production and some growth parameters (plant height and leaf area) in energy crops (Zema et al., 2012). Urbano et al. (2017) reported a minimum 48% higher yield relative to traditional irrigation, showing that the nutrients present in treated wastewater were adequate to sustain plant growth. Farmers can lower their use of synthetic fertilizers and water supply costs by using treated wastewater for irrigation. In places where water is scarce or in great demand, this water can be more affordable or subsidized than freshwater. Additionally, treated wastewater enables agricultural enterprises to comply with sustainability and water management regulations (Shanmugam et al., 2022).

Determining the most suitable treatment method for the use of treated wastewater in agriculture requires evaluating the economic feasibility of different technologies, as each option differs in terms of capital expenditure (CAPEX), operation and maintenance costs (OPEX), energy requirements, and land needs (Gao et al., 2022; Wahid et al., 2024). For instance, membrane bioreactors (MBRs) provide high-quality water but are costly due to high energy consumption and the need for membrane replacement (Gao et al., 2022). Advanced oxidation processes (AOPs) are effective for removing micropollutants; however, their high chemical and energy demands make them economically suitable only in special cases (Foglia et al., 2021). Conventional biological treatment systems offer moderate water quality while maintaining lower costs, making them generally a balanced solution for agricultural irrigation (Foglia et al., 2021). Nature-based solutions, particularly constructed wetlands, provide low energy and operational costs but may not be feasible in all regions due to high land requirements and seasonal performance variability (Wahid et al., 2024). Additionally, low-cost tertiary treatments such as filtration and disinfection can be combined with conventional systems to improve water quality while keeping costs manageable (Foglia et al., 2021). Therefore, the literature emphasizes that the most economically appropriate approach is often based on the “fit-for-purpose” principle, selecting optimized combinations of conventional biological treatment and low-cost tertiary or nature-based systems according to the required water quality for agricultural use (Wahid et al., 2024).

Reuse Trends by Country and the Potential of Treated Wastewater for Agronomic Applications

The reuse of TWW for agricultural purposes varies widely across the world, reflecting differences in climatic conditions, water availability, regulatory frameworks, and technological infrastructure. In recent years, several countries have adopted strategic policies to incorporate wastewater reuse into their national water security and food sustainability agendas (Mizyed, 2025). Israel remains the world leader in wastewater reclamation, reusing over 85% of its TWW for agricultural irrigation (Obijanya et al., 2025). The country’s success stems from its advanced MBR systems, strong governance, and public acceptance. The Shafdan wastewater treatment plant alone treats over 370,000 m³/day of municipal wastewater and supplies reclaimed water to the Negev desert for high-value crop cultivation (Messing and Sela, 2016). AI-driven monitoring systems are increasingly used to optimize irrigation scheduling and ensure microbial safety (Liu et al., 2025). Spain leads Europe in this field, reusing approximately 71% of its treated wastewater. However, in some regions, this rate can exceed 25%. For example, the Baix Llobregat wastewater treatment plant processes 400,000 m³ of wastewater daily, reusing 95% of it. This plant uses treated water for various purposes, including agricultural irrigation, drinking water production, and biogas production (Ortega and Iglesias 2009). Reuse projects in regions such as Murcia and Valencia integrate tertiary treatment, UV disinfection, and real-time monitoring for irrigation of orchards and vineyards. Spanish regulations (Royal Decree 1620/2007) set strict quality standards for agricultural reuse, aligning with the EU Water Framework Directive (Verónica Carabias et al., 2023). In the United States, wastewater reuse for irrigation is growing, particularly in water-scarce states such as California, Arizona, and Florida. California alone reuses over 700 million m³/year, primarily for landscape and agricultural irrigation (Luthy et al., 2020). The focus is on decentralized treatment systems and the adoption of IoT-enabled smart irrigation networks (Kisekka, 2024). India and China, which together produce over 25 billion m³ of municipal wastewater annually, hold immense potential for wastewater reuse but still face infrastructural and policy barriers (Qadir et al., 2025). In India, less than 10% of wastewater is safely reused, but pilot projects in Gujarat and Tamil Nadu are showcasing large-scale agricultural reuse initiatives supported by public–private partnerships (Bassi, 2023). China’s “Water Ten Plan” emphasizes wastewater treatment and resource recovery, with AI-assisted monitoring systems now being piloted in several industrial–agricultural clusters (Qu et al., 2022). In the arid MENA region, wastewater reuse has become an environmental necessity rather than an option. Countries such as Saudi Arabia, Jordan, and the United Arab Emirates have integrated reuse into national water policies, with reuse rates reaching 30–40% (Mateo-Sagasta et al., 2022). Jordan’s As-Samra plant reuses nearly 90% of its effluent for irrigation, providing a sustainable source of water for the Jordan Valley (Almanaseer et al., 2020). Turkey generates approximately 3 billion m³ of municipal wastewater annually, of which only a small portion (about 2–3%) is reused, primarily for irrigation and industrial cooling (TÜİK, 2023). However, the Turkish National Water Plan (2019–2023) and the Zero Waste Blue initiative emphasize the reuse of TWW to mitigate water scarcity in the face of climate change (Nas et al., 2020). Several pilot projects, including those in Konya and Şanlıurfa, demonstrate the technical feasibility of TWW reuse for irrigation of cereals and horticultural crops (Çay and Kanber, 2013).

