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Wastewater reuse in agriculture: A review

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Abstract
Water scarcity is a growing global crisis worsened by the anticipated increase in the population to 10.2 billion by the year 2050, which is expected to boost the food demand by 60%. This rising demand for food will place additional pressure on already limited freshwater resources. Agriculture, particularly irrigation is the largest consumer for freshwater accounting for about 71.7% of global water withdrawal. The conventional water remains constant indicating that many of the countries will face severe water shortage by the year 2050. Wastewater represents an underutilized resource that can be treated and reused for agriculture. In India, where water stress is significant due to rapid urbanization and population growth, wastewater generation is expected to rise sharply. The types of wastewaters can vary according to their sources, necessitating the selection of appropriate treatment options tailored to each specific type of wastewater. The nation has advanced its sewage treatment capabilities, and estimates suggest that millions of hectares of agricultural land can be irrigated with treated wastewater. Utilizing treated wastewater reduces fertilizer consumption, boosts farmer's income and improves agricultural yield. However, improper treatment of wastewater can lead to the accumulation of heavy metals, posing significant health risks to both humans and animals. Consequently, while the advantages of employing treated wastewater in agriculture are considerable, it is essential to adopt effective treatment methods to minimize any potential adverse effects on health and the environment. The adoption of wastewater irrigation is a viable strategy to address global water scarcity while promoting sustainable agricultural practices and reducing environmental impacts.

Keywords: Water scarcity, wastewater irrigation, sewage water, agricultural production

1. Introduction
The global population is projected to reach approximately 9.4 to 10.2 billion by the year 2050, signifying a substantial growth of 22 to 32% (Anonymous, 2022) [24]. In tandem with this population surge, the demand for food is predicted to escalate 60% by 2050 (Alexandratos and Bruinsma, 2012) [8]. Additionally, estimates indicate that nearly 50% of the world's population reside in areas vulnerable to water scarcity, a figure projected to rise to 58% by 2050 (Khayyam and Tariq, 2022; Veldkamp *et al*., 2017) [70, 135]. The global annual water withdrawal from natural water sources is estimated to be around approximately 4250 km^3, of which agricultural sector is the predominant user, accounting for about 71.7% of this total withdrawal (Anonymous, 2021) [23]. Irrigation is considered as the main user of freshwater which accounts for approximately 80% of the total freshwater usage, and will account for an additional 15% by 2050 (Anonymous, 2017) [17]. The annual renewable water resources (ARWR) $capita^{-1}$ in 87 out of 180 countries are predicted to decline below 1700 m^3 annually by the year 2050. Additionally, by 2050, there will be 45 nations with absolute water shortage, defined as having an ARWR $capita^{-1}$ less than 500 m^3 (Baggio *et al*., 2021) [27]. The increasing demand for water in industrial, agricultural, and domestic sectors creates a significant need for this vital resource while generating substantial volumes of domestic and industrial waste water (Widyarani *et al*., 2022) [142]. Unfortunately, over 80% of this wastewater is released without treatment, infiltrating into the ground and posing a potential risk to groundwater table and the water bodies (Joseph *et al*., 2019) [66]. Global wastewater discharge has reached 400 Bm^3 annually leading to the contamination of approximately 5500 Bm^3 of water each year (Zhang and Shen, 2019) [146]. It is anticipated that wastewater generation would increase by 24% by 2030 and 51% by 2050 (Qadir *et al*., 2020) [107]. It is crucial to understand that this wastewater is "used" water that has been polluted due to human activities. This resource, often neglected and undervalued, represents an untapped reservoir with significant potential for reuse (Anonymous, 2023) [25].

The use of wastewater in agriculture dates back to Ancient Greece, where arid regions facing prolonged drought and crop failures utilized treated sewage as an irrigation source (Angelakis *et al*., 2018) [19]. Water recycling in agriculture enhances water availability for domestic and industrial activities, reducing competition among users and preventing overexploitation of water bodies (Paranychianakis *et al*., 2015; Voulvoulis, 2018; Tzanakakis *et al*., 2020) [100, 138, 134]. It is estimated that more than 20 million hectares of land are irrigated using non conventional water resources (Rusănescu *et al*., 2022) [115]. The reuse of treated wastewater can serve as a primary alternative to augment water resources, particularly in arid regions as it represents an additional source of renewable water (Chojnacka *et al*., 2020; Hussain and Qureshi, 2020) [41, 62]. Due to the scarcity of available freshwater resources and inadequate wastewater management practices, approximately 3.5 million hectares of land worldwide are irrigated with untreated or partially treated wastewater (Thebo *et al*. 2017; Zhang and Shen 2019) [131, 146] highlighting the urgent need for effective water treatment options in wastewater irrigation. The main goal of waste water treatment should be removal of contaminants, suspended particles, toxins and pathogens, allowing the treated water to be safely released back into the environment for various uses (Silva, 2023) [125]. Domestic water and treated wastewater contain various nutrients, including nitrogen (N), phosphorus (P), potassium (K), and sulfur (S). However, the significant quantities of N and P present in wastewater can be readily absorbed by plants, which is why it is commonly utilized for irrigation purposes (Poustie *et al*., 2020; Sengupta *et al*., 2015) [106, 117].

