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Effects of Treated Greywater Irrigation on Soil Fertility Properties in Akure, Nigeria: A Three-Season Field Study

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ABSTRACT

The quality of water used for irrigation significantly influences soil fertility and crop productivity. This study investigated the effects of treated greywater irrigation on soil physicochemical properties across three dry seasons in Akure, Nigeria. Untreated greywater sourced from a dormitory at the Federal University of Technology, Akure (FUTA) was treated in a constructed wetland planted with common reed (*Phragmites australis*). The treated greywater (TG) was assessed for conformity with irrigation standards. A drip irrigation system was employed across a Randomized Complete Block Design (RCBD) with three treatments (raw greywater, treated greywater, and freshwater) and three replicates per season over 2016, 2017, and 2018 dry seasons. Soil samples were collected and analysed for pH, total organic matter (TOM), total nitrogen (TN), phosphorus (P), and potassium (K). Water and soil data were subjected to analysis of variance (ANOVA) with Tukey's Honestly Significant Difference (HSD) test at 5% significance level. Treated greywater irrigation improved selected soil fertility indicators, including pH, TOM, and macronutrients. At the 5% probability level, ANOVA revealed significant relationships between soil pH, TOM, TN, P and K and the irrigation water's temperature, pH, total dissolved solids, total suspended solids, fecal coliform, chloride, nitrate, and magnesium contents. Future research on the effects of this irrigation water composition on crop quality is necessary, as this study is crucial for farmers working with depleted soil to restore its fertility condition. The findings confirm that treated greywater is a viable irrigation source capable of improving soil macronutrient status when properly managed.

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INTRODUCTION

Greywater refers to domestic wastewater excluding toilet effluent, characterized by lower pathogen loads and higher reuse potential compared to blackwater. The exact sources of greywater vary by country and organization, but they include water from sinks, showers, bathtubs, washing machines, and dishwashers. This makes it easier to treat and safer to handle because it has fewer pathogens than black water, which is toilet effluent. It can be used on-site for a variety of non-potable uses, such as landscape or crop irrigation and toilet flushing. Soil fertility in Nigeria varies across regions, with many areas facing challenges. In the Southern Guinea Savanna, soils generally have medium to poor fertility status, requiring careful management for arable cropping (Adeboye et al., 2011). The semi-arid zone struggles with nitrogen deficiency, emphasizing the potential role of legumes in improving soil fertility (Carvalho et al., 2014). In the Sudan Savanna, soils commonly have low organic carbon, total nitrogen, and available phosphorus levels, with some areas also lacking calcium, magnesium, and copper (Shehu et al., 2015). Southwestern Nigeria faces rapid soil degradation due to nutrient mining, soil loss, and climate change impacts (Ande et al., 2017). To address soil degradation, several solutions have been proposed. These include the use of cover crops, multiple cropping, agroforestry, and conservation tillage (Bizi and Sidi, 2023; Lal, 2015). Implementing these practices can help improve soil quality by increasing organic matter content, enhancing soil structure, and reducing erosion (Lal, 2015). Other effective methods include shifting cultivation, proper crop combination, mulching, and the use of Vetiver grass (Amakiri, 2004). Irrigation water quality significantly impacts soil physicochemical properties. Poor-quality water can increase soil salinity, electrical conductivity, and sodium levels, while potentially decreasing calcium and potassium content (Christine et al., 2023). Prolonged irrigation with unsuitable water can lead to soil degradation, affecting fertility and productivity (Gemeda and Yadeta, 2024). The Sodium Adsorption Ratio (SAR) and Electrical Conductivity (EC) of irrigation water are crucial factors influencing soil structural stability (Rengasamy, 2018). The quality of irrigation water, including parameters like electrical conductivity, sodium adsorption ratio, and residual sodium carbonate, can affect soil physicochemical properties, potentially leading to increased soil sodium and salt levels (Gemeda and Yadeta, 2024). However, existing models relating SAR and EC to predict soil structural impacts are not universally applicable across all soil types (Rengasamy, 2018). Regular monitoring of irrigation water quality and soil properties is essential to assess and mitigate negative effects (Gemeda and Yadeta, 2024). Proper management of irrigation water composition is vital for maintaining soil health and ensuring sustainable agricultural practices in irrigated systems (Gemeda and Yadeta, 2024; Christine et al., 2023; Rengasamy, 2018).

Greywater treatment methods encompass physical, chemical, biological, and advanced oxidation processes (AOPs) (Moussa et al., 2024). Physical methods alone

are insufficient for removing organics, nutrients, and surfactants, while chemical approaches effectively treat low-strength greywater (Shqerat and Al-Tabbal, 2025). Biological processes combined with physical filtering and disinfection are considered practical and cost-effective, with membrane bioreactors (MBR) being particularly suitable for urban housing (Shqerat and Al-Tabbal, 2025). Recent studies have explored chemical treatments, including coagulation, adsorption, and AOPs, which show promise in mineralizing recalcitrant organic compounds and removing xenobiotic organic compounds (XOCs) (Boyjoo et al., 2013). A gravity-governed flow method using gravel, sand, and activated carbon demonstrated significant reductions in various parameters, including biological oxygen demand (64%), chemical oxygen demand (42%), turbidity (74%), and electrical conductivity (66%), suggesting its potential for non-potable reuse applications such as irrigation and car washing (Gautam et al., 2021).

Constructed wetlands (CWs) are effective, low-cost systems for treating greywater, offering a sustainable solution for areas without sewage infrastructure (Parra et al., 2021; Li et al., 2014). These systems utilize natural materials like sand and gravel, along with macrophyte plants, to remove pollutants such as BOD, COD, TSS, pathogens, and detergents (Qomariyah et al., 2017). Vertical flow CWs, in particular, have shown promising results, with studies reporting high removal efficiencies for various water quality parameters (Pillai and Vijayan, 2012; Alao et al., 2021; Alao et al., 2022; Alao et al., 2025). The choice of plant species is crucial for optimal performance, with some plants outperforming others in pollutant removal (Pillai and Vijayan, 2012; Parra et al., 2021; Alao et al., 2022; Alao et al., 2025). To further enhance treatment efficacy, CWs can be combined with advanced oxidation processes like TiO_2-based photo-catalytic oxidation, potentially allowing treated greywater to meet standards for non-potable reuse or even groundwater recharge (Li et al., 2014). Overall, CWs offer a viable option for decentralized greywater treatment and water conservation in tropical and semi-arid environments.

Despite growing adoption of greywater irrigation in West Africa, few studies have quantified the long-term effects of treated greywater on soil macronutrient dynamics specifically under drip irrigation systems in Nigeria. Most existing studies focus on wastewater generally, without distinguishing greywater fractions or evaluating multi-season impacts on key fertility parameters such as total organic matter, nitrogen, phosphorus, and potassium (Akponikpe et al., 2011; Nwaokobia et al., 2018; Alao et al., 2022). Furthermore, there is limited regional evidence linking specific water biochemical parameters to measurable soil fertility changes in humid tropical soils (Chauhan et al., 2024; Jaoude et al., 2024). This study addresses this gap by investigating the effects of treated greywater irrigation on soil physicochemical properties across three consecutive dry seasons in Akure, Nigeria, using a constructed wetland treatment system with common reed (Phragmites australis).

