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Influence of Fertigation with Anaerobically Treated Domestic Wastewater on Soil Chemical Properties, Growth and Yield Characteristics of Greenhouse Maize Plants

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ABSTRACT: Irrigation with effluents is becoming widespread around the world because of uncertain rain-fed agriculture and water scarcity. Hence, the objective of this paper is to investigate the influence of fertigation with anaerobically treated domestic wastewater on soil chemical properties, growth and yield characteristics of greenhouse maize plants using standard methods. Application of treated effluents for irrigation of crops in greenhouses may have impact on soil nutrients and crop yield depending on the origin of wastewater and the type of treatment. A greenhouse experiment was carried out to explore the effects of irrigation with wastewater treated in an anaerobic digester integrated with an Anaerobic Baffled Reactor (ABR) on chemical properties of soil, maize yield and growth characteristics. Three replications of plots irrigated with treated effluent (treatment) and plots irrigated with fresh water (control) were used. The treated wastewater pH was 7.78±0.3, with higher concentrations of BOD_5, COD, PO_4^-, NO_3-N and NH_3-N than fresh water. Irrigation using anaerobically treated wastewater showed significant improvement ($P<0.05$) in soil PO_4^- and organic matter, but had no effect on soil salinity and alkalinity. Leaf length and leaf area Index significantly increased ($P<0.05$) by 12.2% and 32.02% respectively in treatment plots. Yield characteristics: weight of 1000 grains, mass of grains per cob and yield of grains portrayed significant improvement ($P<0.05$) in treatment plots. In treatment plots, grain yield was 44.9% higher, grains were 13.9 % heavier and weight of grains per cob was 32.1% higher than those from the control plots. Thus, short-term irrigation with anaerobically treated domestic effluent from the anaerobic digester integrated with ABR enhanced the yield of greenhouse maize. On long-term application, soil monitoring is advised every farming cycle for early detection undesirable changes to inform the required remedial measures.

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Key words: anaerobic digester; fertigation; growth and yield attributes; greenhouse maize.

Irrigation with treated sewage is a growing agricultural practice globally due to uncertain rain-fed agriculture and water scarcity (Jiménez, 2006; Drechsel *et al.*, 2015). According to studies, climate change contributes to variations in rainfall patterns and the frequency of extended dry periods, which impacts agriculture and result in economic retardation (Vincent *et al.*, 2016). Besides, high cost of fertilizer also raises concerns on the cost of food production and food security which need interventions for alternatives (Jiménez, 2006; Drechsel *et al.*, 2015; Ku *et al.*, 2021). According to reports, about 70 percent of global water from all available sources is utilized in irrigation agriculture (Siebert *et al.*, 2010). This imply that water scarcity has a profound impact on agriculture which calls for alternative sources. While experiencing water scarcity, 70%-80% of water supplied turns into wastewater which is collected, treated and disposed in water bodies (World Food Program, 2009). Reusing treated wastewater for crop irrigation offers advantages such as wastewater management with zero discharge, reliable food yield and nutrient recovery (Angelakis *et al.*, 2018). When used for crop irrigation, treated wastewater contains macronutrients

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and micronutrients in varying concentrations that are likely to promote plant growth and yield (Widaa and Elamin, 2020; de Lemos *et al.,* 2021; Dinesh *et al.,* 2021), but it is rarely used to improve food production. Maize is used as a staple food for more than 80% of Tanzanians (Mkonda and He, 2017) and according to NBS (2014), more than 90% of households in Tanzania grow maize. Thus, water reuse for maize irrigation could provide reliable food for the majority through diverse available sources of wastewater but this needs more evidences. It is estimated that more than 10 percent the global population consumes food irrigated using both treated and untreated wastewater (Ungureanu *et al.,* 2020). This necessitates a broader understanding of the impact of various treated wastewaters based on the sources and the types of wastewater treatment technologies used and the farming practices on the chemical properties of soil and yield of crops. The current study contributes to the existing body of knowledge on water reuse by focusing on effects of wastewater treated in an anaerobic digester integrated with an ABR in series on maize growth and yield attributes, as well as soil chemical properties. Studies in Sudan, South Africa and Iran on application of treated municipal wastewater for irrigation; and in India using distillery and beverage effluents for fertigation of maize, revealed improved results on the yield and growth characteristics of maize plants (Bame *et al.,* 2014; Mousavi and Shahsavari, 2014; Widaa and Elamin, 2020; Dinesh *et al.,* 2021; Ku *et al.,* 2021). Moreover, similar to treated wastewater, other sdudies found enhanced yields and growth characteristics of maize fertigated with diluted untreated wastewater (Alabadi *et al.,* 2018; Younas *et al.,* 2020). Nevertheless, treated wastewater from domestic sewage treatment plants might not contain sufficient nutrients for enhanced plant growth, as in Da Fonseca *et al.* (2005), who found that fertigation with treated effluent didn't significantly enhance maize yield when compared to water from the well. This may be due in part to the generation sources of wastewater and the method of treatment used, both of which influence the amount of plant nutrients, organic matter and other amendments of soil in the treated effluents. In addition to low nutrients in treated effluent, other factors could be leaching of nutrients beyond the root zone associated to the soil type and rainfall events during the farming cycle (Lehmann and Schroth, 2002).