Table 1. Reuse patterns by country and the possible applications of TWW in agriculture.

Country/Region	Reuse Rate (% of TWW)	Main Application	Technological Focus	Policy/Framework
Israel	>85%	Agricultural irrigation	MBR, UV disinfection, AI monitoring	National Water Reuse Strategy
Spain	20–25%	Orchard & vineyard irrigation	Tertiary + AI-based control	EU Directive & Royal Decree 1620/2007
USA	~15%	Agriculture & landscaping	IoT, AI decision-support systems	State-level reuse guidelines
China	~10%	Agriculture & industrial reuse	AI-based water management	“Water Ten Plan”
India	<10%	Crop irrigation (pilot-scale)	Low-cost hybrid systems	National Sanitation Policy
MENA (avg.)	30–40%	Irrigation of cereals & forage crops	Digital twins, desalination integration	National Reuse Strategies
Turkey	2–3%	Pilot agricultural reuse	Sensor-based monitoring, MBR	National Water Plan (2019–2023)

The data reveal that while advanced economies such as Israel and Spain lead in large-scale reuse due to robust infrastructure and governance, emerging economies hold significant untapped potential. With continued investment in AI technologies, smart monitoring, and regulatory harmonization, global agricultural reuse could increase by 60–70% by 2050 (WWAP, 2023).

Innovative Approaches in Agricultural Reuse of Urban Treated Wastewater

TWW is an essential alternative water supply that improves resource sustainability in the global context of growing water shortages and climate sensitivity. Reducing reliance on current groundwater and surface water supplies and preserving the biological life of these water bodies are two benefits of using TWW for irrigation (Koyuncu and İmer, 2016). Using TWW for irrigation has several advantages as long as the required treatment procedures and technical procedures are followed. These include offering a substitute water source during dry seasons; lowering the pollution load of surface water resources; treating wastewater further before it mixes with groundwater; lowering the need for artificial fertilizers because TWW satisfies the soil’s organic matter requirements; facilitating the cost-effective and environmentally friendly disposal of urban wastewater; and relieving pressure on water consumption by recycling a potentially wasted resource (Belhaj et al., 2016). Producing irrigation-quality water from domestic wastewater requires advanced treatment technologies capable of removing

organic contaminants, nutrients, pathogens, and emerging pollutants such as pharmaceuticals and microplastics (Mansouri et al., 2021). While conventional secondary treatment can reduce biochemical oxygen demand (BOD) and suspended solids (SS), it is insufficient to meet the microbiological and chemical standards required for safe agricultural reuse. Hence, tertiary and quaternary treatment processes including membrane filtration, advanced oxidation, adsorption, and disinfection, have become essential components of modern reuse systems (Qadir et al., 2020). Recent research emphasizes hybrid systems integrating physical, chemical, and biological processes to maximize removal efficiency while minimizing environmental impacts (Jiao et al., 2022). A comparative summary of major technologies is shown below:

Membrane-Based Technologies: Membrane processes, such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO), offer high-quality effluent suitable for irrigation by effectively removing suspended solids (SS), bacteria, and dissolved salts. UF and NF systems are increasingly integrated into municipal treatment plants to meet WHO and FAO reuse standards. For instance, UF membranes combined with UV disinfection have achieved up to 99.99% removal efficiency of *E. coli* in reclaimed water used for drip irrigation, demonstrating their suitability for agricultural applications (Mazuki et al., 2020). However, membrane fouling and energy consumption remain major operational challenges, as fouling mechanisms such as pore blocking, biofilm formation, and scaling can significantly reduce flux and increase maintenance costs (AlSawaftah et al., 2021). In response, recent studies have explored AI-driven predictive maintenance and fouling control models, utilizing ML, explainable AI, and feature engineering techniques to predict fouling behavior and optimize cleaning schedules (Liang et al., 2025).

