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ORIGINAL RESEARCH

Critical attributes and considerations for selecting irrigation systems for wastewater

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ABSTRACT

With increasing global population, the gap between the supply and demand for water is widening and poses a threat to human existence. In the face of water scarcity, urban wastewater is increasing in its attention as an alternate water source for crop production. However, several challenges such as toxicity hazards, salinity build-up and health concerns have been identified with the use of wastewater in agriculture. There are several technological solutions that can help ameliorate or lower the level of contamination associated with using wastewater for irrigation. This paper explores the use of some irrigation technologies to abate the toxicity and health concerns associated with wastewater irrigation. The paper identifies some decision parameters for the selection of identified irrigation technologies and subjects them to multi-criteria decision analysis (MCDA) to rank them based on the level of exposure of the crop and irrigator/field worker to contamination among other relevant criteria. This paper validates that limiting the contact of the wastewater with the edible parts of the crop, especially for leafy vegetables, can minimize contamination to the crop and field workers. Though not totally without constraints, the identified irrigation methods present prospects for a cleaner and more sustainable production with regard to wastewater usage in agriculture. Sub-surface drip irrigation systems were identified as the best irrigation system for filtered and treated wastewater followed by surface drip and pitcher irrigation. Irrigators can fall back on some of these identified methods for wastewater application for sustainable crop production and maximized food safety.

Keywords: Wastewater, Irrigation, Peri-urban Agriculture, Crop Quality, Crop Nutrition, Irrigation Technologies

Introduction

Rural-to-urban and peri-urban migration is increasingly diminishing agricultural lands within and around urban communities. The relocation of individuals from rural areas into the cities looking for jobs and better livelihoods has also resulted in an increase in urban food demands. In response to this situation, a high number of urban and peri-urban tenants also creates livelihood opportunities by farming on any available piece of land especially, wetlands, to meet the growing food demand of the urban populace. These urban and peri-urban farmers concentrate their production on high-value crops which are also highly perishable (Follmann *et al.*, 2021), utilising any available water source for their production. Due to the increasing demand for fresh vegetables, urban and peri-urban agriculture has gained momentum in year-round production to meet this demand. Fianko and Korankye (2020), reported that between 50 – 90 % of vegetables consumed by urban dwellers are cultivated near cities or in peri-urban areas. Producers in these areas usually use polluted and untreated wastewater to irrigate their crops. Sources of water for urban and peri-urban farms are mostly from rivers, streams and drains which usually carry wastewater from households. The external nature of pollution of these water sources for agriculture forces irrigators to make production cleaner by limiting contamination of the crop and any further pollution of water bodies.

Irrigated agriculture withdraws the most water when it comes to world water consumption. In areas with dry climates, irrigation water use ranges from 50 – 85 % of total water use (Puy *et al.*, 2021). Wastewater has served as a viable source to supplement agricultural water demands (Morris *et al.*, 2021). The reuse of wastewater for irrigation is one of the non-conventional water resources targeted to overcome the envisaged water crises associated with climate change and its variabilities. Ungureanu (2020) estimated that about 20 million hectares of land are irrigated using wastewater worldwide. According to the World Water Assessment Programme's forecast, by 2030, more than half of African countries would face economic water scarcity. As a coping mechanism, Abdallah and Mourad (2021), projected that most of the urban agriculturists in the cities of distressed countries would rely heavily on low-quality water and wastewater for irrigation. Agodzo *et al.* (2003) estimated an increase in urban wastewater generation in Ghana from about 530,346 m^3/day (36 %) in 2000 to about 1,452,383 m^3/day (45 %) in 2020. This huge amount can be put to greater use when diverted into wastewater irrigation (Hashem and Qi, 2021).

Wastewater irrigation can be categorized as planned or unplanned, depending on the availability of irrigation infrastructure, the level of control by government agencies, and the degree of social acceptance (D'Andrea *et al.*, 2015). In Ghana, informal urban and peri-urban irrigation is about ten times more in terms of the total area under cultivation than in official irrigation schemes (Yeliliere *et al.*, 2018). As in many other developing countries, urban water bodies in Ghana are heavily contaminated with untreated wastewater (Amuah *et al.*, 2022). However, wastewater is a reliable source of water supply, usually free-of-charge, and continuously available in urban market vicinity. Even though the reuse of wastewater in agriculture has become a widespread practice (Takyi *et al.*, 2022), this resource contains substantial amounts of beneficial nutrients as well as toxic pollutants, which is both an opportunity and a challenge for agricultural production (Alghobar and Suresha, 2015; Chaoua *et al.*, 2019). Organic matter, phosphorus, potassium, and nitro-

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gen in wastewater may improve soil fertility which results in enhanced plant growth and development leading to increased agricultural productivity (Rehman *et al*., 2023). Fagan (2015), reported that plants irrigated with wastewater benefited from the nutrients present, which resulted in an increase in growth especially at the early stages of a crop's development.

Chemical characteristics of sewage water vary with the source of the supply, the sewage system, the season, and the nature of industrial discharge into the system. A major concern in using sewage effluent in irrigation is the presence of high concentrations of hazardous constituents, such as trace elements (e.g., zinc, copper and nickel), which can be harmful to plants at excessive levels (Sathya *et al*., 2022). For all crops, phytotoxicity may occur only because of long-term accumulation in the soil. Heavy metals, such as cadmium, chromium, and lead, can be taken up by the plants, resulting in toxic concentrations in the food chain or polluting groundwater and surface water by deep percolation or runoff. Many of the trace elements present in wastewater originate from industrial effluent. However, many of the trace elements in raw sewage are effectively removed into sludge generated by primary sedimentation and secondary clarification (Kesari *et al.,* 2021).