2. Wastewater and its composition

The term "wastewater" refers to any water that has been degraded in quality due to human activities. It refers to water whose physical, chemical, or biological characteristics have been modified by the introduction of specific substances, rendering it unsafe for human consumption. It is made up of 99.94% water by weight and remaining 0.06% is dissolved or suspended materials (Ali *et al*., 2019) [10]. Typical wastewater may also include microorganisms, inorganic compounds, and various biodegradable organic materials such as proteins, carbohydrates, fats, along with pathogenic substances (Ma *et al*., 2001) [79].

3. Sources of Wastewater

Wastewater can be categorized into conventional and non conventional sources based on its origin and the processes involved in its generation. Conventional water refers to the water resources derived from the natural processes of the hydrological cycle, including sources such as rivers, streams, lakes, reservoirs and aquifers. In contrast, non conventional water originates from sources like seawater, storm water, agricultural drainage, cooling water from thermoelectric plants, hydraulic fracturing water, industrial processed water, domestic wastewater, and commercial discharges. Non conventional sources of water are gaining more attention because of their potential to be reused for human activities (Morote *et al*., 2019; Omran, 2019) [91, 95]. This reuse can address water scarcity in agriculture and promote a circular water economy. The core concept of circular economy is shifting the focus from non renewable natural resources to recovering resources from waste, thereby creating economic, social and environmental advantages (Lieder and Rashid, 2016) [77]. Rooftop harvested rainwater (RHRW) refers to rainwater collected from the runoff of building rooftops and stored in engineered system. Compared to rainfall that falls directly to the ground, RHRW typically contains fewer contaminants and can be an excellent source of supplemental water (Campisano *et al*., 2017; Gurung and Sharma, 2014) [33, 60]. In South Africa, rainwater harvested from rooftops has been utilized for generations, with ten thousand of households relying on it as their primary source (Mwenge Kahinda and Taigbenu, 2011) [93]. Stormwater, collected from the ground and storm drains, can be a valuable non traditional water source that improves surface water quality, reduces urban flooding risk, and enhances watershed hydrology. Zhang *et al*. (2020) [49] quantified the benefits of stormwater harvesting (SWH) for improving surface water quality through a sensitivity analysis and demonstrated significant pollution reduction. Greywater, a subset of municipal wastewater is defined and characterized in various ways globally. Generally, it refers to wastewater generated from all non toilet plumbing fixtures in a household, including water from kitchens, bathrooms and laundry (Ghaitidak and Yadav, 2013) [58]. Grey water can be diverted and drained to outdoor irrigation systems after filtration, and some systems divert the grey water to a constructed wetland for additional treatment (Allen *et al*., 2010) [15]. Desalinated water (DSW) is brackish or seawater that has dissolved minerals, salts and other contaminants removed through purification. Brackish water contains a higher salt concentration than freshwater but lower than that of seawater. Desalinated water provides a consistent water supply independent of rainfall, which is crucial for regions with limited fresh water sources (Silber *et al*., 2014) [124]. The Table 1. shows the major sources and characteristics of wastewater.

Table 1: Major sources and characteristics of wastewater

Source	Characteristics	References
Inorganic industrial wastewater	TSS: 1,605-14,500 mg L^{-1} Heavy metals: 0.5-2.5 mg L^{-1} Salt ions: 1,400-11,000 mg L^{-1}	(Moosavirad *et al*., 2015) [90]
Municipal wastewater	TSS: 1,367-1,939 mg L^{-1} COD: 1,868-2,540 mg L^{-1}	(Cartagena *et al*., 2013) [34]
Petrochemical wastewater	TDS: 30,000 mg L^{-1} TOC: 60 mg L^{-1}	(Osman *et al*., 2019) [96]
Tannery effluent	TDS:14500±10 mg L^{-1} TSS: 6080±10 mg L^{-1}	(Chowdhury *et al*., 2015) [46]
Domestic wastewater	TDS:250-850 mg L^{-1} TSS: 350-1200 mg L^{-1}	(Pescod, 1992) [102]
Agricultural wastewater	TSS:110-140 mg L^{-1} COD: 350-430 mg L^{-1}	(Ali *et al*., 2021) [11]
Pulp/paper waste water	SS: 570 mg L^{-1} Conductivity: 2860-5600 µS cm^{-1}	(Pizzichini *et al*., 2005 ; Soloman *et al*., 2009) [105, 128]