Advanced Oxidation Processes (AOPs): AOPs such as ozonation (O_3), UV/ H_2O_2 , and Fenton-based systems can degrade recalcitrant organic compounds and emerging pollutants that persist through conventional biological treatment (Pandis et al., 2022). These technologies are particularly useful in removing endocrine-disrupting chemicals and pharmaceutical residues from effluent intended for high-value crops. AOPs are often coupled with activated carbon or membrane filtration to enhance overall treatment performance (Ghaedi et al., 2025). AI and ML algorithms have recently been employed to optimize AOP operational parameters, such as oxidant dosage and contact time, minimizing both energy use and by-product formation (da Costa et al., 2025).

Adsorption and Ion Exchange Techniques: Activated carbon (GAC and PAC) adsorption remains one of the most effective polishing steps for removing trace organics, color, and odor. Emerging adsorbents, such as biochar, zeolites, and metal-organic frameworks (MOFs), offer improved regeneration and cost-effectiveness (Krajčovičová et al., 2023). In agricultural reuse, these technologies ensure compliance with irrigation water quality guidelines regarding chemical oxygen demand (COD) and total dissolved solids (TDS) (Ghaedi et al., 2025). Moreover, the integration of AI-assisted modeling enables real-time adsorption capacity prediction and breakthrough curve optimization (Lakshmi et al., 2021).

Biological Nutrient Removal (BNR) and Constructed Wetlands: For nutrient management, biological nutrient removal (BNR) processes such as anoxic–aerobic sequencing batch reactors (SBRs) and MBRs are widely applied to reduce nitrogen and phosphorus in reclaimed water (Liu et al., 2017). MBRs, in particular, combine biological degradation with membrane separation, producing effluent suitable for unrestricted irrigation. Constructed wetlands (CWs) offer a low-cost, nature-based alternative, using plant–microbe interactions for pollutant removal. Hybrid CWs integrating AI-based monitoring systems have achieved nutrient removal efficiencies above 90% while maintaining ecological sustainability (Xu and Liu, 2025).

Disinfection and Pathogen Inactivation: Ensuring microbial safety is crucial for reuse applications. Chlorination, ozonation, and UV irradiation are the most common disinfection methods. Recent advances include electrochemical disinfection and UV-LED systems, which provide efficient pathogen inactivation with minimal chemical by-products (Augsburger et al., 2021).

Hybrid and Integrated Systems: The most promising configurations combine multiple Technologies e.g., MBR–UV–AOP or UF–activated carbon ozone to achieve comprehensive pollutant removal and pathogen control. These integrated systems can produce effluent of near-potable quality, suitable for sensitive crops or aquifer recharge (Asheghmoalla and Mehrvar, 2024). AI-driven decision-support tools are now being incorporated into hybrid systems for process optimization, anomaly detection, and predictive control, thus ensuring consistent irrigation-quality water (Zamfir et al., 2025). A summary of technological advances in wastewater treatment for agricultural reuse is shown in Table 2.

A literature summary of studies conducted worldwide on innovative approaches to agricultural reuse of urban treated wastewater is given below.

Innovative wastewater management technologies could allow for the reusing of roughly 50 billion m^3 of water annually to alleviate water scarcity, according to a study that looked at creative approaches to biological, physicochemical, and membrane-based processes for sustainable wastewater management. Additionally, energy recovery from these processes could lead to 20 TWh in energy savings annually (Ulusoy et al., 2024). Around the world, 72% of freshwater resources are used for agriculture. It is anticipated that this sector's water supply-demand imbalance would grow as a result of growing water supply pressure and unmet water demand. Water availability is increased and freshwater usage is decreased when TWW reuse is used as an alternative agricultural water source. Its implementation is contingent upon its societal acceptance and safety. Effluent from two WWT plants in the Bekaa was characterized to evaluate the quality, environmental, and health risks of TWW reuse for irrigation reuse in order to ascertain the willingness of Lebanese farmers in the Bekaa Valley and consumers in the larger Lebanese communities to use safe TWW reuse in agriculture at large. The findings showed that farmers and consumers were quite eager to utilize and accept the usage of safe TWW reuse for irrigation (Hajjar et al., 2025). In order to explore the possibility of using MBR technology for agricultural irrigation in Granada, Spain, quality characteristics of wastewater treated with this technique were examined. According to the findings, wastewater treated using MBR technology has quality characteristics that are appropriate for agricultural irrigation, providing a possible way to

