Assessment of soil and water physical and chemical properties for crop production in the Nyarubogo irrigation scheme, Rwanda

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Abstract

Agricultural production is significantly influenced by the soil and water quality, especially in irrigation systems, where poor management may result in degraded soil and lower crop yields. This study is noteworthy because it tackles the problems of nutrient imbalances, salinity, and acidity in the Nyarubogo irrigation system. This study aimed to assess the irrigation scheme's soil and water quality to spot any hazards to crop productivity and suggest suitable mitigation measures. A wide range of characteristics, such as pH, nutrient content, total dissolved solids (TDS), magnesium adsorption ratio (MAR), soluble sodium percentage (SSP), adsorption ratio (SAR), and electrical conductivity (EC), were determined on a comprehensive set of soil and water samples. The results showed that, with pH values ranging from 5.1 to 6.9, most of the soils in the study area are acidic, which may hinder crop development and nutrient availability. Furthermore, the soil demonstrated a moderate cation exchange capacity (CEC), suggesting a respectable ability to retain nutrients. The SAR of the water samples in this study ranged from 0.22 to 0.28 meq/l, indicating that water was suitable for irrigation and that no adverse effects were anticipated. It is evident from the high MAR values found in irrigation water that cautious management is required to avoid long-term soil deterioration. To lessen the negative consequences of acidity, salinity, and nutrient imbalances, this research emphasizes the need to routinely monitor the soil and water and use specific soil management techniques. The findings establish a basis for enhancing soil health and maintaining agricultural output, giving farmers and agricultural managers involved in the Nyarubogo irrigation project crucial information.

Keywords: Soil quality, Water quality, irrigation scheme, Rwanda

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Introduction

Agricultural production is significantly influenced by soil and water quality, especially in areas where crop yields depend on irrigation. The interplay between soil properties and irrigation techniques may substantially impact crop production and farm sustainability in these locations. In heavily irrigated agricultural systems, the most frequent problems are those related to nutrient imbalances, salinity, and soil acidity (Majeed & Muhammad, 2019). These issues provide serious difficulties for farmers and agricultural planners as they might result in decreased soil fertility, subpar crop development, and lower yields (Wali et al., 2019). For agricultural ecosystems to remain healthy and to ensure food security, it is crucial to comprehend and manage soil and water quality.

Many agricultural areas have a problem with acidity in their soil, frequently caused by natural soil-forming processes and made worse by specific agricultural practices, including acidifying fertilizers (Osman, 2018). Acidic soils may restrict the availability of critical elements that are necessary for plant development, such as magnesium (Mg), calcium (Ca), and phosphorus (P) (Sahin et al., 2017). Furthermore, situations that might be harmful to plant health and lower agricultural output arise when soil pH drops because toxic substances like aluminum (Al) and manganese (Mn) become more soluble in the soil (Bolan et al., 2005). This emphasizes the need to keep an eye on the pH of the soil and put remedial measures in place to lessen soil acidity in agricultural areas.

Significant issues in irrigated agriculture include salinity and sodicity, especially when water quality is impaired. Elevated sodium (Na) concentrations in the soil may cause structural disturbances, resulting in inadequate aeration and water infiltration, the two essential elements for a healthy root system (Wali et al., 2021). The Soluble Sodium Percentage (SSP) and Sodium Adsorption Ratio (SAR) are significant measures of sodicity that provide light on the possible dangers of sodium buildup in soils. Elevated SAR and SSP levels may cause the soil's physical characteristics to deteriorate, making it more challenging for crops to get nutrients and water (Wali et al., 2021). These characteristics must be managed effectively to stop soil deterioration and keep agricultural production high.

The sustainability of agricultural activities is mainly dependent on the quality of irrigation water and soil-related factors. The quality of water and its appropriateness for irrigation may be determined by many parameters, including pH, EC, TDS, MAR, and Total

Dissolved Solids (TDS). (Ayers, R. S., and Westcot, 1985) found that low-quality water may worsen the salinity and sodicity of the soil, further jeopardizing agricultural production and soil health. It is crucial to monitor these water quality characteristics to ensure that crops get the nutrients they need for optimum development and that irrigation techniques do not contribute to long-term soil deterioration.

Prior research has shown how low soil and water quality affect agricultural yields, highlighting the need for focused interventions (Evans et al., 2019; Sharma et al., 2016; Wolka et al., 2018). Nyarubogo irrigation scheme, like many other comparable agricultural systems in sub-Saharan Africa, has substantial obstacles concerning soil and water quality, which are essential for maintaining agricultural production. Several studies have examined the effects of soil acidity, salinity, and sodicity on crop yields (Adongo et al., 2015; Omar et al., 2024; Tessema et al., 2023). These studies have emphasized the significance of monitoring soil pH, Sodium Adsorption Ratio (SAR), Soluble Sodium Percentage (SSP), and related parameters to maintain soil health. Additionally, studies have demonstrated the critical role that water quality plays in influencing soil salinity and sodicity levels in irrigated agriculture, with a focus on elements like Electrical Conductivity (EC), Total Dissolved Solids (TDS), and Magnesium Adsorption Ratio (MAR)

However, despite the extent of literature on these topics, there is limited knowledge concerning the Nyarubogo irrigation scheme. There is little empirical information on how soil and water quality problems appear in the specific environmental and agricultural circumstances of the Nyarubogo area. However, research has often concentrated on the consequences of these problems in larger contexts or other geographic places. Furthermore, since its implementation, no known research has been done on soil and water's physical and chemical characteristics in the Nyarubogo irrigation scheme. This study intends to fill this gap by thoroughly evaluating the soil and water quality characteristics and their implication for crop production in the Nyarubogo irrigation system. To achieve the aim of this study, the specific objectives were 1) to assess the physico-chemical parameters of soil and their effect on crop production and 2) to assess the physico-chemical parameters of water and their effect on crop production. This is important for developing management plans that are focused and customized to the particular circumstances of the Nyarubogo irrigation scheme. Further, the findings from this study could help promote local livelihoods and food security by addressing the critically essential concerns of soil acidity, salt, and water quality.

Materials and methods

Description of the study area

Nyarubogo irrigation scheme is located in Nyanza District, Rwanda, between two latitudes of 2^{o} 15'S and 2^{o}25'S and two longitudes of 29^{o}50" E and 29^{o}55" E with a mean altitude of 1,376 m. Water used in the irrigation scheme comes from the ephemeral Nyarubogo River. The scheme is for paddy production, implemented on 174 ha. It receives water from the Nyarubogo Dam, which has a capacity of 500,000 m3 and is constructed across the Nyarubogo River. The scheme spans three sectors (Kibirizi, Busoro, and Muyira). Water flows by gravity to the Nyarubogo irrigation scheme from the dam.

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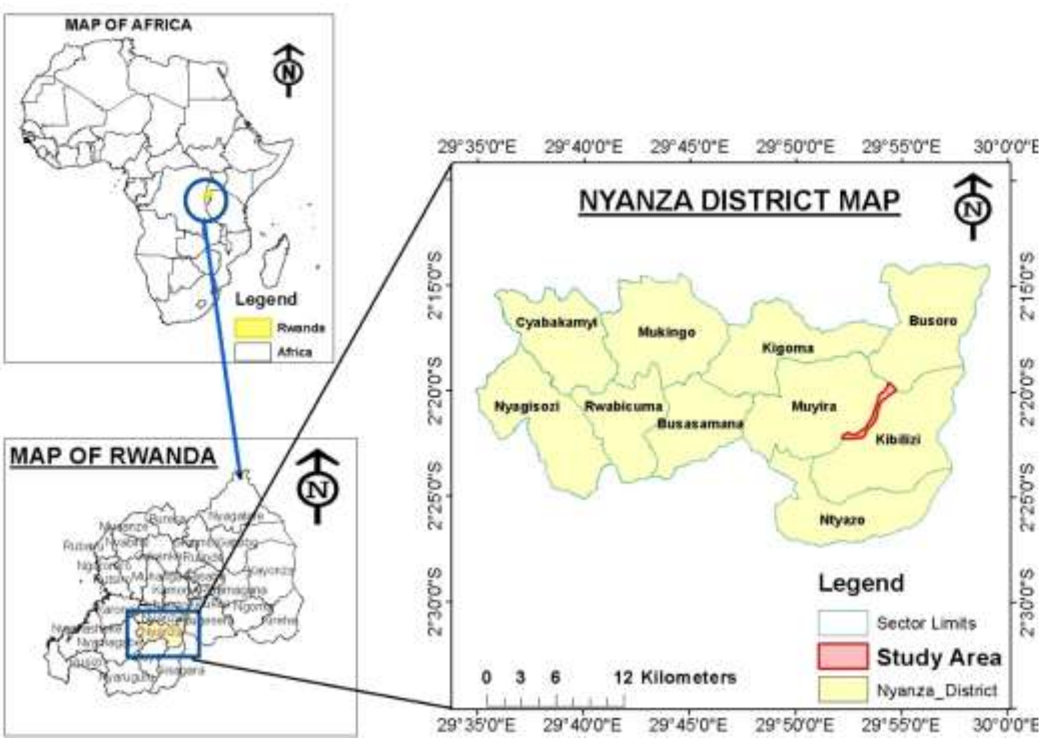

Figure 1: Location of the study area Map

Climate

Nyanza District is characterized by a tropical climate with two main seasons: the rainy season (November to April) and alternating with the dry season (May to October). According to the Rwanda Meteorological Agency, the average annual rainfall ranges between 1001-1050 mm and the average yearly temperature of about 25°C (RMA, 2024).

Agricultural activities

Farming and raising livestock are the two main agricultural pursuits in the research region. Paddy, beans, bananas, maize, sorghum, and vegetables are the primary income and food crops farmed. Small ruminants, poultry, and dairy cattle are livestock that support the local population's way of life. Farmers frequently employ zero grazing to increase milk yield and decrease epidemics. (Nyanza-District, 2013).

Scheme layout

Water from the main canal is discharged into the right and left secondary earth canals (SC). Water is released into tertiary canals (TC) from each secondary canal. Gravity supplies water to the farms of the scheme through the tertiary canals. The plan also includes a main drain and field drains (Figures 1 and 2), and the steering basin in (Figure 2) stands for chute or drop structure.