4. Prospects of Wastewater Irrigation

Water stress has become a perennial concern in India due to rapid and unregulated rise in water demand for domestic, agricultural, and industrial needs (Bassi *et al*., 2022) [28]. The estimated wastewater generation from Class I cities and Class II towns in India is at 29,129 MLd^{-1}, with an expected increase to 33,212 MLd^{-1} due to a 30% increase in urban population. India has made notable advancements in enhancing its sewage treatment capacity, from 18,883 MLd^{-1} in 2014 to 26,869 MLd^{-1} in 2020. The proportion of treatment capacity relative to total sewage generation is anticipated to grow from 41% in 2010 to 80% in 2050, with an estimated 96,378 MLd^{-1} of treated wastewater available for reuse (CPCB, 2021). The irrigation sector had access to about 8,603 Mm^3 of treated wastewater in 2021, which could be potentially used to irrigate around 1.38 M ha of land. In India, around 73,000 hectares of land are irrigated using wastewater (Singh *et al*., 2022) [127]. The potential benefits of wastewater irrigation for agriculture and industries in the country are significant. Utilizing treated wastewater for irrigation has been found to significantly enhance crop yields by 30-40%, decrease fertilizer use by more than 50%, increase farmer's income by 30%, and generate economic advantages of approximately 17,000 rupees $hectare^{-1}$ (Ravikumar *et al*., 2014) [112]. The sewage generated from India's largest cities has the capacity to irrigate around 24.7 million hectares of land with 7.5 cm of water, despite the loss of 30% during transit and other operations. This potential irrigation area is expected to grow even more when runoff from rainwater that usually flows into sewage drains is taken into consideration. Different crops have distinct irrigation needs, with vegetable, fodder, and grain production systems requiring varying quantities of water (Minhas *et al*., 2015) [86]. Wastewater from urban areas in India, if used for irrigating cereal crops, has the potential to generate around Rs. 400 billion annually and create job opportunities equivalent to about 280 million person days. Nutrients present in wastewater are considered as a valuable source for farmers as they can be used for profitable food and fodder production. Peri urban agriculture benefits from using wastewater as a reliable water source from sewage drains, unlike rainwater or canal water can be inconsistent. The abundance of essential elements found in wastewater, including nitrogen, phosphorous, potassium and sulphur reduces the need for additional fertilizers. Calculations show that wastewater can contribute approximately 1.65 million Mg of nitrogen, 0.26 million Mg of phosphorus, and 2.25 million Mg of potassium annually when 70% of sewage is used for irrigation. Micronutrients such as zinc (Zn) and copper (Cu) are also present in wastewater, providing additional benefits for plant growth. More than 4 million mg of plant nutrients may be found in sewage effluents, which make up over 13% of all fertilizer nutrients manufactured and used in Indian agriculture (Minhas *et al*., 2022) [87]. Utilizing wastewater for irrigation provides an alternative to conventional fertilizers while also helping to reduce nutrient pollution in water bodies, minimize unpleasant odours, and lower health risks for local residents. Reusing wastewater for irrigation not only helps in decreasing harmful greenhouse gas (GHG) emissions but also contributes to energy and electricity conservation. Different treatment systems, such as aerobic and anaerobic processes, emit varying levels of GHGs $unit^{-1}$ of biochemical oxygen demand. Research indicates that carbon stocks in soils and plant biomass significantly increase with the use of sewage water for irrigation, aiding in carbon sequestration. As per the estimates in India, the potential for sewage irrigation to mitigate GHG emissions is around 72 million metric tons of carbon dioxide equivalent (Lal *et al*., 2020) [72]. In a study conducted by (Kumar *et al*., 2014) [71] provided a comprehensive analysis of the potential of reducing fertilizer use by utilizing treated wastewater (TWW). The nutrient contributions from TWW showed that each million litres per day (MLD) of treated wastewater can supply approximately 0.62 to 0.73 tonnes of essential nutrients. When compared to the typical fertilizer requirements of vegetable crops, approx. 156 kg per hectare nutrient inputs from TWW represents a substantial potential for fertilizer savings.

5. Effect of Wastewater Irrigation

5.1 Field crops and vegetables

According to Dubey *et al*. (2024) [53] wastewater irrigation resulted in a 10% increase in sunflower yield, which was linked to enhancements in head diameter (15.3 cm), the number of achenes per head (467), and the weight of 100 achenes (69 g). Similarly, wastewater irrigation boosted toria crop yield by 11%, with increase in siliquae $plant^{-1}$ (179), seeds $siliqua^{-1}$ (12.1), test weight (4.6 g) compared to that of freshwater irrigation. Alghobar and Suresha (2016) [9] studied the impact of untreated wastewater (UWW) and treated wastewater (TWW) irrigation on rice growth and yield. Results showed that UWW produced higher tiller number $plant^{-1}$ (15.48), followed by TWW (13.97) and ground water (12.21). Panicle length was significantly higher with UWW, however, the number of grains $panicle^{-1}$ showed no significant increase with wastewater use. Ground water irrigation recorded higher yield $plant^{-1}$ (20.17 g), while TWW and UWW resulted in lower yields of 18.32 g and 17.13 g respectively. The study concluded that trace metals in wastewater hindered growth and yield improvements in rice. Antolinos *et al*. (2020) [26] investigated the effect of DSW irrigation on two tomato varieties grown in soil and soilless systems and concluded that DSW did not negatively affect consumer acceptance or fruit quality.