manage water resources sustainably (Bermúdez et al., 2024). Aeration, sedimentation, and artificial wetlands are examples of natural treatment techniques for wastewater. Their applicability in agricultural irrigation was examined, and it was determined that natural systems effectively treat wastewater and produce water quality appropriate for safe use in agricultural irrigation (Shamshad, J. and Rehman, 2025). In agriculture, it is preferable to repurpose TWW for agricultural irrigation. The characteristics of the TWW and the intrinsic and extrinsic qualities of the soil determine how plants react to TWW irrigation. Muscarella et al. (2024) examined how tomatoes cultivated in five distinct soil types responded to TWW irrigation using both an inorganic NPK solution and tap water. The findings showed that TWW is a useful tool for agricultural irrigation. The potential of treated wastewater to improve soil fertility and decrease the usage of chemical fertilizers was evaluated in a research looking at its suitability for agricultural irrigation. It has been noted that applying treated wastewater improves soil fertility, which in turn boosts agricultural output (Obijanya et al., 2025). In Colombo, Sri Lanka, the effects of urban agriculture methods on wastewater treatment and reuse were investigated. By boosting public acceptability, urban agriculture was found to be an efficient wastewater treatment technique that also supports sustainable water management (Dona et al., 2025). Portugal's potential for increasing wastewater reuse was evaluated, with particular attention to the Tagus River and the Ribeiras do Oeste Basins. Eight large WWT plants were found that have a lot of potential to be used again for irrigation in the tourism and agriculture industries. Five treatment lines, including filtration and disinfection techniques, were examined in the study along with prices, quality standards, and technical choices. The results demonstrated that the cost of recovered water may be reduced by up to €1.66/m³, be competitive with other water sources, and vary from €0.02/m³ to €0.83/m³. According to Areosa et al. (2024), the planned reuse projects have the potential to minimize the water requirements of almost 2,000 hectares of golf courses and agricultural land, quadrupling regional reuse rates and doubling national rates. In semiarid areas, water shortage is becoming a bigger issue. Since TWW is a readily available and reasonably priced water supply, many farmers have turned to it. In a two-year research, Abou Jaoude et al. (2025) examined the effects of irrigating maize and potatoes using secondary and tertiary TWW as opposed to freshwater. TWW reuse's effects on crop output, soil microorganisms, soil characteristics, and potato tuber health were examined. It was shown that using TWW to irrigate potatoes and maize greatly improved soil fertility and organic matter content without causing heavy metal contamination, but it also had a detrimental effect on salinity and microbial contamination. To overcome these obstacles, the need of TWW management and monitoring is thus underlined. An investigation on the role of treated wastewater from Ethiopia's Bole-Lemi Industrial Park in agricultural sustainability examined the nutrients (phosphorus and nitrogen) in the wastewater to evaluate its economic and water security benefits. The outcomes demonstrated that TWW improved soil nutrient enrichment, decreased fertilizer expenses, and enhanced water security in agricultural output (Ebissa et al., 2025). A thorough plan to tackle the problems of growing water shortages brought on by urbanization and climate change was created by a research looking at the sustainable integration of treated wastewater into municipal water management systems. According to the study's findings, integrating TWW provides a thorough plan for guaranteeing that everyone has access to clean water (Michalopoulos and Kalavrouziotis, 2025).

Table 2. Comparison of advanced wastewater treatment technologies for irrigation water production.

Technology	Target Pollutants	Advantages	Limitations	AI Integration Potential
Ultrafiltration (UF) / Nanofiltration (NF)	Suspended solids, pathogens, salts	High-quality effluent, compact design	Fouling, high energy cost	Predictive maintenance, fouling control
Advanced Oxidation (O ₃ , UV/H ₂ O ₂)	Micropollutants, pharmaceuticals	Effective oxidation, disinfection	By-product formation, high cost	Process optimization, dosage control
Adsorption (GAC, biochar, MOFs)	Trace organics, color, odor	Low-cost, regenerable adsorbents	Limited capacity, regeneration need	Breakthrough prediction, capacity modeling
BNR / MBR	Nutrients (N, P), organics	High nutrient removal, stable effluent	Membrane fouling, sludge production	AI for process control, aeration optimization
Constructed Wetlands	Organics, nutrients, pathogens	Low energy, ecological benefits	Land-intensive, variable performance	AI-assisted nutrient removal monitoring
UV / Electrochemical Disinfection	Pathogens, viruses	Chemical-free, quick response	High capital cost	Real-time microbial risk prediction
Ultrafiltration (UF) / Nanofiltration (NF)	Suspended solids, pathogens, salts	High-quality effluent, compact design	Fouling, high energy cost	Predictive maintenance, fouling control

