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A survey of irrigation water and soil quality that likely impacts paddy rice yields in Kilimanjaro, Tanzania

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Abstract

In this study, the impacts of irrigation water quality and soil characteristics on paddy rice yields were investigated. Standard spectroscopy and spectrometry methods were used to analyze irrigation water and irrigated soil samples. The irrigation water had sodium adsorption ratio (SAR) values ranging from 0 to 3. The corresponding electrical conductivity (EC) values were between 0.2 and 0.7 dS/m and accounted for 14% of all samples—posing slight to moderate infiltration problem. Neither Na⁺ nor Cl⁻ levels were high enough to cause toxicity problems in the irrigation water. For B, 54% of the samples were found to have moderate toxicity whereas ~ 14% of the samples indicated severe B toxicity in the irrigation water. For bicarbonate, about 86 and 14% of the irrigation water indicated slight-to-moderate and severe potential detrimental effect to plant growth, respectively. All trace elements in the irrigation water were too low to cause any harmful effect. Although soil EC, organic carbon (OC), and pH indicated favorable level, there were high standard deviation (SD) values in soil Fe and Zn. The mean value of Fe in soils was 19.8 mg/kg, indicating signs of Fe-deficiency. High SD values were also found in the total N (TN) content of the studied soils. Furthermore, a low soil K content was observed in the analyzed soil samples. Appropriate fertilizer application for improving nutrient deficiencies in the study area is highly recommended. Furthermore, on-farm management practices need to be guided by scientific findings from the present as well as other studies.

Keywords Irrigated soils characteristics · Irrigation water quality · Rice production · Smallholder rice farming · Kilimanjaro irrigation water · Tanzania

1 Introduction

Efforts have been made to improve irrigated farm yields in developing countries to meet the growing demands for rice. Despite such efforts, productivity is still lower than the genetic potential of 10 t ha⁻¹. Paddy rice is grown in Africa using diverse production practices. These diverse production practices, ranging from primitive to highly mechanized methods, have led to variations in productivity [1].

In Tanzania, paddy rice is one of the most widely grown crops and is the second most important food crop [2]. The country has more than 21 million hectares suitable for paddy rice production. Paddy rice is grown under three

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major ecosystems namely, rain-fed, upland, and irrigated. The rain-fed ecological system covers 74% of the current rice hectares with yields ranging from 1.0 to 2.0 t ha⁻¹ while the irrigated ecosystem is about 20% with yields ranging from 2.5 to 4.0 t ha⁻¹; the remaining 6% is under upland ecology [3]. Thus, variations in paddy yields in Tanzania and sub-Saharan Africa may be due to ecology, rainfall patterns, water quality and quantity, soil characteristics, rice varieties, diseases and pests, and other factors.

The irrigated ecosystem provides readily available water for paddy production. This accessibility to irrigation water coupled with high solar radiation and low incidence of pest and diseases may result into high paddy rice yields. However, the quality of irrigation water has been reported to influence paddy yields. The effects are usually related to the irrigation water physico-chemical properties. Issues related to irrigation water quality include high salinity levels which affect nutrients availability, high Na⁺ levels which cause soil infiltration problems for irrigation water and toxicity of some elements when their levels in irrigation water are in excess. Dissolved salts and trace elements in irrigation water are usually due to natural weathering of the earth's crust or as a result of anthropogenic activities such as disposal of improperly treated wastewater and sludge as well as excessive use of fertilizers. Therefore, improved management practices of irrigation water quality may be necessary for higher paddy rice yields.

Soil properties have also been reported as a contributing factor to rice growth. Usually, nutrient content and availability in soils determine the chemical properties of that soil. Soils with high organic matter (OM) content are known to hold more nutrients necessary for paddy growth. Also, as soil OM content increases from 0.5 to 3.0%, the available water-holding capacity in the soil also increases [4]. Therefore, low OM or losses of OM in the soils can significantly reduce paddy rice yields.

Tanzania, like other developing countries in sub-Saharan Africa, is struggling to improve its rice yields. For instance, in the present study area, rice yields have been ranging from 0.4 to 3.8 t ha⁻¹ (average 1.87 t ha⁻¹; Table S3—Supplementary Material). These yields were low compared to those in countries such as Egypt and USA where the average rice yields are close to 10 t ha⁻¹ [5]. Smallholder paddy rice growers at the present study sites have been complaining about uneven and low production leading to low family income. Therefore, this study aimed at assessing the impacts of irrigation water quality and soil characteristics on paddy rice productivity in the area that has been poorly investigated.

2 Materials and methods

2.1 Area and general methods

The study was carried out at one of the irrigated areas/sectors in the Kilimanjaro region of Northern Tanzania (Fig. 1). The study area is located in Mwangi District. It shares borders with Simanjiro District to the West, Moshi District to the North, the Republic of Kenya to the East and Same district to the South. The studied sectors abstract their water from the Ivonokwa and Mtindi springs, which supply water to Kivulini, Bogoyo, and Nanyori.

The sampling sites were randomly selected, and their respective geographical positioning were determined using a handheld geographical positioning system (GPS) device (Garmin International, Inc., East Street 151 East Street, Olathe, Kansas). A QGIS software Version 2.1.8 was used to prepare the map showing sampling points in the study area. The study area was further divided into three sectors i.e., Kivulini, Nanyori, and Bogoyo using the three main canals as points of reference (Fig. 2). The sectors were used for comparison purposes. The one-way analysis of variance (ANOVA) for the three sectors was computed using the SigmaPlot software; the degree of freedom, *F*- and *P*-values are presented in Tables S1 and S2 in the Supplementary Material.

A reconnaissance survey was conducted prior to irrigation water and soil sample collection (Supplementary Material, Table S3). It was found that the amount of the irrigation water that was supplied to the individual farms through the irrigation canals was enough to meet paddy rice water requirements. Therefore, water supply to the rice farms was not a problem. The farmers that were interviewed revealed that they used fertilizers during the S0–S1 stage, following the Counce et al. [6] rice development staging system) to facilitate seed germination. They also revealed that they applied fertilizers to boost rice growth around Counce et al.'s V3–V7 stages. Boosting fertilization was done 14 days after transplanting. The final fertilization round was conducted during the R6–R7 stages [6] as paddy rice approached maturity.

Fig. 1 Map of the study area. Map A represents Tanzania country with all the regions. Map B represents Kilimanjaro region and Map C represents the study region. The details of map C are shown in Fig. 2

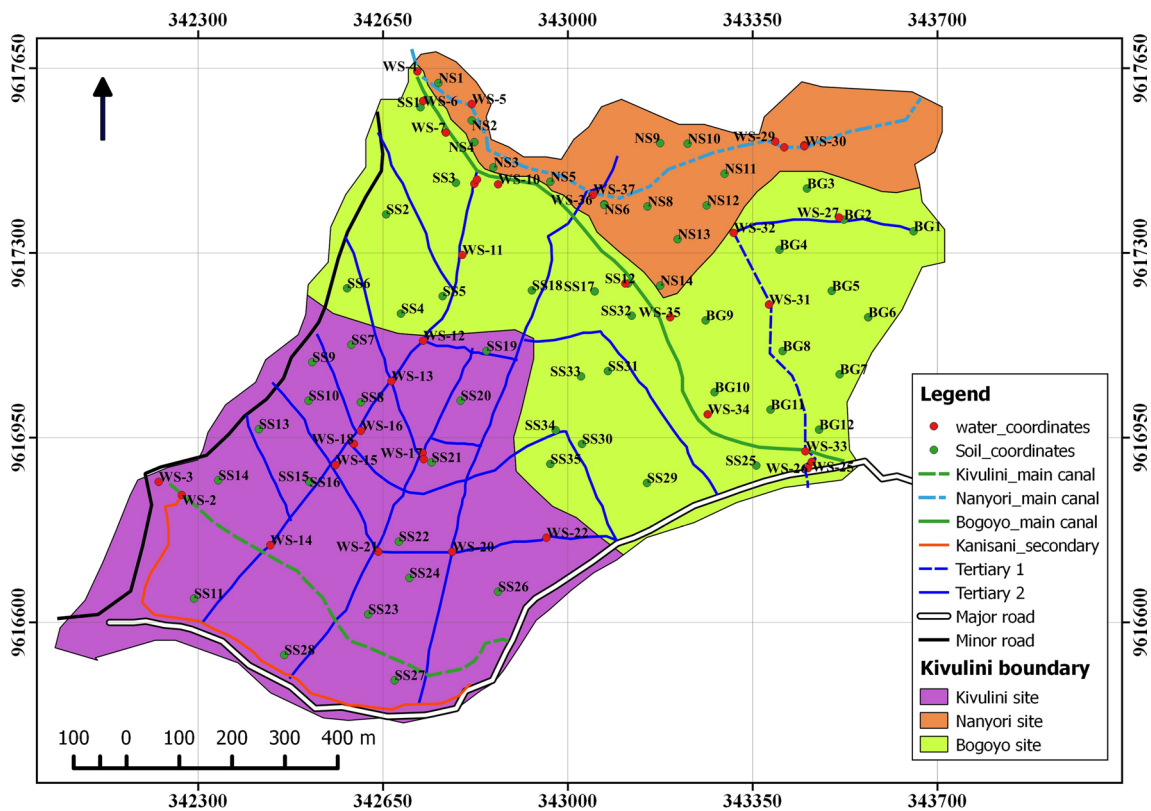
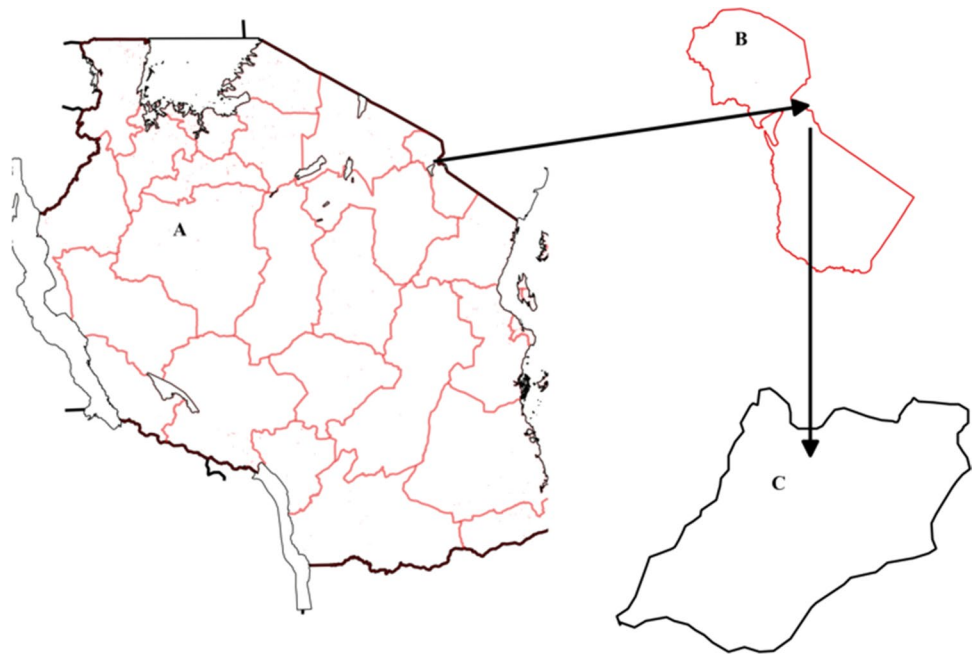


Fig. 2 Layout map of the sampling area. The map shows three areas of Kivulini (purple), Bogoyo (green) and Nanyori (orange) where irrigation water and soil samples for this study were collected

2.2 Irrigation water sampling

Irrigation water and soil sample collection was performed in July 2018. The farmers in the study area have two growing seasons. A season from February to May (long rain season) and the one from August to December that experiences short

rains. The irrigation water is mostly needed in the August to December season. That was the target of the present study. The limitation of this study is that sampling in different months may yield different results as this study is a representation of a dry season. A total of 37 irrigation water samples were collected and stored in 1.0 L glass bottles with Teflon-lined lids. Before sample collection, the bottles were triple rinsed with deionized water. All other sampling procedures are described below.