Ait-Mouheb *et al*. (2022) [7] conducted an experiment over 2 years growth cycles on lettuce and leek. They compared the effects of treated wastewater (TW), untreated waste water (UW), and fresh water (FW) with conventional fertilization on lettuce and leek yields. It was concluded that the yield of lettuce produced by FW irrigation and traditional fertilization was 43 to 85% lower than that of TW. Rinaldi *et al*. (2003) [113] reported that irrigation with industrial wastewater irrigation could reduce the wheat yield. Similarly, Hu *et al*. (2009) [61] conducted experiments using domestic wastewater irrigation and found a negative effect on crop yield. Several studies have demonstrated the beneficial impact of sewage irrigation on crop yields. For example, Mojid *et al*. (2016) [89] found that yield of wheat was considerably higher with wastewater irrigation (4.61 t ha^{-1}) than with groundwater irrigation (4.04 t ha^{-1}). Recent studies indicate a notably positive impact on corn and rice yield (Tran *et al*., 2019) [132]. However, there was a wider increase in yield, ranging from 2 to 10 times, highlighting the need for further research.

A meta-analysis was performed to assess the effect of wastewater irrigation on crop yield. The maximum increase

recorded was 1,089.00%, while the minimum decrease was-50% (Wang *et al*., 2022) [140]. This variation indicates substantial differences in the effects of wastewater irrigation on crop yield across various studies. The results suggested that the impact of wastewater irrigation could differ significantly based on several factors, and this divergence emphasized the importance of effective policy making in crop irrigation with wastewater. The literature survey has been showed that wastewater has been effectively used to irrigate variety of field crops and vegetables Table 2.

Table 2: Effect of wastewater irrigation on various field crops and vegetables

Crops	Type of wastewater	Reference
Cabbage, Cauliflower, Spinach, Lettuce, Radish	Sewage water	El-Nahhal (*et al*., 2013) [55]; Rattan (*et al*., 2005) [111]; Wang (*et al*., 2012)
Rice	Sewage water	(Rattan *et al*., 2005) [111],
Egyptian clover	Sewage water	(Rattan *et al*., 2005) [111]
Maize, Sorghum	Sewage water	(Rattan *et al*., 2005) [111]
Tomato	Tertiary treated wastewater	(Cirelli *et al*. 2012) [44].
Eggplant	Treated wastewater	(Cirelli *et al*., 2012) [44]
Onions	Both untreated and treated municipal wastewater	Winpenny (*et al*., 2010) [143]; Farhadkhani (*et al*., 2018) [57]
Broccoli	Untreated wastewater	Beneduce (*et al*., 2017) [31]; Libutti (*et al*., 2018) [75]
Pototoes	Untreated wastewater	Winpenny (*et al*., 2010) [143]

5.2 Fodder crops

In a study conducted by Vennila (2023) [136] revealed a significant yield increase of 22.3% in fodder cowpea when sewage water was used in conjunction with farmyard manure and inorganic nutrients. Al-Karaki (2011) [14] investigated the effect of tertiary treated sewage on the production of fodder barley in a hydroponic system. The findings suggested that the yield of fodder barley was significantly greater (320 t ha^{-1}) when irrigated with tertiary treated sewage wastewater (WW) compared to tap water (TW) or mixture of wastewater and tap water. Water use efficiency was also enhanced with WW irrigation, as plants needed only 1.26 m^3 to produce 1 ton of green fodder, compared to 1.56 m^3 required for tap water irrigation. The use of treated wastewater irrigation in conjunction with organic and inorganic fertilizers significantly increased the yield of both dry and green fodder. Treated wastewater irrigation with 100% inorganic fertiliser produced significantly higher green and dry fodder yields of 431.0 and 76.7 t ha^{-1} $year^{-1}$ than all other treatment combinations (Senthilkumar *et al*., 2021) [118]. In a study conducted by Abusamra *et al*. (2022) [6] on constructed wetlands demonstrated their effectiveness in treating domestic wastewater, achieving over 75% organic material removal and 18% nitrogen removal, with treated effluent meeting legal standards for reuse in fodder irrigation. The use of treated wastewater for irrigating Bermuda grass (*Cynodon dactylon*) has demonstrated 34% higher above ground dry weight compared to freshwater irrigated plants (Licata *et al*., 2022) [76].

5.3 Agroforestry

A study by Divya *et al*. (2006) [50] on the use of sewage water for afforestation revealed that tree species irrigated with sewage water exhibited greater height and basal diameter compared to those irrigated with bore well water. Measurements taken at 3, 6, 9, 12, and 15 months after planting (MAP) showed that the percentage increase in height and basal diameter varied among different tree species under sewage water irrigation relative to bore well water irrigation. At 3 MAP, *Casuarina equisetifolia* showed a 15% increase in height and 18% in basal diameter, *Tectona grandis* 39% and 20%, *Azadirachta indica* 24% and 20%, and *Eucalyptus tereticornis* 23% and 18%. The tree species demonstrated varying degrees of growth improvement when irrigated with sewage water over different time intervals, highlighting the beneficial effects of sewage water on tree growth and afforestation initiatives. Treated wastewater is a sustainable strategy for promoting the growth of forest species, especially in salt affected areas. *Atriplex nummularia*, is a tree which can thrive in salt affected soils and accumulate essential minerals. Treated wastewater irrigation offers a solution in afforestation initiatives and can enhance the soil quality (Zouari *et al*., 2019) [149]. Murali *et al*. (2022) [92] opined that effluent from paper board industry serve as a viable source for irrigation and fertigation within agroforestry systems.