Irrigation practices involving the use of contaminated wastewater can pose extensive public health issues to farmers and consumers, particularly where crops are eaten raw. It is beneficial to assess and mitigate the health risks to the farmers themselves, to population groups residing in the immediate production vicinity and to the public who may consume contaminated wastewater-irrigated crops by making production cleaner and less risky (Valipour and Singh, 2016). Irrigation technologies can become a major front for clean technology usage when it comes to the use of wastewater in agriculture. Clean irrigation technologies could support the global agricultural system toward these goals. Experience also suggests that reuse of treated wastewater could significantly augment the quantity of available water and help control water quality when used appropriately and with the needed caution (Khan *et al*., 2022).

There are several practices that can be adopted to aid in the appropriate and effective use of wastewater in crop production. However, no single approach can singlehandedly do away with the effects of wastewater contamination on crop production (Drechsel *et al.,* 2022). Many different approaches and practices can be integrated and combined into a satisfactory control system; thus, reducing the health and environmental hazards associated with the use of wastewater in agriculture. The FAO irrigation and drainage paper 47 (FAO, 1992) highlights three on-farm strategies and approaches that can be considered with wastewater irrigation. Two of these approaches are the conveyance and application methods used to deliver irrigation water to crops. The mode of applying the water to the crops is argued to have a substantial effect on crop contamination. Several irrigation methods are discussed in this paper, alongside their pros and cons with regard to the use of wastewater. This paper, however, does not reach beyond the conveyance and application methods for the use of wastewater in urban and peri-urban agriculture. This paper aims at throwing light on wastewater for irrigation in peri-urban agriculture and identifies suitable irrigation systems that can minimize contamination and other associated risks of its use in Ghana.

Key Drivers of Wastewater Irrigation

Urban and peri-urban areas would continue to generate wastewater in huge volumes. This wastewater is generated from industries, households, and agricultural fields. The global wastewater discharge is estimated at 400 billion m^3/year, polluting approximately 5500 billion m^3 of water/year, as reported by Zhang & Shen, (2017). Wastewater usually consists of 99% water and 1% suspended, colloidal, and dissolved solids (Koul *et al*., 2022). Though the use of wastewater is widespread, data to support its usage globally is generally lacking.

According to the Global Water Intelligence (2010) report, 7.1 billion m^3/year of wastewater was reused for irrigation and industrial purposes. Although the use of untreated wastewater is a risk to the well-being of farmers and consumers, they do give critical livelihood benefits and serve to boost food security within the cities. Tzanakakis (2020) enumerated the principal driving forces of wastewater irrigation, with population growth, urbanization, and water scarcity at the forefront. In dense and rapidly growing regions, whenever increasing volumes of wastewater are being produced, insufficient financial and coping capacities constrain the establishment of comprehensive wastewater management systems for proper collection, treatment, and use of wastewater to respond to the infrastructural needs of urbanization (Obaideen *et al*., 2022). Increasing water scarcity and degradation of freshwater resources by urban dwellers (United Nations World Water Assessment Programme, 2017) within and around the cities have also pushed growers to use the same water resources for irrigation purposes. These water resources are also fed with wastewater from city homes, making it a reliable year-round source of water for irrigation purposes.

The available nutrients in wastewater are making the resource increasingly popular. Wastewater contains essential elements for plant growth such as nitrogen and phosphorus (Tymchuk *et al*., 2020). The use of wastewater is a form of nutrient and water recycling, and this often reduces downstream environmental impacts on soil and water resources. Unfortunately, the polluted water is also a source of water for irrigating vegetables, which are often eaten raw. The water quality of most wastewater is well below the WHO guideline value of 1000/100 mL of faecal coliforms for irrigated crops and <100/100 mL coliforms for crops of restricted irrigation (World Health Organization, 1989). Currently, the most common way community treatment plants dispose of wastewater after treatment is to discharge it to surface waters, increasing the flow and discharge of these waters. Diverting, storing and integrating these waters into agricultural landscapes can help avert the load the discharge of wastewater presents to surface waters and, subsequently, conserve these waters for potable use (Bernabé-Crespo *et al.,* 2023).

Poverty and the quest for jobs have also been identified as key drivers that significantly influence the use of wastewater for crop production (Ali *et al.,* 2021). Untreated wastewater in developing countries such as Ghana, is usually accessed without any substantial cost to farmers and irrigators. It also has a naturally high nutrient content (nitrogen and phosphorus), which reduces or even eliminates the need for expensive chemical fertilizers.

Risks and drawbacks of using wastewater for irrigation

The health concerns associated with the use of wastewater for crop production are a major concern worldwide. Wastewater reuse must be properly planned to maximize the socioeconomic and environmental benefits while minimizing the hazards associated with its use (Mehmood *et al*., 2022). Some of the environmental hazards include soil degradation problems such as salinization, toxicity due to sodium, chloride and boron ions, reduced aeration and pore-clogging due to suspended solids in wastewater, reduced soil hydraulic conductivity, heavy metal accumulation and other soil structural degradation issues (Schacht and Marschner, 2015). Concentrations of heavy metals in the soil and increase in salt content in wastewater-irrigated soils are increasingly becoming a global concern. Increased microbial load on fresh vegetables, as well as the exposure of farmers to harmful pathogens (e.g., bacteria, viruses, protozoa, or helminths) and chemicals, are also grave health concerns associated with the use of wastewater (Balali *et al*., 2020). Other concerns such as irregular crop growth due to the nutrient dynamics of wastewater and the leaching of excessive nutrients into the groundwater are also some grower and policy issues. Heavy metals such as lead and cadmium that may be present in wastewater can reduce soil productivity and percolation to aquifers may cause aquifer pollution with these heavy metals.