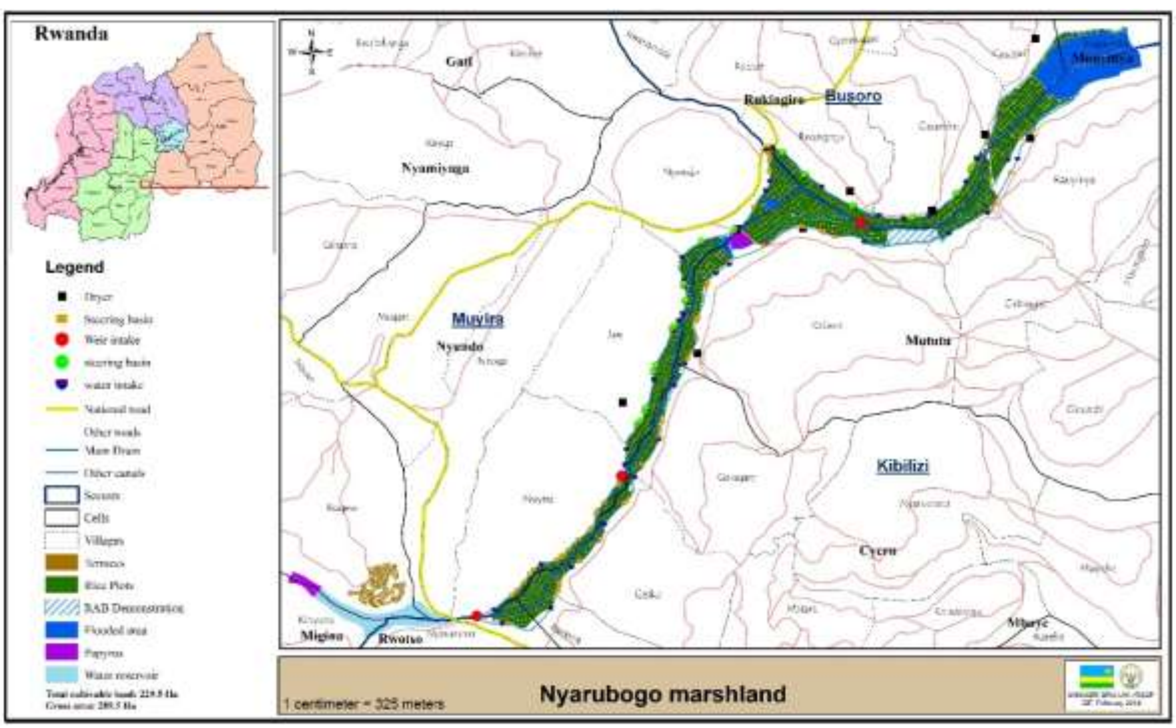

Figure 2: Nyarubogo Irrigation Scheme layout (Source: Rwanda Agriculture Board)

Soil sampling

Soil samples were taken at a depth of 0 to 30 cm from eight sites spread in the three main zones of the scheme: three samples from upstream, three from the middle, and the last two samples from downstream to ensure a good representation of the study area. Soil samples were obtained from every location using the auger tool. Afterward, a labeled plastic bag containing a representative sample of roughly one kilogram of soil samples from the sampled sites was carried to the Rwanda Agriculture and Animal Resources Development Board (RAB-Rubona Station) for analysis. The samples were air-dried in the laboratory shed and then ground to have particles able to pass through a 2-mm sieve to determine the physical and chemical fertility parameters of soil.

Soil Physical and chemical analysis

In the laboratory, every soil sample was tested for necessary physicochemical indicators, as mentioned in the following procedure: Soil pH was determined in a suspension of 1:2.5 soil water (W/V) using a glass electrode pH meter (Zhang et al., 2019). Exchangeable acidity was determined by the method of Mclean (1982) as described by (Udo et al., 2009) by using 1M KCI as the extracting solution and titrating with 0.01M NaOH, using phenolphthalein as the indicator. Electrical conductivity (EC) was determined with a conductivity cell by measuring the electrical resistance of a 1 5 soil: water suspension. Ca, Mg, K, and Na; a soil sample was extracted with an excess of 1M Ammonium acetate ($NH_4C_2H_3O_2$) solution such that the maximum exchange occurs between the NH_4 and the cations originally occupying exchange sites on the soil surface. The amounts of exchangeable sodium and potassium are determined by a Flame photometer, and calcium and magnesium in the extract are determined by an atomic absorption spectrophotometer. Lanthanum or strontium is added as a releasing agent to prevent the formation of refractory compounds (Okalebo et al., 2002). Organic carbon was determined by the dichromate oxidation procedure (Okalebo et al., 2002). The total Nitrogen by Kjeldahl method is based on the wet oxidation of soil organic matter and botanical materials using sulfuric acid and digestion catalyst and converting organic nitrogen to the ammonium form (AFNOR, 1995). Available phosphorus was determined by extracting 0.03 M ammonium three fluoride and 0.025M hydrochloric acid based on the Bray 1 method (Okalebo et al., 2002) and quantified by UV spectrophotometer (Moberg, 2001). Soil texture (or particle size distribution) is a stable soil characteristic that influences the physical and chemical properties of the soil. The first stage in a particle size analysis is the dispersion of the soil into the individual particles. These are the sand (2.00-0.05 mm), silt (0.05-0.002mm), and clay (<0.002 mm) fractions. The hydrometer method will determine soil texture (Bouyoucos, 1962). The sulfur in the soil sample was determined by extracting Potassium dihydrogen phosphate (KH_2PO_4) based turbidity method (Okalebo et al., 2002).

On the other hand, The exchangeable sodium percentage was calculated using the standard equation, which uses Na^+ and cations exchange capacity (CEC). The Sodium Adsorption Ratio (SAR) was estimated from Ca, Mg, and Na^+ concentrations. An alternative to ESP for predicting the exchangeable sodium fraction of soil equilibrated with a given solution is the sodium absorption ratio (SAR), which is a relationship between soluble sodium and soluble divalent cations(Miller RW and Donahue RL, 1997). A very high risk to plant growth exists in soils with SAR values greater than 13, exchangeable sodium percentage (ESP) greater than 15, and electrical conductivity (EC) more significant than four µS/m (Eynard et al., 2003). SAR was computed using the formula in Equation 1 (Essington, 2015):

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

$$ESP = \frac{Na^+}{CEC} * 100 \quad (2)$$

Water sampling and analysis

The water samples were taken in November 2023; eight samples were collected using plastic bottles from the dam upstream, middle, and downstream of the irrigation scheme.

Water samples from irrigation systems were brought to the laboratory and subjected to standard analytical procedures (Table 1) to measure general parameters like pH, EC, and TDS (Total Dissolved Solids). Analyses were conducted on both anions and significant cations, including calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), and potassium (K^+).

The anions like bicarbonates (HCO_3^-), carbonates, nitrates (NO_3^-), sulfate (SO_4^{2-}), and chloride (Cl^-) were assessed as well. From data collection to analysis, every step followed (APHA, 1999) and (Hem, 1991).

Table 1: ***Laboratory instruments and analytical methods used for physical and chemical parameters analysis as per APHA (1999)*** [a] ***and Hem (1991)*** [b]

Parameter	Unit	Analytical Method	Reagents	Reference
pH		pH/EC/TDS/meter	Ph 4,7 and 9.2	a
Electrical Conductivity (EC)	µS/CM	pH/EC/TDS/meter	KCl	a
Total dissolved Solids (TDS)	mg/l	Gravimetric	HCl	b
Calcium (Ca^{2+})	mg/l	EDTA titrimetric	EDTA, Sodium hydroxide, and murexide	a
Potassium K^{+}	mg/l	Flame photometric	NaCl and KCl	a
Sodium Na^{+}	mg/l	Flame photometric	NaCl and KCl	a
Magnesium Mg^{2+}	mg/l	Calculation	MgH = TH-CaH Mg= MgH X Eq.Wt of Mg xNormality of EDTA	a
Chloride Cl^{-}	mg/l	Titrimetric	AgNO3, Potassium, Chromate	a
Nitrate NO_3^{-}	mg/l	UV-Visible Spectrophotometer	KNO3, Phenol disulfonic acid, ammonia	a
Sulfates SO_4^{2-}	mg/l	UV-Visible Spectrophotometer	HCl, Ethyl alcohol, NaCl, Barium chloride, sodium, sulfate	a
Bicarbonates HCO_3^{-}	mg/l	Titrimetric	Hydrosulfuric acid, phenolphthalein, methyl orange	a

Laboratory-measured water parameters and units

All measured water parameters are shown in Table 2, and units are in mg/l for all except electrical conductivity, which was measured in µS/cm.

Table 2. *Laboratory measured water physical and Chemical parameters (mg/l)*

Sampling Points	Location			pH	E.c	TDS	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	SO_4^{2-}	Cl-	NO_3^-
	Lat	Long	Alt (m)		µS/cm	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
P1	-2.331076	29.90495	1377.4	6.77	207	139	13.2	8.29	4.31	1.39	61.75	12	8.1	4.9
P2	-2.323306	29.926818	1354.8	4.99	221	148	14.1	9.88	5.11	1.42	69.53	14	7.9	7.8
P3	-2.324848	29.927801	1355.4	5.41	211	141	13.6	7.68	4.12	1.44	63.98	9	7.5	4.7
P4	-2.338579	29.899078	1377.9	6.5	335	225	12.3	8.24	4.67	1.39	62.89	10	7.4	5.1
P5	-2.355335	29.892965	1392.5	5.1	262	176	12.7	8.56	5.09	1.74	64.67	11	8.1	5.4
P6	-2.368608	29.883747	1403.3	6.28	208	139	13	7.98	4.78	1.52	64.97	9	8.3	3.9
P7	-2.368472	29.877738	1409.4	6.69	1800	1206	13.3	8.03	4.69	1.73	59.32	11	8.7	7.9
P8	-2.367491	29.877692	1411.7	6.91	1230	824	11.6	8.22	5.11	1.49	55.16	12	8.8	7.4
Max				6.91	1800	1206	14.1	9.88	5.11	1.74	69.53	14	8.8	7.9
Min				4.99	207	139	11.6	7.68	4.12	1.39	55.16	9	7.4	3.9
Mean				6.08	559	375	13	8.36	4.74	1.52	62.78	11	8.1	5.89
SD				0.79	611	409	0.78	0.67	0.37	0.14	4.25	1.69	0.5	1.57
CV				0.13	1.09	1.09	0.06	0.08	0.08	0.09	0.07	0.15	0.06	0.27

Lat. : Latitude, Long : Longitude, Alt : Altitude

Quality of irrigation water determination

The following features of irrigation water are crucial in assessing its quality:

Salinity Hazard

Salinity hazard is measured by electrical conductivity (EC), which reflects total dissolved solids (TDS) in water; salinity hazard is the water quality guideline that has the most significant impact on crop productivity (Ayers and Westcot, 1985)

Since crop yield is directly correlated with the amount of water transpired through the crop, irrigation water with a high EC can cause a physiological drought condition and reduce yield potential. In other words, even though the field seems to have enough moisture, the plants wilt because their roots cannot take up the moisture (Mikunthan et al., 2010).