On the basis of the available data, the objective of this paper is to investigate the influence of fertigation with anaerobically treated domestic wastewater on soil chemical properties, growth and yield characteristics of greenhouse maize plants.

MATERIALS AND METHODS

Description of the research area: The present study was carried out in Tanzania at Ardhi University. The University has Sanitation Biotechnologies Research Centre (SBRC) with the wastewater treatment system for wastewater emanating from the staff houses is one the component of the Centre. The treatment system has a digester integrated in-line with an ABR as the main treatment components; and an underground effluent tank. The effluent was used in the study to irrigate maize as source of nutrients and irrigation water. The effluent was pumped to a raised tank using a submersible sewage sludge pump Model SSP-1.0, from which it gravitated to the experimental plots via the drip irrigation schemes (Figure 1). The texture of the soil at the experimental site was determined and found to be sandy-clay with 6% silt, 28% clay, and 66% of sand.

Description of the experiments: This study was carried out to investigated the influence of fertigation with treated domestic wastewater on soil chemical properties, yield and growth characteristics of maize grown in the greenhouse using plots in three replications. The greenhouse was utilized to mitigate the effect of pests and rainwater on nutrient leaching and washout from plants in-order to account for the effect of irrigation water on soil chemical properties, yield and growth characteristics of maize plants. The greenhouse's walls were made of shading net and it was roofed with a polythene sheet. The findings on soil chemical properties, yield and growth characteristics were compared between the treatment experimental plots (TEP) and control experimental plots (CEP) in three replications. The treatment experiment used treated sewage to irrigate the plots, while the control experiment used tap water to irrigate the plots. A surface drip irrigation system was installed to restrict contacts with the fertigation water (treated wastewater) and to optimize water use efficiency. The drip irrigation scheme was made up of drip pipes sized 16 mm and fittings such as valves, start connectors, emitters and end connectors. Maize seeds were sown on July 1, 2020, and harvested on October 20, 2020. Maize grain seeds were sown in lines 60 cm apart and 25 cm apart along the line, which corresponded to the space between emitters along the dripping pipes. Maize grain seeds were purchased from the certified seed sellers at Mwenge in Dar es Salaam.

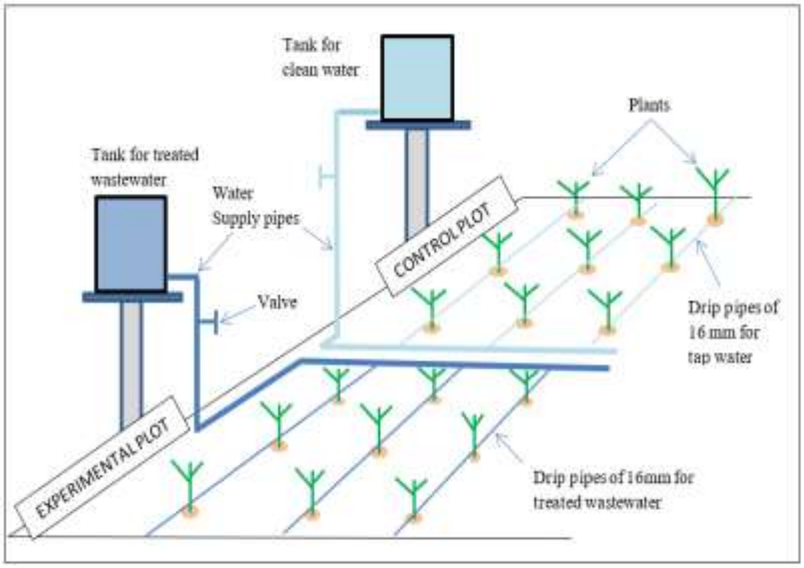


Fig 1. Layout of treatment and control experimental plots.

Sampling and data collection on growth and yield characteristics of maize plants: The maize plants were sampled using the method described by Balengayabo *et al.,* (2022a) and Buriro *et al.* (2015). The treatment and control plots each had 18 maize plants sampled, with 6 plants from each of the three triplicate sub-plots. The number of plants sampled was determined using a systematic random sampling approach. The growth characteristics were monitored using a non-destructive method. Number of leaves, lengths and widths of leaves and Plant height were all measured (Dinesh *et al.,* 2021; Ku *et al.,* 2021; Onuorah, 2021). As shown in equation (1), the number of leaves, lengths, and widths of leaves were used to calculate the Leaf Area Index (LAI) for maize plants using the method described by Balengayabo *et al.,* (2022a) and Dinesh *et al.,* (2021).

$$\text{LAI} = \frac{\text{L}\times\text{B}\times\text{N}\times 0.796}{\text{Spacing of plants (cm)}} \ldots\ldots\ldots\ldots (1)$$

N: number of leaves, **B**: breath of the leaf (cm), **L**: length of the leaf (cm) and 0.796 is a constant.