These reviewed studies underscore that the agricultural reuse of urban TWW has evolved from a supplementary water management strategy into a central pillar of sustainable resource governance under conditions of water scarcity and climate stress. Innovative treatment technologies ranging from membrane bioreactors and natural treatment systems to hybrid physicochemical processes have demonstrated their capability to produce effluents that meet irrigation standards while simultaneously contributing to energy recovery and nutrient recycling. Empirical findings from diverse regions such as Lebanon, Spain, Sri Lanka, Portugal, and Ethiopia reveal a strong correlation between TWW use and improvements in soil

fertility, crop productivity, and economic efficiency, alongside high levels of societal acceptance when safety and quality are ensured. However, challenges related to salinity, microbial contamination, and long-term soil health persist, emphasizing the importance of continuous monitoring, adaptive management, and robust governance frameworks. Overall, the integration of TWW into agricultural systems represents a technically feasible, economically viable, and environmentally sound approach to achieving circular water use. When supported by innovation, public engagement, and policy alignment, it holds substantial promise for advancing water security, climate resilience, and sustainable food production in the coming decades.

AI Applications in Agricultural Reuse of Urban Treated Wastewater

Reusing wastewater for irrigation is a crucial way to address the freshwater shortage and food crises brought on by population expansion and climate change, and it aligns with the ideas of sustainable development and a circular economy. However, the complex nonlinearities in wastewater reuse are difficult for existing methodologies to handle, which prevents their widespread adoption. The complex dynamics of irrigation and wastewater treatment two crucial phases in wastewater reuse can be efficiently captured and managed by artificial intelligence (AI), which makes it a viable technology for further advancement. With an emphasis on technological constraints, regulatory incompatibilities, and implementation gaps, this paper seeks to critically analyze the use of AI in wastewater treatment and agricultural reuse. An overview of research on AI applications in agricultural reuse of urban treated wastewater is provided below. Figure 1 shows artificial intelligence technologies commonly used in wastewater treatment research.

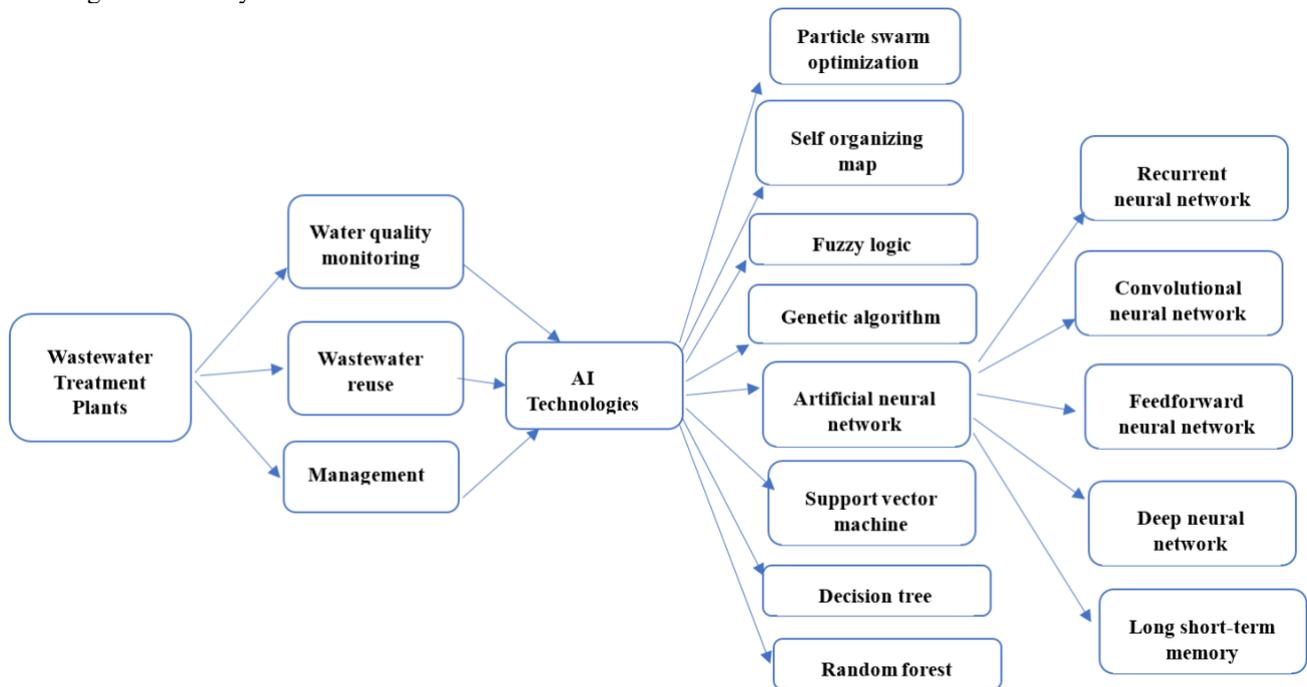


Figure 1. Artificial intelligence applications in wastewater treatment plants.