Recent studies have explored the effects of treated greywater irrigation on soil properties and crop productivity. Irrigation with treated greywater can improve soil fertility parameters, including increased concentrations of phosphorus, iron, and copper (Mohammad and Mazahreh, 2003; Hajlaoui et al., 2022). However, raw greywater may lead to soil hydrophobicity and increased fecal coliform levels (Travis et al., 2010). Treated wastewater irrigation has shown positive impacts on soil chemical properties and crop yields compared to groundwater irrigation (Abdel-Aziz, 2015). While treated greywater can enhance soil nutrient status and organic matter content, it may also increase soil salinity and decrease pH (Mohammad and Mazahreh, 2003). Importantly, properly treated greywater has not shown significant negative effects on plant growth or soil microbial contamination (Travis et al., 2010; Hajlaoui et al., 2022). These findings suggest that treated greywater can be an effective irrigation source, but proper management and monitoring are essential to minimize potential adverse effects on soil quality (Lopes et al., 2016; Hashem and Qi, 2021). When appropriate management techniques are used, using wastewater for irrigation can enhance soil health (de Nicolás et al., 2022). Many researchers found that soils irrigated with treated wastewater had much higher levels of effective phosphorus, total nitrogen, and total potassium than soils irrigated with freshwater (Guo et al., 2019). Ahmad et al. (2013) found that land watered with sewage effluent had higher potassium availability than soil irrigated with freshwater from the Nile. The exchangeable ions are also greatly increased by continuous irrigation with wastewater (Singh et al. 2025). Considering these factors, composition of irrigation water from treated greywater was utilized to improving the fertility status of soil in Akure, Nigeria.

MATERIALS and METHODS

Study Area

The investigation was conducted behind the Jadesola Akande female hostel on the Obanla campus of the Federal University of Technology, Akure (FUTA), located in Ondo State, Nigeria. Akure is located at latitude 7°14' N and longitude 5°08' E. The area has a tropical humid climate with two dissimilar seasonal patterns.

Greywater Collection and Treatment

Greywater from a hostel was used, and water from showers, bathtubs, kitchens, and bathroom sinks was directed into a system intended for initial filtration and pretreatment. This water passed through 128 mm-diameter pipes to a filtration tank, where bigger suspended particles were eliminated by an initial filtration procedure. A layered filtration medium consisting of layers with gravel particles smaller than 32 mm, 24 mm, and 16 mm was used to screen out items including food debris, hair, and lint. For finer filtration, a fine sand layer with a diameter of 0.2 mm was placed on top.

Following this pre-filtration phase, the partially treated greywater was transferred into the created wetland via a smaller pipe with a diameter of 32 mm (Figure 1). Common reed (*Phragmites australis*), a plant chosen for its ability to facilitate the treatment process, was added to this wetland, which was constructed using a similar gravel and sand mixture as the filter tank. By retaining the greywater in the wetland system for two days, the combined impacts of microbial activity, plant absorption, and sedimentation within the substrate allowed for additional purification (Figure 1). The wetland was designed using the UN-HABITAT (2008) approach: an average flow rate (Q_d) of 1.09 m^3/day was calculated from the bed area, hydraulic conductivity, and slope, giving a working volume of approximately 2.18 m^3 (bed porosity × area × 0.45 m depth) and a hydraulic retention time of two days, consistent with the 2–7-day range reported by Crites (1994) for sub-surface flow constructed wetlands. The corresponding hydraulic loading rate was 1.21 m/day, within the 1.2–4.7 m/day range of Tchobanoglous (1993) and Crites (1994), and the design is further supported by Alao et al. (2022) and Pillai and Vijayan (2012). After this period of retention, the processed wastewater—now known as treated greywater—was gathered and prepared for possible irrigation repurposing.

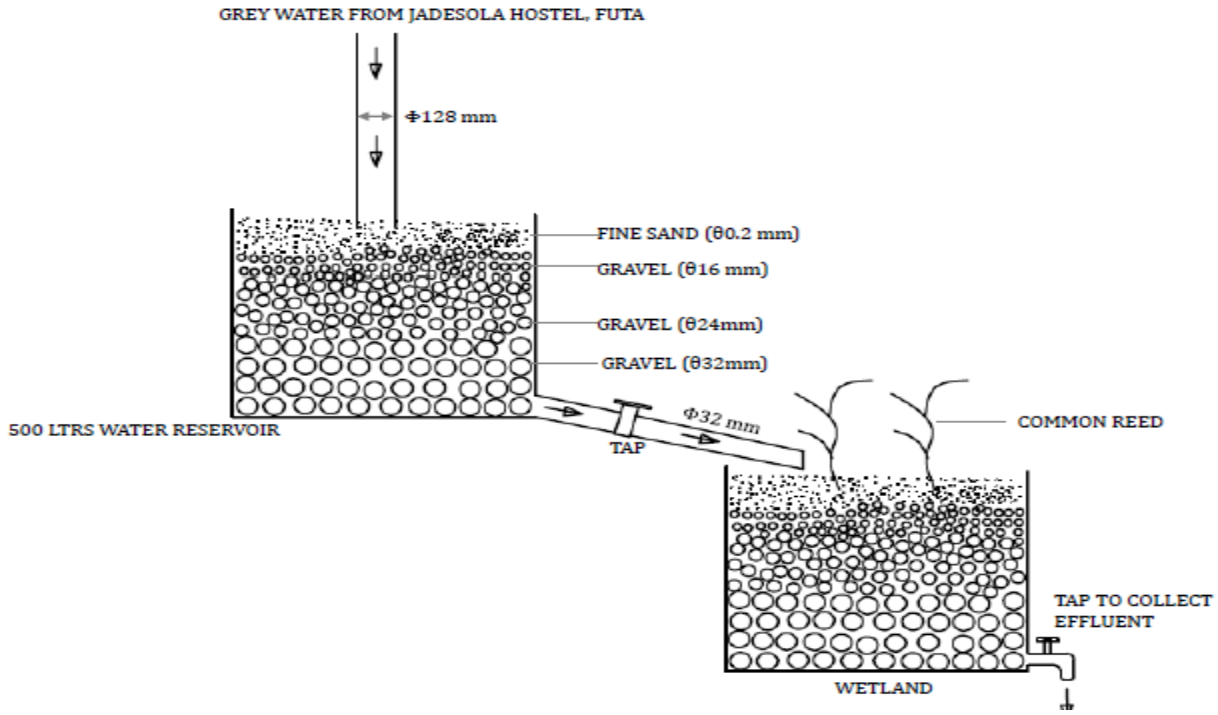

Figure 1. Greywater Treatment Setup

Water Sampling and Analysis

Raw greywater and treated greywater were the two sources of water samples collected in polyethylene bottles from the study site for analysis. The parameters assessed were temperature and pH, chemical factors like total suspended solids (TSS), biochemical

oxygen demand (BOD), total nitrogen (TN), total phosphorus (TP), chemical oxygen demand (COD), electrical conductivity (EC), manganese, iron, and various anions (sulfates, chlorides, and nitrates), and microbiological factors like fecal coliforms (FC) and *E. coli*. Temperature was measured in situ with a thermometer; pH and electrical conductivity were determined immediately after collection in situ using a pH meter and an EC meter (Motsara and Roy, 2008). Calcium and magnesium were determined titrimetrically using standard EDTA (APHA, 2005), sodium and potassium were measured by flame photometer, and chloride was measured by titration with $AgNO_3$. BOD and COD were determined by the standard Open Reflux Method, and TSS by the gravimetric method for total suspended non-filterable solids (APHA, 2005). Heavy metals (Ni, Cd, Zn, Cu, Pb) were tested at the Sustainable Laboratory, Akure, Nigeria.