Wastewater treatment can be classified into 4 levels, depending on the extent and technology used in the treatment. Organic and inorganic solids, grease and oils are usually removed from wastewater using primary treatment methods such as screening, settling and flotation. Primary treatment can also involve conditioning processes such as neutralization and/or equalization before either disposal or discharge to a secondary treatment facility (Englande *et al*., 2015). Secondary treatment often involves both aerobic and anaerobic biological processes, in which complex organic matter in the wastewater is decomposed or oxidized by simple microorganisms. Conventional secondary treatments also utilize oxidation ponds, activated sludge, trickling filters and aerated lagoons (Butler *et al.*, 2017). The active sludge process is usually employed in larger communities for the continuous recycling of biological sludge.

Coagulation, filtration or micro-screening, chlorination and activated carbon adsorption are all classified as tertiary treatment methods (Samer, 2015). These methods remove suspended particles, biological oxygen demand and some nutrients. It also reduces turbidity and excessive nutrients that support eutrophication and eliminates residual pathogens. Advanced treatment methods such as reverse osmosis, ultrafiltration, distillation, electrodialysis, and ion exchange are classified as quaternary treatments. The main aim at this level of filtration is to remove any undesirable content including excess salts and upgrade the water to the level of potable water.

Wastewater treatment and reuse in Ghana

There are several concepts of different wastewater treatment methods and infrastructure some of which include constructed wetlands, waste stabilization ponds (WSP), membrane bioreactor (MBR), vermi-biofiltration (VBF), sand filters and other land treatment methods (Biswas *et al*., 2021). When sand filters were used by Mensah and Udofia (2018), an analysis of the water quality parameters revealed that most of the effluent wastewater pollutant content met the set guidelines, while others were unacceptable when compared with EPA (Ghana) guidelines. The ability of sand filters to effectively deal with key pollutants suggests that the treatment plant was efficient.

Korajkic *et al.* (2023), investigated the use of sunlight to remove fecal bacteria and coliphage in a single batch of water stored and exposed to sunlight for three days. They found sunlight exposure to be effective for the removal of bacteria and coliphage. Bansah and Suglo (2016) assessed waste stabilization ponds (WSP) for the treatment of sewage. They analyzed for microbiological and physicochemical contaminants. Results from this research (Bansah and Suglo, 2016) met recommended microbiological and chemical quality guidelines for wastewater reuse in Ghana. The question of whether farmers engaged in urban and peri-urban farming are willing to pay for treated or recycled water was answered by Amponsah *et al.* (2016). They reported that approximately 60 % of vegetable farmers would pay for treated water for their irrigation at a fee. If farmers are not willing to pay for treated wastewater, nature-based solutions for wastewater treatment such as constructed and natural wetlands can be considered. Globally, constructed and natural wetlands have been used for more than thirty years to reclaim agricultural runoff and urban/municipal wastewater. Wetlands are suitable for urban and peri-urban wastewater treatment due to their ease of operation, ability to cope with variable influent loads and its environmental advantages in cushioning storms, interrupting runoff and floods and serving as habitation for certain plants and animals.

Zachariah *et al.* (2020), identified stabilization ponds as the most dominant wastewater treatment method. While measures that promote the direct use of certain types of untreated wastewater may be relatively easy to implement, the cost of developing treatment systems for recovering wastewater from certain specific human activities may be prohibitive in some cases (United Nations World Water Assessment Programme, 2017). Financial and technical constraints in many developing countries make an all-inclusive wastewater collection and treatment a long-term future strategy. Risk management and interim solutions are required in the near future to prevent adverse environmental and health impacts from wastewater irrigation (Khalid *et al*., 2018).

Wastewater for soil and crop productivity

Wastewater reuse in agriculture reduces the amount of waste released into the ecosystem and supplements freshwater use for irrigation (Ganjegunte *et al.,* 2018). Wastewater is also an important low-cost resource for agricultural production (Rusanescu *et al.,* 2022). Macronutrients (such as N, P, K) as well as micronutrients (Fe, Cu, Zn, Mn) and organic matter available in wastewater (Sánchez–González *et al*., 2017) enhance soil fertility and make nutrients readily available to plants (Pizzeghello *et al*., 2021). The available nutrients in wastewater also reduces the need for chemical fertilizers by increasing and supplementing soil's available nutrients (Figure 1), resulting in net cost savings for farmers. Wastewater reuse can be said to provide benefits in terms of improved yields (Figure 2), water for irrigation and value in cost of money saved in input costs such as water and fertilizers.

Research findings on the effect of wastewater on crop production have been inconsistent. However, most studies have revealed a positive effect of wastewater on soil and crop production. De Carlo *et al.* (2020) have reported increased productivity associated with wastewater usage with most crops given higher than their potential yields with wastewater irrigation. Ali (2019) showed an increase in the grain yield of maize with the application of wastewater compared to freshwater (Figure 2).

Studies on maize grain yields, involving the use of treated wastewater revealed significant differences ($P \leq 0.05$) in increasing maize yield as compared with the effect of fresh or potable water (Figure 2). These results could be attributed to the fact that treated wastewater is enriched in macro and micronutrients, a fact in agreement with the findings of Elamin *et al.* (2020). It also agrees with the finding of Balengayabo *et al.* (2022), which stated that using treated wastewater to irrigate crops increased crop yield by 30 – 40 %. Yerli *et al.* (2023), stated that under-treated wastewater irrigation, the yield production of maize was increased, and attributed this rise to the improvement in the soil's physical characteristics, which enhanced nutrient uptake.