Sodium Hazard

While the salinity EC level of irrigation water is the primary factor limiting plant growth, certain soil textures may reduce yield when water with an imbalanced sodium content is applied. It becomes toxic when sodium builds up in plant tissues and surpasses the crop's tolerance limit. A high sodium content in irrigation water compared to its calcium and magnesium content can reduce the amount of water that penetrates the soil. This can lead to soil clays swelling and dispersing, surface crusting, and pore plugging, making the soil nearly impermeable to rain or irrigation water, and decreasing the amount of water that moves downwards into and through the soil. Additionally, roots of actively growing plants may not receive enough water even though water pools on the soil surface after irrigation. Sodium hazard is quantified by the SAR (Sodium Adsorption Ratio), which gauges how suitable water is for irrigation in agriculture (Rachel, 2010).

The amount of sodium absorbed by the soils and the SAR values of irrigation water are significantly correlated. Excessive amounts of colloidally adsorbed sodium cause the soil's physical structure to break down when high SAR water is used repeatedly. When the soil dries out, it gets compacted and harder to penetrate with water (Gangwar et al., 2020; Khodapanah, 2009). In additional SAR, sodium content in water is determined through SSP, Sodium percentage (%Na).

pH Affect

Normal irrigation water pH ranges are 6.0 to 8.5. Water outside this range may contain toxic ions or result in nutritional imbalances, while low pH may accelerate irrigation system corrosion where it occurs. High pH levels above 8.5 frequently cause high concentrations of carbonate (CO_3^-) and bicarbonate (HCO_3^-) (Bauder et al., 2014).

Chloride Hazard

In irrigation water, chlorine is a common ion. Chloride is necessary for plants in minimal amounts, but it can be toxic to sensitive crops in high concentrations. Injury symptoms such as leaf burn or leaf tissue drying appear if the chloride contamination in the leaves exceeds the crop's tolerance (Bauder et al., 2014).

Magnesium Hazard

Although necessary for plant growth, calcium and magnesium ions may also contribute to soil aggregation and deformability. Elevated levels of calcium and magnesium in irrigation water can raise soil pH, which lowers phosphorus availability. Water that has calcium and magnesium concentrations greater than 20 meq/l and five meq/l, respectively, is not suitable for use in growing crops (Shahinasi and Kashuta, 2008)

Sulfate

sulfate (SO4) is a common element in water and has little impact on soil other than raising the overall salinity level. Plant phosphorus availability is decreased by irrigation water containing high levels of sulfate ions. Although a range of less than 20 meq/l of SO4 is preferred, a concentration of sulfate in water more than 20 meq/l will cause the soil to become acidic (Khalil and Arther, 2010).

Calculation of other water parameters

Other helpful water quality parameters were calculated using different formulas, and laboratory water parameter results were primary data. Irrigation water quality parameters, such as total hardness (TH), sodium adsorption ratio (SAR), sodium percentage (%Na), permeability index (PI), salinity index or potential salinity (PS), soluble sodium percentage (SSP), magnesium adsorption rate (MAR), and Kelly's ratio were calculated using different formulas appearing in table 3. Considering that cations and anions were expressed in mg/l and to calculate other water parameters, these ions (cations and anions) need to be expressed in milliequivalent per litre (meq/l), equation 3 was adopted for this conversion.

$$\frac{meq}{l} = \frac{\left(\frac{mg}{l}\right) * Valence}{Atomic\ weight} \quad (3)$$

Table 3. *Irrigation Water Parameters and their Formulas*

Equation Number	Parameter	Formula (ions unit is in meq/l)	Reference
4	Soluble Sodium Percentage	$SSP = (\frac{Na^{+}}{Ca^{2+} + Mg^{2+} + K^{+}})*100$	Todd, 1995
5	Sodium Adsorption Ratio	$SAR = \frac{Na^{+}}{\sqrt{(Ca^{2+} + Mg^{2+})/2}}$	Richards, 1954; USEPA,2012
6	Magnesium Adsorption Ratio	$MAR = \frac{Mg^{2+}}{Ca^{2+} + Mg^{2+}}$	Raghunath, 1987
7	Kelley's Ratio	$KR = \frac{Na^{+}}{Ca^{2+} + Mg^{2+}}$	Kelly, 1963
8	Permeability Index	$PI = \left(\frac{Na^{+} + \sqrt{HCO_3^{-}}}{Ca^{2+} + Mg^{2+} + Na^{+}}\right) * 100$	Doneen, 1964
9	Potential Salinity	$PS = Cl^{-} + 0.5 * SO_4^{2-}$	Doneen, 1961
10	Total hardness	$TH = [\left(2 * \frac{Ca^{2+}}{40}\right) + \left(2 * \frac{Mg^{2+}}{24}\right)] * 50$	Sawyer and McMcartly, 1967
11	Percentage Of Sodium (%Na)	$\%Na = \left(\frac{Na^{+} + K^{+}}{Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}}\right) * 100$	Doneen, 1962

Table 4. *Standard classification of irrigation water quality (FAO, 1985)*

Indicator	Suitability appraisal	Standard range	Indicator	Suitability appraisal	Standard range
	Excellent	<450		Excellent	<20
TDS **(mg/l)**	Good	450-750	SSP **(%)**	Good	20-40
	Permissible	750-2000		Permissible	40-60
	Unsuitable	>2000		Doubtful	60-80
	Excellent	<250		Unsuitable	>80
EC (µs/Cm)	Good	250-750		Good	< 1.25
	Permissible	750-2250	RSC	Medium	1.25-2.5
	Unsuitable	>2250		Bad	>2.5
TH **(mg/l)**	Soft	<75	PI **(%)**	Excellent	>75
	moderately hard	75-150		Good	25-75

Indicator	Suitability appraisal	Standard range	Indicator	Suitability appraisal	Standard range
	Hard	150-300		Unsuitable	<25
	Very hard	>300		Excellent to Good	<5
	Excellent	<10	PS **(meq/l)**	Good to injurious	5--10
SAR **(meq/l)**	Good	10--18		Injurious to unsatisfactory	>10
	Fair	18-26	KR	Suitable	<1
	Poor	>26		Unsuitable	>1
	Excellent	<20	MAR **(meq/l)**	Acceptable	<50
%Na **(%)**	Good	20-40		non-acceptable	>50
	Permissible	40-60			
	Doubtful	60-80			
	Unsuitable	>80			

Statistical analysis

Statistical analysis through the SPSS computer program was used to determine the mean, coefficient of variation, maximum and minimum, and standard deviation values for each parameter; these values were compared to the available standard to judge the quality of soil and water for irrigation and crop production, Diagrammes 6.77 hydrochemistry computer software was adopted to classify irrigation water.

Results

Soil parameters

Three types of soil conditions, saline, saline-sodic, and sodic soils, can arise from the accumulation of salts. To distinguish between salt-related soil with poor and dense structure (sodic soil) and soil with good structure (non-sodic soil), chemical tests are conducted to determine the chemical composition of the soil. The primary causes of salt-related issues are the leaching of pollutants from solid waste dumps, irrigation water, cultural practices (primarily fertilization), and salt water intrusion. To understand the soil's salinity hazards, it is necessary to examine its pH, EC, OM(org. C), Ca_2^+, Mg_2^+, Na^+, and K^+ characteristics as well as its Exchangeable Sodium Percentage (ESP), Cation Exchange Capacity (CEC), and Sodium Absorption Ratio (SAR).

Soil physical and Chemical properties

The results for soil physical chemical are summarized in Table 5 for laboratory results and Table 6 for calculated parameters, and these tables indicate maximum, minimum, mean, standard deviation, and coefficient of variation values for all tested soil parameters.

Table 5: *Soil parameters tested in laboratory*

No	Location			pH	EC	Total N	Org.C	Av.p	Ca	Mg	K	Na	CEC	Sand	Silt	Clay
	Latitude	Longitude	Elevation (m)	KCl	(µ/Cm)	(%)		(mg/Kg)	(meq/100g)					(%)		
1	-2.367483	29.885238	1398.3	5.2	526	0.34	3.73	1.94	7.42	2.72	0.3	0.76	26.9	57	18	25
2	-2.364500	29.885594	1396.3	5.1	101	0.16	1.71	1.55	3.66	0.88	0.13	0.25	12.7	43	28	29
3	-2.352253	29.894364	1385.5	5.6	61	0.12	1.28	2.72	3.01	0.68	0.08	0.17	7.1	65	12	23
4	-2.336774	29.898833	1375.5	5.3	72	0.22	1.93	2.72	5.27	1.1	0.1	0.22	14	51	18	31
5	-2.336660	29.900680	1373.2	5.7	313	0.24	2.2	1.94	6.89	1.11	0.23	0.69	17.5	37	22	41
6	-2.329101	29.908555	1369.6	5.1	255	0.33	3.72	3.89	6.64	1.36	0.37	0.44	24.5	39	28	33
7	-2.323328	29.927007	1354.6	6.7	824	0.27	3.34	13.21	8.19	2.18	0.41	0.89	17	51	22	27
8	-2.324837	29.927916	1355.5	5.5	315	0.1	0.96	4.27	3.93	1.22	0.16	0.52	11.3	58	19	23
Max				6.7	824	0.34	3.73	13.21	8.19	2.72	0.41	0.89	26.9	65	28	41
Min				5.1	61	0.1	0.96	1.55	3.01	0.68	0.08	0.17	7.1	37	12	23
Mean				5.5	308.4	0.22	2.36	4.03	5.63	1.41	0.22	0.49	16.4	50.1	20.9	29
SD				0.5	260.8	0.09	1.1	3.83	1.93	0.69	0.13	0.27	6.6	9.8	5.4	6
CV				0.1	0.8	0.41	0.47	0.95	0.34	0.49	0.57	0.55	0.4	0.2	0.3	0.2

Calculated soil physical and chemical parameters

Soil Sodium adsorption ratio (SAR), exchangeable sodium percentage (ESP), and carbon to nitrogen ratio (C/N) were calculated from the laboratory-measured parameters data; the used formulas are equation 1 for SAR and equation 2 for ESP. the results of these parameters are found in Table 6.