Experimental Design and Irrigation Treatments

Each treatment plot was linked to a distinct supply (0.16 m^3 capacity reservoirs) placed close to each of the beds at even pressure head of 1.5 m. Field tests were conducted in the dry seasons of 2016, 2017, and 2018, respectively, using drip irrigation as the irrigation technology. Three treatments (raw greywater, treated greywater, and freshwater) each were replicated in three plots per season, giving nine plots per season and 27 total observations across the three dry seasons (2016, 2017, 2018) in a Randomized Complete Block Design (RCBD) experimental design. Raw greywater was used to irrigate the first treatment plots, treated greywater was used to irrigate the second treatment plots, and fresh water irrigation was used for the third treatment.

Pepper Cultivation and Irrigation Management

A drought-resistant hybrid hot pepper variety (*Capsicum annuum*, AVENIR F1, Agritropic, Ibadan) was nursed for eight weeks and then transplanted manually at a spacing of 0.6 m × 0.3 m. Each 2 m × 2 m treatment plot (1 m apart) held 18 stands, giving 54 stands per treatment and 162 stands in total. No supplemental fertiliser was applied; nutrient inputs came from the irrigation water treatments themselves. Irrigation was applied at 1-day intervals based on the calculated irrigation interval. Following crop establishment, the same amount of fresh water, treated greywater, and raw greywater were applied according to the amount of water needed for pepper irrigation (Figure 2).

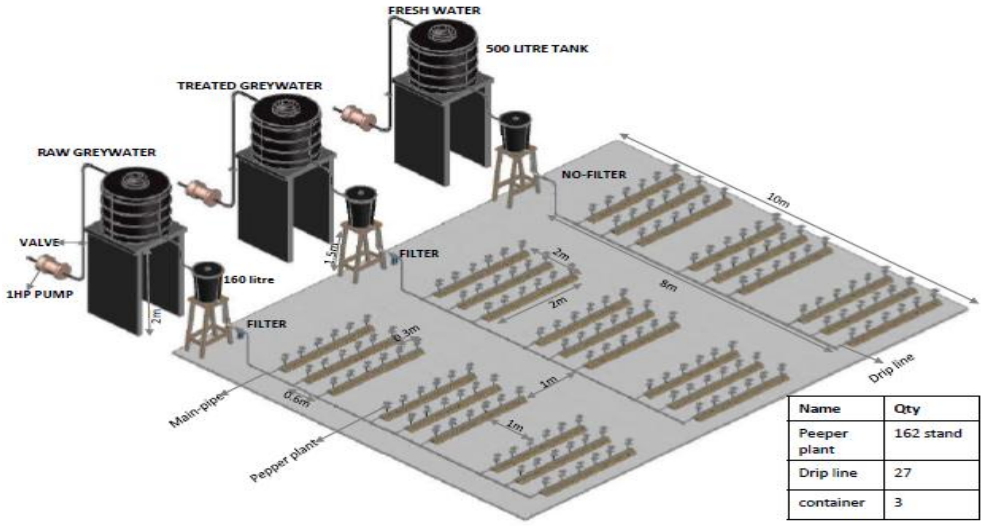

Figure 2. Field Experimental Layout for Planting Pepper Using Different Treatment (2 m × 2 m plots, spaced 1 m apart)

In addition, soil samples were taken from the experimental site to ascertain the soil physicochemical characteristics, including total organic matter, soil pH and the percentage composition of nitrogen, phosphorus and potassium.

Statistical Analysis

The collected were subjected to analysis of variance (ANOVA) using Tukey's Honestly Significant Difference (HSD) test at the 5% level of significance, consistent with the post-hoc test reported under every treatment-comparison table in this study.

RESULTS and DISCUSSION

Note on statistical treatment of Tables 1a–c: the soil-chemistry properties reported in Tables 1a–c are single treatment-level measurements, since no replicate-level soil-chemistry data survive from the source dataset. The Randomized Complete Block Design (RCBD) and Tukey's HSD post-hoc comparisons described in the Methods apply to the pepper growth and yield parameters, whereas the relationships between irrigation-water composition and these soil-chemistry properties (Tables 2–13) were instead assessed using multiple regression, as described below.

Influence of Water used for Irrigation on Soil pH

The pH of the soil before planting was strongly acidic (4.60 – 4.64), a condition unsuitable for optimal agricultural production. After harvesting, the pH of the soil under treated greywater irrigation had risen to the range of 6.40 – 6.52 across the three seasons (Tables 1a - c). This pH would increase the solubility and availability of certain nutrients in soils, such as phosphorus, and also increase other heavy metals (Al-

Jaboobi et al., 2014). After long-term greywater application, the pH of the soil was also reported to rise (Kiran et al., 2012, Abudu et al., 2018). This increase may be ascribed to the high concentrations of certain cations, such as sodium (Na), calcium (Ca), and magnesium (Mg) in the greywater used for a lengthy period of time. The findings indicated that soil irrigated with both freshwater and treated greywater had a small pH increase following irrigation, with values ranging from 6.44 to 6.50, 6.40 to 6.48, and 6.48 to 6.52 for the dry seasons of 2016, 2017, and 2018 respectively. However, these values differed from the soil's initial pH prior to irrigation, which was 4.62, 4.60, and 4.64 for the three seasons, respectively (Tables 1a - c). The experiment's soil was often mildly alkaline, indicating the presence of free lime ($CaCO_3$).

Influence of Water used for Irrigation on Macronutrients of Soil

Following the hot pepper harvest, the experiment revealed an observed increase in the soil's fertility state in terms of macronutrients (Tables 1a - c). As noted above, this increase is reported descriptively rather than as a statistically tested difference, since the values in Tables 1a - c are single treatment-level measurements without replicate-level data or significance grouping. The improvement might be due to irrigation with treated greywater. The macronutrients of the treated greywater were higher than those of fresh water. For example: Calcium (Ca) contents of the soil from treated greywater plots for the three seasons are 35.85, 36.05 and 35.65 cmol/kg respectively, while for fresh water plots, we have 31.00 cmol/kg each; Potassium (K) contents of the soil from treated greywater plots for the three seasons are 27.50, 28.50 and 26.50 cmol/kg respectively, while from fresh water plots, the K contents are 14.00, 13.00 and 15.00 cmol/kg respectively. The outcomes were in line with the prior studies reported by Datta et al. (2000), Abdel-Aziz (2015) and Topare and Wadgaonkar (2023). This is also similar to the report of Saffari and Saffari (2013).