Methods used for measurement of growth characteristics of maize plants: The initial measurement was taken two weeks (W_2) after planting, and subsequent measurements were taken at one-week intervals. The plant heights, lengths of leaves, leaf widths and number of leaves were determined as per methods used by other researchers (Wood and Roper, 2014; Onuorah, 2021; Balengayabo *et al.*, 2022a).

Determination of yield characteristics of maize: The cobs of maize were separated from the stalks and sun dried before being stripped of their husks and silks. Five (5) cobs were randomly selected from each plot to determine the yield characteristics. The number of kernel rows per cob, number and weights of grains per cob, cob length, mass of 1000 grains, and grain yield were the yield characteristics used (Dinesh *et al.,* 2021; Ku *et al.,* 2021; Onuorah, 2021). The details of on the measurement of the yield characteristics are as described in Dinesh *et al.* (2021) and Balengayabo *et al.* (2022a).

Sampling and analysis of irrigation water: During the experiment, treated effluent and clean (tap) water were sampled and analyzed at the Environmental science and technology laboratory of Ardhi University. The samples were collected two times per month and analyzed using standard methods for water and wastewater analysis (Disciglio *et al.,* 2015). The parameters analyzed include: Electrical conductivity (EC), pH, Biochemical oxygen demand (BOD_5), Chemical oxygen demand (COD), Phosphates (PO_4^-), Ammonium-nitrogen (NH_4-N), Nitrate-nitrogen (NO_3-N), Potassium (K), Sodium (Na), and Magnesium (Mg) as shown in Table 1.

Sampling and analysis of soil for chemical properties: Soil samples from the control and treatment plots were collected for analysis of chemical properties before and after irrigation. Soil chemicals tend to accumulate in the root zone of plants whose depth is 0 - 35cm (Khaskhoussy *et al.,* 2015). Soil auger was used to sample soil in the root zone of maize plants at a depth of 0-40 cm. The samples of soils were dried at room temperature and ground using mortar and pestle, followed by sieving with a 2.0 mm soil sieve, Hach Kit, Model SIW-1. The ground soil samples were analyzed for soil fertility parameters such as phosphate (PO_4^-), nitrate- nitrogen (NO_3-N), soil organic matter (SOM), soil salinity (EC), soil alkalinity (pH) and total dissolved salts (TDS) as described below. Metal ions including Sodium (Na^+), Magnesium (Mg^{2+}), Calcium (Ca^{2+}), and Potassium (K^+) were extracted from soil using aqua Regia extractant and analyzed using an Atomic Absorption Spectrophotometer, AAnalyst 100, Perkin Elmer of the USA.

Analysis of Phosphate-Phosphorus and Nitrate-Nitrogen in the soil: The phosphorus was extracted from the soil using Mehlich 2 reagent at a soil-solution ratio (w:v) of 1:10, as described in Hach Co. and Hach, (1992). The available Phosphorus in the soil extracts was determined using the Phosphate-Phosver 3 method using a spectrophotometer, Hach DR 4000U (Hach, 1999). Soil Nitrate-nitrogen was extracted using the calcium sulphate extraction method at a soil-extractant ratio of 100:1 (w:w), as described by Hach Co. and Hach, (1992). The Nitrate-nitrogen-Nitraver V method was used to analyze Nitrate-nitrogen in the soil extracts using the Spectrophotometer, Hach DR 4000U as per method in Hach, (1999).

Analysis of soil organic matter content: The soil organic matter content was analyzed by using the methods described in Ridine *et al.* (2014) and in Balengayabo *et al.*(2022b). The equipment used include: the oven, Hach model 35 GM-2, (USA) for drying the soil samples to remove the moisture content at 105°C for 24 hours; the Muffle furnace, Vecstar model LF 3 (UK), for volatilization of soil organic matter at 560°C for 3 hours and the digital balance, Scientech model ZSA 210 (USA) for weighing the soil samples in crucibles. The standard formulars were used for calculation of the ash content and the soil organic matter content in percentages.

Analysis of soil alkalinity and salinity: Soil alkalinity and salinity was analyzed by using an aqueous extraction method at a soil-water ratio (w:v) of 1:1, as described by Hach Co. and Hach, (1992). Soil alkalinity (pH) and salinity (EC and TDS) were measured by using the pH meter, specifically the pH/EC/TDS/Temperature tester, Hanna Combo model HI 98129.