5.4 Fruit crops

Bedbabis *et al*. (2015) [30] researched Tunisia over 21 months and found that using TWW for irrigation in an olive farm had more yield than using groundwater (GW). The yield per tree was 154kg compared to 90.3kg using GW. Waste water irrigation in aquaculture significantly improved date palm growth and fruit quality in Saudi Arabia, increasing fruit weight and nutrient content (Al-Wabel *et al*., 2024) [17] conducted a study to assess the microbiological quality of soil and orange fruits irrigated with secondary treated wastewater using a drip irrigation system. The results showed that soil and fruit samples were free of Salmonella, and contamination of fruits by faecal indicators was negligible. This contamination was attributed to the drip irrigation system, which prevented direct contact between water and fruits. Irrigation of strawberries with treated wastewater, surface water and blended water increased soil nutrient levels but led to higher salinity from chloride accumulation, negatively impacting plant growth and productivity. Treated wastewater irrigated strawberries also showed elevated microbial contamination, including *E. coli* and other pathogens, necessitating through washing to reduce health risks (Al-Karablieh *et al*., 2024) [13]. Maestre-Valero *et al*. (2020) [26] evaluated the short term agronomic and economic effects of irrigating mandarin orchard with DSW during two crop cycles and found no significant deviations. The effects of using secondary treated municipal wastewater and fresh water for irrigation were compared. The use of secondary treated wastewater resulted in lower yields, while the mixed water approach led to higher yields. The yield reduction was likely due to increased salinity from the less treated wastewater (Pedrero *et al*. 2012) [101].

5.5 Soil

Irrigation with wastewater alters both the microbiological and physiochemical characteristics of the soil. Abegunrin *et al*. (2016) [4] found that the EC and SAR values of the untreated wastewater indicated a moderate to high level limitation for irrigating egg plant and spinach. The application of wastewater led to increased levels of exchangeable bases, CEC, pH, total organic carbon, and total nitrogen in the soil. In a study by Du *et al*. (2022) [52] to examine the impact of piggery wastewater (PW) and saline water treatments (SW) on soil characteristics, found that soil pH decreased by 0.21 units with piggery wastewater and by 0.24 units in saline water treatments. Additionally, there was no discernible change in EC in reclaimed water treatments as compared to the control, although EC values in both PW and SW treatments significantly increased by 5.8 to 20.9%. These findings suggest that PW can enhance soil structure and aeration.

In a study conducted by Roohi *et al*. (2016) [114] investigated the effects of irrigating soil with textile wastewater revealed that both the type of wastewater and the duration of incubation significantly influenced the enzymatic properties of the soil. Soil dehydrogenase activity was increased by the application of wastewater, it increased soil dehydrogenase activity from 35.46±0.58 mg triphenyl formazan 12 h^{-1} g $soil^{-1}$ in distilled water treated soil to 45.32±0.74 mg in soil treated with 100% wastewater. Additionally, the microbial metabolic quotient (qCO_2) also showed a significant increase in response to the wastewater application, with values ranging from 0.71±0.11 in distilled water treated soil to 1.68±0.34 in soil treated with 100% wastewater. Coppola *et al*. (2004) [45] reported that irrigating soil with wastewater led to an increase in soil bulk density, which was attributed to the accumulation of organic matter. In contrast, Abd-Elwahed (2018) [3] observed a slight decrease in the bulk density of soil that had been irrigated with wastewater over an extended period. Pan *et al*. (2012) [98] found that irrigation with treated wastewater led to an increase in soil microbial biomass and enhanced soil enzyme activities (including invertase, alkaline phosphatase, dehydrogenase, urease, and catalase) compared to soils irrigated with fresh water. The use of treated wastewater for irrigation increased soil salinity with a notable rise of 6.34% in electrical conductivity compared to fresh water irrigated plots, while also providing substantial nutrient inputs that reduced the need for synthetic fertilizers (Licata *et al*., 2022) [76]. Shifting from wastewater to treated wastewater irrigation may trigger the mobilization of potentially toxic elements like Cd, Zn and As due to variations in pH and soil depth. This could enhance their bioavailability in crops and groundwater, highlighting the need for long term monitoring and comprehensive risk assessment strategies (Rivera *et al*., 2023) [147]. Treated wastewater irrigation can led to higher abundance of nitrifying and nitrogen fixing bacteria, compared to soil irrigated with fresh. The effects of wastewater irrigation on soil properties on various places have been shown in the Table 3.