Influence of Water used for Irrigation on Soil Fertility

The organic matter (OM) of soil irrigated with treated greywater increased from 1.12 – 3.00, 1.10 – 2.40 and 1.14 – 2.00 for 2016, 2017 and 2018 dry seasons respectively (Tables 1a - c). This designates that treated greywater irrigation, relative to the pre-irrigation baseline and to raw greywater, helps to improve the soil fertility after the harvesting of hot pepper. It should be noted that the freshwater plots recorded slightly higher post-irrigation TOM than the treated-greywater plots in all three seasons (2016: 3.30 vs. 3.00%; 2017: 3.50 vs. 2.40%; 2018: 3.10 vs. 2.00%; Tables 1a - c); the TOM benefit attributed to treated greywater in this study is therefore relative to the untreated baseline and to raw greywater rather than to freshwater. This also indicates that treated greywater provides the essential nutrients (N, P, K) needed to the crop. This followed what Kiran et al. (2012) and Victor Junior et al. (2025) noted in their studies on effect of greywater irrigation on soil fertility and was confirmed by Abdel-Aziz

(2015). Sodium absorption ratio, SAR, of the soil from treated greywater and fresh water treatment plots are 5.19 and 4.31, 5.39 and 4.31 as well as 5.18 and 4.31 for 2016, 2017 and 2018 dry seasons respectively. The low values recorded enable the soil to be softened and in return increases the infiltration rates of water and air into the soil thereby improving the structure of the soil (Arshad and Shakoor, 2017; Singh et al. 2025). This is in conformity with the research of Nwaokobia et al. (2018) where the influence of greywater irrigation on the crop growing of African Spinach caused a decrease in SAR of soil. These were below the critical value of 13, hence, less likely to cause sodicity hazards in the soil (Tables 1a - c).

Table 1a. Soil Properties before and after Irrigation in year 2016 dry season at the Experimental Site

Soil properties	**Before Irrigation**	**After Irrigation**	
		Treated Greywater	**Fresh Water**
pH	4.62	6.44	6.50
% WHC	18.87	24.00	26.00
% porosity	50.06	58.50	54.00
% TOM	1.12	3.00	3.30
% TN	0.18	0.19	0.20
% MC	9.36	10.65	12.06
Na (cmol/kg)	57.80	33.50	20.00
K (cmol/kg)	21.00	27.50	14.00
Mg(cmol/kg)	5.48	5.85	12.00
Ca(cmol/kg)	30.21	35.85	31.00
Available P (mg/kg)	0.16	10.77	8.12
SAR	13.70	5.19	4.31

Table 1b. Soil Properties before and after Irrigation in year 2017 dry season at the Experimental Site

Soil properties	**Before Irrigation**	**After Irrigation Treated Greywater**	**Fresh Water**
pH	4.60	6.40	6.48
% WHC	20.87	26.00	28.00
% porosity	51.06	58.00	55.00
% TOM	1.10	2.40	3.50
% TN	0.16	0.17	0.20
% MC	10.36	11.65	14.05
Na (cmol/kg)	57.40	34.50	20.00
K (cmol/kg)	21.00	28.50	13.00
Mg(cmol/kg)	5.40	4.90	12.00
Ca(cmol/kg)	30.21	36.05	31.00
Available P (mg/kg)	0.18	10.07	8.12
SAR	13.70	5.39	4.31

Table 1c. Soil Properties before and after Irrigation in year 2018 dry season at the Experimental Site

Soil properties	Before Irrigation	After Irrigation Treated Greywater	Fresh Water
pH	4.64	6.48	6.52
% WHC	16.87	22.00	24.00
% porosity	49.06	59.00	53.00
% TOM	1.14	2.00	3.10
% TN	0.20	0.21	0.20
% MC	8.36	9.65	10.05
Na (cmol/kg)	58.20	32.50	20.00
K (cmol/kg)	21.00	26.50	15.00
Mg(cmol/kg)	5.56	3.80	12.00
Ca(cmol/kg)	30.21	35.65	31.00
Available P (mg/kg)	0.14	11.47	8.12
SAR	13.76	5.18	4.31

General limitation applying to Tables 2–13 (Equations 1–12)

Each of the seven-predictor regression models presented in this section (Equations 1–12, Tables 2–13) is fitted to 27 plot-level observations that are drawn from only nine distinct water-by-season predictor profiles (three water types × three seasons), because the water-composition predictors are constant across the three replicate plots within each treatment-season combination while the dependent soil or yield variable still varies plot-to-plot. With seven predictors describing nine effective predictor combinations, every model in this section is close to saturated, which mechanically inflates the reported R^2 (76.95%–99.99% across Equations 1–12) regardless of the model's true predictive strength. These R^2 values should therefore be read as a property of this replicate structure rather than as evidence of a generalisable predictive relationship.

Effect of Water used for Irrigation's Composition on Change in the Soil pH

Table 2 depict the effect of the biochemical characteristics of the water used for irrigation which include the Nitrates (NO^{3-}). Sulphates (SO_4^{2-}), Fecal coliforms (FC), Chloride (Cl^-), Magnesium (Mg), Sodium (Na) and Potassium (K) on the variation in the pH of the soil. According to the table, given that the NO^{3-}, FC, and K of the water used for irrigation have higher calculated Fisher's values of 8.852, 7.106, and 4.443, respectively, with low probability values of 0.0078, 0.0153, and 0.0486 that are below the 5% standard probability level, the analysis of variance (ANOVA) demonstrates that the variation in pH is significantly ($P < 0.05$) dependent on these factors. In addition the SO_4^{2-}, Mg, Cl^- and Na have probability values that are above 0.05, hence does not have significance ($P < 0.05$) influence on the change in the pH. However, as

demonstrated in equation 1, the pH change was mathematically expressed as a function of the water used for irrigation's biochemical characteristics. This equation indicates that, with a standardized root mean square error of 0.120937, the biochemical characteristics of the water used for irrigation can significantly explain roughly 82% of the soil's pH change.

$$pH = 5.38544 + 0.25415NO_3^- + 0.00004SO_4^{2-} + 0.00172FC - 0.04393Cl^- + 0.49919Mg - 0.06840Na - 0.24942K \quad (1)$$

Furthermore, the results indicate that the pH of the soil will rise significantly ($P < 0.05$) for every unit increase in the NO^{3-}, $SO4^{2-}$, FC, and Mg of the water used for irrigation. This result agrees with Angin et al. (2005), Mutengu et al. (2007), Kiziloglu et al. (2008), Salar et al. (2021) and Singh et al. (2025), who explained that the use of treated wastewater for irrigation can have detrimental effects on soil quality. Similarly, Shqerat and Al-Tabbal (2025) reported a significant rise in soil pH following prolonged tomato irrigation with treated greywater in Jordan, attributing the change to elevated cation concentrations consistent with those observed in this study. Chauhan et al. (2024) also documented comparable pH elevation patterns in soils irrigated with municipally-treated wastewater over multiple growing seasons.