Sodium absorption ratio: The sodium absorption ratio (SAR) for irrigation waters and soil samples was calculated using the standard formulae as described in Khaskhoussy *et al.,* (2015) shown in Eq (2). SAR is a measure of soil sodicity.

$$\mathrm{SAR} = \frac{[\mathrm{Na}^{+}]}{\sqrt{[\mathrm{Mg}^{2+}]+[\mathrm{Ca}^{2+}]}} \;\ldots\ldots\ldots\; (2)$$

Where, SAR = Sodium adsorption ratio and [Mg^{2+}], [Na^+] and [Ca^{2+}] are the respective concentrations of Magnesium (Mg^{2+}), Sodium (Na^+), and Calcium (Ca^{2+}) in Meq/l.

Statistical data analysis: The data was analyzed by using the INSTAT 3 software at the confidence interval of 5%. The difference in soil chemical parameters, yield and growth characteristics of maize crop between control and treatment plots was considered significant at $P \leq 0.05$.

RESULTS AND DISCUSSIONS

Characteristics of irrigation water: Table 1 presents the results on the chemical characteristics of water used for irrigation of maize plants in the treatment and control plots. The treated effluent was weakly alkaline with the average pH of 7.78±0.33, EC, 0.598±0.11dS/m and TDS, 400.62±47.2 mg/L. The concentrations of chemical parameters in the treated wastewater were BOD_5 , 92.4±39.60 mg/L; COD, 130.8±32.67 mg/L; Sodium (Na), 17.82±1.10 mg/L; Magnesium (Mg), 7.68±0.44 mg/L; Calcium (Ca), 16.02±4.62 mg/L; Potassium (K), 11.76±3.94 mg/L; Nitrate, 2.64±1.21 mg/L; Phosphate, 33.75±4.9 mg/L and SAR, 1.066±1.2 Meq/L. Similar parameters were lower for tap water compared to treated wastewater; except the average pH, 8.16±0.23; Sodium (Na), 47.26±1.46 mg/L; Magnesium (Mg), 36.18±3.47 mg/L; Calcium (Ca), 65.41±3.28 mg/L; Potassium (K), 32.59±1.79 mg/L and SAR, 1.23±0.22 Meq/L. Phosphorus, ammonium-nitrogen, nitrate-nitrogen, and potassium concentrations were higher in treated effluent than in tap water, which are important soil nutrients for plant nourishment of plants. Higher ammonium-nitrogen is a characteristic feature for treated sewage from anaerobic treatment system because of the conversion of organic nitrogen into ammonium-nitrogen (Chan *et al.*, 2009; Hedaoo *et al.*, 2012). Ammonium-nitrogen may be directly uptaken by plants or converted and uptaken in the form of nitrate-nitrogen (HACH, 1993). More concentrations of nutrients in treated effluents from the anaerobic digester with the ABR compared to tap water, contributes to the improvement of soil fertility when used for irrigation (Balengayabo *et al.,* 2022b; Angelakis *et al.*, 2018). The BOD concentration in treated wastewater contributes to the soil's organic matter content and improves its humus content which is a good soil conditioner (Tsigoida and Argyrokastritis, 2019). Soil humus improves moisture content of the soil, metal retention, increases soil microbial activity, and enhances the formation of organometallic contents (WHO and UNEP, 2006), which contribute in improvement of soil fertility for plant growth and yield. Furthermore, soil organic matter decomposes, resulting in the production of ammonium-nitrogen, an important plant nutrient (Adejumobi *et al.*, 2014). Under slightly to moderate water quality restrictions, all chemical parameters, including macronutrients and micronutrients in both irrigation waters, were lower than the permissible limits specified by WHO and UNEP, (2006) for irrigation water.

The effect of irrigation water on the chemical properties of soil: Table 2 shows the effects of irrigation water on soil chemical properties. The effects of treated wastewater on soil fertility parameters, soil alkalinity, soil salinity parameters and soil sodicity are discussed in detail in the subsequent sections.

Table 1. Characteristic of water used for irrigation of maize plants in the experimental plots.

No.	Parameters analyzed	Units	Mean concentrations in irrigation water (n = 5)		FAO standards	P-Values
			Tap water	Treated wastewater		
1	pH		8.16±0.23	7.78±0.33	6.5 - 8.4	≤0.05
2	EC	dS/m	0.44±0.22	0.598±0.11	0 - 3.0	≤0.05
3	TDS	mg/L	298.23±24.6	400.62±47.2	0 - 2000	≤0.05
4	Nitrate (NO_3-N)	mg/L	0.63±0.08	2.64±1.21	5 - 30	≤0.05
5	NH_3-N	mg/L	0.169±0.02	12.42±10.12	0 - 5	≤0.05
6	Nitrite (NO^-)	mg/L	0.01±0.002	0.024±0.01		ns
7	Phosphate (PO_4^-)	mg/L	2.17±0.89	33.75±4.9	0 - 2	≤0.05
8	BOD_5	mg/L	12.76±1.34	92.4±39.60	0 - 30	≤0.05
9	COD	mg/L	36.40±3.69	130.8±32.67	0 - 90	≤0.05
10	Sodium (Na)	mg/L	47.26±1.46	17.82±1.10		≤0.05
11	Magnesium (Mg)	mg/L	36.18±3.47	7.68±0.44	0.2	≤0.05
12	Calcium (Ca)	mg/L	65.41±3.28	16.02±4.62		≤0.05
13	Potassium (K)	mg/L	32.59±1.79	11.76±3.94	0-2	≤0.05
14	SAR	Meq/L	1.23±0.22	1.066±1.2	0-6	ns