Table 6: *Calculated soil parameters*

No	EC (dS/m)	soil texture	ESP %	SAR	C/N
1	0.53	Sandy Clay Loam	2.8	0.3	11
2	0.10	Clay Loam	2	0.2	10.7
3	0.06	Sandy Clay Loam	2.4	0.1	10.7
4	0.07	Sandy Clay Loam	1.6	0.1	8.8
5	0.31	Clay	3.9	0.3	9.2
6	0.26	Clay Loam	1.8	0.2	11.3
7	0.82	Sandy Clay Loam	5.2	0.4	12.4
8	0.32	Sandy Clay Loam	4.6	0.3	9.6
Max	0.82		5.2	0.4	12.4
Min	0.06		1.6	0.1	8.8
Mean	0.31		3.0	0.2	10.5
SD	0.26		1.4	0.1	1.2
CV	0.85		0.5	0.4	0.1

Soil reaction

The pH of soil samples from the study area ranges between 5.1 and 6.7 with an average of 5.5; the distribution of samples shows soils classified as neutral, moderately acidic, strongly acidic, and very strongly acidic and have 12.5, 25, 50, and 12.5% of the samples respectively (Bruce & Rayment, 1982). When evaluating the environment and soil fertility, soil pH is a crucial indicator. For instance, most crops require a pH between 6.0 and 7.5 to have the best availability of mineral elements (Sanchez et al., 2003). More samples fall in strongly acid and in this range of acidity, soil experienced deficiency in plant nutrients like P, Ca, k, N, Mg and organic matter which are necessary for crop growth, while the concentration of Al and Mn, B, Zn, Cu, Fe increase towards into a toxic range to plants and thus reduce crop yield production (Makoi & Ndakidemi, 2009).

Total nitrogen and available phosphorus

Total nitrogen results of the soil samples vary from 0.1 to 0.34 % (Table 5). All samples collected fall into the low to medium class according to (Kileo, 2000 and Msanya et al., 1996); organic carbon percentages are quantified from 0.96 to 3.73 (Table 5), presenting the low, medium, high, and very high classes with more samples in medium, available phosphorus data are in the range of 1.55 to 13.21 mg/kg with this parameter, soil samples are in low to the medium where 87.5% of samples are in low class according to(Kileo, 2000; Msanya et al.,1996), these low to medium values of soil available nutrients are likely explained by the acidic condition of the soils and irrigation water observed in the study area.

Cation exchange capacity

The soil was classified as low, medium, and high in terms of its cation exchange capacity (CEC), which ranged from 7.1 to 26.9 meq/100g (Table 5) (NSS, 1990). Positively charged ions exchanging at the surface of negatively charged colloids is called cation exchange capacity. Soil can better hold on to mineral elements with a higher CEC. Based on research, exchangeable base content is low in soils with CEC values of 6–12 meq/100g (NSS, 1990).

Exchangeable sodium percentage (ESP)

Exchangeable Na ranges from 0.17 to 0.89 meq/100g for all sample soils (Table 5); hence, soils are classified as low, medium, and high. Out of the total samples tested, 37.5 % was rated as low Na, 37.5% as medium Na, and 25% as high Na (Msanya N B, 2012), which correlates to ESP values of 1.6 to 5.2% as minimum and maximum values of the results of this study (Table 6). The physical and hydraulic properties of soil, including aggregate stability, permeability, and hydraulic conductivity, can be adversely affected by elevated exchangeable sodium percentages (ESP) (Tanji, 2012).

Sodium adsorption Ratio (SAR)

Sodium adsorption Ratio (SAR) was calculated using equation 1 for the present study and varies between 0.1 to 0.4 (Table 6), which classifies the soil as excellent for sustaining irrigation and crop development (Ravikumar, 2014); soil presents a problem to plant growth when the SAR of soil is greater than 13, Soil structure weakens with an increase in SAR (sodium); water may move through soil more slowly and infiltrate the soil at a slower rate.

Saline Soil

Saline soils have sufficient neutral soluble salts, which negatively impacts the growth of most crop plants. Sodium sulfate and chloride make up the majority of the soluble salts. However, there are also noticeable amounts of chlorides and sulfates of Ca^{2+} and Mg^{2+} in saline soils. Table 7 describes these soils as having an electrical conductivity of the saturated (EC) more significant than four dS/ m, an exchangeable sodium percentage (ESP) of less than 15, and a sodium adsorption ratio (SAR) of less than 13. Usually, the pH of the soil is lower than 8.5. Soil salinity prevents water from being absorbed by plants, causing a physiological drought that lowers the amount of water available for plant use. Even if the soil is sufficiently wet, osmotic pressure prevents plant roots from taking up the water. Early on in their lives, during germination and growth, plants are typically most sensitive to salinity (Senon et al., 1989).

Table 7: ***Classification of the salt-affected soils (USSL Staff, 1954)***

Salt affected soil	Soil ph	Electrical conductivity (EC)	Sodium adsorption ratio	Exchangeable sodium percentage	Soil physical structure
None	<8.5	<4	<13	<15	Flocculated
Saline	<8.5	>4	<13	<15	Flocculated
Sodic	>8.5	>4	>13	>15	Dispersed
Saline-sodic	<8.5	>4	>13	>15	Flocculated

Sodic soil

These soils contain sodium salts, primarily Na_2CO_3, which can cause alkaline hydrolysis. In earlier literature, these soils were called "alkali" soils. According to Table 7, the sodic soils have EC less than four dS/ m, ESP more than 15, and SAR more than 13. The majority of sodium is interchangeable. Soil solution contains minimal amounts of free salts. More than 8.5 is the pH of the soil. Strongly alkaline conditions may arise in these soils due to irrigation, and pH values of 10 or higher are typical.

Sodic soils present poor conditions for plant growth. The excess exchangeable sodium and high pH result in clay dispersion, and soils have an unstable structure. Soil permeability by water and air is restricted, and soil physical condition worsens to facilitate plant growth development due to soil compaction level; the soil pH creates nutritional imbalances, including plant-soil nutrient deficiency and toxicity of specific ions. (Senon et al.,1989) reported that Sodic soils typically have poor physical characteristics, such as inadequate water infiltration and air exchange, which can hinder plant growth. Less infiltration, less hydraulic conductivity, surface crusting, and decreased crop yield are the main consequences of soil sodicity, according to (Krista & Bauder, 2009). The results in the present study show that the soil samples are not sodic.

Water physical and chemical parameters

The primary water parameters from the laboratory analysis results were converted from mg/l to meq/l using equation 3. Total dissolved solids were kept in their initial units, and the electrical conductivity unit was changed from μS/cm to dS/m (1Ds/m =0.001 μS/cm). The results are summarized in Table 8.

Table 8: ***Laboratory measured Water physical and chemical in milliequivalent per litre (meq/l)***

Sampling Points	pH	EC	TDS	Ca2+	Mg2+	Na+	K+	HCO3-	SO42-	Cl-	NO3-
		dS/m	mg/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l
P1	6.8	0.2	138.7	0.66	0.68	0.19	0.036	1.01	0.25	0.23	0.08
P2	5.0	0.2	148.1	0.71	0.81	0.22	0.036	1.14	0.29	0.22	0.13
P3	5.4	0.2	141.4	0.68	0.63	0.18	0.037	1.05	0.19	0.21	0.08
P4	6.5	0.3	224.5	0.62	0.68	0.20	0.036	1.03	0.21	0.21	0.08
P5	5.1	0.3	175.5	0.63	0.70	0.22	0.045	1.06	0.23	0.23	0.09
P6	6.3	0.2	139.4	0.65	0.66	0.21	0.039	1.06	0.19	0.23	0.06
P7	6.7	1.8	1206.0	0.67	0.66	0.20	0.044	0.97	0.23	0.25	0.13
P8	6.9	1.2	824.1	0.58	0.68	0.22	0.038	0.90	0.25	0.25	0.12
Max	6.9	1.8	1206.0	0.71	0.81	0.22	0.045	1.14	0.29	0.25	0.13
Min	5.0	0.2	138.7	0.58	0.63	0.18	0.036	0.90	0.19	0.21	0.06
Mean	6.1	0.6	374.7	0.65	0.69	0.21	0.039	1.03	0.23	0.23	0.09
SD	0.8	0.6	409.2	0.04	0.05	0.02	0.004	0.07	0.04	0.01	0.03
CV	0.1	1.09	1.09	0.06	0.08	0.08	0.094	0.07	0.15	0.06	0.27

Calculated water Physical and chemical parameters

After using the mentioned formula from Table 3 for total hardness (TH) , Magnesium Adsorption Ratio (MAR), Sodium Adsorption Ratio (SAR), sodium percentage (%Na), permeability index (PI), Soluble sodium Percentage (SSP), salinity index or potential salinity (PS), Kelly's ratio (KR) parameters of water, table 9 illustrates the results for these parameters for each water sampling point including the maximum, minimum, mean, standard deviation and coefficient of variation for every calculated water parameter.

Table 9: ***Calculated water Physicochemical parameters***

Sampling Points	TH	MAR	SAR	%Na	PI	SSP	PS	KR
	mg/l	%		%	%	%		
P1	67.57	50.86	0.23	14.26	78.07	13.62	0.35	0.14
P2	76.52	53.54	0.26	14.55	74.09	14.30	0.37	0.15
P3	65.90	48.29	0.22	14.17	80.87	13.32	0.31	0.14
P4	65.18	52.41	0.25	15.58	81.39	15.28	0.31	0.16
P5	67.47	52.60	0.27	16.57	80.16	16.00	0.34	0.17
P6	65.78	50.29	0.26	15.90	81.90	15.46	0.33	0.16
P7	66.81	49.82	0.25	15.77	77.76	14.88	0.36	0.15
P8	63.23	53.91	0.28	17.19	79.42	17.19	0.37	0.18
Max	76.52	53.91	0.28	17.19	81.90	17.19	0.37	0.18
Min	63.23	48.29	0.22	14.17	74.09	13.32	0.31	0.14
Mean	67.31	51.46	0.25	15.50	79.21	15.01	0.34	0.15
SD	3.98	1.96	0.02	1.10	2.55	1.27	0.03	0.01
CV	0.06	0.04	0.08	0.07	0.03	0.08	0.07	0.09

The values of general parameters (pH, EC, TDS), concentrations of various anions (Cl^-, SO_4^{2-}, NO_3^-, HCO_3^-, and CO_3^{2-}), and cations (Ca^{2+}, Mg^{2+}, Na^+, and K^+) are shown in table 8. The values of water quality indices (TH, SAR, %Na, PI, PS, SSP, MAR, and KR) are found in Table 9. The pH scale shows how acidic or basic a substance is. The water in Nyarubogo irrigation scheme had an average pH of 6.1±0.8 (Table 8); irrigation water typically has a pH between 6.0 to 8.5 (Shahinasi and Kashuta, 2008), and the pH of water samples in this study range from 5.0 to 6.9, this resulted from the samples from P2, P3 and P5 which are out of the standard ranking in irrigation water, except for pH, other measured water parameters (Ca_2^+, Mg^{2+}, Na^+ and K^+ Cl^-, SO_4^{2-}, NO_3^-, and HCO_3^-) are in normal rank and acceptable for irrigation purpose (Table 10).