Table 2. Effect of Biochemical Properties of the Water used for Irrigation on Soil pH

Source	DF	Sum of squares	Mean squares	F	Pr> F
Model	7	1.266	0.181	12.369	< 0.0001
NO_3^-	1	0.129	0.129	8.852	0.0078
SO_4^{2-}	1	0.0003	0.0003	0.018	0.8933
FC	1	0.104	0.104	7.106	0.0153
Cl^-	1	0.014	0.014	0.951	0.3417
Mg	1	0.002	0.002	0.166	0.6878
Na	1	0.019	0.019	1.300	0.2684
K	1	0.065	0.065	4.443	0.0486
Error	19	0.278	0.015		
Corrected Total	26	1.544			

These include reduced soil pH and increased salinity. Decreasing of soil pH is perhaps due to the included acidic components in wastewater which was converted to acidic compounds and led to reduction in pH value (Salar et al., 2021; Chauhan et al., 2024). A unit decline in the Cl^- and Na will raise the variation in the pH of the soil.

The influence of the physicochemical characteristics of the water used for irrigation which include the T, pH, COD, BOD, TSS, EC, and TDS on the variation in the soil pH using ANOVA is shown in Table 3. The table indicates that the pH of the water used for irrigation has the greatest influence on the change in soil pH, followed by the T and EC contents of the water used for irrigation. TSS and BOD have the least significant ($P < 0.05$) effects on soil pH.

A unit rise in the pH, BOD, and TDS contents of the water used for irrigation will raise the pH of the soil, while a unit reduction in the T, COD, TSS, and EC contents of the

water used for irrigation will raise the pH of the soil, according to Equation 2, which shows the pH change as a function of the physicochemical characteristics of the water used for irrigation

pH = 12.45587 - 0.29516T + 0.42766pH - 0.01028COD + 0.01325BOD - 0.01705TSS - 0.72496EC + 0.00222TDS (2)

Equation 2's goodness of fit parameter demonstrates that, with a normalized root mean square error of 0.088854, the physiological features of the water used for irrigation can account for approximately 90.29% of the variation in soil pH.

Table 3. Effect of Physicochemical Features of the Water used for Irrigation on Soil pH

Source	DF	Sum of squares	Mean squares	F	Pr> F
Model	7	1.394	0.199	25.228	< 0.0001
T	1	0.361	0.361	45.785	< 0.0001
pH	1	1.291	1.291	163.528	< 0.0001
COD	1	0.125	0.125	15.798	0.0008
BOD	1	0.110	0.110	13.933	0.0014
TSS	1	0.108	0.108	13.736	0.0015
EC	1	0.187	0.187	23.716	0.0001
TDS	1	0.176	0.176	22.264	0.0001
Error	19	0.150	0.008		
Corrected Total	26	1.544			

Effect of Irrigation Water Composition on Change in the Total Organic Matter (TOM) of the Soil

Table 4 depicts the effect of the biochemical features of the water used for irrigation on the variation in the TOM of the soil. According to the table, ANOVA indicates that the variation in TOM significantly ($P < 0.05$) relies on the chloride content of the water used for irrigation followed by the FC and K of the water used for irrigation as they depict a greater calculated Fisher's value of 9.628, 6.894 and 4.799 respectively with low probability values that are less than 5% standard probability level. In addition, the nitrate, sodium and magnesium contents have the minimum significance ($P < 0.05$) influence on the variation in the TOM.

Nonetheless, equation 3 provides a mathematical expression of the change in total organic matter as a function of the irrigation water's biochemical characteristics. This equation demonstrates that, with a standardized root mean square error of 0.219886, the biochemical characteristics of the water used for irrigation can account for approximately 89.29% of the variation in the soil's TOM.

$TOM = 15.69182 - 0.06398NO_3^- + 0.00094SO_4^{2-} + 0.00308FC - 0.25410Cl^- - 1.89318Mg + 0.07731Na - 0.47129K$ (3)

Furthermore, the results indicate that a significant ($P < 0.05$) increase in soil TOM will occur for every unit increase in SO_4^{2-}, FC, and Na of the water used for irrigation. This is consistent with a number of studies that demonstrate that irrigation with treated

wastewater improves the amount of organic matter in the soil (Kiziloglu et al., 2008; Chauhan et al., 2024). Victor Junior et al. (2025) similarly found that treated wastewater irrigation significantly elevated organic matter content in degraded semi-arid soils in Brazil, attributing the improvement to organic loading from the applied water — a mechanism directly comparable to the greywater application observed in this Nigerian study. Furthermore, Jaoude et al. (2024) confirmed that treated wastewater reuse enhanced soil organic carbon, validating the TOM improvements documented here. A unit drop in the NO^{3-}, Cl^{-} and Mg will raise the change in the TOM of the soil.

Table 4. Effect of Biochemical Features of the Water used for Irrigation on Soil TOM

Source	DF	Sum of squares	Mean squares	F	Pr> F
Model	7	7.661	1.094	22.637	< 0.0001
NO3-	1	0.008	0.008	0.170	0.6850
SO42-	1	0.151	0.151	3.124	0.0932
FC	1	0.333	0.333	6.894	0.0166
Cl-	1	0.465	0.465	9.628	0.0059
Mg	1	0.035	0.035	0.724	0.4053
Na	1	0.024	0.024	0.502	0.4870
K	1	0.232	0.232	4.799	0.0412
Error	19	0.919	0.048		
Corrected Total	26	8.580			

The influence of the physicochemical features of the water used for irrigation on the change in the soil total organic matter (TOM) using ANOVA is shown in Table 5. The table depict that the change in the soil TOM highly depends on the T of the water used for irrigation followed by the TDS and TSS contents of the water used for irrigation while the COD and BOD have the least significant ($P < 0.05$) influence on the soil TOM. The variation in the TOM as a function of the physicochemical features of the water used for irrigation is shown in Equation 4. The equation states that the soil TOM would rise with a unit increase in the irrigation water's pH, BOD, TSS, and EC contents and fall with a unit decrease in the irrigation water's T, COD, and TDS contents.

$$TOM = 17.31027 - 0.55176T + 0.08402pH - 0.00166COD + 0.00427BOD + 0.02927TSS + 0.50347EC - 0.00303TDS \quad (4)$$

The physicochemical characteristics of the water used for irrigation can significantly explain around 99.27% of the variation in the soil TOM (R^2 = SS-model ÷ SS-total = 8.517 ÷ 8.580, computed from Table 5), with a root mean square error of approximately 0.058, according to the goodness of fit parameter of the created model (Equation 4).