COD: Chemical Oxygen Demand; BOD_5: Biochemical Oxygen Demand at 5 days; TDS: Total Dissolved Solids; SAR: Sodium Adsorption Ratio; EC: Electrical Conductivity

Table 2. The effect of irrigation water on the chemical properties of soil

S/N	Parameters	Units	Concentrations in plots irrigated with treated wastewater		Concentrations in plots irrigated with tap water	
			Before irrigation	After irrigation	Before irrigation	After irrigation
1	pH		8.08±0.05	8.05±0.03	8.06±0.04	8.2±0.22
2	EC	dS/m	0.43 ±0.06	0.47 ±0.05	0.41 ±0.06	0.51 ±0.03
3	TDS	mg/L	225.0±27.5	235.7±66.0	231.4±18.9	258.7±9.0
4	Organic matter content	%	2.5±0.4	7.1±1.3 [a]	2.4 ±0.5	5.2 ±0.4
5	Nitrate (NO_3-N)	mg/L	12.0±1.9	8.1 ±1.6	11.1 ±1.9	7.8±1.3
6	Phosphate (PO_4^-)	mg/L	29.7±8.1±16.24	33.7±12.9 [a]	13.1 ±5.4	9.4±3.6
7	Sodium (Na^+)	mg/L	29.4±20.9	39.4±23.9	17.4±10.1	26.9±10.9
8	Magnesium (Mg^{2+})	mg/L	65.7±14.4	55.2±9.9	124.2±32.7	84.0±21.8
9	Calcium (Ca^{2+})	mg/L	499.7±269.3	883.5±18.42	206.1±40.59	563.2±118.4
10	Potassium (K^+)	mg/L	18.3±13.7	10.3±1.1	20.6±4.7	19.5±3.2
11	SAR	Meq/	1.8±0.2	2.1±0.5	2.1±0.8	2.1±0.6

Data are in Mean ± standard deviation (n = 3), a = Denotes parameters with significant difference

The impact of irrigation water on soil fertility parameters: Part of the results in Table 2 indicate soil fertility parameters including potassium (K^+), phosphate (PO_4^-), nitrate-nitrogen (NO_3-N) and soil organic matter content (SOM). Irrigation with treated wastewater portrayed a mixed results on soil fertility parameters; it led to the increase of soil PO_4^- and SOM, while it reduced NO_3-N and K^+ after harvesting in line with other studies (Balengayabo *et al.*, 2022b). The SOM increased significantly (P = 0.037) about three times from 2.5±0.4 % to 7.1±1.3%, whereas soil PO_4^- increased by 13.2% from 29.7±8.1 mg/l to 33.7±12.8 mg/l, but the increase was not significant (P>0.05). The increase in soil PO_4^- may be associated with PO_4^- in treated wastewater and the increase of SOM may be linked with concentrations of BOD_5 and COD in treated wastewater as reported in Table 1 in line with other studies (Adejumobi *et al.*, 2014; Erel *et al.*, 2019; Widaa and Elamin, 2020). SOM improves soil fertility by increasing the soil's ability to hold water, increasing aggregate stability, and producing nutrients during decomposition (Adejumobi *et al.*, 2014). On the contrary to PO_4^- and SOM, irrigation with treated sewage resulted into decrease of soil NO_3-N and K^+, though the decrease was not significant (P>0.05). The results show that NO_3-N decreased by 32.5% from 12.0±1.9 mg/l to 8.1±1.6 mg/l after harvesting, while K^+ decreased by 43.7% from 18.3±13.7 mg/l to

10.3±1.1 mg/l. The decrease in NO_3-N and K^+ levels could be linked to uptake by maize plants, leaching, and volatilization of NO_3-N as reported by Disciglio *et al.* (2015). Comparison of levels soil fertility parameters in treatment and control plots revealed that the concentration of soil PO_4^- was significantly higher (P = 0.0348) in treatment plots after harvesting; while the concentrations of NO_3-N, SOM and K^+ did not differ significantly (P>0.05) between control and treatment plots.