Seventeen (17) irrigation water samples were collected from irrigation ditches located on 17 individual farms whereas the other 20 irrigation water samples were collected from the main drainage and distribution canals. During water sample collection, some physico-chemical properties of water were recorded onsite using a multi-parameter device (Model HI 9828, HANNA Instruments, Italy). Data recorded onsite included the irrigation water pH, EC, TDS, temperature, salinity, dissolved oxygen (DO) and the oxidation reduction potential (ORP). The bottles were then sealed, labeled, preserved in a cool box, and transported to the Nelson Mandela African Institution of Science and Technology (NM-AIST) laboratory for further analyses. At NM-AIST, the samples were acidified using analytical grade HNO₃ to a pH less than 2. The irrigation water samples were then refrigerated at 4 °C to minimize microbial activity and undesirable physicochemical reactions before further analysis.

2.3 Sampling of irrigated soils

Soil samples were collected across the three regions shown in Fig. 2 at the same time as when the water samples were collected. A total of 61 soil samples were collected at a depth of 0 to 20 cm at different locations in the study area. The 'up to 20 cm' is the depth of tillage that is common for irrigated rice growing in Tanzania. The presence of a hardpan limits the depth to which farmers can go when tilling the rice fields and the avoidance of the disruption of the soil's water retention capacity thereof. To obtain one representative sample on a site, six points were randomly selected across a field/farm; the six soil samples were composited and thoroughly mixed before a final composite sample of 0.5 kg was removed for analysis. The composite samples were stored in labeled zip-top bags and transported to the NM-AIST laboratory for analysis. Accordingly, all other soil sampling procedures were followed using the recommendations in the literature [7].

2.4 Laboratory methods

Irrigation water samples were analyzed for cations (Ca²⁺, Mg²⁺, K⁺, Na⁺), anions (SO₄²⁻, PO₄²⁻, CO₃²⁻, HCO₃⁻, Cl⁻, NO₃⁻) and heavy metals (Fe²⁺, Zn²⁺, Cu²⁺, Mn²⁺, B, As, Cd, Cr²⁺, Pb²⁺, Ni²⁺ and Al³⁺) using the methods explained in Table 1.

Moreover, SAR (in meq/L) for irrigation water samples was calculated using a standard Eq. (1) [8]:

$$\text{SAR} = \frac{[\text{Na}^+]}{\sqrt{\frac{[\text{Ca}^{2+}] + [\text{Mg}^{2+}]}{2}}} \quad (1)$$

where [Na⁺], [Ca²⁺], and [Mg²⁺] are concentrations of sodium, calcium and magnesium ions in the irrigation water samples, respectively.

Soil samples were analyzed for OC, EC, pH, Fe²⁺, Zn²⁺, N, P and K⁺ using standard methods for soil analysis. A summary of methods used for measurement of irrigated soil quality is presented (Table 2).

3 Results

3.1 Irrigation water and salinity problems

When the EC values were converted to dS/m, the results indicated that 14% of the assessed irrigation water samples had EC values < 0.7 dS/m (Table 3). The remaining 86% of the assessed irrigation water samples indicated slight to moderate restriction level. No sample had EC values in the severe category of restriction for irrigation use.

3.2 Analysis of SAR levels

All the irrigation water samples' SAR values fell between 0 and 3 (Table 4). When interpreted alongside the corresponding EC values, the results indicated that only 14% of the irrigation water samples had EC values between 0.2

Table 1 Different laboratory methods applied for the measurement of irrigation water quality

Quality parameter	Symbol	Method/equipment used for measurement
Sulfate	SO_4^{2-}	SulfaVer 4 Turbidity method
Phosphate	PO_4^{2-}	PhosVer 3 Ascorbic method
Nitrate	NO_3^-	NitraVer Cadmium Reduction method
Boron	B	BorVer Carmine method
Chloride	Cl^-	Argentometric Titration method, using standard AgNO_3 titrant and potassium chromate indicator solution
Carbonate and bi-carbonate	CO_3^{2-} and HCO_3^-	Titration method with ethylene diamine tetra-acetic acid (EDTA) using Erio T as end point of titration
Sodium, potassium	Na^+ , K^+	PPP7 Flame Photometer using standard solutions of Na^+ and K^+
Calcium, magnesium	Ca^{2+} , Mg^{2+}	Titration method with ethylene diamine tetra-acetic acid (EDTA) using Erio T as end point of titration
Trace elements	Fe^{2+} , Zn^{2+} , Cu^{2+} , Mn^{2+} , As, Cd, Cr^{2+} , Pb^{2+} , Ni^{2+} , Al^{3+}	Atomic absorption spectrometer (AAS) (PerkinElmer Analyst 100)

Table 2 Different methods used for measurement of irrigated soil quality parameters

Quality parameter	Symbol	Method/equipment used in measurement
Electrical conductivity, pH	EC, pH	A portable meter using a soil to water ratio of 1:2 with potassium chloride reagent
Organic carbon	OC	Mixing the sample with chromic acid and H ₂ SO ₂
Total nitrogen	Total N (TN)	The Micro-Kjeldahl digestion, distillation followed by titration
Available phosphorus	Available P	Olsen method
Potassium	K ⁺	Flame Photometer method
Iron, zinc	Fe ²⁺ , Zn ²⁺	Atomic absorption spectrophotometer (AAS) after digestion and extraction of samples

and 0.7 dS/m. The remaining 86% of the irrigation water samples had EC values > 0.7 dS/m. None of the 37 samples had EC values below 0.2 dS/m.

3.3 Water pH and EC levels

Irrigation water pH levels for the Kivulini sites ranged from 6.25 to 7.42 with a mean value of 6.64 ± 0.45 (Table 5) while that of the Nanyori samples ranged from 6.27 to 7.23 and averaged 6.6 ± 0.35 (Table 6). For the Bogoyo area, the pH values ranged from 6.23 to 7.35 with an average value of 6.71 ± 0.37 (Table 7). The ANOVA values showed that there were no statistically significant differences in pH levels among the three areas surveyed ($F = 1.09$, $P = 0.35$) (Table S1). The EC values for the Kivulini area varied from 662 to 1365 $\mu\text{S cm}^{-1}$ with a mean value of $942.62 \pm 188.85 \mu\text{S cm}^{-1}$ (Table 5) and that of the Nanyori area varied from 669 to 1027 $\mu\text{S cm}^{-1}$ with an average value of $856.86 \pm 139.96 \mu\text{S cm}^{-1}$ (Table 6). The Bogoyo area (Table 7) had its EC values ranging from 656 to 1515 $\mu\text{S cm}^{-1}$ with a mean value of $1013.53 \pm 265.58 \mu\text{S cm}^{-1}$. The ANOVA showed no statistical significant difference in EC levels among the three sub-regions in EC levels ($F = 0.42$, $P = 0.66$) (Table S1).

3.4 Irrigation water essential elements

For the Kivulini area (Table 5), the concentrations of Ca²⁺ ranged from 32.06 to 76.15 mg L⁻¹ and averaged $52.11 \pm 13.98 \text{ mg L}^{-1}$ while for the Nanyori region (Table 6) the Ca²⁺ concentrations ranged from 40.08 to 64.13 mg L⁻¹ with an average value of $55.54 \pm 10.96 \text{ mg L}^{-1}$. The Ca²⁺ levels for the Bogoyo study area ranged from 32.06 to 76.15 mg L⁻¹ with a mean value of $52.58 \pm 10.97 \text{ mg L}^{-1}$ (Table 7). The one-way ANOVA showed that there were no significant differences in Ca²⁺ levels among the areas surveyed ($F = 0.36$, $P = 0.7$) (Table S1). The Mg²⁺ levels for the Kivulini area ranged from 21.87 to 75.33 mg L⁻¹ and averaged $37.35 \pm 16.35 \text{ mg L}^{-1}$ (Table 5) while that of the Nanyori area ranged from 23.09 to 39.37 mg L⁻¹ with a mean value of $31.24 \pm 5.18 \text{ mg L}^{-1}$ (Table 6). The Bogoyo area had Mg²⁺ levels ranging from 23.09 to 52.97 mg L⁻¹ with an average value of $34.96 \pm 9.15 \text{ mg L}^{-1}$ (Table 7). Similar to the preceding cations mentioned above, the ANOVA showed no statistically significant difference in Mg²⁺ levels among the three areas surveyed ($F = 2.81$, $P = 0.08$) (Table S1).

The K⁺ levels for the Kivulini area ranged from 2.03 to 12.46 mg L⁻¹ with a mean value of $4.75 \pm 2.83 \text{ mg L}^{-1}$ (Table 5); for the Nanyori area the values ranged from 3.41 to 28.90 mg K⁺ L⁻¹ (Table 6) with a mean value of $14.47 \pm 7.38 \text{ mg L}^{-1}$. For the Bogoyo sector (Table 7), the K⁺ levels ranged from 4.36 to 56.20 mg L⁻¹ with a mean value of $18.06 \pm 13.11 \text{ mg L}^{-1}$. The ANOVA values revealed that there were no significant differences in K⁺ levels among the three areas ($F = 0.47$, $P = 0.63$) (Table S1). The Na⁺ levels in the Kivulini sites (Table 5) ranged from 3.61 to 39.98 mg L⁻¹ with a mean value of $19.66 \pm 10.32 \text{ mg L}^{-1}$ while that of the Nanyori area (Table 6) ranged from 8.85 to 23.38 mg L⁻¹ with an average value of $14.95 \pm 4.55 \text{ mg L}^{-1}$. The Bogoyo area (Table 7) had Na⁺ levels ranging from 3.41 to 56.2 mg L⁻¹ with a mean value of $16.5 \pm 12.7 \text{ mg L}^{-1}$. The ANOVA output showed no statistically significant differences in Na⁺ levels among the three areas surveyed ($F = 0.36$, $P = 0.70$) (Table S1).