Table 5. Effect of Physicochemical Features of the Water used for Irrigation on Soil TOM

Source	DF	Sum of squares	Mean squares	F	Pr> F
Model	7	8.517	1.217	367.967	< 0.0001
T	1	1.263	1.263	382.004	< 0.0001
pH	1	0.050	0.050	15.072	0.0010
COD	1	0.003	0.003	0.985	0.3334
BOD	1	0.011	0.011	3.449	0.0789
TSS	1	0.320	0.320	96.712	< 0.0001
EC	1	0.090	0.090	27.311	< 0.0001
TDS	1	0.328	0.328	99.067	< 0.0001
Error	19	0.063	0.003		
Corrected Total	26	8.580			

Effect of Water used for Irrigation's Composition on Variation in the Total Nitrogen (TN) Contents of the Soil

Table 6 shows the influence of biochemical features of the water used for irrigation on the change in TN contents of the soil. The table shows that all the designated biochemical features of the water used for irrigation, except sulphates, had significant effects on the change in TN of soil at 5% probability level. Additionally, the outcomes indicated that the fecal coliform level of the water used for irrigation had the greatest Fisher's value and the second-highest chloride content, while nitrates had the least significant impact on the change in soil TN ($P < 0.05$).

Table 6. Influence of Biochemical Features of the Water used for Irrigation on Soil's Total Nitrogen

Source	DF	Sum of squares	Mean squares	F	Pr> F
Model	7	0.011346	0.001621	255.857	< 0.0001
NO_3^-	1	0.000045	0.000045	7.161	0.0149
SO_4^{2-}	1	0.000001	0.000001	0.086	0.7727
FC	1	0.004178	0.004178	659.467	< 0.0001
Cl-	1	0.001041	0.001041	164.334	< 0.0001
Mg	1	0.000585	0.000585	92.287	< 0.0001
Na	1	0.000738	0.000738	116.439	< 0.0001
K	1	0.000225	0.000225	35.489	< 0.0001
Error	19	0.000120	0.000006		
Corrected Total	26	0.011467			

Equation 5 illustrates how the multivariable regression model was used to establish the relationship between the variation in soil nitrogen and the chemical features of the water used for irrigation. It reveals that the designated biochemical features of the water used for irrigation can significantly ($P < 0.05$) explain 98.95% of the variation in

soil nitrogen with a standardized root mean square error of 0.002517. It also shows that a reduction in the sulphate and fecal coliform contents will significantly ($P < 0.05$) raise the change in soil's total nitrogen.

$$TN = 0.68707 + 0.00476NO_3^- - 1.79320E\text{-}6SO_4^{2-} - 0.00034FC + 0.01202Cl^- - 0.24461Mg + 0.01347Na + 0.01467K \quad (5)$$

The analysis of variance (ANOVA) for the change in total nitrogen contents of the soil and the influence of the physicochemical features of the water used for irrigation was presented in Table 7. This result indicates that changes in the total nitrogen content significantly ($P < 0.05$) depend on the T and pH of the water used for irrigation, while other parameters have no significant effect on the change in the soil TN. The physicochemical features with the highest Fisher's value was determined to be the factor with the most significant effect ($P < 0.05$) on the soil TN.

Nevertheless, as demonstrated in equation 6, a multiple linear regression model was created to numerically represent the variation in soil TN as a function of the irrigation water's physicochemical characteristics. According to the model, the variation in the designated physicochemical features of the irrigation water could account for approximately 76.95% of the variation in the soil's TN. Increases in T, COD, TSS, and EC will raise the soil's total nitrogen content. Similar findings were reported by Akponikpe et al. (2011); Balengayabo et al. (2022); Negi et al. (2022) and Khajah et al. (2023). It is well recognized that N and P are important macronutrients that crops need for sufficient growth. A reduction in the pH, BOD, and TDS of the water used for irrigation will significantly ($P < 0.05$) raise the soil's total nitrogen contents.

$$TN = -0.39020 + 0.02399T - 0.01168pH + 0.00043COD - 0.00061BOD + 0.00004TSS + 0.02510EC - 0.00007TDS \quad (6)$$

Table 7. Influence of Physicochemical Features of the Water used for Irrigation on Soil Total Nitrogen

Source	DF	Sum of squares	Mean squares	F	Pr> F
Model	7	0.008823	0.001260	9.059	< 0.0001
T	1	0.002388	0.002388	17.166	0.0006
pH	1	0.000963	0.000963	6.922	0.0165
COD	1	0.000217	0.000217	1.556	0.2273
BOD	1	0.000233	0.000233	1.678	0.2107
TSS	1	0.000001	0.000001	0.004	0.9519
EC	1	0.000224	0.000224	1.613	0.2194
TDS	1	0.000168	0.000168	1.207	0.2857
Error	19	0.002644	0.000139		
Corrected Total	26	0.011467			

Effect of Irrigation Water Composition on Variation in the Soil Phosphorous (P)

Table 8 depict the influence of the biochemical characteristics of the water used for irrigation which include the Nitrates (NO_3^-), Sulphates (SO_4^{2-}), Fecal coliforms (FC), Chloride (Cl^-), Magnesium (Mg), Sodium (Na) and Potassium (K) on the variation in the phosphorous (P) contents of the soil. According to the table, ANOVA shows that the variation in P significantly ($P < 0.05$) depends on the fecal coliform (FC) of the water used for irrigation. Sulphates have no significant effect ($P < 0.05$) on the phosphorous contents of the soil because its probability value is above 5%. But according to equation 7, which shows that the biochemical characteristics of the water used for irrigation can significantly explain about 99.98% of the change in the P of the soil with a standardized root mean square error of 0.048148, the change in P was mathematically expressed as a function of the water used for irrigation's biochemical characteristics.

$$P = 22.27964 + 0.34065NO_3^- + 0.00006SO_4^{2-} - 0.00942FC + 0.29197Cl^- - 6.84993Mg + 0.37944Na + 0.45581K \quad (7)$$

Consequently, the result demonstrates that a unit rise in NO^{3-}, SO_4^{2-}, Cl^-, Na and K of the water used for irrigation will result in a significant ($P < 0.05$) rise in the soil phosphorous contents, while, a unit drop in the FC and Mg will raise the change in the P of the soil.

Table 8. Effect of Biochemical Features of the Water used for Irrigation on Phosphorous Contents of the Soil

Source	DF	Sum of squares	Mean squares	F	Pr> F
Model	7	179.426	25.632	11057.036	< 0.0001
NO_3^-	1	0.233	0.233	100.339	< 0.0001
SO_4^{2-}	1	0.001	0.001	0.245	0.6260
FC	1	3.126	3.126	1348.477	< 0.0001
Cl-	1	0.615	0.615	265.118	< 0.0001
Mg	1	0.459	0.459	197.784	< 0.0001
Na	1	0.585	0.585	252.430	< 0.0001
K	1	0.217	0.217	93.619	< 0.0001
Error	19	0.044	0.002		
Corrected Total	26	179.470			

The effect of the physicochemical features of the water used for irrigation which include the T, pH, COD, BOD, TSS, EC, and TDS on the variation in the phosphorous (P) contents of the soil using ANOVA is shown in Table 9. The table depict that the change in the soil P highly depends on the temperature of the water used for irrigation, while other parameters have no significant ($P < 0.05$) influence on the soil P contents.