The impact of irrigation water on soil salinity, alkalinity and sodicity: The results on soil alkalinity as measured by pH, soil salinity as measured by EC and TDS, and soil sodicity as measured by SAR are displayed in Table 2. The results show a very slight changes in soil pH from 8.08±0.05 to 8.05±0.03 after irrigated farming cycle. Comparison of levels of soil pH in treatment and control plots revealed no significant difference (P>0.05) indicating low effect of treated domestic wastewater from the digester combined in-line with ABR on soil alkalinity in line with (Khaskhoussy *et al.,* 2015; Urbano *et al.,* 2017; Nyagatare *et al.,* 2021). Soil salinity (EC) influence the ability plant roots to absorb water. The EC as one of the soil salinity parameters increased slightly by 4.4% from 0.43±0.06 dS/m to 0.47±0.05 dS/m; while the TDS increased by 4.7% from 225.0±27.5 mg/l to 235.7±66.0 mg/l in line with Mwangi *et al*. (2019). However, the increase of soil salinity parameters (EC and TDS) was not significant (P>0.05). Additionally, comparison of the results in treatment and control revealed that there wasn't a significant difference in soil fertility parameters, signifying that initial irrigation of greenhouse maize with domestic wastewater treated in the digester with ABR had fairly no effect on soil salinity. The soil sodicity denoted by SAR, slightly increased by 16.7% from 1.8±0.2 Meq/l to 2.1±0.5 Meq/l. The increase of SAR was also not significant (P>0.05) when compared to the baseline data. Further comparison of levels of SAR in treatment and control plots after irrigation, revealed no significant different (P>0.05) indicating that irrigation with treated effluent had no effect on oil sodicity. However, previous studies reported the increased soil sodicity on prolonged irrigation with treated sewage (Al Omron *et al.*, 2012; Abd-Elwahed, 2019), which calls for planned soil monitoring after every farming cycle.

The effect of treated domestic wastewater on maize growth characteristics: Table 3 and 4 displays the results on growth characteristics of maize plants monitored for seven consecutive weeks, from W_3 to W_9 after planting in treatment and control plots respectively.

Table 3. Mean growth characteristics of greenhouse maize in treatment plots.

Growth period (Weeks)	**Mean growth characteristics of maize plants (n = 18)**				
	Plant Length (cm)	**Leaf Length (cm)**	**Leaf Width (cm)**	**Number of Leaves**	**Leaf Area Index (LAI)**
W_3	66.8±11.4	82.5±7.5	5.5±1.1	8±0.7	122.9±33.5
W_4	71.8±11.3	86.3±7.4	6.4±1.1	10±0.6	174.4±4.7
W_5	98.5±13.4	88.9±6.3	7.8±0.7	11±1.1	250.2±51.4
W_6	133.6±21.9	89.7±6.3	8.1±0.6	11±1.0	267.4±52.6
W_7	147.1±24.2	90.1±5.8	8.3±0.5	12±1.4	280.8±59.5
W_8	152.2±22.6	91.8±4.7	8.4±0.4	13±0.8	308.8±36.7
W_9	154.2±22.5	93.2±7.3	8.5±0.6	13±0.5	316.1±39.6

Data are in Mean ± standard deviation

Table 4. Mean growth characteristics of greenhouse maize in control plots

Growth period (Weeks)	**Mean growth characteristics of maize plants (n =18)**				
	Plant Length (cm)	**Leaf Length (cm)**	**Leaf Width (cm)**	**Number of Leaves**	**Leaf Area Index (LAI)**
W_3	55.2±15.5	63.7±22.6	4.8±1.3	8±1.8	83.5±53.6
W_4	59.5±15.8	67.2±22.9	5.2±1.2	9±1.8	106.0±63.9
W_5	70.6±17.0	74.1±20.7	6.5±1.2	10±1.6	167.0±81.7
W_6	102.2±22.9	81.0±7.5	6.9±1.1	11±1.8	196.4±66.0
W_7	125.4±28.4	82.0±7.9	7.2±1.2	11±1.6	213.2±70.7
W_8	132.0±23.6	82.5±8.1	7.3±1.2	12±1.3	228.9±71.5
W_9	135.7±22.1	83.3±7.3	7.6±0.9	12±1.0	239.4±59.3

Data are in Mean ± standard deviation

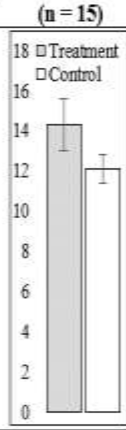
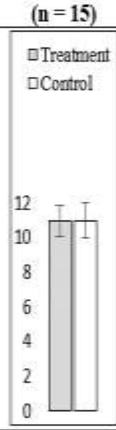
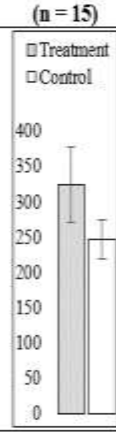
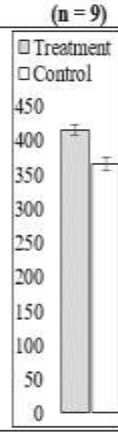
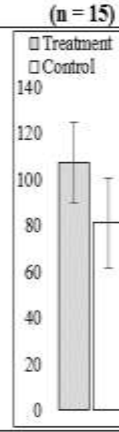
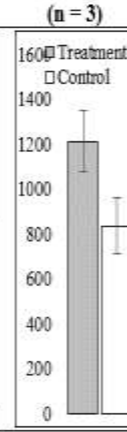
Plant Heights: The results in Table 3 and 4 show that there was an increasing trend of plant heights in the treatment and control plots from the first to the end of monitoring week. The mean plant height ranged from 66.8±11.4 cm (W_3) to 154.2±22.5 cm (W_9) for maize plants in treatment plots, while it ranged from 55.2±15.5 cm (W_3) to 135.7±22.1 cm (W_9) for plants in the control plots. The mean increase rate of plant heights in treatment plots was 14.56±13.3 cm per week and 13.42±11.4 cm per week for plants in control plots. Therefore, irrigation with treated sewage improved plant height which may be associated with the observed nutrient difference in treated effluent and improved soil fertility parameters, particularly soil PO_4^- and organic matter content (Ku *et al.,* 2021; Balengayabo *et al.,* 2022a). The availability and uptake of nutrients from soil solutions promote root development, healthy growth, and plant development (Dinesh *et al.,* 2021). Comparison of mean heights of plants at the end of monitoring week (W_9) show that plants in treatment plots were 13.6 % taller than their counterpart maize plants in control plots. However, the data analysis results revealed that the mean heights of plants at W_9 and mean height increase rate per week of plants from treatment and control plots were not significantly different (P>0.05).