The use of AI applications in water and wastewater (prediction, optimization, monitoring, and IoT integration) was systematically reviewed in a literature review and application categorization (soft-sensor, treatment optimization, early warning, and decision-support). The study found that AI can greatly improve treatment performance and reuse potential (particularly with quality prediction and online monitoring); however, regulations, data quality, and model transferability remain challenges (Alprol et al., 2024). The most popular applications were effluent parameter estimation, membrane system fouling estimation, and online sensor soft-sensor development, according to a study that classified commonly used methods, reviewed publications, and evaluated field analysis in order to bibliometrically analyze the growth trends of AI applications in wastewater treatment and which algorithms are applied to which problems. These findings reinforced the scientific infrastructure of quality estimation and risk reduction studies for agricultural reuse (Baarimah et al., 2024). Table 3 presents the AI and machine learning applications used to optimize the reuse of treated wastewater for agricultural irrigation, along with the treatment types and key findings.

Using IoT sensors and ML, an automated irrigation decision system was created to improve water conservation in agriculture by analyzing sensor data gathered from fields, such as temperature and humidity. It has been proposed that such systems can facilitate the automated and secure use of treated wastewater in regulated regions, and the decision tree-based model showed good accuracy in irrigation start/stop choices (Aydn et al., 2021). Several ML models were trained using chemical properties and process data for 149 pharmaceuticals and personal care products (PPCPs), and classification/regression models were employed in order to predict the removal efficiency of numerous PPCP compounds monitored in treatment processes, thus aiding in the determination of which effluents are suitable for agricultural use. According to the findings, the ML models contributed to a risk-based evaluation of the circumstances in which treated wastewater is appropriate for use in agriculture by accurately forecasting the removal rates of particular PPCPs after treatment (Choi et al., 2025). The effects of treated wastewater on crop development and soil physicochemical properties, and its suitability for agricultural irrigation (WWTP: secondary wastewater and membrane wastewater) were evaluated. Loamy soil was used to produce carrot seedlings, and the seedlings were then irrigated until maturity using tap water,