The phosphorus (P) levels in the Kivulini area ranged from 0.14 to 0.82 mg L⁻¹ with a mean value of $0.24 \pm 0.18 \text{ mg L}^{-1}$ (Table 5) and that of the Nanyori area ranged from 0.19 to 0.25 mg L⁻¹ with an average of $0.22 \pm 0.02 \text{ mg L}^{-1}$ (Table 6). The Bogoyo area had P levels ranging from 0.11 to 0.95 mg L⁻¹ with a mean value of $0.38 \pm 0.25 \text{ mg L}^{-1}$ (Table 7). Furthermore,

Table 3 FAO guidelines for interpretation of water quality for irrigation [9] vs. field data from the studied area considering salinity effect

Parameter (unit)	Salinity measure					
	EC (dS/m)			TDS (mg/L)		
Degree of restriction	None	Slight to moderate	Severe	None	Slight to moderate	Severe
FAO guideline	< 0.7	0.7–3.0	> 3.0	< 450	450–2000	> 2000
<i>Levels in field samples for the current study</i>						
Site name						
WS-1	0.66			429		
WS-2	0.93			601		
WS-3	0.82			535		
WS-4	0.67			436		
WS-5	0.71			461		
WS-6	0.96			624		
WS-7	1.13			735		
WS-8	0.93			603		
WS-9	0.92			599		
WS-10	0.99			646		
WS-11	1.46			1462		
WS-12	1.37			1365		
WS-13	0.82			533		
WS-14	0.84			543		
WS-15	0.95			619		
WS-16	1.05			683		
WS-17	1.19			779		
WS-18	1.09			703		
WS-19	0.95			618		
WS-20	0.89			579		
WS-21	0.82			534		
WS-22	0.82			533		
WS-23	0.98			636		
WS-24	0.98			637		
WS-25	0.98			632		
WS-26	1.16			754		
WS-27	1.52			983		
WS-28	1.03			667		
WS-29	0.86			560		
WS-30	0.99			642		
WS-31	1.17			759		
WS-32	1.37			890		
WS-33	0.66			424		
WS-34	0.71			458		
WS-35	0.66			427		
WS-36	0.67			434		
WS-37	0.79			510		

the ANOVA values indicated that the Kivulini area differed significantly from the Nanyori and Bogoyo areas in P levels ($F=4.10$, $P=0.03$) (Table S1).

Table 4 FAO guidelines for interpretation of water quality for irrigation [9] vs. field data from the studied area considering infiltration and sodium toxicity effect

Parameter (unit)	Infiltration measure				
	SAR (meq/L)		EC (dS/m)		
Degree of restriction			None	Slight to moderate	Severe
FAO guideline	SAR 0–3	with EC =	> 0.7	0.7–0.2	< 0.2
	SAR 3–6	with EC =	> 1.2	1.2–0.3	< 0.3
	SAR 6–12	with EC =	> 1.9	1.9–0.5	< 0.5
	SAR 12–20	with EC =	> 2.9	2.9–1.3	< 1.3
	SAR 20–40	with EC =	> 5.0	5.0–2.9	< 2.9
<i>Levels in field samples for the current study</i>					
Site name					
WS-1	0.32		0.66		
WS-2	0.57		0.93		
WS-3	0.97		0.82		
WS-4	0.21		0.67		
WS-5	0.41		0.71		
WS-6	0.48		0.96		
WS-7	1.72		1.13		
WS-8	0.31		0.93		
WS-9	0.37		0.92		
WS-10	0.64		0.99		
WS-11	0.51		1.46		
WS-12	0.53		1.37		
WS-13	0.64		0.82		
WS-14	0.56		0.84		
WS-15	0.33		0.95		
WS-16	0.24		1.05		
WS-17	0.84		1.19		
WS-18	0.71		1.09		
WS-19	0.35		0.95		
WS-20	0.50		0.89		
WS-21	0.22		0.82		
WS-22	0.10		0.82		
WS-23	0.11		0.98		
WS-24	0.09		0.98		
WS-25	0.75		0.98		
WS-26	0.13		1.16		
WS-27	0.61		1.52		
WS-28	0.58		1.03		
WS-29	0.45		0.86		
WS-30	0.47		0.99		
WS-31	0.31		1.17		
WS-32	0.20		1.37		
WS-33	0.41		0.66		
WS-34	0.33		0.71		
WS-35	0.29		0.66		
WS-36	0.26		0.67		
WS-37	0.29		0.79		

Table 5 Physico-chemical properties of the irrigation water from the Kivulini area

SITE ID	pH	EC ($\mu\text{S}/\text{cm}$)	Ca ²⁺ mg/L	Mg ²⁺	K ⁺	Na ⁺	P	Cr	Al ³⁺	NO ₃ -N	SO ₄ ²⁻	Cl ⁻	HCO ₃ ⁻
WS1	7.36	662		26.24	2.05	11.69	0.18			1.2	6	0.1	310
WS2	7.42	925	44.09	31.59	4.71	22.8	0.21			1.1	3	0.2	460
WS3	7.41	823	40.08	43.25	7.41	35.2	0.14			1.1	8	0.1	310
WS12	6.58	1365	76.15	75.33	3.35	25.48	0.82			0.5	0	0.2	460
WS13	6.56	820	52.1	21.87	3.63	19.03	0.21			0.5	6	0.3	260
WS14	6.27	836	68.14	24.30	3.21	16.87	0.24			1	5	0.1	210
WS15	6.49	953	48.1	31.59	2.49	13.09	0.23			0.1	8	0.2	360
WS16	6.52	1053	32.06	35.96	2.03	12.21	0.19			0.5	7	0.1	650
WS17	6.33	1198	76.15	30.38	12.46	39.98	0.22			0.5	0	0.4	650
WS18	6.50	1085	60.12	43.25	6.78	26.6	0.19			1.2	0	0.2	300
WS20	6.33	891	48.1	27.95	4.34	19.66	0.19			0.5	2	0.1	390
WS21	6.27	823	44.09	66.58	4.45	9.41	0.16			1.3	8	0.1	260
WS22	6.25	820	48.10	27.22	4.82	3.61	0.2			1.3	8	0.2	310
Avg.±SD	6.64±0.45	942.62±188.85	52.10±13.98	37.35±16.35	4.75±2.83	19.66±10.31	0.24±0.18			0.83±0.40	4.69±3.28	0.18±0.09	379.23±140.79
Min	6.25	662	32.06	21.87	2.03	3.61	0.14			0.1	0	0.1	210
Max	7.42	1365	76.15	75.33	12.46	39.98	0.82			1.3	8	0.4	650

Site ID	Fe ²⁺ mg/L	Zn ²⁺	Mn ²⁺	Cu ²⁺	B ³⁺	As	Cd ²⁺	Cr	Al ³⁺	Mo ²⁺	Ni ²⁺	Pb ²⁺
WS1	2.01	0.22	BDL	0.01	1.2	BDL	BDL	0.01	1.1	0.01	0.11	0.22
WS2	0.96	0.29	BDL	0.01	0.4	BDL	BDL	0.08	1.2	BDL	0.06	0.34
WS3	0.28	0.22	BDL	0.03	1.3	BDL	BDL	0.03	0.91	0.01	0.07	0.35
WS12	1.25	0.12	BDL	0.01	0.2	BDL	BDL	0.02	0.51	0.01	0.02	0.84
WS13	1.33	0.58	0.09	0.01	0.4	BDL	BDL	0.05	0.62	BDL	0.06	0.75
WS14	1.07	0.79	0.11	0.01	2.5	BDL	BDL	0.03	0.18	0.01	0.05	1.26
WS15	0.80	0.81	0.08	0.01	3.7	BDL	BDL	BDL	0.26	0.01	0.02	1.87
WS16	0.72	1.18	0.05	0.01	1.0	BDL	BDL	BDL	0.16	BDL	0.07	1.83
WS17	0.56	0.12	0.07	0.04	1.8	BDL	BDL	BDL	0.29	BDL	0.05	0.74
WS18	0.13	0.13	0.06	0.12	1.6	BDL	BDL	BDL	0.85	BDL	0.08	0.53
WS20	0.54	0.26	0.04	0.01	2.9	BDL	BDL	0.04	1.09	BDL	0.04	1.34
WS21	0.67	0.24	0.04	0.09	1.4	BDL	BDL	0.03	1.02	BDL	0.05	1.50
WS22	0.61	0.16	0.07	0.06	0.5	BDL	BDL	0.04	0.97	BDL	0.04	1.73
Avg.±SD	0.84±0.49	0.39±0.34	0.07±0.02	0.03±0.04	1.45±1.056	N/A	N/A	N/A	0.70±0.38	N/A	0.06±0.02	1.02±0.61
Min	0.13	0.12	0.04	0.01	0.2	BDL	BDL	BDL	0.16	BDL	0.02	0.12
Max	2.01	1.18	0.11	0.12	3.7	BDL	BDL	0.08	1.2	0.01	0.11	1.87

BDL: Below detection limit; N/A: not applicable; SD: standard deviation

Table 6 Physico-chemical properties of the irrigation water collected from the Nanyori area