Leafy growth characteristic of maize plants: The Leafy growth characteristic of maize plants include the mean number of leaves, mean leaf length and widths and mean LAI of maize plants whose results are shown in Tables 3 and Table 4 for treatment and control plots respectively. Figure 2 shows the physical appearance of maize plants in treatment and control plots in the greenhouse. The mean number of leaves ranged from 8±0.7 (W_3) to 13±0.5 (W_9), mean leaf length ranged from 82.5±7.5 cm (W_3) to 93.2±7.3 cm (W_9) and mean leaf width ranged from 5.5±1.1 cm (W_3) to 8.5±0.6 cm (W_9) for plants in the treatment plots; while for plants in the control plots the mean number of leaves ranged from 8±1.8 (W_3) to 12±1.0 (W_9), mean leaf length ranged from 63.7±22.6 cm (W_3) to 83.3±7.3 cm (W_9) and the mean leaf width ranged from 4.8±1.3 cm (W_3) to 7.6±0.9 cm (W_9). The rates of change of growth attributes were observed to be 0.8±0.7 increase in number of leaves per week, 1.78±1.25 cm increase in leaf length per week and 0.5±0.48 cm increase in leaf width per week, for plants in the treatment plots. While for plants in the control plots, the rates of change of growth attributes were observed to be 0.7±0.5 number of leaves per week, 1.45±1.20 cm increase in leaf length per week and 0.47±0.38 cm increase in leaf width per week. Comparison of plants in the treatment and control plots revealed that the plant leaves were 12.24% longer, 11.84% wider and the number of leaves were 8.33% more for maize plants in treatment plots than in control plots. The mean leaf length of maize plants in the treatment plots was very significantly longer (P = 0.0025) than the mean leaf length of maize plants in the control plot, as observed in Figure 2. Similar analysis revealed no significant difference (P>0.05) for mean number of leaves and mean leaf width of maize plants in the treatment and control plots. The mean LAI ranged from 122.9±33.5 (W_3) to 316.1±39.6 (W_9) for maize plants in treatment plots and 83.5±53.6 (W_3) to 239.4±59.3 (W_9) for maize plants in control plots. The results indicate that the average LAI at W_8 for plants in in treatment plots was greater by 32.03 % than that of plants in control plots. The mean increased rate of LAI was 32.20±26.4 per week for maize plants in treatment plots and 25.98±18.3 per week for maize plants in control plots. The results indicate that the rate of increase of LAI of maize plants in treatment plots was 23.94% greater than the rate of increase of maize plants in control plots. Data analysis revealed that the mean LAI of plants in the treatment plots was significantly higher (P = 0.0282) than the plants in the control plots, which supports the observed differences. Improved growth characteristics of maize plants in treatment plots associated with irrigation with treated effluent was observed by other authors, though the treated wastewater differed in terms of sources and treatment employed. Ku *et al.* (2021) found significantly improved growth characteristics in maize irrigated with treated effluent from the brewery industry, whereas Dinesh *et al.* (2021) reported higher growth characteristics for maize irrigated with treated effluent from the distillery industry in India. Furthermore, Khan *et al.,* (2010) found that sorghum irrigated with treated municipal effluent from the stabilization ponds in Pakistan had significantly improved growth characteristics (plant height, number of leaves per plant, and leaf area). Nyomora, (2015) reported higher growth characteristics of rice irrigated with treated wastewater from the stabilization ponds in Tanzania. In addition to soil factors, irrigation with treated wastewater from the digester combined in-line with ABR improved soil nutrients and organic matter that enhanced plant growth and development in line with other studies (Widaa and Elamin, 2020; de Lemos *et al.,* 2021; Dinesh *et al.,* 2021). On the contrary, irrigation with treated wastewater may not supply sufficient quantity of nutrients for nourishing plants which is largely influenced by the wastewater generation sources and the typologies of the treatment plants used (Da Fonseca *et al.,* 2005).