Selection Criteria for Suitability Ranking

In using the Multi-Criteria Decision Analysis (MCDA), the context for the evaluation was defined in which eight irrigation technologies (sprinkler, watering can, bubbler/microjet, subsurface drip, surface drip, furrow, border, and pitcher) were selected for the study. The objective of the ranking exercise was to

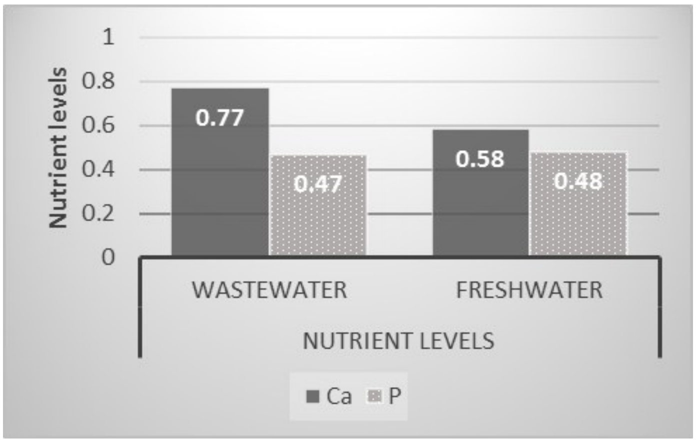

Figure 1 Nutrient levels in soil as irrigated with wastewater and

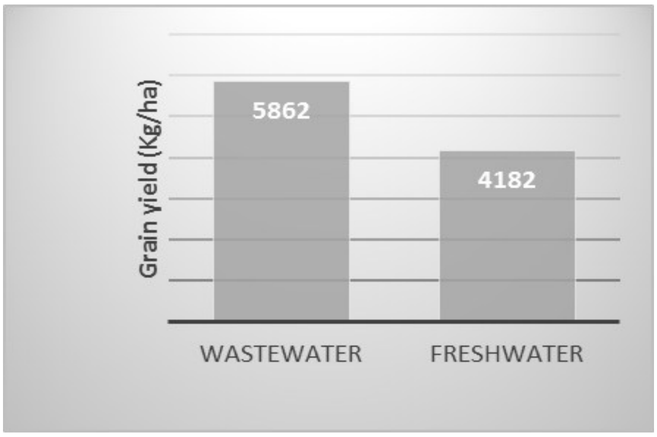

Figure 2 Grain yield in maize irrigated with wastewater and freshwater

identify which of the pre-selected irrigation systems was more suitable for wastewater irrigation. The suitability criteria were based on food safety (as expressed by contamination to the crop), the safety of the field worker or irrigator, the efficiency of the irrigation system and the impact of the wastewater on the environment (as runoff or seepage). Each criterion was weighed on a 3-point ordinal scale where 1 was the least desirable, 2 was moderately desirable and 3, was the most desirable. The criteria were measured and weighed against the suitability criteria of minimizing contamination and other associated risks with the use of wastewater in irrigation. An evaluation matrix was constructed for the identified criteria (Table 1). The rated values were scored and ranked with the highest weight being desirable and the lowest weight being least desirable. The recommendation for appropriate irrigation technology suitable for wastewater irrigation was based on results from the MCDA as shown in Table 1.

Ease of operation

Most irrigation systems are designed to make the crop watering process more convenient, by helping to reduce the amount of manpower needed for the watering process, and ultimately save time as well (Olamide *et al*., 2022). The ease of operation criterion sought to identify the ease with which the irrigation systems can be operated with minimal human contact and reduced labour throughout the system. With wastewater use, automation helps eliminate direct contact with irrigation equipment and water along the distribution path. Automation of irrigation systems is defined by Koech and Langat (2018), as the use of equipment that allows the irrigation process to proceed with minimum human involvement, except for periodic inspections and routine maintenance. Automated systems that eliminate major forms of contact during distribution are ranked highest on a 3-point scale. Fully automated systems were ranked 3, followed by partially automated at 2 and then manually operated systems at 1.

Application method

Irrigation water is applied by several application methods. Some of these methods are spraying under pressure, flooding on the soil surface, applying beneath the soil surface, and applying in drops or bubbles around the crop's root zone. The selection of any one of these methods is dependent on several factors such as soil type, water supply and its quality, the topography of the land, farm power or available energy and crops to be irrigated (Civilsdaily, 2017). With wastewater irrigation, how water is applied in-field gives an indication of how much of the crop is exposed to the wastewater. In the ranking matrix used, an irrigation system that allows for limited contact was rated highest on the 3-point scale used; thus, overhead spray (where wastewater touches foliage and fruits) was rated 1, Midriff spray (where wastewater touches stem and some leaves but not fruits) was rated 2, whereas localized (where wastewater is applied directly at the base of a crop) was rated 3.

Contamination to crop

According to Helmecke (2020), production systems that minimize irrigation water contact with the edible portion of the crop reduced the risk of contamination. Infield contaminations to the crop should be minimized as much as possible when using wastewater for crop irrigation. Application methods that do not expose the wastewater to the foliage of the crop also minimize contact with field workers. A system that has low contamination to the edible portion of the crop is most preferred and ranked highest on the 3-point scale.