Site ID	pH	EC ($\mu\text{S}/\text{cm}$)	Ca ²⁺ mg/L	Mg ²⁺	K ⁺	Na ⁺	P	NO ₃ -N	SO ₄ ²⁻	Cl ⁻	HCO ₃ ⁻	
W55	7.23	711	56.11	32.81	2.58	13.65	0.25	0.1	0	0.1	300	
WS19	6.28	953	64.13	23.09	3.09	13.09	0.19	0.5	0	0.5	360	
WS28	6.55	1027	40.08	39.37	4.81	23.38	0.22	0.4	1	0.1	460	
WS29	6.8	862	60.12	30.13	2.33	16.99	0.21	0	1	0.1	360	
WS30	6.75	990	64.13	30.13	2.21	16.09	0.21	0.3	1	0.2	310	
WS36	6.27	669	64.13	28.19	1.75	8.85	0.21	0.6	1	0.1	300	
WS37	6.33	786	40.08	34.99	1.66	12.59	0.25	0.1	2	0.1	440	
Avg. \pm SD	6.60 \pm 0.35	856.86 \pm 139.96	55.54 \pm 10.96	31.24 \pm 5.18	2.62 \pm 1.08	14.95 \pm 4.55	0.22 \pm 0.02	0.29 \pm 0.23	0.86 \pm 0.69	0.17 \pm 0.15	361.43 \pm 65.94	
Min	6.27	669	40.08	23.09	1.66	8.85	0.19	0	0	0.1	300	
Max	7.23	1027	64.13	39.37	4.81	23.38	0.25	0.6	2	0.5	460	
Site ID	Fe ²⁺ mg/L	Zn ²⁺	Mn ²⁺	Cu ²⁺	B ³⁺	As	Cd ²⁺	Cr	Al ³⁺	Mo ²⁺	Ni ²⁺	Pb ²⁺
W55	1.24	0.85	0.02	0.01	0.8	BDL	BDL	0.04	1.12	0.01	0.08	1.45
WS19	0.35	0.02	0.05	0.14	1.3	BDL	BDL	BDL	0.96	BDL	0.04	1.84
WS28	0.23	0.96	0.04	0.01	0.3	BDL	BDL	0.04	0.52	BDL	0.01	1.27
WS29	0.32	1.08	0.05	0.01	0.5	BDL	BDL	0.02	1.43	BDL	0.01	1.81
WS30	0.26	1.19	0.07	0.03	1.1	BDL	BDL	0.02	1.59	BDL	0.14	0.96
WS36	1.53	0.37	0.07	0.05	0.6	0.01	BDL	0.02	0.89	BDL	0.1	0.73
WS37	1.63	0.61	0.11	0.01	2.4	BDL	BDL	0.02	0.54	0.01	0.07	0.36
Avg. \pm SD	0.79 \pm 0.64	0.73 \pm 0.42	0.06 \pm 0.03	0.04 \pm 0.05	1.0 \pm 0.7	N/A	N/A	N/A	1.01 \pm 0.41	N/A	0.06 \pm 0.05	1.20 \pm 0.55
Min	0.23	0.02	0.02	0.01	0.3	BDL	BDL	BDL	0.52	BDL	0.01	0.36
Max	1.63	1.19	0.11	0.14	2.4	0.01	N/A	0.04	1.59	0.01	0.14	1.84

BDL: Below detection limit; N/A: not applicable; SD: standard deviation

Table 7 Physico-chemical properties of the irrigation water collected from the Bogoyo area

Site ID	pH	EC (µS/cm)	Ca ²⁺ mg/L	Mg ²⁺	K ⁺	Na ⁺	P	NO ₃ -N	SO ₄ ²⁻	Cl ⁻	HCO ₃ ⁻	
WS4	7.35	670	64.13	33.53	1.41	7.41	0.24	0.4	0	0.1	230	
WS6	6.93	958	44.09	39.37	3.06	19.77	0.57	0.3	7	0.1	260	
WS7	7.33	1132	44.09	31.59	3.76	56.2	0.82	0.3	0	0.2	290	
WS8	6.91	930	32.06	24.3	1.78	11.39	0.19	0.2	1	0.3	380	
WS9	6.9	923	52.1	30.62	2.05	15.31	0.17	0	7	0.1	300	
WS10	6.82	994	52.1	31.59	3.29	23.58	0.95	0.2	1	0.2	320	
WS11	7.28	1462	52.1	39.85	3.97	24.05	0.39	0.5	0	0.1	550	
WS23	6.23	979	64.13	34.02	5.48	4.36	0.11	0.5	0	0.1	390	
WS24	6.3	976	52.1	35.48	4.02	3.41	0.22	0.2	3	0.4	330	
WS25	6.25	975	44.09	34.02	6.66	23	0.33	0.1	0	0.1	290	
WS26	6.43	1159	48.1	39.37	4.47	5.43	0.17	0.3	0	0.1	420	
WS27	6.63	1515	52.1	52.25	2.57	28.9	0.76	0.4	1	0.4	620	
WS31	6.62	1169	44.09	23.09	2.05	11.63	0.22	1.2	1	0.1	500	
WS32	6.54	1369	76.15	52.97	1.36	9.2	0.31	1	2	0.1	490	
WS33	6.4	656	60.12	24.3	3.25	15.66	0.51	0.2	3	0.1	320	
WS34	6.85	705	68.14	44.96	2.39	11.53	0.36	1.9	3	0.2	310	
WS35	6.33	658	44.09	23.09	2.28	9.67	0.22	0.2	4	0.1	250	
Avg.±SD	6.71±0.37	1013.53±265.57	52.58±10.97	34.96±9.15	3.17±1.45	16.5±12.72	0.38±0.25	0.46±0.48	1.94±2.30	0.16±0.11	367.65±112.67	
Min	6.23	656	32.06	23.09	1.36	3.41	0.11	0	0	0.1	230	
Max	7.35	1515	76.15	52.97	6.66	56.2	0.95	1.9	7	0.4	620	
Site ID	Fe ²⁺ mg/L	Zn ²⁺	Mn ²⁺	Cu ²⁺	B ³⁺	As	Cd ²⁺	Cr	Al ³⁺	Mo ²⁺	Ni ²⁺	Pb ²⁺
WS4	1.34	0.87	0.07	0.08	3.9	BDL	BDL	0.05	0.82	0.01	0.1	0.42
WS6	0.59	0.91	BDL	0.02	0.8	0.02	BDL	0.01	1.23	BDL	0.05	1.54
WS7	0.35	1.61	BDL	0.06	0.8	0.01	BDL	0.01	0.52	BDL	0.05	1.82
WS8	0.82	1.05	0.03	0.01	0.2	BDL	BDL	0.01	0.82	BDL	0.03	0.64
WS9	0.27	0.17	BDL	0.01	9	BDL	BDL	0.02	1.23	BDL	0.04	0.85
WS10	0.62	0.23	0.06	0.01	1.4	BDL	BDL	0.02	1.5	BDL	0.04	1.68
WS11	0.96	0.14	BDL	0.01	3.3	BDL	BDL	0.02	1.21	0.01	0.01	2.24
WS23	0.61	0.31	0.05	0.04	0.8	BDL	BDL	BDL	0.12	BDL	0.09	1.25
WS24	1.9	0.28	0.07	0.01	1.7	BDL	BDL	0.03	0.15	BDL	0.04	1.63
WS25	1.28	0.11	0.08	0.03	1	BDL	BDL	0.02	0.08	BDL	0.04	1.27
WS26	0.56	0.12	0.01	0.02	0.3	0.02	BDL	0.01	0.05	BDL	0.02	1.91
WS27	0.14	0.12	0.08	0.02	0.1	BDL	BDL	0.01	0.63	BDL	0.02	0.97

Table 7 (continued)

Site ID	Fe ²⁺ mg/L	Zn ²⁺	Mn ²⁺	Cu ²⁺	B ³⁺	As	Cd ²⁺	Cr	Al ³⁺	Mo ²⁺	Ni ²⁺	Pb ²⁺
WS31	0.87	0.88	0.07	0.04	0.4	BDL	BDL	0.04	1.45	BDL	0.07	0.53
WS32	0.91	0.72	0.04	0.09	1.8	BDL	BDL	0.04	2.08	BDL	0.1	0.52
WS33	1.34	0.42	0.07	0.06	3.7	BDL	BDL	0.03	1.57	BDL	0.02	0.45
WS34	2.19	0.1	0.08	0.04	0.5	BDL	BDL	0.02	0.96	BDL	0.03	0.36
WS35	1.98	0.61	0.01	0.04	1.8	BDL	BDL	0.04	0.85	BDL	0.06	0.42
Avg.±SD	0.98±0.61	0.51±0.44	0.06±0.03	0.03±0.03	1.85±2.19	N/A	N/A	N/A	0.89±0.59	N/A	0.048±0.028	1.09±0.62
Min	0.14	0.1	0.01	0.01	0.1	BDL	BDL	BDL	0.05	BDL	0.01	0.36
Max	2.19	1.61	0.08	0.09	9	0.02	N/A	0.05	2.08	0.01	0.1	2.24

BDL: Below detection limit; N/A: not applicable; SD: standard deviation

3.5 Irrigation water anionic composition

The Kivulini area, indicated in Table 5, had NO_3^- -N levels ranging from 0.1 to 1.3 mg L^{-1} with a mean value of $0.83 \pm 0.41 \text{ mg L}^{-1}$ while the Nanyori area's NO_3^- -N ranged from zero to 0.6 mg L^{-1} with an average value of $0.29 \pm 0.23 \text{ mg L}^{-1}$ (Table 6). The NO_3^- -N levels for the Bogoyo area ranged from zero to 1.9 mg L^{-1} with a mean value of $0.46 \pm 0.5 \text{ mg L}^{-1}$ (Table 7). The ANOVA output values showed that the Kivulini area differed significantly in NO_3^- -N levels with the areas of Nanyori and Bogoyo ($F = 3.44, P = 0.04$) (Table S1). The SO_4^{2-} levels in the Kivulini area ranged from zero to 8 mg L^{-1} and averaged $4.7 \pm 3.3 \text{ mg SO}_4^{2-} \text{ L}^{-1}$ (Table 5) while that of the Nanyori area ranged from zero to 2 mg L^{-1} with a mean value of $0.86 \pm 0.69 \text{ mg L}^{-1}$ (Table 6). The Bogoyo area had its SO_4^{2-} levels ranging from zero to 7 mg L^{-1} with mean value of $1.9 \pm 2.3 \text{ mg L}^{-1}$ (Table 7). On the other hand, the ANOVA values indicated that there were statistically significant differences in SO_4^{2-} levels among the area surveyed. The Kivulini area differed from the rest ($F = 0.88, P = 0.01$) (Table S1).

The Cl^- levels in the Kivulini area ranged from 0.1 to 0.4 mg L^{-1} with a mean value of $0.18 \pm 0.09 \text{ mg L}^{-1}$ while in Nanyori area, it ranged from 0.1 to 0.5 mg L^{-1} with an average value of $0.17 \pm 0.15 \text{ mg L}^{-1}$. For the Bogoyo area, the Cl^- levels ranged from 0.1 to 0.4 mg L^{-1} with a mean value of $0.16 \pm 0.11 \text{ mg L}^{-1}$ (Tables 5, 6 and 7). The ANOVA values indicated no statistically significant differences in Cl^- levels among the surveyed areas ($F = 0.88, P = 0.42$) (Table S1). The Kivulini area had HCO_3^- levels ranging from 210 to 650 mg L^{-1} and averaged $379.23 \pm 140.78 \text{ mg L}^{-1}$ while that of the Nanyori area ranged from 300 to 460 mg L^{-1} with a mean value of $361.43 \pm 65.94 \text{ mg L}^{-1}$. The Bogoyo area had HCO_3^- levels ranging from 230 to 620 mg L^{-1} with a mean value of $367.65 \pm 112.67 \text{ mg L}^{-1}$ (Tables 5, 6 and 7). Furthermore, The ANOVA values indicated that there were no statistically significant differences in the HCO_3^- levels among the surveyed areas ($F = 1.10, P = 0.34$) (Table S1).