Table 3: Effect of wastewater irrigation on soil properties of various places

Wastewater type	Location	Soil property affected	Key findings	Reference
Treated waste water (TWW)	Tunisia	Chemical (pH, EC, SAR, OM)	Decreased soil pH (by 0.2 units), increased EC, SAR, and OM.	Bedbabis *et al*. (2015) [30]
Secondary treated wastewater (STWW)	Iran	Chemical (EC, SAR)	Increased soil EC, and SAR	Farhadkhani *et al*. (2018) [57]
Treated wastewater +sewage sludge	Algeria	Chemical (OM, nutrients), Biological (Microbial activity)	Increased OM and nutrient content (N, P, K); enhanced microbial activity; slight salinity increase	Cherfouh *et al*. (2018) [40]
Treated wastewater	Tunisia	Biological (microbial activity, enzyme response)	Altered soil microbial activity and enzyme response	(Mkhinini *et al*., 2019) [88]
Treated wastewater	Spain	Chemical (Na, P, OM), Physical (EC)	Increased soil sodium, EC, P and OM	(Castro *et al*., 2013) [37]

6. Risks of Wastewater Irrigation

6.1. Heavy metal accumulation

The movement of potentially toxic elements from soil to plant tissues is influenced by various factors including chemical speciation, metal type, and the variety of plant. Irrigation with wastewater can result in the build up of heavy metals such as cadmium, chromium, copper, nickel, lead, and zinc in plants like *Brassica oleracea*, *Beta vulgaris*, and *Spinacea oleracea* (Chopra and Pathak, 2015) [42].

The crops and fields irrigated with untreated wastewater had a higher levels of heavy metal deposition compared to those irrigated with treated wastewater. The choice of irrigation method has profound effect on environmental and agronomic outcomes of wastewater irrigation. Drip irrigation was found to be effective in reducing heavy metal deposition in both the edible portion of the crop and the soil, a benefit attributed to the lower discharge rates inherent in drip irrigation systems (Pal *et al*., 2023) [97].

Chaoua *et al*. (2019) [39] reported that wastewater irrigation significantly contributed to heavy metal accumulation in crops, with soil tainted with zinc, copper, lead and cadmium. Zinc>lead>copper>cadmium was the general pattern of heavy metal concentrations in all samples. The daily intake of cadmium and lead surpassed the permissible limits, raising health concerns. The Health Risk Index (HRI) ranged from 0.054-0.174 for zinc, 0.031-0.242 for copper, 2.407-7.973 for lead and 0-5.059 for cadmium, with values greater than one for cadmium and lead indicating a potential health risk. Dotaniya *et al*. (2018) [51] stated that while sewage water contain low levels of heavy metals prolonged use of this water can lead to the accumulation of substantial amounts of heavy metals in the soil. Abdel-Sabour *et al*. (2000) [2] noted that extended irrigation with wastewater contaminated by heavy metals significantly increased the heavy metal content in the soil. Various crops can accumulate heavy metals when irrigated with wastewater (Table 4.)

Table 4: Accumulation of Heavy Metals in Various Crops Due to Wastewater Irrigation

Crops	Heavy metal	Reference
Wheat, Rice, Vegetables	Cd, Pb and Ni	(Singh *et al.* 2010) [126]
Vegetables	Cd and Pb	(Shariatpanahi and Anderson, 1986) [122]
Lemon grass	Cd, Cr, Ni and Pb	(Lal *et al*., 2013) [73]
Olive trees	Ni, Pb, Cr	(Batarseh *et al*., 2011) [29].
Vegetable, Forage crops	Ni, Cr, Cd, Pb, As	(Turner *et al*., 2016) [133]
Spinach, coriander, carrot, tomato, and cauliflower	Pb, Ni, and Cd	(Khan *et al*., 2013) [73]
Lettuce and spinach	Zn, Cr	(Qureshi *et al*., 2016) [109]
Medicago sativa	Zn, Cu, Cr, As, Cd,Pb	(Li *et al*. 2005) [74]

6.2. Human and animal health

Numerous ailments can result from various discharged organisms found in untreated or treated wastewater, such as bacteria, viruses, helminths, pathogens, and protozoa. Due to the variability in pathogen concentrations, these microorganisms are often detected using indicators like *E. coli*, which serves as a proxy for assessing the level of faecal contamination (Carvajal *et al*., 2017) [35]. Srikanth and Naik (2004) [130] found that the prevalence of giardiasis among farmers irrigating with wastewater in Asmara, Eritrea. The data revealed that giardiasis prevalence was 7% among residents who consumed only vegetables grown with untreated wastewater, compared to just 1% for residents in similar towns in Eritrea without crops irrigated with wastewater. Gumbo *et al*. (2010) [59] found that farmers and their families in Malamulele, South Africa, exhibited a higher prevalence of helminth infections compared to control villages. Amahmid *et al*. (2023) [18] revealed that the primary pathogenic parasites associated with diseases such as trichuriasis, ascariasis, and giardiasis are *Trichuris*, *Ascaris*, and *Giardia*, respectively, which can be contracted through the consumption of crops and soil irrigated with wastewater. The negative effects of wastewater use extend beyond humans, affecting various species, including fish and frogs. A study conducted by Zaibel *et al*. (2016) [144] explored the effects of treated wastewater on fish health in an artificial reservoir in the Negev desert of Israel, which regularly receives treated effluent. The research involved monitoring of pollutants in fish tissues and employed histopathological techniques to asses overall health of the fish population. The results showed that fish exposed to treated wastewater had varying level of infections. Iqbal *et al*. (2021) [64] examined heavy metal concentrations at various locations irrigated with different water qualities, while also evaluating the levels in buffalo milk fed with fodder irrigated with wastewater. To evaluate possible exposure, they employed the human health risk index (HRI) and the total target health quotient (TTHQ). The results showed that the TTHQ values surpassed 80 for cultivated fodder and 40 for buffalo milk. Furthermore, the HRI values for most heavy metals exceeded 1, indicating a considerable risk to carcinogenic exposure for both humans and animals in regions using wastewater irrigation. Wastewater irrigation resulted in increased Fe concentration in soil plant system, with fodder crops accumulating Fe from contaminated crop. This poses a risk of Fe transfer into grazing animals, potentially affecting their health and the safety of animal products (Khan *et al*., 2022) [69]. A study conducted by Panigrahi *et al*. (2019) [99] found that fecal coliforms were present in treated wastewater, with their levels exceeding the maximum concentration limits for irrigation water as recommended by the World Health Organization. Ceci *et al*. (2023) [38] found that hydroponic barley feed produced from recycled urban wastewater is safe for lactating cows and has no discernible negative impacts on the production metrics, animal health, and milk quality. The study supports the use of tertiary treated wastewater in hydroponic systems for fodder and forage production, underscoring its potential for wider use in agriculture.