Contamination to irrigator or field worker

Infield contaminations to field workers should be minimized as much as possible when using wastewater for crop irrigation. An application that does not expose the wastewater to the foliage of the crop also minimizes contact with field workers. A system that does not expose field workers to wastewater is most preferred and ranked highest on the 3-point scale.

Application efficiency

Application Efficiency (AE) is a performance criterion that expresses how well an irrigation system performs when it is operated to deliver a specific amount of water (Radmanesh *et al*., 2023). In irrigation management, the goal is to ensure that all areas of the field receive a set amount applied uniformly on the field or more specifically, applied where it is most needed. Systems with a high potential to spread water uniformly or apply water where it is most needed are deemed efficient and ranked highest at 3 points.

Water use efficiency

When irrigating with wastewater, water use efficiency (WUE), which is simply defined as the proportion of the water applied through irrigation that is productively or beneficially used by the plant is an important evaluation criterion. According to Perez-Blanco (2020), an irrigation system that enhances WUE leads to water savings which may be used to irrigate more cropped land. It is particularly relevant when water is a limiting factor for production. Most areas where wastewater is used for irrigation experience some level of water scarcity and seeks to efficiently use water. In selecting irrigation systems for wastewater irrigation, greater emphasis is placed on systems that are water-use efficient.

Table 1 Selection criteria matrix and ranking

	Selection criteria	Sprinkler (Centre pivot, Lateral move)	Watering can	Micro sprinkler, Bubbler, micro-jet	Drip		Border	Furrow	Pitcher
					Surface	Sub surfaces			
1	**Ease of application**	3	1	3	3	3	2	2	3
2	**Application method**	1	1	3	3	3	2	2	3
3	**Contamination to irrigator or field worker**	1	1	2	3	3	1	2	3
4	**Contamination to crop**	1	1	2	3	3	2	2	2
5	**Application efficiency**	3	1	3	3	3	2	2	3
6	**Water use efficiency**	2	1	3	3	3	1	2	3
7	**Potential for runoff/ seepage**	2	2	2	3	3	1	2	3
8	**Weed infestation**	1	1	2	2	3	1	2	2
9	**Energy demand**	1	3	1	2	2	3	3	2
10	**Clogging potential**	1	3	2	1	1	3	3	1
	Total Score	16	15	23	26	27	18	22	25
	Ranking	7th	8th	4th	2nd	1st	6th	5th	3rd

Potential for runoff/seepage

This criterion measures how much of the wastewater would find its way back to pollute surface or ground waters or how much irrigation water would be lost during conveyance to the field. According to Elkamhawy (2021), seepage losses may consume up to approximately 14 % of the total water supplied to an irrigation scheme. A major priority when selecting irrigation systems suitable for wastewater irrigation is to limit water losses along the conveyance channel. Water lost whether by seepage or evaporation is inevitably water lost for productive purposes. A system that limits water losses in the system and eventually also limits runoff can help abate overflow into surface waters or deep percolation which can eventually reach and pollute groundwater and other surface waters.

Weed infestation

In modern irrigation systems, the design emphasis is made on systems that suppress or limit weed growth in-field (Bhat and Qayoom, 2022). Wastewater contains substantial amounts of nutrients that can easily aid the growth of weeds and support the activities of autotrophs. A system that limits the widespread application of the wastewater would also inevitably limit the growth of weeds and some other pathogens.

Energy demand

Agricultural irrigation is an important component of the water-energy-food nexus. The high costs of fuels and electricity tariffs affect irrigation-related decision-making (Picazo *et al*., 2018). An irrigation system where energy use is optimized or omitted is an added advantage. Systems that use clean energy sources such as photovoltaic are also seen as sustainable and very much preferred, though initial costs may be high.

Clogging potential

In wastewater irrigation, clogging can occur due to the activities of microorganisms and solid or organic contaminants in the wastewater (Al-Mefleh *et al*., 2021). Under low-pressure systems, sediments can settle in pipes and tubes and eventually cause clogging in emitters. Though filtration is always recommended when using wastewater for irrigation, an irrigation system least susceptible to clogging is preferred.

Suitable irrigation methods for peri-urban wastewater irrigation in Ghana

The matrix ranking shown in Table 1 is discussed here with respect to the irrigation technologies identified. Bellwood-Howard *et al*. (2015) identified some of the irrigation technologies outlined in the matrix as suitable for wastewater irrigation. Alegbeleye (2023) also identified overhead irrigation methods such as sprinklers and watering cans, as having the highest potential to transfer pathogens to vegetables when wastewater is used. The multi-criteria decision matrix used (Table 1) also ranked these two application methods (watering can and sprinkler) as the least suitable for wastewater irrigation. The irrigation systems are discussed in the preferred order in the proceeding sub-headings.

Subsurface drip irrigation systems

Drip irrigation (also known as trickle irrigation), like other pressurized systems, conveys water to the base of a crop through a series of pressurized pipes. In some cases, the water is pumped into an overhead tank and distributed by gravity through laterals to the drip emitters, whilst in other instances, the water is pumped directly to the field for distribution. Drip irrigation systems can have water application and crop water use efficiency as high as 90 – 95 % when properly designed, installed and manage (Mutema *et al*., 2023).

Sub-surface drip irrigation systems have the highest application ease (Table 1) as well as the best application efficiency and weed suppression (moderate for surface drip systems and high for sub-surface drip systems). Because drip emitters are buried in these systems (as shown in Figure 3), weed growth is suppressed and usually limited to areas around the emitters. Ap-

Figure 3 Subsurface irrigation showing pipes laid beneath the soil (Derewenko, 2020)

plication of microbial-contaminated irrigation water using subsurface drip irrigation has been shown to reduce contamination of crops including lettuce at harvest compared to furrow irrigation (Beauvais *et al*, 2021).