3.6 Trace elements in irrigation water

In this study, the Fe^{2+} levels in the Kivulini area ranged from 0.13 to 2.01 mg L^{-1} with an average value of $0.84 \pm 0.49 \text{ mg L}^{-1}$ while for the Nanyori area, it ranged from 0.23 to 1.63 mg L^{-1} with a mean value of $0.79 \pm 0.64 \text{ mg L}^{-1}$. The Bogoyo area had Fe^{2+} levels ranging from 0.14 to 2.19 mg L^{-1} with an average value of $0.98 \pm 0.61 \text{ mg L}^{-1}$ (Tables 5, 6, 7). The ANOVA indicated that there were no statistically significant differences in the Fe^{2+} levels among the three areas surveyed ($F = 0.39, P = 0.68$) (Table S1). The Zn^{2+} levels for the Kivulini area ranged from 0.12 to 1.18 mg L^{-1} with an average value of $0.39 \pm 0.34 \text{ mg L}^{-1}$ while that of the Nanyori area ranged from 0.02 to 1.19 mg L^{-1} with an average value of $0.73 \pm 0.42 \text{ mg L}^{-1}$ (Tables 5, 6). The Bogoyo area had Zn^{2+} levels ranging from 0.1 to 1.61 mg L^{-1} (Table 7). The ANOVA values indicated that there were no statistically significant differences in Zn^{2+} levels among three areas surveyed ($F = 1.66, P = 0.21$) (Table S1).

The Mn^{2+} levels in the Kivulini region ranged from 0.04 to 0.11 mg L^{-1} with a mean value of $0.07 \pm 0.02 \text{ mg L}^{-1}$ (Table 5) while the Nanyori area had the Mn^{2+} levels ranging from 0.02 to 0.11 mg L^{-1} with an average value of $0.06 \pm 0.03 \text{ mg L}^{-1}$ (Table 6). Likewise, the Bogoyo area had the Mn^{2+} levels that ranged from 0.01 to 0.08 mg L^{-1} with a mean value of $0.06 \pm 0.03 \text{ mg L}^{-1}$ (Table 7). The ANOVA output indicated that there were no statistically significant differences in Mn^{2+} levels among three areas surveyed ($F = 0.87, P = 0.43$) (Table S1). Moreover, the Cu^{2+} levels in Kivulini area ranged from 0.01 to 0.14 mg L^{-1} with a mean value of $0.03 \pm 0.04 \text{ mg L}^{-1}$ while for the Nanyori area Cu^{2+} ranged from 0.01 to 0.14 mg L^{-1} and averaged $0.04 \pm 0.05 \text{ mg L}^{-1}$ (Tables 5, 6). The Bogoyo area had Cu^{2+} levels ranging from 0.01 to 0.09 mg L^{-1} with a mean value of $0.03 \pm 0.03 \text{ mg L}^{-1}$ (Table 7). The ANOVA further indicated that there were no statistically significant differences in Cu^{2+} levels among three areas surveyed ($F = 0.64, P = 0.53$) (Table S1). The B levels for the Kivulini sites ranged from 0.2 to 3.7 mg L^{-1} with a mean value of $1.45 \pm 1.06 \text{ mg L}^{-1}$ while the Nanyori area had B levels ranging from 0.3 to 2.40 mg L^{-1} with a mean value of $1 \pm 0.71 \text{ mg L}^{-1}$ (Tables 5, 6). The Bogoyo area had B levels ranging from 0.1 to 9 mg L^{-1} with a mean value of $1.85 \pm 2.19 \text{ mg L}^{-1}$ (Table 7). Furthermore, for B, 32.4, 54.1, and 13.5% of the irrigation water samples indicated no toxicity, moderate toxicity, and severe toxicity, respectively [9, 10]. Likewise, the ANOVA values indicated that there were no statistically significant differences in B levels among three areas surveyed ($F = 1.07, P = 0.35$) (Table S1).

3.7 Heavy metals in irrigation water

The Al^{3+} levels in Kivulini area ranged from 0.04 to 1.2 mg L^{-1} and averaged $0.7 \pm 0.4 \text{ mg L}^{-1}$ while the Nanyori area had Al^{3+} levels ranging from 0.52 to 1.59 mg L^{-1} with an average value of $1.01 \pm 0.41 \text{ mg L}^{-1}$ (Tables 5, 6). Likewise, the Bogoyo area had Al^{3+} levels ranging from 0.05 to 2.08 mg L^{-1} with a mean value of $0.89 \pm 0.59 \text{ mg L}^{-1}$ (Table 7). The ANOVA values

indicated that there were no statistically significant differences in Al^{3+} levels among three areas surveyed ($F = 1.12$, $P = 0.34$) (Table S1). 89% of Mo^{2+} levels in the three areas were below the detection limit (BDL) of 0.01 mg L^{-1} (Table 5). The rest of the Mo^{2+} levels ranged from 0.0 to 0.01 mg L^{-1} . The ANOVA values indicated that there were no statistically significant differences in Mo^{2+} levels among three areas surveyed ($F = 0.04$, $P = 0.96$) (Table S1). For Ni^{2+} , the levels in the Kivulini area ranged from 0.02 to 0.11 mg L^{-1} with a mean value of $0.06 \pm 0.02 \text{ mg L}^{-1}$ while for the Nanyori area the Ni^{2+} levels ranged from 0.01 to 0.14 mg L^{-1} with a mean value of $0.06 \pm 0.05 \text{ mg L}^{-1}$ (Tables 5, 6). The Bogoyo area had Ni^{2+} levels ranging from 0.01 to 0.1 mg L^{-1} with mean value of $0.05 \pm 0.03 \text{ mg L}^{-1}$ (Table 7). The ANOVA values indicated that there were no statistically significant differences in the Ni^{2+} levels among the three areas surveyed ($F = 1.42$, $P = 0.26$) (Table S1).

The Pb^{2+} levels in the Kivulini area ranged from 0.12 to 1.87 mg L^{-1} with a mean value of $1.02 \pm 0.61 \text{ mg L}^{-1}$ while the Nanyori area had Pb^{2+} levels ranging from 0.36 to 1.84 mg L^{-1} with average value of $1.2 \pm 0.5 \text{ mg L}^{-1}$ (Tables 6, 7). The Bogoyo area had Pb^{2+} levels ranging from 0.36 to 2.24 mg L^{-1} with a mean value of $1.09 \pm 0.62 \text{ mg L}^{-1}$ (Table 7). The ANOVA values indicated that there were no statistically significant differences in Pb^{2+} levels among the three areas ($F = 1.38$, $P = 0.87$) (Table S1). For As and Cd, their levels in all three areas were below the detection limit of 0.01 mg L^{-1} (Table 5). In contrast, for Cr, the minimum value was below the method detection and the maximum value was 0.08 mg L^{-1} in the Kivulini samples; values for the Nanyori area indicated a 'no detection' minimum and a maximum value of 0.04 mg L^{-1} (Tables 5, 6). Likewise, for the Bogoyo sites, there was a 'no detection' value for one sampling site and a maximum of $0.05 \text{ mg Cr L}^{-1}$ (Table 7).

3.8 Irrigation water classification using Piper diagram

The Piper diagram was plotted segregating the water samples based on the sampling areas (Kivulini, Bogoyo, and Nanyori) (Fig. 3). Ca^{2+} and Mg^{2+} dominated the cationic composition whereas Cl^- , CO_3^{2-} , and HCO_3^- were the dominant anionic facies.

3.9 Soil EC and pH variations

The soil EC levels for the Kivulini area ranged from 220 to $1925 \mu\text{S cm}^{-1}$ with a mean value of $468 \pm 369.31 \mu\text{S cm}^{-1}$ while for the Nanyori area the soil EC ranged from 195 to $930 \mu\text{S cm}^{-1}$ with a mean value of $428.29 \pm 221.62 \mu\text{S cm}^{-1}$ (Tables 8, 9). Likewise, for the Bogoyo area, the EC values ranged from 195 to $930 \mu\text{S cm}^{-1}$ with mean value of $425.21 \pm 167.43 \mu\text{S cm}^{-1}$ (Table 10). The ANOVA values indicated that there were no statistical significance difference in EC levels among three plots in EC values ($F = 0.09$, $P = 0.92$) (Table S2).

For soil pH, the Kivulini area (Table 8) had values ranging from 6.31 to 8.23 with an average value of 7.43 ± 0.60 while for the Nanyori area (Table 9) the pH ranged from 6.75 to 8.87 with a mean value of 7.74 ± 0.59 . The Bogoyo area had its pH values ranging from 7.22 to 10.09 with a mean value of 7.92 ± 0.60 (Table 10). The ANOVA for the pH values indicated no statistically significant difference in the pH levels among the three areas surveyed ($F = 1.17$, $P = 0.32$) (Table S2).

3.10 Soil organic carbon (OC)

The soil OC levels in Kivulini area ranged from 0.1 to 2.4% with a mean value of $1.48 \pm 0.78\%$; in the Nanyori area the OC ranged from 0.5 to 1.7% with a mean value of $1.29 \pm 0.37\%$ (Tables 8, 9). The Bogoyo area had its OC levels ranging from 0.6 to 2.4% with a mean value of $1.40 \pm 0.47\%$ (Table 10). The ANOVA values for the OC indicated that there were no statistically significant differences in the OC levels among three sites surveyed ($F = 0.47$, $P = 0.63$) (Table S2).