7. Wastewater Treatment Methods for irrigation

Conventional treatment occurs in four distinct stages: preliminary, primary, secondary, and tertiary treatments. Preliminary treatment focuses on eliminating large solids and debris from the wastewater. Primary treatment employs physical methods such as sedimentation and flotation to separate organic and inorganic solids. During secondary treatment, the effluent undergoes biological processes to remove remaining organic materials and suspended solids. Finally, tertiary treatment encompasses all additional operations aimed at removing pollutants that were not addressed in the earlier stages (Abdel-Raouf *et al*., 2012) [1]. Quach-Cu *et al*. (2018) [108] reported that disinfection processes in tertiary wastewater treatment plants significantly decreased the presence of potential resistance genes. Petousi *et al*. (2019) [109] studied that tertiary treated wastewater positively influenced the yield and growth of young grapevines, whereas secondary treated wastewater had a negative impact on fruit safety when compared to fresh water. In a study conducted by Pedrero *et al*. (2012) [101] revealed that irrigation with secondary treated municipal wastewater reduced yields in lemon tree orchard, a combination of tertiary treated municipal wastewater and fresh water resulted in higher yields, likely due to salinity issues associated with the less treated wastewater.

Conventional wastewater treatment methods can improve the quality of ordinary wastewater, but they are insufficient to handle the wastewater generated by expanding industrial operations. Frequently, this industrial effluent has a greater concentration of contaminants that are difficult to eliminate using conventional techniques. The main factors that prompted the development of new or enhanced wastewater treatment technologies are legislation and significant fines for disposing of wastewater. As a result, new or advanced treatments have been introduced for the treatment of industrial wastewater. Anaerobic and aerobic methods are utilized successfully to treat organic wastewater due to their cost effectiveness and environmental friendliness. Anaerobic technologies can offer added benefit of using less energy than their counterparts (Crini and Lichtfouse, 2019) [47]. Some notable technologies which are being utilized for the treatment of wastewater in irrigation are membrane filtrations, membrane bioreactors, biofilms and advanced oxidation. In India, the most widely used sewage treatment technologies are sequencing batch reactors (SBR), which

accounts for 30% of the market, followed by activated sludge processes (ASP) at 20%, and Moving bed biofilm reactors (MBBR) at 12% (CPCB, 2021). Effective treatment methods, such as biological treatment systems, constructed wetlands, and sustainable irrigation practices, can reduce the adverse impacts of agricultural wastewater on ecosystems, safeguard water resources, and ensure the sustainable management of agricultural operations. Waste stabilization ponds (WSPs) consist of a combination of anaerobic, facultative, maturation, and high rate algal ponds, which can be configured either in series or in parallel, depending on specific conditions. They offer significant advantages in terms of both capital and maintenance costs (Liu *et al*., 2018) [78]. Verbyla *et al*. (2016) [137] emphasized that Waste Stabilization Ponds (WSPs) as the most effective wastewater treatment systems due to their efficiency in pathogen removal and low maintenance costs. Pinninti *et al*. (2021) [104] found that properly maintained and operated wastewater stabilization ponds can achieve an efficiency of 70-80% in removing organic matter and nutrients. In contrast, ponds using duckweed or hyacinth plants typically have a lower efficiency of 40-50%. The quality of the treated effluent is significantly influenced by the pond configuration, as noted by Sonkamble *et al*. (2018) [129]. In a study conducted by Marella *et al*. (2022) [84] reported that the use of periphyton biofilm-based technologies to control non-point source (NPS) pollution in agricultural systems. Wahid *et al*. (2021) [139] reported that fertilizer drawn forward osmosis (FDFO) as a potential alternative to recover and reuse water and nutrients from agricultural wastewater, such as palm oil mill effluent that consists of 95% water and is rich in nutrients. Abourached *et al*. (2016) [5] utilized Microbial Fuel Cell (MFC) technology to treat wastewater prior to its use in irrigation. The study was carried out in the semiarid regions of California. The analysis demonstrated that Microbial Fuel Cell (MFC) technology is a feasible method for reclaiming wastewater that satisfies irrigation standards. Manjunath *et al*. (2019) [82] conducted a field experiment to investigate the impact of engineered constructed wetland (ECWL) treated and untreated domestic wastewater irrigation on the growth, yield, and water productivity of cluster beans. The study found that domestic waste water yielded 8874 kg ha^{-1} more than fresh water, but was comparable to treated wastewater alternated with domestic wastewater. In general, the use of right irrigation system, choosing a cropping pattern with suitable and efficient irrigation management, and regular checking of the quality of water, soil and plant may greatly lessen the detrimental effect of treated wastewater by implementing cautious and preventive measures against infections. Advanced methods used in wastewater irrigation for agriculture Table 5.