Table 10: *Guidelines for interpretation of irrigation water quality*

Water parameter	Units	Normal ranking in irrigation water	Range in Nyarubogo Irrigation Scheme
Electrical Conductivity (EC_w)	dS/m	0-3	0.2 - 1.8
Calcium (Ca^{2+})	meq/l	0-20	0.58 – 0.71
Magnesium (Mg^{2+})	meq/l	0-5	0.63 – 0.81
Sodium (Na^+)	meq/l	0-40	0.18 – 0.22
Bicarbonate (HCO_3^-)	meq/l	0-10	0.9 – 1.14
Chlorine (Cl^-)	meq/l	0-30	0.21 – 0.25
Sulfate (SO_4^{2-})	meq/l	0-20	0.19 – 0.29
Potassium (K^+)	meq/l	0-0.052	0.036 – 0.045
pH	1-14	6.0-8.5	5.0 – 6.9

Adapted from Shahinasi and Kashuta (2008)

Magnesium Adsorption Ratio (MAR)

The MAR was calculated by equation 6 (Table 3), and results ranged from 48.29 to 53.91 percent, with an average value of 51.46 % (Table 9). The MAR divides irrigation water into two major categories: water with a MAR of more than 50% is deemed inappropriate (Unsuitable) (Table 4). The magnesium adsorption ratio can be used to determine which alkali metal element predominates in water. In most waters, calcium and magnesium usually are in equilibrium. In this balance, more magnesium in the water hurts crop productivity (Qadir et al., 2018).

Salinity hazard

The salinity hazard of water is used to test if water is suitable for irrigation; the significant parameters to be checked to judge the salinity hazard of water are total dissolved solids and electrical conductivity of water:

Total dissolved solid values were 138.69 to 1206 mg/l with a mean of 374.7 mg/l (Table 8). And water samples are classified into permissible which is presented by two water samples (P7 and P8) equal to 25% of samples, and excellent category with six samples equivalent to 75 % of study samples. The whole values are within acceptable as no water sample presented a TDS of more than 2000 mg/l (Table 4)

Electrical conductivity (EC) ranges from 207 to 1800 µS/cm (Table 8), and 50%, 25%, and 25% of water samples fall into excellent, reasonable, and permissible suitability classes, respectively. Water in the Nyarubogo irrigation scheme is safe for irrigation as no sample is classified as unsuitable according to FAO, 1985 and according to (DNR, 1997). results vary from very low to medium saline suitable for the sensitive, moderately sensitive, and moderately tolerant crops, with 75 % of samples in the low saline category (Table 11). Based on the values obtained from these two parameters, water in the Nyarubogo irrigation scheme does not present a salinity hazard; therefore, it is suitable for irrigation practices.

Table 11: ***Irrigation water salinity ratings based on electrical conductivity (DNR, 1997)***

EC (dS/m)	Water salinity rating	Plant Suitability	Range Nyarubogo
<0.65	Very low	Sensitive crops	0.21-0.34
0.65 - 1.3	Low	Moderately sensitive crops	1.23
1.3 - 2.9	Medium	Moderately tolerant crops	1.8
2.9 - 5.2	High	Tolerant crops	
5.2 - 8.1	Very high	Very tolerant crops	
>8.1	Extreme	Generally, too saline	

Furthermore, Soil infiltration problems occur for different values of sodium adsorption ratio and electrical conductivity of irrigation water; FAO guidelines (Misstear and Banks, 2006), based on these two water parameters,

classify the intensity of water to cause soil infiltration problems into none, slight to moderate and severe (Table 12). The results show that irrigation water in the Nyarubogo scheme falls in none and slight to moderate restriction degrees. In detail, 75% of the samples are subtle to moderate and with low electrical conductivity values closer to 0.2 dS/m, the water quality limit to create severe soil infiltration problems. A slight-to-moderate infestation problem is concerning despite the results showing no salinity threat; this is especially true given that there is no clear schedule for scheme leaching practices. Thus, using this irrigation water over an extended period with no regular leaching activities will result in significant soil infiltration issues and affect plant growth and crop production.

Table 12: *FAO (2006) guidelines for interpretation of water quality for irrigation*

		Infiltration measures			
Paremeter (Unit)	**SAR (meq/l)**		**EC (dS/m)**		
Degree of restriction			**None**	**Slight to moderate**	**Severe**
	0-3	And EC=	>0.7	0.7-0.2	<0.2
	3-6	And EC=	>1.2	1.2-0.3	<0.3
	6-12	And EC=	>1.9	1.9-0.5	<0.5
	12-20	And EC=	>2.9	2.9-1.3	<1.3
	20-40	And EC=	>5.0	5.0-2.9	<2.9

The salinity index and irrigation water's hardness are essential factors affecting crop productivity and soil quality. The amount of calcium and magnesium ions in water that affects how well it lathers with soap is called total hardness. However, the salinity index gauges the amount of salt in water, affecting plant development and soil composition (Ansari et al., 2021). Effective irrigation management depends on monitoring these variables to guarantee the best possible crop yield and soil health. Equation 9 and eEquation10 (Table 3) were used to get the values of these parameters.

The Total hardness of the tested water samples was found to be in the range of 63.23 mg/l to 76.52 mg/l (Table 9). These results revealed that 87.5 % of the samples are classified as soft water while 12.5 % are classified as moderately complex. Consequently, the water in Nyarubogo irrigation scheme presents a good condition for agricultural activities (FAO, 1985) (Table 4). The study area's average potential salinity or salinity index was 0.34 meq/l, with 0.31 as the minimum and 0.37 as the maximum values (Table 9). Water in the study area falls from excellent to good, given that all results for the salinity index are less than five meq/l (Table 4).

Sodium hazard

Sodium hazard in soil has a direct relationship with the SAR of water used to irrigate crops on that soil, as mentioned in the previous section of the study. SAR is crucial in determining whether water is suitable for irrigation since it causes the sodium hazard in irrigation water (Gholami & Srikantaswamy, 2009). Because of the high SAR value, the soil becomes compact and complex when it gets dry, which lowers the rates at which air and water seep into the soil and affects its structure. This issue is also connected to several variables, including the kind of soil and the salinity rate (Hailu & Mehari, 2021). Problems with water infiltration arise from high sodium ion levels in irrigation water, which alter soil's hydraulic conductivity (permeability). This is because when exchangeable sodium replaces calcium and magnesium in the soil, it adsorbs the soil clays and disperses the soil particles. In other words, if calcium and magnesium are the main cations adsorbed on the soil exchange complex, the soil will typically be easily cultivated and have a permeable and granular structure (Tas et al., 2022). SAR in this study was obtained through equation 1, and the results for all samples are between 0.22 to 0.28 meq/l, a range which is less than 10 meq/l (table 9), and by this range, water in this study area is classified as excellent (Table 4)

Soluble Sodium Percentage

Soluble sodium Percentage (SSP) is a crucial component in the analysis of the sodium hazard. Water with an SSP of more than 50% may lead to an accumulation of sodium, which will deteriorate the physical characteristics of the soil; it may also result in reduced soil permeability and inhibited plant growth development (Bhandari & Joshi, 2013). According to (FAO, 1985), water with ssp from 60% and above starts to be doubtful to unsuitable for crop irrigation (Table 4).SSP was calculated with the help of equation 4 (table 3), and all answers from the water-collected samples ranged from 13.32 – 17.19 % (Table 9).

The permeability index (PI) is an additional metric for determining whether water is suitable for irrigation. The permeability index measures long-term irrigation water use, which affects the permeability of the soil. It is influenced by the soil's sodium, calcium, magnesium, and bicarbonate content (Rawat et al., 2018). (Doneen, 1964)developed a permeability index (PI) based criterion for determining whether water is suitable for irrigation. The soil's Na+, Mg2+, Ca2+, and HCO3- ion concentrations impact its permeability (Ghazaryan & Chen, 2016). PI is computed via equation 8 (Table 3).

Table 9 illustrates the results for this parameter, which are under a range of 74.09% as a minimum value to 81.9% as the maximum value, and this domain classified tested water samples into good and suitable classes that stimulate soil permeability in good conditions for crop growth because these results are in the domain which enhances plants interaction with soil-water (Naidu et al., 2020).

Salinity index (Kelly's Ratio)

Kelly's ratio is used to classify water for irrigation. (Kelly WP, 1940) and (Paliwal, 1967) used sodium as a comparison with calcium and magnesium to compute this parameter; Alkali hazards are represented by amounts of Na, Ca, and Mg in water (Dhembare, 2012). Na concentration is compared to Ca and Mg to calculate Kelly's Ratio parameter. In most waters, Ca and Mg remain in their equilibrium states. Equation 7 (Table 3) is used to compute Kelly's ratio. Waters with an excess of sodium are indicated by a Kelly's ratio greater than one. Therefore, waters with Kelly's ratio of less than one are suitable for irrigation, whereas those with a greater than one are not (Kelly WP, 1940). the results in this study area for this ratio vary from 0.14 to 0.18, with an average value of 0.16 (Table 9).

Table 13: ***Classification of Nyarubogo irrigation water according to the standard (FAO,1985)***

Indicator	Suitability appraisal	Standard range	Measured range	Sample reference number	(%)
	Excellent	<450		P1,P2,P3,P4,P5,P6	75
TDS (mg/l)	Good	450-750	138.69-1206		
	Permissible	750-2000		P7,P8	25
	Unsuitable	>2000			
	Excellent	<250		P1,P2,P3,P6	50
EC(µs/Cm)	Good	250-750	207- 1800	P4,P5	25
	Permissible	750-2250		P7,P8	25
	Unsuitable	>2250			
	Soft	<75		P1,P3,P4,P5,P6,P7,P8	87.5
	moderately hard	75-150	63.23-76.52	P2	12.5
	Hard	150-300			
TH (mg/l)	Very hard	>300			
	Excellent	<10		P1,P2,P3,P4,P5,P6,P7,P8	100
SAR (meq/l)	Good	10--18	0.22 – 0.28		
	Fair	18-26			
	Poor	>26			
	Excellent	<20		P1,P2,P3,P4,P5,P6,P7,P8	100
	Good	20-40			
	Permissible	40-60	14.17 – 17.19		
	Doubtful	60-80			
%Na (%)	Unsuitable	>80			
	Excellent	<20		P1,P2,P3,P4,P5,P6,P7,P8	100
	Good	20-40			
	Permissible	40-60	13.32-17.19		
	Doubtful	60-80			
SSP(%)	Unsuitable	>80			
	Excellent	>75		P1,P3,P4,P5,P6,P7,P8	87.5
PI (%)	Good	25-75	74.09-81.9	P2	12.5
	Unsuitable	<25			
	Excellent to Good	<5		P1,P2,P3,P4,P5,P6,P7,P8	100
PS (meq/l)	Good to injurious	5--10	0.31-0.37		
	Injurious to unsatisfactory	>10			

Indicator	Suitability appraisal	Standard range	Measured range	Sample reference number	(%)
KR	Suitable	<1	0.14-0.18	P1,P2,P3,P4,P5,P6,P7,P8	100
	Unsuitable	>1			
MAR (%)	Acceptable	<50	48.29-53.91	P1,P2,P4,P5,P6,P8	75
	non-acceptable	>50		P3, P7	25

US Salinity Laboratory and Wilcox diagrams

A significant correlation exists between the SAR of irrigation water and the amount of sodium the soil absorbs. Soils' physical state is affected by the high concentration of Na+ salts in them. The soil's texture makes plowing difficult (Jahanbazi et al., 2023). The two diagrams for classifying the suitability of irrigation water were drawn through Diagrammes 6.77 software. The USSL diagram (USSL, 1954) provides comprehensive details on the analysis related to SAR. The USSL diagram (Figure 3) uses a plot between SAR and EC to classify irrigation water quality. For all Samples, 50% were found to fall into the S1–C1 (low -low), 25% into S1C2 (low – medium), and 25% into S1C3 (low-high) categories. This suggests that the sampling location water was suitable for irrigation use. Another graphical method for determining the suitability of irrigation water is the Wilcox diagram. It uses an EC versus SSP data set (Figure 4). All of the samples were in the Excellent and Good regions, indicating that irrigation water from Nyarubogo is viable for irrigation activities.