3.11 Soil nutrient levels

The Kivulini area had total N levels ranging from 86 to 2069 mg kg^{-1} with a mean value of $1388.95 \pm 648.26 \text{ mg kg}^{-1}$ and that for the Nanyori sites total N ranged from 132 to 1896 mg kg^{-1} with a mean value of $979.5 \pm 515.26 \text{ mg kg}^{-1}$ (Tables 8, 9). The Bogoyo sites had N levels ranging from 572 to 2155 mg kg^{-1} with an average value of $1251.46 \pm 432.78 \text{ mg kg}^{-1}$ (Table 10). The ANOVA values indicated that there were no statistically significant differences among the three areas ($F = 2.37$, $P = 0.10$) (Table S2). The Kivulini sites had P levels ranging from 116.12 to

Fig. 3 Piper diagram showing chemical composition of irrigation water in three areas (Kivulini, Bogoyo, and Nanyori). The bottom left ternary shows the cations while bottom right ternary shows the anions. The top diamond-shaped chart represents both anions and cations distribution in the three areas surveyed

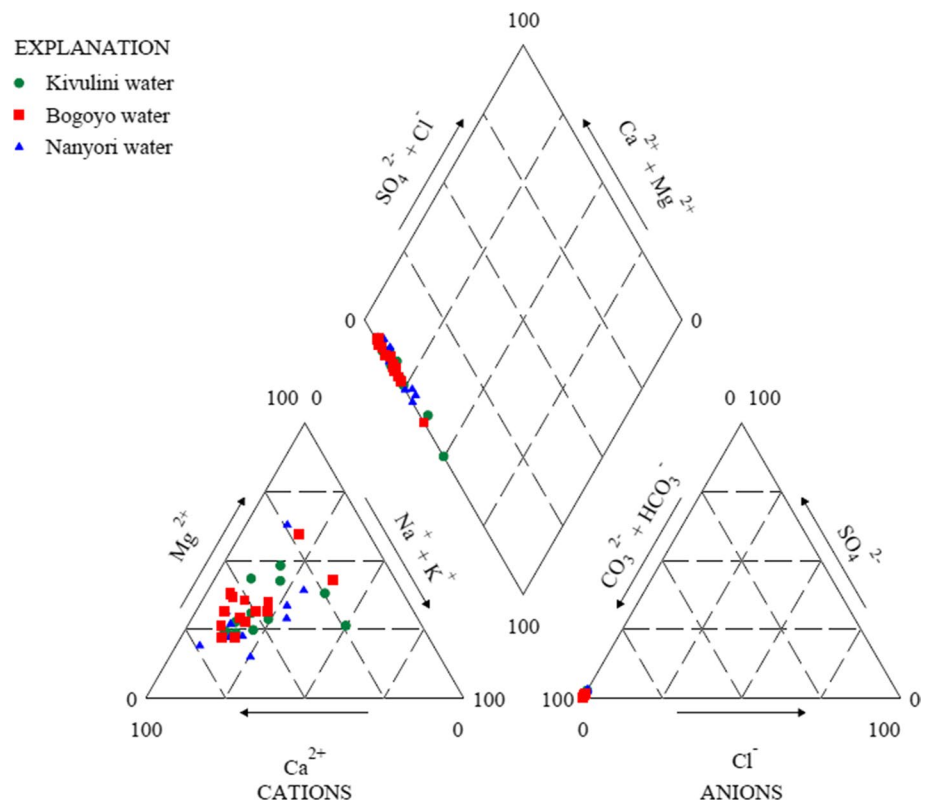


Table 8 Physico-chemical properties of the soils collected from the Kivulini area

Site ID	pH	EC (mS/cm)	OC (%)	K mg/kg	Fe	Zn	P	TN
SS7	7.58	404	2.2	20.12	5.51	90.17	142.446	1465
SS8	7.59	236	2.3	11.7	13.19	128.2	178.201	1983
SS9	7.65	323	2.4	13.48	3.28	72.42	159.341	2069
SS10	7.71	338	2.3	11.37	15.92	35.41	355.014	2069
SS11	8.23	320	2.3	11.34	5.01	83.36	227.709	1983
SS12	7.94	380	2.1	13.14	3.86	70.91	234.781	1810
SS13	7.77	346	1.2	14.26	4.13	68.37	198.371	1780
SS14	6.49	546	0.9	11.54	7.01	15.97	116.12	776
SS15	7.27	498	1.2	10.73	17.18	43.84	182.523	172
SS16	6.89	390	1.6	13.48	14.97	21.57	199.026	1379
SS19	7.33	303	2.3	13.9	3.64	35.54	129.479	1896
SS20	7.69	220	2.1	12.028	10.81	48.72	170.736	1810
SS21	6.81	322	0.3	11.604	169.49	49.52	133.016	1983
SS22	7.41	480	0.2	11.543	4.84	67.9	678.952	1509
SS23	6.31	296	0.1	13.812	9.48	12.78	136.159	86
SS24	8.14	395	1.3	16.182	4.43	17.97	166.807	690
SS26	6.31	636	1.2	11.694	22.88	169.74	481.533	1034
SS27	8.14	542	1.5	12.24	3.76	44.33	234.781	1293
SS28	7.85	1925	0.7	16.433	169.49	94.65	946.547	603
Avg. ±SD	7.43 ± 0.6	468.42 ± 369.32	1.48 ± 0.78	13.19 ± 2.32	25.73 ± 50.97	61.65 ± 40.18	266.92 ± 215.56	1388.95 ± 648.26
Min	6.31	220	0.1	10.73	3.28	12.78	116.12	86
Max	8.23	1925	2.4	20.12	169.49	169.74	946.547	2069

Table 9 Physico-chemical properties of the soils collected from the Nanyori area

Site ID	pH	EC (mS/cm)	OC (%)	K mg/kg	Fe	Zn	P	TN
NS1	8.23	285	1.4	22.75	11.26	8.78	168.771	578
NS2	8.10	488	0.5	14.538	58.83	37.14	173.486	431
NS3	7.95	320	0.5	13.863	42.47	35.39	171.027	376
NS4	8.03	582	1.2	13.772	4.26	13.98	166.807	517
NS5	8.10	600	1.6	49.855	35.82	26.36	156.591	1379
NS6	7.48	306	1.6	9.97	7.4	20.77	117.692	1552
NS7	8.03	930	1.7	15.408	6.85	28.75	136.945	1896
NS8	7.14	195	1.4	12.773	8.12	25.56	109.048	1034
NS9	8.05	776	1.2	13.372	9.13	27.37	113.352	132
NS10	7.44	247	1.2	17.627	24.45	63.5	136.945	1034
NS11	8.87	387	1.5	8.899	154.85	146.18	144.41	1293
NS12	7.01	240	1.4	15.373	7.89	5.48	386.447	862
NS13	7.14	404	1.4	12.438	16.64	18.37	151.09	1207
NS14	6.75	236	1.4	9.181	21.19	8.39	108.262	1422
Avg. ± SD	7.74 ± 0.59	428.29 ± 221.62	1.29 ± 0.37	16.42 ± 10.26	29.23 ± 39.57	33.29 ± 35.72	160.06 ± 69.25	979.5 ± 515.26
Min	6.75	195	0.5	8.89	4.26	5.48	108.26	132
Max	8.87	930	1.7	49.86	154.85	146.18	386.45	1896

946.55 mg kg⁻¹ with a mean value of 266.92 ± 215.56 mg kg⁻¹ whereas for the Nanyori area, the P levels ranged from 108.26 to 386.44 mg kg⁻¹ with a mean value of 160.06 ± 69.25 mg kg⁻¹ (Tables 8, 9). The Bogoyo area had P levels ranging from 54.79 to 433.99 mg kg⁻¹ with an average value of 227.21 ± 113.58 mg kg⁻¹ (Table 10). The ANOVA values indicated no statistically significant differences in P levels among the three areas surveyed ($F = 2.84$, $P = 0.07$) (Table S2).

The K levels for the Kivulini sites ranged from 10.73 to 20.12 mg kg⁻¹ with a mean value of 13.19 ± 2.32 mg kg⁻¹ while for the Nanyori sites the K⁺ levels ranged from 8.90 to 49.86 mg kg⁻¹ with a mean value of 16.42 ± 10.26 mg kg⁻¹ (Tables 8, 9). The Bogoyo sites had K⁺ levels ranging from 8.83 to 24.07 mg kg⁻¹ with an average value of 13.15 ± 3.52 mg kg⁻¹ (Table 10). The ANOVA values indicated no statistically significant differences in K⁺ levels among the three areas surveyed ($F = 1.84$, $P = 0.17$) (Table S2).

3.12 Soil trace elements

The Fe²⁺ levels for the Kivulini sites ranged from 3.28 to 169.49 mg kg⁻¹ with an average value of 25.73 ± 50.97 mg kg⁻¹ whereas for the Nanyori plot the Fe²⁺ levels ranged from 4.26 to 154.85 mg kg⁻¹ with a mean value of 29.23 ± 39.57 mg kg⁻¹ (Tables 8, 9 and 10). The Bogoyo sites had Fe²⁺ values ranging from 2.66 to 61.73 mg kg⁻¹ with a mean value of 11.21 ± 13.64 mg kg⁻¹ (Table 10). The ANOVA values indicated that there were no statistically significant difference in Fe²⁺ levels among the surveyed areas ($F = 1.27$, $P = 0.29$) (Table S2).

The Kivulini sites had Zn²⁺ levels ranging from 12.78 to 169.74 mg kg⁻¹ with mean value of 61.65 ± 40.18 mg kg⁻¹ whereas for the Nanyori area, the Zn²⁺ levels ranged from 5.48 to 146.18 mg kg⁻¹ with an average of 33.29 ± 35.72 mg kg⁻¹ Tables 8, 9, 10. The Bogoyo sites had Zn²⁺ levels ranging from 3.99 to 204.09 mg kg⁻¹ with a mean value of 52.14 ± 47.94 mg kg⁻¹ Table 10. The ANOVA statistics indicated no statistically significant difference in Zn²⁺ levels among three areas surveyed ($F = 1.67$, $P = 0.20$) (Table S2).

Table 10 Physico-chemical properties of the soils collected from the Bogoyo area

Site ID	pH	EC (mS/cm)	OC (%)	K mg/kg	Fe	Zn	P	TN
SS1	7.63	930	1.3	13.13	8.32	98.13	125.372	1340
SS2	7.51	195	1.6	13.67	6.61	110.23	127.122	1379
SS3	7.92	776	1.5	18.46	5.92	76.95	234.388	690
SS4	7.66	247	2.4	11.01	61.73	204.09	230.852	1552
SS5	7.61	387	2.4	12.13	3.84	15.18	172.307	2069
SS12	9.48	240	2.3	12.09	4.27	39.54	235.174	2155
SS17	7.45	523	1.5	15.48	43.55	23.01	125.943	1293
SS18	7.76	564	2.1	18.49	4.88	148.17	136.159	1810
SS25	7.41	511	1.3	11.543	4.84	67.9	122.407	1509
SS29	8.04	513	0.9	16.433	5	94.65	433.99	603
SS30	7.82	573	1.6	24.073	14.9	109.01	410.415	1379
SS31	10.09	373	1.3	15.107	3.42	39.94	384.875	1121
SS32	7.72	353	1.5	11.374	2.66	51.12	373.874	1293
SS33	7.91	265	1.6	15.11	5.95	22.36	397.449	1983
SS34	7.22	398	0.9	15.919	3.28	5.59	423.381	776
SS35	8.66	307	1.2	15.264	5.47	5.37	396.381	572
BG1	8.2	323	1.6	9.036	16.9	15.27	116.298	1450
BG2	7.77	338	1.8	9.027	7.8	42.27	142.522	1270
BG3	7.74	320	1.5	9.082	4.3	46.73	151.483	1164
BG4	7.79	380	1.2	10.724	7.29	36.27	165.922	1030
BG5	7.72	346	1	11.642	34.78	20.37	184.488	862
BG6	8.14	546	1.3	10.528	3.42	29.95	199.419	1034
BG7	8.02	498	1.1	10.289	3.98	41.14	190.382	948
BG8	7.89	390	1	8.83	3.49	12.65	233.209	1552
BG9	7.66	523	1.1	12.865	16.51	23.56	177.808	948
BG10	7.7	564	0.9	11.119	11.38	71.09	280.359	1621
BG11	7.49	303	0.6	10.375	7.93	3.99	134.98	776
BG12	7.84	220	0.8	15.373	11.38	5.48	54.785	862
Avg. ±SD	7.92 ± 0.6	425.21 ± 167.43	1.4 ± 0.47	13.15 ± 3.52	11.21 ± 13.64	52.14 ± 47.94	227.21 ± 113.58	1251.46 ± 432.78
Min	7.22	195	0.6	8.83	2.66	3.99	54.785	572
Max	10.09	930	2.4	24.073	61.73	204.09	433.99	2155
Median	7.765	383.5	1.3	12.11	5.935	39.74	187.435	1281.5

4 Discussion

4.1 Irrigation water EC and TDS

The irrigation water EC or total dissolved solids (TDS) values are indicators of salinity. Saline waters have high levels of both EC and TDS due to dissolved salt ions. Highly saline waters affect crop water availability and may lead to a condition known as physiological drought [10]. The results in Table 3 indicated that the EC concentrations in 14% of the samples posed no salinity problems to the irrigated fields whereas the remaining water samples indicated slight to moderate restriction level compared to the world Food and Agriculture Organization (FAO) guidelines and standards of other countries such as China [11]. Although the one-way ANOVA indicated no statistically significant variations for the three areas (Table S1), the area-specific TDS analysis indicated the following trends: Bogoyo > Kivulini > Nanyori.