Surface drip irrigation systems

Due to the localized application of water in drip systems, weed infestations are usually low, and its growth though supported by the nutrients present in the wastewater used may also be localized. Herbigation, a process whereby herbicides are applied to the field through irrigation water (Hariharasudhan *et al*., 2017), can be easily used to control weeds in drip-irrigated systems.

Figure 4 Surface drip irrigated okra

Both surface and sub-surface drip irrigation systems cause less contamination to crops than furrow and sprinkler irrigation (Yang *et al*., 2023) when wastewater is used. This is because water is applied directly or near the base of the crop (Figure 4), saving the foliage from any form of contamination from the wastewater. The area between rows remains drier, facilitating spraying, harvesting, and other cultural operations. The grower and consumer are less at risk of pathogen contamination, except in cases where fruits that have fallen in the application range of the emitters are picked for consumption.

Drip irrigation is also preferred when the wastewater is in short supply. It saves water and prevents runoff or total contamination of the entire field. Soil salinity and sodicity issues are also restricted to a particular area when drip irrigation is used. Excessive leaching of nutrients into groundwater is also subsided. Drip emitters are highly susceptible to clogging. Secondary and tertiary treatment of wastewater is required before drip irrigation systems are used as even a small percentage of emitters being clogged can affect the uniformity of water application to the fields.

Pitcher irrigation

Pitcher irrigation is one of the water-saving, low cost and simple methods whose efficiency has been proven many times by researchers in arid and semi-arid zones (Kaburu *et al*., 2021). Pitcher irrigation employs the use of porous surfaces or porous seeping tubes to deliver water directly to the base of a crop (Figure 5). They are usually placed at the most active water uptake area of crops. Water slowly seeps out into the root zone in the soil through the permeable walls of the pitchers (Ansari *et al*., 2015). At low evaporation rate, the positive pressure head inside the pitcher and the saturated hydraulic conductivity control the seepage rate, whereas, at a high evaporation rate, the negative pressure head at the outer surface of the pitcher is considerable (Babiker *et al*., 2021). The pitchers are usually buried in the soil, and water is supplied endlessly to these tubes from a point source (Cai *et al*., 2019).

The stable soil moisture maintained by pitcher irrigation enables crops to be grown in saline soil or with saline water where conventional irrigation would not work (Zaman *et al*, 2018). The high potential of efficient application and uniform water distribution makes these systems attractive and appealing for the safe use of wastewater. Najafi *et al* (2016), reported that clay pitcher has a high ability to absorb some heavy metals, especially Pb and Zn.

Figure 5 Pitcher irrigation showing wetted area (Prabu, 2015).

Pitcher irrigation systems scored relatively higher in terms of their ease of operation, application efficiency, contamination to crop and irrigator /field worker, potential for runoff and minimum weed invasion than five other irrigation systems (Table 1). Energy demand is also low as this system can be operated by gravity.

Micro-sprinklers, micro-jets and bubblers

Some micro-sprinklers are designed to wet the soil surface in proximity to the base of the crop or midriff/stems of the crops. Micro-jets work similarly to micro-sprinklers. However, they can be easily directed to spray right under the base of a crop/plant. In these systems, wastewater is conveyed under pressure through a closed network of pipes and valves and delivered to the soil or crop base through emitters or sprinkler heads. All these systems are automated, doing away with direct contact with irrigation equipment by an irrigator.

A partial set system subjects itself to constant removal and positioning in the field and can pose a significant contamination threat to a field worker or irrigator. Manually operating such systems can expose the operator to contamination. Though some forms of contamination may occur, using micro-sprinklers can minimize contact of the wastewater with the foliage and fruits. Primary treatment of the wastewater such as screening, sedimentation, and media filtration (gravel or sand) is advised for use in such systems. Advanced filtration systems are also needed to prevent clogging of pipes and micro-sprinklers. Bubblers and microjets come in 4th in ranking (Table 1) in terms of their suitability for wastewater irrigation. Its suitability is seen in its ease of application, application efficiency and water use efficiency.

Bubbler emitters come in laminar and turbulent flow types. The lamina flow types are more prone to clogging than the turbulent flow types. Though some form of primary treatment of wastewater is recommended, the turbulent flow types are a much better fit for wastewater irrigation. Primary and secondary treatments that remove all suspended solids are recommended for use with micro-sprinklers, micro-jets, and bubblers to reduce interference with liquid flow in the pipes. Pipes should be flushed from time to time to clean settled sediments and solids in the pipe network.

Furrow irrigation methods

Furrow irrigation (Figure 6) is an example of a surface irrigation method. Surface irrigation methods account for 95 % of the world's irrigated area (Okasha *et al*., 2022). Furrow and border irrigation systems are two common types of surface irrigation methods in Ghana. Surface irrigation releases water directly into the soil with minimal contact with crop foliage. Siting of the wastewater pond or reservoir can be done at the edges of the fields to facilitate operations and field activities.

Furrow irrigation systems release water into channels (furrows) for distribution along a gradient till it reaches the end of the furrow or channel (Figure 5). Water infiltrates the soils on either side of the channel to irrigate crops. The crop is usually grown on the ridges between the furrows. Furrow irrigation is suitable for a wide range of soil types, crops, and land slopes (Goncalves *et al*., 2021). Planting on ridges (which are always elevated than the furrows) and releasing irrigation water to the furrows ensures minimal contact of the wastewater to the crop.