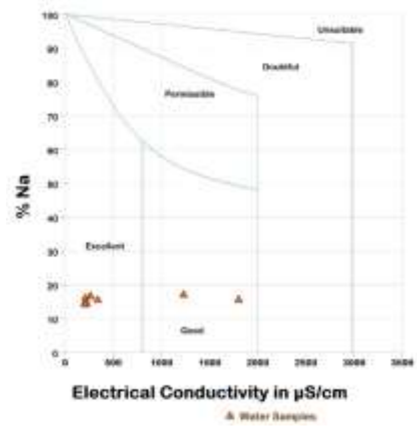

Figure 3: Wilcox diagram

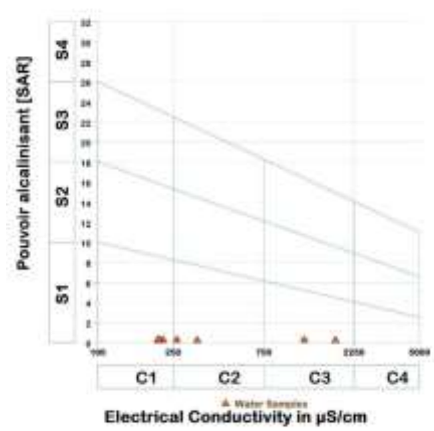

Figure 4: USSL diagram

Note: C1&S1: low, C2&S2: Medium, C3&S3: High, C4&S4: Very High

Discussion

The soil and water analysis results conducted in the Nyarubogo irrigation system offered important water quality information for the scheme. The pH range of the detected soil, which was between 5.1 and 6.9, indicates the existence of acidic conditions that may have a negative impact on crop development. The acidity of the soil may cause shortages in some nutrients, especially in the nutrients that are necessary for the best possible development of plants: phosphorus (P), calcium (Ca), potassium (K), nitrogen (N), magnesium (Mg), and organic matter. Strongly acidic soils may have higher concentrations of manganese (Mn) and aluminum (Al), which may further impede root growth and lower crop output (Faria et al., 2021). This discovery is consistent with prior research findings that acidic soils may decrease the availability of nutrients and make certain elements more poisonous, eventually resulting in lower agricultural output (Agegnehu et al., 2021).

The pH of the soil and irrigation water are correlated, which implies that irrigation techniques may be causing the soil in the Nyarubogo project to become more acidic. Over time, water that falls below the ideal pH range of 6.5-8.4 for irrigation will worsen soil acidification (Koech, 2016), which can impact the soil's ability to act as a buffer and the availability of nutrients, increased levels of H^+ and Al^{3+} in the soil, activated heavy metal ions like Mn^{2+}, Pb^{2+}, Cu^{2+}, and Cd^{2+}, and intensified the leaching loss of base cations like Ca^{2+}, K^+, Mg^{2+}, and Na^+ were the consequences of soil acidification, which decreased soil fertility and reduced crop yield (Renkou, 2018). This is in line with the findings of (Malakar et al., 2019), who discovered that the irrigation water's quality significantly influences soil production and health. The findings suggest that maintaining agricultural yields in this region may depend on improving irrigation water quality or using soil management techniques to mitigate acidity.

The soil samples' low to medium concentrations of accessible phosphorus (1.55 to 13.21 mg/kg) and total nitrogen (0.1% to 0.34%) point to restricted nutrient availability, which may impede crop development and yield. A lack of nitrogen may result in stunted growth and low crop yields since nitrogen is essential to chlorophyll (Fahad et al., 2021). Since phosphorus is essential for plant root growth and energy transmission, low phosphorus levels are especially worrying. The results are consistent with research by (Stewart et al., 2020), who highlighted the necessity for fertilization techniques to increase soil fertility and boost crop productivity and identified comparable difficulties in nutrient-deficient soils.

With an average value of 16.4 meq/100g, the soil's cation exchange capacity (CEC) suggests a modest potential to hold onto vital nutrients. Low CEC soils are generally weathered and have a reduced capacity to support plant growth with sufficient mineral elements, such as calcium, according to Sanchez and Logan (1992). In this study, 75 % of samples have CEC more than 12 meq/100g, and the average value is 16.4 meq/100g, which classifies the soil as medium; hence, the soils have a good capacity to sustain crop growth development in general. The results here are slightly more than those found by (Basnett, 2023), and this difference may be due to the low concentration of organ carbon found in that study comparing the one in the present research. It is generally acknowledged that between 25 and 90% of the total CEC of mineral soil surface horizons can be attributed to soil organic matter (SOM) (Bashir et al., 2021). The presence of exchangeable sodium was found to range from 0.17 to 0.89 meq/100g, which raises concerns about possible sodium toxicity as 25% of samples are classified as having high Na (Mulat et al., 2018), reduced permeability, poor water penetration, and loss of soil structure are all consequences of high exchangeable salt levels that may have a detrimental effect on crop output (Frene et al., 2024). Although there is a slightly high presence of exchangeable sodium, the exchangeable sodium ratio (EPS) falls within a suitable domain (1.6 to 5.2%) to sustain crop productivity; it also implies that the soil has a decent ability to sustain crop development, According to Shrivastava and Kumar, (2015), 15 % is the critical ESP value above which the majority of crops, including crop yield reduction, are negatively affected. Therefore, the results of ESP of soils from the Nyarubogo irrigation scheme do not affect crop growth.

The pH in the soil of Nyarubogo irrigation scheme has a clear correlation with the pH of irrigation water, which varied from 5.0 to 6.9 and cosignificante among the major sources of soil acidity in the area. The results are similar to those (Zhang et al., 2019). Results in this study confirm that all soil samples tested fall into non-salt-affected soil (Table 7); therefore, soils are not saline to affect crop productivity, (Maina et al., 2012) reported similar findings during the soil salinity assessment in irrigation land.

The soluble sodium percentage (SSP), electrical conductivity (EC), and total dissolved solids (TDS) are among the water quality measures that further highlight the possible difficulties that farmers in the Nyarubogo scheme may encounter. Although the TDS readings show that the water is within allowable bounds for irrigation, the variations in SSP (13.32% to 17.19%) and EC (207 to 1800 µS/cm) raise the possibility of localized problems with salt and sodium buildup. Elevated SSP levels may cause soil sodicity, which is harmful to crop development, and high EC values can limit the amount of water available to plants (Hailu & Mehari, 2021).

Results showing a magnesium adsorption ratio (MAR) of more than 50% suggest that irrigation water is not acceptable for long-term usage without proper management. An imbalance in soil cations, especially calcium and magnesium, which are crucial for preserving soil fertility and structure, might result from high MAR levels (Silva Neto et al., 2019). Magnesium ions have detrimental effects on the soil when the value of MAR is more than 50% (FAO, 1985). When irrigation water contains more magnesium than calcium, this Mg saturation condition accelerates the destruction of soil structure and decreases productivity. Crop yield is lowered when irrigation water with a high magnesium concentration turns the soil alkaline (Arshad and Aamir, 2018). Due to the higher magnesium content concerning the total divalent cations, a large amount of magnesium may indeed be adsorbed on soil particles and have a negative impact on the physical properties of the soil (Ishiguro & Koopal, 2016) by creating "magnesia's alkaline," which can result in adverse effects on soil properties that are comparable to the risks associated with an excess of sodium adsorbed ions. In this study, only 25 % of the tested water samples have a MAR value less than 50%, while 75 % of examined samples show MAR is more than 50%; therefore, they fall into the unsuitable category for irrigation; thus, the water from the study area has more Mg than Ca is safe for irrigation. Although the water in Nyarubogo shows Ca and Mg to be in the standard ranking range (Table 10), the present imbalance of these two cations may affect the scheme crop productivity. These results are closer to those found by (Bouaroudj et al., 2019). Soil permeability reduction, a noticeable decline in crop productivity, and progressive deterioration of soil structure are the consequences of irrigation water with high magnesium (Oster et al., 2016). Using this water continuously may cause soil deterioration and lower crop yields; thus, it's essential to utilize water management techniques to lower these risks (Hussain et al., 2002); amendments that supply the required calcium amount can lessen the effects of magnesium in soils and water (Qadir et al., 2018)

In this study, the SAR of water samples was calculated, and the results show that all samples fall within the range of 0.22 to 0.28 meq/l, which is less than ten meq/l (table 9), and this range classifies these samples into excellent; therefore, no adverse consequences are present when is used in irrigation, these results are similar to (Wantasen et al., 2021) in Talawaan who found that SAR for all tested samples to less than ten meq/l and conclude that water in their respective study area is suitable for irrigation. Na% is a standard definition for the sodium content of irrigation water. The concentration of sodium in water induces Ca^{2+} and Mg^{2+} ion exchange. This exchange process reduces soil permeability, leading to inadequate internal drainage. Sodium decreases permeability and is considered a significant ion for irrigation water classification due to its reactivity with soil (Zaman et al., 2018). For agricultural purposes, the water quality is assessed using Na%. Plant growth is retarded by high Na% irrigation water (Oster, J. D., & Rhoades, 2018). Na% is calculated by dividing the total number of cations in water by their relative proportion (Eq 11) (Table 3). The Percentage of sodium was found in a range of 14.17 to 17.19 % (Table 9), and these values confirm that 100% of samples are presenting in excellent category; for this parameter, water is safe when utilized to sustain irrigation activities and crop production.