Fig 2. Physical appearance of maize plants in treatment and control plots in the greenhouse

The influence of treated effluent on the yield characteristics of greenhouse maize: The results on the yield attributes of maize including mean cob lengths, mean numbers of kernel rows per cob, mean number of grains per cob, mean grain weights per cob, mean weight of 1000 maize grains and mean grain yield per hectare are depicted in Table 5.

Table 5. Yield characteristics of greenhouse maize in treatment and control plots

Yield characteristics of maize plants	Cob length (cm) (n = 15)	Number of Kernel rows per cob (n = 15)	Number of grains per cob (n = 15)	Weight of 1000 grains (g) (n = 9)	Grains' weight per cob (g) (n = 15)	Grain yield per plot (Kg/ha) (n = 3)
						
Treatment	14.3±1.3	11±0.9	323.0±53.6	414.5±6.9	107.2±17.7	1212.3±136.1
Control	12.1±0.7	11±1.0	246.2±27.1	364.7±9.6	81.1±19.6	836.2±122.4

Kernel rows per cob, cob length, and number of grains per cob and grains weight per cob: The mean cob lengths from treatment and control plots were 14.3±1.3 cm and 12.1±0.7 cm respectively as presented in Table 5. The results show that on average the cobs from treatment plots were by 18.2 % longer than the counterpart control plots, but the difference wasn't significant (P = 0.1198). The average number of kernel rows per cob from treatment plots was 11±0.9, while it was 11±1.0 for maize from control plots. The results indicate that the average number of rows was almost the same in treatment and control plots. The results on the average number of grains per cob was 323±34.5 and 246±68.4 respectively from the treatment and control plots. The results indicate that the average number of grains per cob in treatment plots was 31.2 % higher than the control plots though the difference wasn't significant ($P \geq 0.05$). The average weight of grains per cob was 107.2±9 g in treatment plots and 81.1±15.7 g in control plots. The comparison of average grain weights per cob revealed 32.1% higher in treatment than and control plots. This was supported by statistical data analysis which showed that the average weight of grains per cob was significantly high (P = 0.0294) in treatment compared to the control plots. This imply that grains from the treatment plots had better quality compared to the counterpart control plots. In summary, the results indicate that maize yield characteristics particularly the number of grains per cob, kernel rows per cob, cob length, and cob grains weight were higher in treatment than control plots, though some were not statistically significant. The findings are in-line with the findings reported by other authors but using treated effluents from diverse sources and different treatment technologies (Kokkora *et al.,* 2015; Dinesh *et al.*, 2021; Ku et *al.*, 2021) and without the greenhouse. Improved maize yield characteristics in treatment plots may be linked to the observed improvement in soil fertility parameters especially SOM and PO_4^- influenced by irrigation with treated domestic effluent from the digester connected in-line with the ABR.

Mass of 1000 grains and grain yield: The results in Table 5 show that the mean weight of 1000 grains were 414.5±6.9 g from treatment plots and 364.7±9.6 g from control plots. The grains in the treatment plots were 13.9% heavier than the grains in the control plots. The 1000 mean grains weight from the treatment plots was significantly superior (P≤0.05) than those from the control, implying that grains from plots irrigated with treated wastewater were of higher quality than grains from the control plots. The results on the mean grain yields per plot indicated that the yield from the treatment and control plots were 1212.3±136.1 Kg/ha and 836.2±122.4 Kg/ha, respectively. The grain yield from the treatment plots was 44.9% higher compared to the control plots, which was supported by statistical data analysis (P = 0.0235). Higher yield in the treatment plots may be attributed to irrigation with treated domestic wastewater which improved soil fertility parameters by supplementing the soil with essential nutrients and organic content as reported in section 3.2.1. The findings are in line with other studies as reported by Kokkora *et al.* (2015); Dinesh *et al.* (2021) and Ku *et al.* (2021) in which it was reported that maize yield characteristics were higher in plots irrigated with treated effluent. The yield in treatment plots may also be related with the observed growth attributes, particularly LAI which was found higher in plots irrigated with treated wastewater. Higher values of LA indicate the improved photosynthetic capacity of maize plants which lead into the observed improved grain yield in treatment plot as compared to control plots (Rhodustalfs *et al.,* 2020; Dinesh *et al.,* 2021; Ku et *al.,* 2021).

Conclusion: Fertigation of a greenhouse maize with anaerobically treated domestic wastewater improved soil organic (SOM) matter and phosphate (PO_4^-), that contributed to improvement of soil fertility. The yield and growth characteristics of greenhouse maize plants in treatment plots were significantly (P<0.05) improved, attributed to improved soil fertility. Fertigation of maize in the greenhouse with anaerobically treated domestic wastewater had no effect on soil alkalinity, salinity and sodicity. Each post-harvest soil monitoring is required for remediation of undesirable soil changes.

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