Two types of furrow irrigation schedules, i.e., the fixed furrow and alternate have been tested for tomato production at the CSIR-Crops research institute under a Global Challenges Research Fund (GCRF) funded project called Recirculate. In using fixed furrow irrigation, one furrow is chosen by every sequential ridge to receive irrigation water for the entire duration of the crop's growing season. The alternate furrow irrigation method engages the use of both furrows beside a ridge though only one is provided with water at every irrigation event. Both methods can reduce water use by about 50 % through the manually operated fixed furrow system ensures comparatively less labour and field engagements as the alternate furrow systems. To further reduce labour and human contamination arising from contact with the distribution system, both systems can be easily automated.

Furrow irrigation systems are less likely to be affected by sediments in the irrigation water or other physical water quality issues (as shown in the clogging potential in Table 1). Contamination risks still exist due to the exposure of the wastewater in the field, and farmers are usually cautioned to use protective clothing in-field and restrict the use of wastewater irrigation with surface irrigation systems to crops that are not eaten raw.

Border irrigation systems

Border irrigation is characterized by long strips of well-leveled land that are encircled by bunds or ridges. Water is conveyed to irrigate the enclosed land using siphons/piles, pipes, channels, or gates. A pane of water drifts down the grade within the border, guided by the bunds on either side (Rheindorf and Wodak, 2018). Automation of the system can ensure minimum human contamination with the wastewater. Adoption of furrow and border irrigation systems for wastewater irrigation will reduce, significantly, the direct contact between wastewater and vegetables, especially the edible part.

Figure 6 Furrow irrigated maize crop

Additionally, in furrow and border irrigation, wastewater would be exposed to sunlight, which to some extent serves as a treatment for the wastewater. Silverman *et al*. (2014) reported that sunlight exposure was found to be important for the removal of bacteria and coliphage. Border irrigation methods apply water on the surface and are less likely to contaminate high-hanged growing fruits. However, for low-lying crops and root crops, the possibility of contamination may still be high.

Sprinkler irrigation

This system involves the conveyance and distribution of water using pressurized pipe networks. The pressurized system produces aerosols, fog, or mist, usually above the crop foliage. In using pressurized systems for wastewater irrigation, aerosol spraying (such as those from sprinklers, center pivots, and rain guns) should only be used when the water has been treated to such standards that, risks from pathogens are curtailed. In any other case, aerosol spraying should be avoided when wastewater is used as the irrigation water source.

Watering cans

The watering can (Figure 7) method is one of the commonest irrigation methods used by farmers, especially for vegetable production in Ghana. A watering can has an average capacity of about 15 litter (Kim *et al*., 2023). A filled watering can is manually tilted towards the spout where water is sprayed over the crops through a shower spout. This process is repeated until the desired cropped area is sufficiently irrigated. The watering can may be manually used to apply water overhead, midriff, or at the base of a crop. However, farmers usually prefer to use it to apply water overhead of crops. This increases the contamination risk when wastewater is used.

Though relatively cheap and easy to operate, the contamination risks associated with the use of the watering can cannot be overlooked. Due to the direct handling of the watering can and unavoidable contact with the water it carries, it has been ranked as the least suitable for wastewater irrigation. Its use for wastewater irrigation should be avoided entirely if possible. In cases that application of wastewater with watering can cannot

Figure 7 Watering can application in vegetable production

be avoided, rigorous treatment of the wastewater should be done. Simple treatment methods such as ponding and exposure to sunlight for several days can remove some pathogens and allow for use in some agricultural crops. Irrigators or farm workers should also protect themselves by wearing personal protective equipment (PPE).

Other low-contamination irrigation techniques

Irrigated Zai pits

Zai is a farming technique that uses shallow dug-out pits, usually 20 - 40 cm in diameter, to a depth of about 10 to 20 cm in the soil during the preseason to catch water and, also, serve as a site for the application of nutrients and supplementary irrigation (Odour *et al*., 2021). The dugout earth is heaped around the pit to improve the water retention capacity of the pit and, also, avoid excess water intrusion into the pit. Composted organic matter is usually added to the pits at an average recommended rate of 0.6 kg/pit and, after the first rainfall, the matter is covered with a thin layer of soil, and the seeds placed in the middle of the pit (Paul *et al*., 2019).

Zai pits are an innovation that addresses issues of land degradation, soil fertility, and soil moisture (Kebenei *et al*., 2021) and can be adopted as a great landform for applying wastewater to crops. The Zai pit system helps to concentrate nutrient and water availability for a long period of time because of the organic matter residues at the bottom of the pit (Nasike, 2019) as well as the reactivation of biological activities in the soil which may help to reduce the potency of pathogens in wastewater. In irrigating with wastewater, the pits can be major emitter points for micro-sprinklers, micro-jets, bubblers, pitchers and drip irrigation. Leaching the pits also becomes easy since all other accumulations (heavy metals, salts or pathogens) are concentrated within the pit zone for easy identification and remediation.

Partial rootzone drying technique

The partial rootzone drying (PRD) technique is an irrigation technique that improves water use efficiency without significant yield reduction to the crop. It involves the control and management of water stress (Simbeye *et al*., 2023) accomplished by irrigating half of the plant root zone, while the other half is allowed to dry out partially (Urlic *et al.,* 2020). After a stipulated time, the procedure is then reversed, and the previously dry side is also given water while the previously well-watered side is also left to dry out partially (Dbara *et al*., 2016). During the early stages of water stress, Abscisic Acid (ABA) a hormone, is synthesized in the drying roots of the crop (Alemu, 2020). ABA is transported to the leaves where it reduces water loss through transpiration. In other words, a plant's root system is initially starved in order to train the plant to be more efficient with the water it is allotted, thus extending photosynthetic activity (Iqbal *et al*., 2020).