All results obtained for Soluble sodium Percentage (SSP) are less than 20 %; this also confirms that 100 % of the samples were in the excellent category (Table 4); therefore, there is no restriction to use this water in irrigation activities as no any samples found to be in the doubtful or unsuitable category. After a thorough observation of the results of these water parameters (Total dissolved solid, Sodium adsorption ratio, Soluble sodium Percentage), it is clear to note that the source of irrigation water in this study area does not show any sodium hazard, which may adversely affect crop production.

The results of the Permeability index (PI) and Kelly's ratio in this study indicated that the water used in Nyarubogo irrigation is suitable for irrigation based on the standards found in the present research. According to the computed PI values, 87.5% of the water samples fall into the "excellent" category, while 12.5% fall into the "Good" category (Table 13). Results show a good correlation with those found by (Ismail et al., 2023) in Egypt, where all water samples were in a suitable category to indicate water quality for irrigation.

Waters that have Kelly's ratio of less than one are, therefore, suitable for irrigation, whereas those that have a ratio greater than one are not (Kelly WP, 1940); Kelly's ratio values in this study are in the range of 0.14 to 0.18, the present values are less than one to all tested samples and this indication that water in Nyarubogo irrigation scheme is suitable for irrigation, results are in the same projects those published by (Cadraku & Beqiraj, 2023).

Amostter samples fell within the permissible class for irrigation in different parameters, but there are still possible dangers related to soil infiltration issues, according to the study of salt hazards based on TDS and EC values. According to (Syed et al., 2021), excessive salinity water may decrease the soil's capacity to hold onto moistulowering, lowering agricultural output. Currently, water and soil from Nyarubogo irrigation scheme do not show severe problems relevant to salinity; however, results from this research emphasize how crucial it is to keep an eye on soil and water salinity to maintain sustainable farming methods and crop yields, the results are the same as the ones found by (Mohanavelu et al., 2021) who suggest routine monitoring salinity levels in both soil and water to prevent the long-term degradation of land and contrast with the ones found by (Chemura et al., 2014; Chen et al., 2010).

Conclusion and Recommendations

Conclusion

A combination of scientific data obtained at the farm, country, and global levels is imperative to achieve high yields of crops. The availability of nutrients in both the irrigation water and the soils affects the yields of different crops. Therefore, research on the interactions between nutrients, soil, water, and plants is crucial. Similar studies to this one inform farmers, agricultural extensionists, researchers, and policymakers about the potential influences of soil and irrigation water quality on the productivity of crops in general. Results in this study reveal that soil and water quality indicators such as pH were in the acid range for most soil and water samples; there is plant nutrient deficiency in this range. Furthermore, findings show Total Nitrogen, available P, and Organic Carbon were found as limiting factors to soil crop production in the area, while other tested physicochemical properties of soil and water were found in an acceptable range to sustain crop production planted in the scheme. Although irrigation water does not present saline and sodicity conditions, the Magnesium adsorption ratio of water used in irrigation practices needs more attention to reduce it to the acceptable range, as no known regular leaching is conducted in the scheme to prevent soil structure destruction in the future. Further research is recommended to regulate the pH of both soil and water, increase plants' nutrients, and set regular leaching procedures in the Nyarubogo irrigation scheme.

Recommendations

Based on the findings of this research, the following are the recommendations:

Farmers in the Nyarubogo irrigation scheme are advised to use lime and organic matter as soil amendments to mitigate the soil's acidity and the resulting nutrient deficits. TEnhancingsoil structure, increasing nutrient availability, and neutralizing soil acidity will promote better crop development and increase productivity.

In the Nyarubogo irrigation scheme, water management techniques that reduce the danger of soil salinity and sodicity, given the moderate MAR and SSP values in irrigation water, should be used. This involves rotating crops with species that can withstand salt, using gypsum to offset sodium buildup, and closely monitoring irrigation water quality to stop more soil deterioration.

continuous monitoring of the factors that determine the soil and water quality should be monitored, such as pH, MAR, SSP, and EC. Farmers and agricultural managers should use adaptive management techniques based on the monitoring data to maintain the sustainability of soil health and agricultural production in the Nyarubogo irrigation system.

Conflicts of Interest

There are no possible conflicts of interest among them relevant to this study.

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References

Adongo, T. A., Abagale, F. K., & Kranjac-berisavljevic, G. (2015). Soil Quality of Irrigable Lands of Irrigation Schemes in Northern Ghana. *IJISET - International Journal of Innovative Science, Engineering & Technology*, 2(8), 314–326.

AFNOR. (1995). *Qualité du Sol-Dosage de L'azote Total- Méthode de Kjeldahl Modifiée; AFNOR Association Française de Normalisation*. Association Française de Normalisation.

Agegnehu, G., Amede, T., Erkossa, T., Yirga, C., Henry, C., Tyler, R., Nosworthy, M. G., Beyene, S., & Sileshi, G. W. (2021). Extent and management of acid soils for sustainable crop production system in the tropical agroecosystems: a review. *Acta*

Agriculturae Scandinavica, Section B – Soil & Plant Science, *71*(9), 852–869. https://doi.org/10.1080/09064710.2021.1954239

APHA. (1999). Standard methods for the examination of water and wastewater, 20th edn. *American Public Health Association, Washington DC*.

Arshad, Muhammad and Aamir, S. (2018). Irrigation Water: Quality Criteria. *Soil Salinity and Water Quality*, *October*, 156–182. https://doi.org/10.1201/9780203739242-6

Ayers, R. S., and Westcot, D. W. (1985). *Water quality for agriculture*. FAO.

Bashir, O., Ali, T., Baba, Z. A., Rather, G. H., Bangroo, S. A., Mukhtar, S. D., Naik, N., Mohiuddin, R., Bharati, V., & Bhat, R. A. (2021). Soil Organic Matter and Its Impact on Soil Properties and Nutrient Status. In *Microbiota and Biofertilizers, Vol 2* (pp. 129–159). Springer International Publishing. https://doi.org/10.1007/978-3-030-61010-4_7

Basnett, R. (2023). *ASSESSMENT OF SOIL QUALITY UNDER KINNOW*.

Bauder, T. A., Waskorn, P. L., & Davis, J. G. (2014). Irrigation water quality criteria (Fact Sheet No. 0.506 Crop Series). *Colorado State University Extension*, *0*, 10–13.

Bhandari, N. S., & Joshi, H. K. (2013). Quality of spring water used for irrigation in the Almora District of Uttarakhand, India. *Chinese Journal of Geochemistry*, *32*(2), 130–136. https://doi.org/10.1007/s11631-013-0615-5

Bolan, N. S., Curtin, D., & Adriano, D. C. (2005). ACIDITY. In *Encyclopedia of Soils in the Environment* (pp. 11–17). Elsevier. https://doi.org/10.1016/B0-12-348530-4/00173-9

Bouaroudj, S., Menad, A., Bounamous, A., Ali-Khodja, H., Gherib, A., Weigel, D. E., & Chenchouni, H. (2019). Assessment of water quality at the largest dam in Algeria (Beni Haroun Dam) and effects of irrigation on soil characteristics of agricultural lands. *Chemosphere*, *219*, 76–88. https://doi.org/10.1016/j.chemosphere.2018.11.193

Bouyoucos, G. J. (1962). Hydrometer method improved for making particle size analyses of soils 1. *Agronomy Journal*, *54(5)*, 464–465.

Bruce, R. C., & Rayment, G. E. (1982). *Analytical methods and interpretations used by the Agricultural Chemistry Branch for soil and land use surveys*.

Queensland Department of Primary Industries.

Cadraku, H. S., & Beqiraj, A. (2023). Assessment of water quality in Blinaja River Basin (Kosovo) using the Canadian Water Quality Index (WQI). *Journal of Survey in Fisheries Sciences*, *10*(1), 29–47.

Chemura, A., Kutywayo, D., Chagwesha, T. M., & Chidoko, P. (2014). An Assessment of Irrigation Water Quality and Selected Soil Parameters at Mutema Irrigation Scheme, Zimbabwe. *Journal of Water Resource and Protection*, *06*(02), 132–140. https://doi.org/10.4236/jwarp.2014.62018

Chen, W., Hou, Z., Wu, L., Liang, Y., & Wei, C. (2010). Evaluating salinity distribution in soil irrigated with saline water in arid regions of northwest China. *Agricultural Water Management*, *97*(12), 2001–2008. https://doi.org/10.1016/j.agwat.2010.03.008

Dhembare, J. (2012). Assessment of water quality indices for irrigation of Dynaneshwar dam. Ahmednagar, Maharashtra, India. *Archives of Applied Science Research*, *4 (1):348-*, 348–352.

DNR. (1997). *Salinity Management Handbook*. Department of Natural Resources.

Doneen, L. D. (1964). *Notes on water quality in agriculture*. Department of Water Science and Engineering, University of California.

E.Krista, & Bauder, J. W. (2009). *The Basics of Salinity and Sodicity Effects on Soil Physical Properties Information Highlight For The General Public*. 1–11. https://waterquality.montana.edu/energy/cbm/background/soil-prop.html

Evans, A. E., Mateo-Sagasta, J., Qadir, M., Boelee, E., & Ippolito, A. (2019). Agricultural water pollution: key knowledge gaps and research needs. *Current Opinion in Environmental Sustainability*, *36*, 20–27. https://doi.org/10.1016/j.cosust.2018.10.003

Eynard A, Lal R, W. K. (2003). Salt-affected soils. In *Encyclopedia of Soil Science 1–4*. http://www.dekker.com/servlet/product/DOI/101081EESS120006655%3E [accessed April 2024].

Fahad, S., Sönmez, O., Saud, S., Wang, D., Wu, C., Adnan, M., Arif, M., & Amanullah. (2021). Engineering Tolerance in Crop Plants Against Abiotic Stress. In *Engineering Tolerance in Crop Plants Against Abiotic Stress* (Issue February

2022). https://doi.org/10.1201/9781003160717

FAO. (1985). Water quality guidelines for agriculture, surface irrigation and drainage. *Food and Agriculture Organization*, *Vol. 1*, 29 pp.