4.2 SAR levels and infiltration

Issues related to water infiltration into soils may be interpreted by combining the values of both SAR and EC together (Table 4). A small proportion (14%) of irrigation water samples presented a slight-to-moderate infiltration problems in the study area (Table 4). The remaining proportion of the irrigation water samples had zero FAO restriction for irrigation. Furthermore, all the irrigation water samples assessed did not have severe infiltration problems for the paddy rice fields. Although the results indicated no salinity threat, a slight-to-moderate infiltration problem is a cause for concern especially due to the presence of a hardpan in the studied area and the fact that the farmers do not conduct regular leaching. Therefore, long-term use of this irrigation water will cause serious infiltration problems. The SAR values for the three areas followed the following trend: Kivulini > Bogoyo > Nanyori.

4.3 Chloride, boron, and sodium toxicity

Cl^- levels across all irrigation water samples were well below the FAO guideline value of 4 meq/L [9, 10, 12]. Thus, in the studied area, the irrigation water was safe from Cl^- toxicity for the paddy rice fields. In the present study, B levels were problematic, with ~68% of the irrigation water samples indicating a moderate-to-severe toxicity level (Table 5). For long-term use of irrigation water, B in the irrigation water should not exceed 0.75 mg L^- [10]. The mean B values in all three areas were above the 0.75 mg L^- cut-off point, indicating a possible B toxicity. Moderate Na^+ toxicity in irrigation water occurs when SAR values range between 3 and 9 and there is severe Na^+ toxicity when $\text{SAR} > 9$ [9, 10, 13]. Values of $\text{SAR} < 9$ in irrigation water present no potential irrigation problems [9]. For the present study, there were no Na^+ toxicity issues in the study area (Table 4). For Cl^- ; B; and Na ions, the mean concentrations followed the arrangement of Kivulini > Nanyori > Bogoyo; Bogoyo > Kivulini > Nanyori; and Kivulini > Bogoyo > Nanyori, respectively.

4.4 Variations in water anionic composition

Plants require N to support their growth and productivity. In areas where soils are deficient in N content, N is usually supplied through the application of N-containing fertilizers. Although N is important for plant growth and crop production, its excessive availability is linked to environmental degradation especially when N gets washed into aquatic environment, thereby causing eutrophication in the form of algal bloom. Thus, the FAO recommends that irrigation water with $\text{NO}_3^- \text{-N} < 5 \text{ mg L}^{-1}$ is suitable for irrigation purposes [9]. In the present study, $\text{NO}_3^- \text{-N}$ was found in the following trend: Kivulini > Bogoyo > Nanyori. Meaning that the Kivulini area had the highest mean $\text{NO}_3^- \text{-N}$ and the Nanyori area had the lowest. Furthermore, the ANOVA indicated that the mean $\text{NO}_3^- \text{-N}$ levels in the Kivulini samples significantly differed from the $\text{NO}_3^- \text{-N}$ means for the Nanyori and Bogoyo areas (Table S1). High levels of SO_4^{2-} in irrigation water has been linked with intensive use of synthetic fertilizers. Excessive SO_4^{2-} levels adversely affect the uptake of Ca while increasing the adsorption of Na and K leading to cation imbalances [10]. Overall, in the present study, the maximum SO_4^{2-} levels in the irrigation water was 8 mg L^{-1} in the Kivulini area. The means of SO_4^{2-} for the three surveyed areas were in the order: Kivulini > Bogoyo > Nanyori; with the concentration in the Kivulini sites showing a significant difference with those in the other two areas (Table S1). The levels of SO_4^{2-} in the present study were lower than those that were found in India [14, 15] and China [11].

4.5 Irrigation water trace elements and heavy metals

Heavy metals present in high concentrations in the environmental media may pose a health risk especially when the heavy metals get access to the food chain. Although Fe is toxic to plants, it can contribute to soil acidity and degradation of essential P and Mo elements [10]. In the present study, the area-by-area mean levels of Fe^{2+} indicated that for all samples, Fe concentration in irrigation water did not exceed 1 mg/L (Table 5)—an indication that the studied water was acceptable for irrigation. The order of Fe concentration was as follows: Bogoyo > Kivulini > Nanyori. It is important to note that the mean Fe values in the three areas surveyed did not differ significantly (Table S1). Although the recommended Zn level in irrigation water is 2 mg L^{-1} , excessive Zn is known to be toxic to many plants [10]. Zn toxicity to plants occur at widely varying concentrations, but reduces at pH 6 and above and where organic soils dominate [10]. None of the sites in this study had Zn levels above 2 mg L^{-1} (Tables 5, 6, 7), and the ANOVA indicated no significant difference among

the three areas surveyed (Table S1). In acidic soils, Mn is highly toxic to plants—therefore a restriction of 0.2 mg L^{-1} in the irrigation water has been recommended [10]. Tables 5 and S1 indicate that the Mn levels in the irrigation water were within the acceptable range and without spatial significant differences, respectively. A long-term use irrigation water threshold for Cu levels is at 0.2 mg L^{-1} —because Cu is known to adversely affect many plants in the concentration range of 0.1 to 1 mg L^{-1} [10]. In this study, Cu levels were within the ranges acceptable by FAO and did not vary significantly (Tables 5 and S1). For Al, Mo, Ni, Pb, As, Cd, and Cr, all the measured values in irrigation water were in their acceptable ranges (Tables 5, 6, 7).

4.6 Bicarbonate effects on irrigation water

Of the 37 irrigation water samples, 32 indicated levels of HCO_3^- with slight-to-moderate detrimental effect on plant growth; 5 irrigation water samples, equaling 13.5%, indicated levels of HCO_3^- with potential severe effects on plant growth [9] (Tables 5, 6, 7). For all the irrigation water samples, none indicated levels of HCO_3^- below 1.5 meq/L ($\sim 90 \text{ mg L}^{-1}$), which is a safe threshold set by FAO [9]. It is possible, thus, that the observed low paddy rice productivity and variations in yields among the farmers at the study area, were attributed to elevated HCO_3^- levels and variations.

4.7 Water pH and nutrient levels

The pH in the irrigation samples ranged between 6.3 and 7.4 (Tables 5, 6, 7) and was in an acceptable range for irrigation water [9, 13]. Generally, the N, S, and K levels in the sampled irrigation water were within the recommended limits for agricultural application [9]. K levels in irrigation systems are not regulated because K has slight or no adverse effects on soil properties [16]. For Ca, Mg, and Na, the results from the present study indicated that their average values in the irrigation water across the study area were within the acceptable limits [13].

4.8 Irrigation water classification

In the present study, the Piper diagram was used to elucidate the irrigation water major anionic and cationic composition [15]. The Piper diagram's bottom left ternary showed the cations while bottom right ternary showed the anions (Fig. 3). The middle diamond shape showed the chemical composition of both cations and anions. The diagram is dominated by $\text{Ca}^{2+}\text{-HCO}_3^-\text{-Mg}^{2+}$ indicating the irrigation water had high levels of Ca^{2+} , HCO_3^- and Mg^{2+} ions. Therefore, irrespective of the area from which the samples were collected, the irrigation water had salts comprised mainly of Ca^{2+} , HCO_3^- , and Mg^{2+} ions.

4.9 Soil quality

Sustainable paddy rice productivity needs to take into consideration the paddy soil properties in the irrigated scheme. Globally, soil quality variabilities in paddy fields are well recognized [17]. Paddy rice soil quality parameters such as soil EC, pH, OC, nutrients, and trace elements are important in determining sustained paddy productivity [17]. These parameters were, therefore, examined in the present study and are discussed below.

4.10 Soil EC and pH values

Soil EC values are indicators of soil health—it is a measure of the concentration of salts in soils [18]. Soil EC affects many other productivity indices such as soil microorganism activity, crop yields, nutrient availability, and crop suitability. Soils containing excessive EC values are common in the arid and semiarid regions of the world [18]. Factors that may lead to elevated soil EC levels include local climate, farming practices, irrigation water quality, cropping, soil inherent minerals, and texture. High soil EC levels, although not a direct measure of the presence of certain compounds, has been correlated to the presence of NH_3 ,

SO_4^{2-} , Cl^- , K, and NO_3^- [19]. For the present study, the EC values ranged between 0.2 and 1.9 dS/m. The overall average EC value was 0.45 dS/m. Because the soil EC in the studied area was below 4 dS/m, it shows that the soil in the three areas surveyed did not have salinity problems [20].

Soil pH is another important characteristic in paddy rice production. Rice is known to grow and flourish in soils with pH levels as low as 5.5 [21, 22]. However, low soil pH values may lead to nutrient leaching [23]. Thus, a slight increase

in soil pH may have positive influence on paddy rice growth by improving cationic nutrient retention. In areas such as India, where > 30% of the cultivated land has acidic soils, liming to improve pH has been associated with improved crop production [24]. The majority of the soil samples (93%) in the present study indicated a pH range that is favorable for paddy rice production (Tables 8, 9, 10).

4.11 Soil organic carbon

Soil organic carbon (SOC) content depends on several environmental factors such as temperature, precipitation, soil water content, texture, structure, and depth from the surface. Normally, topsoil (0 to 20 cm depth) in the tropics are known to have the SOC content between 1.0 to 4% [25]. It is known that SOC is important in preserving soil stability in intensively cultivated areas. However, intensive soil cultivation practices may cause changes to the physical properties of soils, causing subsequent structural degradation. Furthermore, stable soil structure has positive influence on crop yields. In the present study, SOC ranged between 0.1 and 2.4% (Table 6). This indicated good SOC in the studied soils.