Equation 8 depicts the variation in the soil P as a function of the physicochemical characteristics of the water used for irrigation. According to the equation, a unit increase in the T, COD, BOD, TSS, EC and TDS contents of the water used for irrigation will increase the phosphorous availability in the soil, while, a unit decrease in the pH

of the water used for irrigation will increase the soil P. These results are consistent with those of Sacks and Bernstein (2011); Akponikpe et al., (2011) and Jaoude et al., (2024) who have a definite pointer that treated wastewater irrigation with wastewater increases soil phosphorus.

$$P = -1.77475 + 0.35238T - 0.07042pH + 0.00423COD + 0.00115BOD + 0.00079TSS + 0.70544EC + 0.00086TDS \quad (8)$$

With a normalized root mean square error of 0.344401, the goodness of fit parameter of the constructed model (Equation 8) demonstrates that the physicochemical characteristics of the water used for irrigation can significantly explain approximately 98.74% of the difference in the soil P.

Table 9. Effect of Physicochemical Features of the Water used for Irrigation on Phosphorous Contents of the Soil

Source	DF	Sum of squares	Mean squares	F	Pr> F
Model	7	177.2166	25.3167	213.441	< 0.0001
T	1	0.5152	0.5152	4.344	0.0509
pH	1	0.0350	0.0350	0.295	0.5933
COD	1	0.0212	0.0212	0.179	0.6774
BOD	1	0.0008	0.0008	0.007	0.9343
TSS	1	0.0002	0.0002	0.002	0.9652
EC	1	0.1773	0.1773	1.495	0.2364
TDS	1	0.0265	0.0265	0.223	0.6420
Error	19	2.2536	0.1186		
Corrected Total	26	179.4702			

Effect of Irrigation Water Composition on Variation in the Potassium (K) Contents of the Soil

Table 10 depicts the influence of the biochemical features of the water used for irrigation on the variation in the potassium (K) contents of the soil. According to the table, ANOVA shows that the variation in potassium significantly ($P < 0.05$) hinge on on the nitrate contents of the water used for irrigation followed by the Mg of the water used for irrigation as they depict a higher calculated Fisher's value of 1350.263 and 728.647 respectively with low probability values of 0.0001 which are less than 5% standard probability level. Sodium and chloride have the least significance ($P < 0.05$) influence on the change in the potassium contents of the soil. However, as demonstrated by equation 9, the change in K was mathematically expressed as a function of the irrigation water's biochemical characteristics. This equation indicates that, with a standardized root mean square error of 0.108802, the biochemical characteristics of the water used for irrigation can significantly explain approximately 99.99% of the change in the soil's K.

$$K = -91.14209 - 2.82389NO_3^- - 0.00592SO_4^{2-} + 0.01366FC + 0.69751Cl^- + 29.71075Mg - 0.81043Na + 2.45229K \quad (9)$$

Furthermore, the findings indicate that a significant ($P < 0.05$) increase in soil K will occur for every unit increase in fecal coliform, chloride, magnesium, and potassium of the water used for irrigation, whereas a unit decrease in nitrate, sulphate, and sodium will result in a rise in the soil's potassium contents.

Table 10. Effect of Biochemical Features of the Water used for Irrigation on the Potassium Contents of the Soil

Source	DF	Sum of squares	Mean squares	F	Pr> F
Model	7	2296.942	328.135	27718.823	< 0.0001
NO_3^-	1	15.984	15.984	1350.263	< 0.0001
SO_4^{2-}	1	5.932	5.932	501.062	< 0.0001
FC	1	6.570	6.570	554.961	< 0.0001
Cl-	1	3.508	3.508	296.302	< 0.0001
Mg	1	8.626	8.626	728.647	< 0.0001
Na	1	2.670	2.670	225.507	< 0.0001
K	1	6.282	6.282	530.653	< 0.0001
Error	19	0.225	0.012		
Corrected Total	26	2297.167			

Table 11 uses analysis of variance to show how the physicochemical features of the water used for irrigation affected the change in the soil's potassium (K) concentrations. According to the table, the EC of the water used for irrigation has the biggest impact on the change in soil K, followed by the pH and TSS contents. The TDS, COD, and BOD have the least significant ($P < 0.05$) effects on the soil's potassium levels.

Table 11. Effect of Physicochemical Features of the Water used for Irrigation on Soil Potassium

Source	DF	Sum of squares	Mean squares	F	Pr> F
Model	7	2294.019	327.717	1978.040	< 0.0001
T	1	2.530	2.530	15.269	0.0009
pH	1	7.392	7.392	44.615	< 0.0001
COD	1	0.972	0.972	5.867	0.0256
BOD	1	1.036	1.036	6.250	0.0217
TSS	1	3.078	3.078	18.579	0.0004
EC	1	11.230	11.230	67.781	< 0.0001
TDS	1	0.108	0.108	0.651	0.4298
Error	19	3.148	0.166		
Corrected Total	26	2297.167			

Equation 10 shows how the physicochemical characteristics of the water used for irrigation affect the soil K content; a unit increase in the irrigation water's BOD, TSS, and EC contents will raise the soil K content, while a unit decrease in the water used for irrigation's T, pH, COD, and TDS contents will raise the soil potassium content.

K = 37.10464 - 0.78082T - 1.02329pH - 0.02869COD + 0.04066BOD + 0.09082TSS + 5.61430EC - 0.00174TDS (10)

a normalized root mean square error of 0.407035, the goodness of fit parameter of the derived model (Equation 10) demonstrates that the physicochemical features of the water used for irrigation can significantly explain approximately 99.86% of the variation in the soil K.

Influence of water used for irrigation's Composition on Yield of Pepper

The ANOVA of the yield of pepper and the influence of the physicochemical features of the water used for irrigation is presented in Table 12. The table shows that the physicochemical features of the water can significantly ($P < 0.05$) explain the variation in the yield of pepper as the obtained overall significance value is less than 0.0001. Based on the sum of square analysis, the physicochemical characteristic with the highest Fisher's value and lowest P value was selected as the variable with the highest significant effect ($P < 0.05$) on the yield of pepper. This finding indicates that the water used for irrigation's T and pH has a substantial ($P < 0.05$) impact on pepper yield variation, followed by TSS, EC, TDS, and BOD. The water used for irrigation's COD had the least and non-significant impact on pepper yield. According to Al-Maskri et al. (2010), accumulation of minerals due to impurities in water used for irrigation increases the EC and salinity of the soil. The effect of variation in the yield as affected by EC in this study is in conformity with the influence of potassium and chloride contents of the water used for irrigation and this agrees with the research of Bolarin et al. (2001), Li and Stanghellini, (2001) and De Lemos et al. (2021).

However, as demonstrated in equation 11, a multiple linear regression model was created to mathematically represent the pepper yield as a function of the physicochemical features of the irrigation water. As deduced from the model, the coefficient of determination (R^2) is 1.000 with root mean square error of 17.80 and this shows that about 100% variation in the yield of pepper was due to the variation in the selected physicochemical characteristics of the water used for irrigation. As explained in the general limitation stated above (preceding Table 2), this R^2 value of 1.000 reflects the same saturated nine-profile experimental structure rather than a generalisable predictive relationship. The RMSE of 17.80 g confirms the residuals are non-zero, so the fit is not a trivial identity.

$$Y = -1.13 + 529.73T - 340.79pH - 1.01COD + 3.66BOD + 25.18TSS\ (mg/L) - 1150EC - 3.15TDS \quad (11)$$

Furthermore, a one-unit rise in the irrigation water's T, BOD, and TSS will result in a 529.73 g, 3.66 g, and 25.18 g increase in pepper output, respectively. If the irrigation water's pH, COD, EC, and TDS are reduced by one unit, the pepper production will rise by 340.79 g, 1.01 g, 1150 g, and 3.15 g, respectively.