secondary wastewater, and membrane wastewater. Bacteriological examinations revealed four log counts of *E. coli* and thermotolerant coliforms in the secondary wastewater, making its use for carrot irrigation hazardous. Although it has been suggested that the use of treated wastewater for agricultural irrigation can increase food production and reduce over-dependence on freshwater resources, it has been reported that WWTP should be disinfected using ozonation and UV disinfection to reduce the risk of microbial contamination (Ofori et al., 2024). Hybrid and ensemble ML techniques, including Hammerstein–Wiener, were used in a study that sought to lower crop and method selection risks by accurately estimating the salinity of treated wastewater used for irrigation (a crucial parameter). Field data was gathered from water samples. It was determined that the application was helpful for assisting judgments about the usage of treated wastewater in water-stressed areas and that the AI-ensemble techniques performed well in salinity estimate (Shah et al., 2024). Water quality indices (IWQI, etc.) for irrigation usage were estimated and classified using a variety of ML methods (RF, SVM, XGBoost, and NN) in order to automate irrigation appropriateness judgments. For unbalanced datasets, some techniques (ensemble, oversampling) were used. According to the findings, properly-trained models performed well in IWQI classification and could automatically identify the agricultural uses of treated water, which would support risk-based management (El Bilali and Taleb, 2024). A research sought to make short-term dynamic projections of wastewater treatment facility discharge volumes in order to improve distribution/irrigation plans. Time-series separation integration and an enhanced transformer design were used to provide short-term forecasts. According to Sun et al. (2024), the model improves water planning for agricultural use by offering precise projections that may be used for choices about water allocation and distribution planning in real-time. ML models were developed utilizing full-scale and laboratory-scale data covering process types and characteristics in order to enhance the quality management of industrial/processed food washwater and assess its potential for agricultural reuse. The findings showed that the machine learning models were able to forecast the quality profile of various washwaters and identify which streams may be safely reused. Decisions on the use of recovered water in certain agricultural applications, such as greenhouses, may be supported by this (Mundi et al., 2021). A ML based system for real-time wastewater flow management and operational optimization was developed by Prabu et al. (2025) by combining deep learning-based flow prediction models with control/optimization layers. According to research, AquaFlowNet improves resource economy and plant operating efficiency, boosting treated water dependability and lowering the possibility that it won't be appropriate for agricultural reuse. Using remote sensing data, AI models have been created to enhance agricultural water management and enable efficient planning of water consumption that has been indirectly recovered. Datasets like MODIS/GLDAS and deep learning have been used to estimate agricultural water demand and optimize irrigation. The findings are appropriate for large-scale water management choices since they show strong R^2 values. When and where to provide treated water to crops may be planned using these models (Ye et al., 2024). Online quality monitoring of treated water is made possible by the integration of multi-parameter spectroscopic data with machine learning classifiers (such as RF and SVM) to allow for immediate quality management prior to discharge to agricultural use and the quick detection of contaminants by spectroscopic measurements. Online identification of different organic pollutants and indicator characteristics has been proven to be successful with spectroscopy + ML. This allows for quick decisions about agricultural reuse (e.g., which water tail is appropriate for which crop) (Yalin et al., 2023). A scalable and reasonably priced wireless sensor network (WSN) system for monitoring and observation applications was created as part of a study on wastewater control and management in the context of irrigation applications. A yearly dataset gathered from sensor nodes at an actual wastewater treatment facility in Morocco was processed using an ANN technique that incorporates the Well-Node approach. With identification rates above 95% and an F1 score of around 96.81%, the chosen ANN showed remarkable performance in terms of wastewater reusability. When dealing with biases, uncertainties, and poor information content in the input data, the system performed quite well. Self-learning capabilities are said to make it possible to make well-informed judgments about consumption or reprocessing, which helps to preserve plants, soil, and the environment while also improving resource management and water use efficiency (Essahlaoui et al., 2023). Traditional statistical approaches find it difficult to handle the complicated and nonlinear challenge of predicting the quality of treated wastewater. In one research, a hybrid ML technique was used to predict important effluent characteristics from an advanced biological wastewater treatment facility in order to evaluate the possibilities for reusing treated wastewater for irrigation. Three years worth of daily influent and effluent water quality data were subjected to three AI models: FLM, ANFIS, and ANN. The best-performing model has a qualitative reuse potential of 69% to 72% for treated wastewater. An estimated 35% of a 20,000-hectare agricultural area might be irrigated by the treated wastewater. The results showed how AI may significantly improve agricultural water reuse practices (Köksal et al., 2025). In one study, the savings achieved by using treated wastewater from a domestic wastewater treatment plant equipped with MBR technology in the İznik district of Bursa province for agricultural irrigation were calculated based on 2019 data. This calculated value was found to be 439,833.03 TL. Consequently, it has been argued that wastewater reuse practices are crucial for ensuring the sustainability of water in nature, both because they provide savings in resource use and because they contribute significantly to the national economy (Adalı and Kılıç, 2020). A GIS-based evaluation of treated wastewater's potential for agricultural reuse was carried out in the Emilia-Romagna region's province of Forlì-Cesena, Italy. According to Mancuso et al. (2022), the findings demonstrated that in the chosen research region, treated wastewater may provide up to 210% of the crop water need during the irrigation season and up to 316% of the yearly crop water requirement in actually irrigated areas. In a study that looked into whether wastewater from a biological package treatment plant which uses the sequencing batch reactor principle and is intended for home use by business employees could be reused for agricultural purposes rather than being released into the receiving environment. Within the parameters of the Water Pollution Control Regulation and the Communiqué on Wastewater Treatment Plant Technical Operations, the appropriateness of biologically treated household wastewater for agricultural irrigation was tested. Based on the wastewater effluent analytical findings from the treatment plant, removal efficiencies of 98%, 97%, and 95% were achieved for the

parameters of SS, COD, and BOD, respectively. The effluents were found to be below the discharge criteria for the receiving environment when assessed under the Water Pollution Control Regulation. Upon evaluating the treatment plant effluent analysis results in accordance with the Wastewater Treatment Plants Technical Procedures Communiqué, it was found that the water's turbidity, electrical conductivity, and sodium levels did not meet the required standards, making it unsuitable for use in agricultural irrigation (Bingül and Altkat, 2017).

Table 3. AI applications for treated wastewater reuse.