Table 5: Advanced methods for wastewater irrigation in agriculture

Method	***Description***	***Reference***
Constructed Wetlands	Engineered systems using plants, soils and microbes to treat wastewater	Nan *et al*. (2020) [94]; Ali *et al* (2018) [12]; Šereš *et al*. 2021 [120]; Milani *et al*. (2020) [85]
Algae-based systems	Algae remove pollutants and produce biomass that can be used for biofuels and fertilizers	Maiga *et al*. (2015) [81]; Delanka-Pedige *et al*. (2020) [49]; Cunha-Chiamolera *et al*. (2024) [48]
Microbial fuel cells	Microorganisms degrade organic matter while generating electricity	Duy Pham *et al*. (2019) [54]
Membrane filtration	Separates particles from liquids using selectively permeable membrane	Kamalesh *et al*. (2024) [67]
Electrocoagulation	Uses electric currents to destabilize contaminants without heavy chemical reliance	Saleem *et al*. (2011) [116]; Al-Othman *et al*. (2022) [16]; Espinoza Márquez *et al*. (2020) [56]
Forward osmosis	Uses semi permeable membrane driven by natural osmotic pressure difference	Casas *et al*. (2024) [36]

9. Multi barrier approach for safe reuse of treated wastewater in agriculture

Ensuring the safe reuse of wastewater for irrigation requires a multi barrier strategy that combines traditional wastewater treatment methods with advanced processes. At a minimum, the treatment should include conventional depth filtration following a biological process or an ultrafiltration membrane complemented by a disinfection unit. This treatment train can address key parameters such as BOD, COD, TSS and *E. coli* as outlined in wastewater reuse regulations and guidelines (Seow *et al*., 2016) [119]. Shaffer *et al*. (2012) [121] combined the sea water reverse osmosis process with forward osmosis for desalination, achieving the desired levels of boron and chloride in irrigation water while enhancing energy efficiency. Bliedung *et al*. (2020) [32] reported the "Hypo Wave project" as a multi barrier approach for the successful integration of specially treated municipal wastewater into hydroponics system, this includes an expanded granular sludge bed reactor (EGSB), a sequencing batch reactor (SBR), a biological activated carbon (BAC) filter and an ozone reactor using an ozone dose of approximately 0.8 mg O3/mg DOC.

10. Climate change and wastewater reuse synergies

Researches have emphasized the environmental advantages of using treated wastewater for irrigation, especially in relation to climate change. According to Lal *et al*. (2020) [72] sorghum irrigated with wastewater significantly contributes to climate change mitigation. After eight years of treated wastewater irrigation, soil organic carbon stocks were increased by 79%, and carbon accumulation increased from 8.49 t ha^{-1} to 9.42 t ha^{-1}. The carbon footprint reductions achieved by utilizing sewage water for fodder production rather than groundwater were adequate to compensate the carbon emissions associated with the treatment of 0.44 and 1.09 million litre day^{-1} of sewage water under 50% and 100% N-P fertilisation, based on an average CO_2-eq release of 0.17 g L^{-1}. Additionally, treated wastewater provided an annual supply of 108 kg of nitrogen, 15 kg of phosphorus, and 25 kg of potassium $hectare^{-1}$, decreasing the reliance on commercial fertilizers and the greenhouse gas emissions linked to their use. Shilpi *et al*. (2019) [123] noted that methane generated from sewage systems has the potential to be utilized for generating heat and power, as well as it can also serve as a fuel source for vehicles. This strategy has the potential to lower net

greenhouse gas emissions and mitigate the climate change impacts. Mao *et al*. (2015) [83] studied the effect of methane emissions from sewage irrigation on the soil and the rhizosphere of rice fields. Their findings revery vealed that sewage irrigation decreased the methane emissions while simultaneously enhancing the population of both methanogens and methanotrophs. Notably, methanotrophs demonstrated a greater sensitivity to copper addition than methanogens, suggesting differential responses of microbial communities to trace metal exposure in these systems.

11. Conclusion

Harnessing the potential of wastewater irrigation requires a multifaceted approach that combines advanced treatment technologies with public education and policy support. By investing in these areas, we can transform wastewater from a hazardous waste into a valuable resource that contributes to sustainable agriculture and water management while protecting public health and environment.

12. References

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