Table 12. Effect of Physicochemical Features of the Water used for irrigation on Yield of Pepper

Source	DF	Sum of squares	Mean squares	F	Pr> F
Model	7	270743909.4576	38677701.3511	122131.5202	< 0.0001
Temp (°C)	1	1164293.4210	1164293.4210	3676.4575	< 0.0001
pH	1	819846.8677	819846.8677	2588.8080	< 0.0001
COD (mg/L)	1	1206.2023	1206.2023	3.8088	0.065884
BOD (mg/L)	1	8414.6491	8414.6491	26.5707	< 0.0001
TSS (mg/L)	1	236594.9596	236594.9596	747.0894	< 0.0001
EC (dS/m)	1	471395.8914	471395.8914	1488.5139	< 0.0001
TDS (mg/L)	1	354825.8747	354825.8747	1120.4240	< 0.0001
Error	19	6017.0898	316.6889		
Corrected Total	26	270749926.5474			

The impact of the water used for irrigation's biochemical features on the overall pepper yield is shown in Table 13, which also demonstrates that all of the chosen biochemical features of the water used for irrigation had a significant impact on the pepper yield at the 5% probability level. The results indicate that the sulphate and potassium contents of the water used for irrigation, with high Fisher's values of 31.43 and 29.33, respectively, have a significant ($P < 0.05$) impact on the pepper yield, followed by magnesium, sodium, and chloride, while nitrate and fecal coliform have the least significant impact.

Table 13. Effect of Biochemical Characteristics of the Water Used for Irrigation on Yield of Pepper

Source	DF	Sum of squares	Mean squares	F	Pr> F
Model	7	269772538.1422	38538934.0203	749.1799	< 0.0001
NO_3^- (mg/L)	1	53996.8497	53996.8497	1.0497	0.3185
SO_4^{2-} (mg/L)	1	1616758.6306	1616758.6306	31.4291	< 0.0001
FC (CFU/100ml)	1	294.5964	294.5964	0.0057	0.940468
Cl^- (mg/L)	1	395393.9269	395393.9269	7.6863	0.01213
Mg (ppm)	1	1394303.6489	1394303.6489	27.1046	< 0.0001
Na (ppm)	1	1328678.9827	1328678.9827	25.8289	< 0.0001
K (ppm)	1	1508661.5475	1508661.5475	29.3277	< 0.0001
Error	19	977388.4052	51441.4950		
Corrected Total	26	270749926.5474			

However, as equation 12 illustrates, a multivariable regression model was used to determine the link between the overall pepper production and the biochemical characteristics of the water used for irrigation. According to the equation's goodness of fit, the coefficient of determination (R^2) between a few chosen biochemical characteristics of the irrigation water and pepper yield is 0.9964. This indicates that the

pepper yield is highly linear with the irrigation's biochemical characteristics, and the developed relationship had an accuracy of 99.64%. The resulting root mean square error was 226.81. A one-unit increase in the irrigation water's nitrate, sulphate, and sodium contents will result in 164.13 g, 3.09 g, and 571.75 g of pepper, respectively. Conversely, a one-unit decrease in the irrigation water's fecal coliform, chloride, magnesium, and potassium contents will result in 0.09 g, 234.19 g, 11945 g, and 1202 g of pepper, respectively. This supports the findings of Jha et al. (2012), who examined the impact of water quality on the productivity and water usage efficiency of irrigated wheat crops and found that the water constituents significantly affected wheat crop yield. Additionally, during their investigation into the impact of varying concentrations of diluted seawater on lettuce yield and quality, Turhan et al. (2016), De Lemos et al. (2021) and Jaoude et al. (2024) reported an increase in lettuce yield with an increase in EC and salinity of the irrigation water. These results concur with those of this investigation as well as the reports of Tzortzakis (2009) and Andriolo et al. (2005).

$$Y = 54805 + 164.13NO_3^- + 3.09SO_4^{2-} - 0.09FC - 234.19Cl^- - 11945Mg + 571.75Na - 1202K \quad (12)$$

CONCLUSION AND RECOMMENDATIONS

The purpose of this study was to investigate how soil fertility in Akure, Nigeria, was impacted by the composition of irrigation water from treated greywater. The findings of a thorough examination demonstrated that the nature of the irrigation water utilized improved selected soil fertility indicators (pH, TOM, and macronutrients). The soil's fertility status in terms of macronutrients as measured after harvest also increased, according to the results of the soil analysis conducted in the research region; as noted in the Results, this increase is descriptive rather than statistically tested, since the underlying soil-chemistry values (Tables 1a - c) are single treatment-level measurements without replicate-level data. Similarly, when treated greywater was used for irrigation, issues related to the use of raw greywater—such as soil pore obstruction caused by excessive salt and chloride concentrations—were reduced. At the 5% probability level, ANOVA of the soil's TOM, TN, P, and K contents in relation to the irrigation water's physiological and biochemical characteristics revealed a significant correlation between them and the irrigation water's temperature (T), TDS, TSS, FC, pH, chloride, nitrate, and magnesium contents. Similarly, at the 5% probability level, an ANOVA examining the physiological and biochemical characteristics of the water used for irrigation reveals a substantial correlation between the total amount of pepper produced and the irrigation water's T, pH, TSS, EC, TDS, BOD, sulphate, and potassium contents. Future research on the effects of this irrigation water composition on crop quality is necessary, as this study is crucial for farmers working with starved soil to restore its fertility condition and, consequently, increase crop output. A further limitation concerns the regression models relating soil and

pepper-yield parameters to irrigation-water composition (Tables 2 - 13): because the 27 plot-level observations are drawn from only nine distinct water-by-season predictor profiles, these seven-predictor models are close to saturated, which mechanically inflates their reported R^2 values; they should therefore be read as a property of the replicate structure rather than as evidence of a generalisable predictive relationship, and a profile-level re-analysis with adjusted R^2 and residual diagnostics is recommended once plot-level data are available. However, this study is limited to a single location under drip irrigation in a tropical humid climate; results may differ under flood or sprinkler irrigation systems or in other agro-ecological zones. Future studies should explore greywater irrigation across multiple locations and crops to enhance generalizability of findings (Victor Junior et al., 2025; Shqerat and Al-Tabbal, 2025).

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Authors' Contribution

Conceptualization: FA, AJO; Methodology: FA, AJO, AAO; Field experiment and data collection: FA; Formal analysis: OOO, DUI, OB; Writing – original draft: FA; Writing – review and editing: AJO, AAO, AMO, OOO, DUI, OB; Supervision: OOO All authors read and approved the final manuscript.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The raw plot-level dataset underlying Tables 1a - 13, including the nine distinct water-by-season profiles used in the regression models, is not currently available for public deposition; interested readers may contact the corresponding author to discuss availability.

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