Treatment Process	AI / ML Application	Removal Efficiency / Key Findings	Reference
Advanced biological wastewater treatment	Hybrid ML: FLM, ANFIS, ANN	Reuse potential for irrigation 69–72%	(Köksal et al., 2025)
Treated wastewater (for irrigation)	Hybrid and ensemble ML (Hammerstein–Wiener)	Accurate salinity estimation for irrigation suitability	(Shah et al., 2024)
Reclaimed wastewater (distribution/irrigation)	Improved transformer + time-series decomposition	Provides precise short-term water volume forecasts for irrigation allocation	(Sun et al., 2024)
Wastewater treatment plant effluent	Deep learning + control/optimization layers (AquaFlowNet)	Improves flow prediction, operational efficiency, and resource economy	(Prabu et al., 2025)
Agricultural water systems (recovered/treated water)	Deep learning on MODIS/GLDAS remote sensing data	Predicts agricultural water demand with high accuracy (high R ²)	(Ye et al., 2024)
Wastewater irrigation system	ANN with Wireless Sensor Network (WSN)	Identification rates >95%; F1 score ~96.8%	(Essahlaoui et al., 2023)

Research indicates that AI enhances wastewater treatment through real-time water quality monitoring, wastewater quality improvement, energy savings, and cost reduction. AI also improves irrigation by enhancing scheduling and water reuse efficiency, lowering hazards like over-irrigation and soil contamination, and boosting agricultural sustainability and output.

CONCLUSION

The review demonstrates that the agricultural reuse of urban TWW has evolved into a strategic and technically feasible solution for addressing global water scarcity, climate change impacts, and sustainable food production challenges. Advanced treatment technologies, including MBR, AOPs, adsorption systems, and constructed wetlands, are capable of producing effluent that meets irrigation standards while also contributing to nutrient recovery and energy efficiency. Hybrid and integrated treatment configurations, particularly when coupled with AI-driven decision-support tools, have proven effective in ensuring consistent water quality, optimizing operational parameters, and mitigating microbial and chemical risks. Empirical evidence from diverse regions, including Europe, the Middle East, South Asia, and North Africa, confirms that TWW reuse can enhance soil fertility, improve crop yields, reduce reliance on chemical fertilizers, and deliver economic benefits, provided that appropriate monitoring and risk management frameworks are implemented. Despite these advancements, challenges remain. Issues such as salinity accumulation, emerging contaminants, long-term soil health effects, limited data availability, and model interpretability constrain broader adoption. Furthermore, regulatory inconsistencies, high infrastructure costs, and limited social acceptance continue to pose barriers, particularly in developing countries. AI and ML applications show considerable potential to overcome technical and operational challenges, yet their integration requires robust datasets, model transparency, and stakeholder trust to ensure reliable, risk-informed decision-making.

Based on the findings, the following recommendations are proposed for researchers, policymakers, and practitioners:

- **Enhanced Monitoring and Data Collection:** Expand long-term, high-resolution monitoring of physical, chemical, and biological water quality parameters to improve AI model training, predictive accuracy, and risk assessment.
- **AI-Integrated Decision Support:** Promote the development and deployment of AI-based tools for real-time monitoring, irrigation scheduling, process optimization, and anomaly detection to ensure safe and efficient water reuse.
- **Hybrid and Fit-for-Purpose Systems:** Prioritize the implementation of hybrid treatment systems combining physical, chemical, and biological processes, tailored to local water reuse requirements and crop sensitivities.
- **Policy Harmonization and Regulatory Frameworks:** Standardize water quality criteria, permitting procedures, and monitoring protocols across regions to facilitate safe agricultural reuse and public confidence.
- **Public Engagement and Capacity Building:** Conduct awareness campaigns, farmer training, and stakeholder education to enhance societal acceptance and adoption of TWW reuse practices.
- **Sustainability and Long-Term Soil Management:** Incorporate salinity control, nutrient balancing, and periodic soil assessments to mitigate potential long-term impacts on soil and crop productivity.

Looking forward, future research should focus on integrating AI with IoT and remote sensing technologies to enable predictive and adaptive irrigation management at regional and farm scales. The development of explainable AI models and hybrid computational approaches can improve transparency, facilitate regulatory compliance, and enhance stakeholder trust. Furthermore, studies addressing the cumulative environmental impacts of long-term TWW application, particularly regarding micropollutants, antibiotic resistance genes, and heavy metal accumulation, are essential to ensure safe and sustainable reuse. Ultimately, the convergence of innovative treatment technologies, AI-driven process optimization, and evidence-based governance can transform TWW reuse into a cornerstone of climate-resilient, resource-efficient, and sustainable agricultural systems globally.

Compliance with Ethical Standards

Peer Review

This article has been reviewed by independent experts in the field using a rigorous double-blind peer review process.

Conflict of Interest

The authors declare no conflicts of interest.

Author Contributions

All authors contributed equally to the study design, data collection, analysis, and manuscript preparation.

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