Results have confirmed that PRD irrigation techniques can improve water use efficiency of crops like tomato (Puertolas *et al,* 2022). According to Elhani (2019), PRD can save irrigation water up to approximately 50% without significant yield loss, while may improve the yield quality. Practical application and promotion of the PRD technique will allow farmers in fresh water-scarce areas to adopt it not only as a strategy for saving water, improving nutrient use and sustaining yield but also for producing food with enhanced nutritive and health characteristics (Jovanovic and Stikic, 2018).

Field maintenance in wastewater irrigation

Appropriate water management practices must be adopted with wastewater irrigation to prevent pathogen build-up, salinization and heavy metal accumulation. If salt is not flushed out of the root zone by leaching or removed from the soil by effective drainage, salinity problems can build up rapidly. Numerous land and soil management practices can be adopted to decrease the adverse effects (such as salinity, sodicity, toxicity and health hazards) that are related to the use of wastewater for irrigation. Leaching and drainage are two important water management practices that can help minimize the salinization of soils (Mohanavelu *et al*., 2021).

Irrigation frequency, pre-planting irrigation and irrigation prior to the rainy season, can reduce the salinity hazard and avoid water stress between irrigation intervals. In order to meet the crop water requirement of crops, increasing the frequency or volume of irrigation will be desirable as it eliminates water stress between irrigation intervals. However, frequent irrigation through irrigation systems such as border and basin irrigation methods, may result in overwatering and ensuing decrease in water use efficiency. On the contrary, localized irrigation methods coupled with frequent applications with smaller amounts could help to overcome salinity problems associated with the use of saline irrigation water (Nachshon, 2018). Pre-planting irrigation is done basically to provide adequate moisture to germinating seeds and young seedlings. A common practice among vegetable growers is to pre-irrigate the field before planting, to avoid water stagnation and wet spots that can occur when irrigation is done after planting or transplanting. A good practice is to use only treated wastewater whenever possible because this reduces both freshwater consumption as well as health and environmental risks (Ungureanu *et al.,* 2020).

One other option that may be available to farmers is the blending of treated sewage with conventional sources of water to obtain a blended water of acceptable salinity level. The blend help obtain water of acceptable salinity level and a superior microbial quality compared to the unblended wastewater. Alternatively, irrigating with treated wastewater interchangeably with other sources instead of blending them can also help reduce unwanted hazards associated with sole wastewater use. For an alternating application strategy to be successful, it requires dual conveyance systems, which comes along with additional costs (Devesa and Dietrich, 2018).

On-farm land development such as land levelling to a specific grade, establishment of adequate infield drainage, deep ploughing and leaching can minimize hazards that may result from the use of wastewater. The adoption of surface irrigation methods such as furrow and basin irrigation requires land grading to achieve high application uniformity and acceptable irrigation efficiency. Layers of clay or soil pan found in stratified soils often impede the free movement of water through and beyond the root zone. This leads to build-up of salts in the root zone. Irrigation efficiency, as well as water movement in the soil, can be greatly enhanced by deep tillage practices (e.g., ploughing, harrowing and ridging). Deep tillage is undertaken to reduce soil compaction and improve soil infiltration rates (Amami *et al*., 2021).

Cultural and crop management practices under wastewater irrigation should be aimed at preventing damage to crops and the soil. Weeding and pesticide application should be done in accordance with the management practice associated with the crop. In some instances, weeding and pesticide application might be carried out more times when wastewater is used. This is because the nutrients found in wastewater similarly support the growth of weeds and some associated crop pests.

Conclusion

This paper has explored several irrigation methods and ranked their suitability for wastewater irrigation. The purpose of this paper was to identify suitable irrigation methods for wastewater irrigation using the multi-criteria decision approach. Some selected irrigation methods were ranked based on several criteria. The preferred methods were those that limit contamination to the crop and irrigator or field worker. The two drip irrigation systems, the subsurface and surface drip irrigation systems ranked first and second respectively followed by the pitcher irrigation, which operates like the drip systems. Sprinkler irrigation system and watering can were ranked 7th and 8th respectively.

Specific irrigation methods such as the surface and subsurface drip irrigation systems, the pitcher system, furrow and basin irrigation, and techniques such as partial root drying and alternate wetting and drying, can limit contamination to crop and field workers. Overhead irrigation methods such as watering cans and sprinkler irrigation systems which have the highest potential to transfer pathogens to crops should be avoided. Farmers should be sensitized, trained, and aided in the adoption of irrigation systems such as border, furrow and drip that ensures minimal contact with crops and irrigation techniques that requires less application of voluminous irrigation water such as deficit irrigation and Zai pits. The integration of agriculture into urban sanitation concepts must be ensured with much emphasis on water and nutrient recycling and reuse. In addition, farmers should be encouraged to adopt low-cost wastewater treatment technologies, such as sunlight exposure and sand and gravel filters.

There is also the need to co-develop and promote cost-effective irrigation solutions that address prevailing technical, institutional, social, behavioural and health challenges associated with wastewater irrigation. More affordable and clean irrigation methods need to be developed and assessed for wastewater use, in the hope of reducing the associated health risks. Such methods should also address the circular irrigation environment, where low tenure security prevents farmers from investing in sophisticated methods or on-site treatment ponds.

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Conflict of Interest Declarations

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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