4.12 Soil macro- and micro-nutrients

Water-soluble nutrients are an important soil characteristic. In the present study, levels of soil macro-nutrients (N, P, and K) as well as micro-nutrients (Fe and Zn) were examined (Table 4). These are important because either their deficiency or their excessive presence has influence on paddy productivity. Major elements, i.e., K, N, and P are usually required by plants in large quantities. Trace elements, e.g., Fe and Zn are required by plants in relatively smaller amounts. In areas such as where the present study was conducted, where plant essential elements may be naturally insufficient, these elements are usually supplied to the soil by means of fertilizers.

Synthetic fertilizers are usually the main source of essential elements in soils with insufficient supply of such elements. However, excessive application of inorganic fertilizers has negative environmental impacts. Globally, the natural reserves of sulphate and phosphate rocks are dwindling, and their supply may not be sustainable in a long term—estimated to be exhausted in the next 25–100 years [26]. Therefore, good on-site fertilizer application and management is important to avoid economic and environmental repercussions. Unchecked overuse of inorganic fertilizers is not uncommon in most developing countries, including Tanzania, because such inputs represent substantial financial outlays for smallholder farmers [27, 28]. Furthermore, remnants of excessive fertilizers used in irrigation schemes usually end up in the receiving water bodies downstream causing eutrophication [29].

In the present study, a high *SD* value of Fe-content in soils was computed (Table 4). First, the overall values of Fe concentration for the three areas surveyed ranged from 2.6 to 169.5 mg/kg soil (Table 4). Second, the overall mean value of Fe was 19.8 ± 36.6 mg/kg soil, i.e., the deviation from the mean was greater than the mean itself. Because the amount of deviation in the samples was too high, the median value is a better measure of central tendency than the mean. The median value in the present study was 7.8 mg/kg ($N=61$). This means that the concentration Fe in most of the 61 samples was close to 7.8 mg/kg soil. This could partly explain the variabilities in paddy rice yields in the studied area owing to soil Fe deficiency. A similar study in irrigated rice-growing regions of southern Brazil, for example, reported Fe levels between 159 and 324 mg/kg [30]. Another study conducted along the Ivory Coast reported Fe-content ranging from 77 to 137 mg/kg soil [31]. In a recent study, it was reported that rice plants containing 10–30 mg/kg of Fe may be regarded as Fe deficient [32].

Zn plays an important role as a structural component of enzymes in both the plants and animals. It is also a regulator and cofactor in many biochemical processes. Zn deficiency in soils is one of the most ubiquitous problems in world agriculture. In mild Zn deficiency, paddy rice yields may be reduced, or grain quality affected with no external signs of Zn deficiency. This is called latent (or “hidden”) Zn deficiency. In cases of severe (or “acute”) Zn deficiencies, the results are indicated by abnormalities in plant development. Visible symptoms of Zn deficiency in plants may include chlorosis and plant stunted growth. There are many soil factors that influence Zn availability to plants including high pH, high concentrations of phosphate, bicarbonate, Na, Ca, and Mg in the soil solution. Thus, rice is a highly susceptible crop to Zn deficiency.

In the present study, the overall soil Zn levels ranged from 3.9 to 204.1 mg/kg (Table 4). The computed overall mean Zn value was 50.8 ± 43.6 mg/kg. Similar to Fe, high variations (indicated by the high *SD* values) in Zn levels were observed. The median Zn level was 37.1 mg/kg. A study by the FAO conducted in 29 countries, revealed that 10 countries out of the 29 had 10% of the soil samples with potential Zn deficiency [33]. In India, 49% of 14,863 soil samples collected from all over the country indicated Zn deficiency [34]. Although total Zn is not a good indicator of Zn deficiency, a correlation

between total and available Zn has been established. Furthermore, it has been indicated that only 1.75% occurs in bio-available forms [35].

A study conducted in Poland, found soil Zn levels ranging between 8.2 and 92.3 mg Zn per kg soil. The mean value was 41.2 ± 24.4 mg/kg whereas the median was 38.05 mg/kg [36]. Another study conducted in China obtained soil Zn concentration in the range of 19.8 to 119 mg/kg soil, with a mean value of 65.5 ± 22.2 mg/kg soil [37]. The median Zn concentration in the soils was found to be 61.8 mg/kg [37]. Although the mean and, somehow, the median values in previous studies were comparable to those obtained in the present study, the deviations were not. The soils in the present study may not be Zn-deficient, but it is probable that plot-to-plot variations in paddy yields may be attributable to the variations in soil Zn content.

N is an important macro-nutrient for plants. Soil N deficiencies lead to poor crop growth and productivity. Excess N in the environment leads to environmental degradation. Elevated N levels may result into paddy lodging and eutrophication of disposed drainage water [38]. The source of N in paddy soils is either through natural supply or by addition through synthetic NPK or organic fertilizers. The amount of N naturally available in the soils is usually insufficient to support paddy rice growth. In most cases, a supply of N to the soils through fertilizers is required. Soil N content vary from place to place due to many factors such as soil type, soil pH, type and amount of fertilizer used, OC content, and climate. For example, in a long-term study on paddy rice soils in eight different regions in China, initial soil TN ranged between 920 and 2,720 mg/kg soil [39].

In the present study, the computed overall mean soil TN value was 1232 ± 540 mg/kg (Table 4). The mean and median (1293 mg/kg) values were similar in magnitude, although the SD value from the mean was high. The overall soil TN-content values ranged from 86 to 2155 mg/kg (Table 4). Although the range in soil TN-content in the present study seems broad, the computed median value indicates that most soil samples had TN concentration around 1293 mg/kg. These values are similar to those reported in paddy rice soils of subtropical China [40]. Some previous studies have linked such high TN levels and variations to long-term fertilizer applications [41, 42]. In 2020 a local newspaper article (printed in Swahili) pointed out that the farmers in the surveyed area mentioned to researchers that they were using high amount of fertilizers and other agricultural inputs but rice production was not improving [43]. Poor on-farm practices related to agricultural inputs such as synthetic fertilizers, organic fertilizers, and pesticides may contribute to the observed variations [27]. Furthermore, such practices are known to cause economic and environmental problem in the agricultural sector [28].

After N, soil P ranks second as the most essential nutrient for plant growth. Similar to N, excess use of P through fertilizer has negative effects on the natural environment. It is therefore imperative to monitor the levels of P in paddy rice soils. Although paddy soil total P-content may be high, only 0.1% of total P (TP) is usually available for plant uptake [44]. Historical data for tropical Asia indicate that in the 1970s the average paddy soil TP in nine Asian countries was 837 ± 668 mg/kg; range in TP concentration was from 10 to 5530 mg/kg soil [45]. The present study used this historical Asian example to lay emphasis on the lack of similar studies in sub-Saharan Africa, and to indicate the historical values of TP in tropical paddy rice soils. Soils in the least developed countries (LDCs or “the Global South”) are known to contain small amounts of available P [46]. A long-term study at Rothamsted, United Kingdom, at a site where superphosphate fertilizer was used over a long time indicated that total P ranged from 780 to 1425 mg/kg in the topsoil (1–23 cm) [46]. Levels of total P in the African Sahel irrigated soils were small compared to the Asian and European values reported above—whereby in soils with long-term application of P-fertilizers, the soil TP concentration was found to range between 135 and 259 mg/kg [47].

In the present paper, the soil available P (Olsen P) was analyzed. The results indicate that the paddy rice soil Olsen P values ranged between 54.8 and 946.5 mg/kg (Table 4). The overall mean Olsen P value was 224.2 ± 149.4 mg/kg. The overall median value was 171 mg/kg, meaning that most soil samples had Olsen P values around the reported median value. A recent study by Shi et al. [48] has indicated an average critical Olsen P value of 3.40 mg/kg for rice. When compared to the values by at Rothamsted in the UK [46], it is obvious that the overall Olsen P values in the present paper were extremely high. The high Olsen P may have had a negative impact on paddy yields. On-farm management that targets sustainable use of P-fertilizers in the studied area is therefore highly recommended. Sustainable application of P-fertilizers is recommended because of three main reasons. First, to improve paddy soil P-content in the area, hence improve crop yields. Second, globally, phosphate-containing rocks from which P-fertilizers are manufacture are rapidly declining [49]. The economic application of P-fertilizers, therefore, is of paramount importance. Third, excessive P content is known to be harmful to the natural environment.

Another highly essential plant macronutrient is K. An appropriate supply of K to plants is known to improve plants' root growth and to improve plant vigor as it helps in preventing lodging and improving plant's resistance to diseases and pests. K is highly mobile in both the soil and plant body. In spite of its importance to soil and plants, studies emphasizing

on the supply of K to soil and plants are sparse. Most studies aim at the supply and management of N and P. A previous study on K in soils and crops of India has recorded K in soil solution ranging between 1 and 10 mg/kg [50].

Slaton et al. [51] recommended soil K level of > 130 mg/kg for improved paddy rice production. In the present paper, the values of K ranged between 8.8 and 49.9 mg/kg soil, with a mean value of 13.9 ± 5.6 mg/kg. It is obvious that these values are too low to support good paddy rice yields. The observed low and highly varied yields reported by smallholder farmers at the study site may be attributable to low availability of K in the soils (Table S3).

5 Conclusions

To achieve high paddy rice yields, a combination of scientific information obtain at a farm and regional level is absolutely necessary. Paddy rice yields are influenced by nutrient availability, not only in the soils but also in the irrigation water. Therefore, studies that are related to nutrient–soil–water–plant interactions are important. Such studies, like the present one, provide information to farmers, agricultural extensionists, researchers and policy makers on how the quality of soils and irrigation water may influence paddy rice productivity. Although the present study focused on only one irrigation area in the Kilimanjaro region of Tanzania, the information and findings herein may be applied elsewhere in sub-Saharan Africa where similar climatic, aquatic and soil conditions prevail. It is important to note that the Asian, European, North American, and Latin American paddy rice ecosystems have been extensively studied. The sub-Saharan Africa paddy rice ecosystems, on the other hand, have only been minimally investigated. Therefore, the present study provides useful information from one of the most inadequately studied regions of the world. Although the physical characteristics of the soils were not part of the focus of the study, the authors recommend a further study into the soil characteristics because they are important for water movement and governance in the soil. Furthermore, the present study focused on the irrigation water and associated soils; however, a further study that investigates the mineral status in plants in the study area is highly recommended.

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Code availability Not applicable.

Declarations

Ethics approval and consent to participate The present study did not involve any human or animal testing.

Competing interests The authors declare no competing interests.

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