Faria, J. M. S., Teixeira, D. M., Pinto, A. P., Brito, I., Barrulas, P., & Carvalho, M. (2021). Aluminium, Iron and Silicon Subcellular Redistribution in Wheat Induced by Manganese Toxicity. *Applied Sciences*, *11*(18), 8745. https://doi.org/10.3390/app11188745

Frene, J. P., Pandey, B. K., & Castrillo, G. (2024). Under pressure: elucidating soil compaction and its effect on soil functions. *Plant and Soil*. https://doi.org/10.1007/s11104-024-06573-2

Gangwar, P., Singh, R., Trivedi, M., & Tiwari, R. K. (2020). Sodic Soil: Management and Reclamation Strategies. In *Environmental Concerns and Sustainable Development* (pp. 175–190). Springer Singapore. https://doi.org/10.1007/978-981-13-6358-0_8

Ghazaryan, K., & Chen, Y. (2016). Hydrochemical assessment of surface water for irrigation purposes and its influence on soil salinity in Tikanlik oasis, China. *Environmental Earth Sciences*, *75*(5), 383. https://doi.org/10.1007/s12665-016-5287-0

Gholami, S., & Srikantaswamy, S. (2009). Analysis of Agricultural Impact on the Cauvery River Water Around KRS Dam. *World Applied Sciences Journal*, *6*(8), 1157–1169.

Hailu, B., & Mehari, H. (2021). Impacts of Soil Salinity/Sodicity on Soil-Water Relations and Plant Growth in Dry Land Areas: A Review. *Journal of Natural Sciences Research*, *12*(3), 1–10. https://doi.org/10.7176/jnsr/12-3-01

Hem. (1991). Laboratory instruments and analytical methods used for physical and chemical parameters analysis. *Environmental Chemistry*.

Ishiguro, M., & Koopal, L. K. (2016). Surfactant adsorption to soil components and soils. *Advances in Colloid and Interface Science*, *231*, 59–102. https://doi.org/10.1016/j.cis.2016.01.006

Ismail, E., Snousy, M. G., Alexakis, D. E., Abdelhalim, A., Ahmed, M. S., & Elsayed, E. (2023). Diagnosis of Groundwater Quality in North Assiut Province, Egypt, for Drinking and Irrigation Uses by

Applying Multivariate Statistics and Hydrochemical Methods. *Water*, *15*(15), 2812. https://doi.org/10.3390/w15152812

JAHANBAZİ, L., HEİDARİ, A., MOHAMMADİ, M. H., & KUNİUSHKOVA, M. (2023). Salt accumulation in soils under furrow and drip irrigation using modified waters in Central Iran. *EURASIAN JOURNAL OF SOIL SCIENCE (EJSS)*, *12*(1), 63–78. https://doi.org/10.18393/ejss.1186388

Kelly WP. (1940). Permissible composition and concentration of irrigated waters. *In: Proceedings of the ASCF, 607*.

Khalil, A. A., and Arther, V. (2010). Irrigation Water Quality Guidelines", Reclaimed WaterProject. *Jordan Valley Authority and German Technical Cooperation*.

Khodapanah, L., Sulaiman, W.N.A. and Khodapanah, N. (2009). Groundwater Quality Assessment for Different Purposes in Eshtehard District, Tehran, Iran. *European Journal of Scientific Research*, *Vol.36*, *No*, pp 543-553.

Kileo, E. P. (2000). Land Suitability Assesment of the Wami Plains in Morogoro, Tanzania with Respect to the Production of the Main Food Crops and Extensive Grazing. Sokoine University of Agriculture, Morogoro.

Koech, E. (2016). Effect of Irrigation Water on Soil Chemical Properties and Rain Water Harvesting in Isinya, Kajiado County. *September*, 59.

M. E. Essington. (2015). *Soil and water chemistry: an integrative approach*. CRC Press.

Maina, M. M., Amin, M. S. M., Aimrun, W., & Sani, I. (2012). Soil salinity assessment of Kadawa Irrigation of the Kano River Irrigation Project (KRIP). *Journal of Food, Agriculture and Environment*, *10*(3–4), 1028–1034.

Majeed, A., & Muhammad, Z. (2019). Salinity: A Major Agricultural Problem—Causes, Impacts on Crop Productivity and Management Strategies. In *Plant Abiotic Stress Tolerance* (pp. 83–99). Springer International Publishing. https://doi.org/10.1007/978-3-030-06118-0_3

Makoi, J. H. J. R., & Ndakidemi, P. a. (2009). The agronomic potential of vesicular-arbuscular mycorrhiza (VAM) in cereals– legume mixtures in Africa. *African Journal of Microbiology Research*, *3*(11), 664–675.

Malakar, A., Snow, D. D., & Ray, C.

(2019). Irrigation Water Quality—A Contemporary Perspective. *Water*, *11*(7), 1482. https://doi.org/10.3390/w11071482

Mikunthan, T., Nishanthiny, S. C., Thushyanthy, M., Barathithasan, T., & Saravanan, S. (2010). Irrigation Water Quality Based on Hydro Chemical Analysis, Jaffna, Sri Lanka Electro coagulation View project Identification of Alage View project Irrigation Water Quality Based on Hydro Chemical Analysis, Jaffna, Sri Lanka. *J. Agric. & Environ. Sci*, *7*(1), 100–102. https://www.researchgate.net/publication/263118906

Miller RW and Donahue RL. (1997). *Soils in our environment* (7th edn).

Misstear B, Banks D, C. L. (2006). *Appendix 3 FAO irrigation water quality guidelines. Water Wells and Boreholes*. FAO.

Moberg, J. (2001). *Soil analysis Manual (revised edition)*. The Royal Veterinary and Agricultural University, Chemistry Department.

Mohanavelu, A., Naganna, S. R., & Al-Ansari, N. (2021). Irrigation Induced Salinity and Sodicity Hazards on Soil and Groundwater: An Overview of Its Causes, Impacts and Mitigation Strategies. *Agriculture*, *11*(10), 983. https://doi.org/10.3390/agriculture11100983

Msanya, B.M; Wickama, J.M; Kimaro, D.N; Magoggo, J.P and Meliyo, J. L. (1996). *Investigation of the Investigation of the environmental attributes for agricultural development in Kitanda village, Mbinga District, Tanzania*.

Msanya N B. (2012). *Guide To General Rating of Some Chemical and Physical Soil*. 1–3.

Mulat, A., Ashenafi, H., & Gezai, A. (2018). Characterization and classification of salt affected soils and irrigation water in Tendaho sugarcane production farm, North-Eastern Rift Valley of Ethiopia. *African Journal of Agricultural Research*, *13*(9), 403–411. https://doi.org/10.5897/AJAR2018.12988

Naidu, M. V. S., Subbaiah, P. V., Krishna, Y. R., & Kaledhonkar, M. J. (2020). Evaluation of groundwater quality for irrigation in various mandals of Nellore District in Andhra Pradesh. *Journal of the Indian Society of Soil Science*, *68*(3), 287–296. https://doi.org/10.5958/0974-0228.2021.00005.0

NSS. (1990). *Laboratory procedures for routine soil analysis* (3rd ed).

Ministry of Agriculture and Livestock Development, National Soil Service (NSS), ARI, Mlingano.

Nyanza-District. (2013). *District development plan.*

Okalebo, J. R., Gathua, K. W., & Paul, L. W. (2002). Laboratory Methods of Soil and Plant Analysis: A Working Manual The Second Edition. *SACRED Africa, Kenya Any*, *SECOND EDI*, 1–131.

Omar, M. M., Massawe, B. H. J., Shitindi, M. J., Pedersen, O., Meliyo, J. L., & Fue, K. G. (2024). Assessment of salt-affected soil in selected rice irrigation schemes in Tanzania: understanding salt types for optimizing management approaches. *Frontiers in Soil Science*, *4*. https://doi.org/10.3389/fsoil.2024.1372838

Osman, K. T. (2018). *Management of soil problems*. Springer.

Oster, J. D., & Rhoades, J. D. (2018). *Water management for salinity and sodicity control. In irrigation with reclaimed municipal wastewater-A guidance manual* (1st Editio). CRC Press. https://doi.org/9781351073905

Oster, J. D., Sposito, G., & Smith, C. J. (2016). Accounting for potassium and magnesium in irrigation water quality assessment. *California Agriculture*, *70*(2), 71–76. https://doi.org/10.3733/ca.v070n02p71

Paliwal, K. (1967). Effect of gypsum application on the quality of irrigation water. *Madras Agric J 59*, 646–647.

Province, Helmand Ansari, A., Mukhlisin, M., Baba, A., & Krishna, L. S. (2021). Water Quality Assessment of Ground and River Water in Lashkar Gah city of Helmand Province, Afghanistan. *International Journal of Pharmaceutical Research*, *13*(01). https://doi.org/10.31838/ijpr/2021.13.01.313

Qadir, M., Schubert, S., Oster, J. D., Sposito, G., Minhas, P. S., Cheraghi, S. A. M., Murtaza, G., Mirzabaev, A., & Saqib, M. (2018). High-magnesium waters and soils: Emerging environmental and food security constraints. *Science of The Total Environment*, *642*, 1108–1117. https://doi.org/10.1016/j.scitotenv.2018.06.090

Rachel, P. (2010). *Effects of water quality on soil, plants and irrigation equipment*. Primary Industries and fisheries.

Ravikumar, P. (2014). Spatial distribution of macronutrients in soils of Markandeya river basin, Belgaum (d), Karnataka (s), India.

Proceedings of the International Academy of Ecology and Environmental Sciences, 4(2), 81.

Rawat, K. S., Singh, S. K., & Gautam, S. K. (2018). Assessment of groundwater quality for irrigation use: a peninsular case study. *Applied Water Science*, *8*(8), 233. https://doi.org/10.1007/s13201-018-0866-8

Renkou, X. U. (2018). *Scientific Issues and Controlling Strategies of Soil Acidification of Croplands in China Scientific Issues and Controlling Strategies of Soil Acidification of Croplands in China*. *33*(2).

RMA. (2024). *Climatology of Rwanda*. https://meteorwanda.gov.rw/index.php?id=30

Sahin, O., Taskin, M. B., Kaya, E. C., Atakol, O., Emir, E., Inal, A., & Gunes, A. (2017). Effect of acid modification of biochar on nutrient availability and maize growth in a calcareous soil. *Soil Use and Management*, *33*(3), 447–456. https://doi.org/10.1111/sum.12360

Sanchez, P. A., Palm, C. A., & Buol, S. W. (2003). Fertility capability soil classification: a tool to help assess soil quality in the tropics. *Geoderma*, *114*(3–4), 157–185. https://doi.org/10.1016/S0016-7061(03)00040-5

Senon, L. S., Saha, U. and Kissel, D. (1989). *Soil Salinity Testing, Data Interpretation and Recommendations* ([40] Szabo). The University of Georgia Agricultural and Environmental Services Laboratories; Cooperative Extension Circular 1019.

Shahinasi and Kashuta. (2008). Guidelines for interpretation of irrigation water quality. *Irrigation and Drainage Journal*.

Sharma, A., Rana, C., & Singh, S. (2016). Soil salinity causes,effect and management in Cucurbits. In *Handbook of cucurbits:Growth, Cultural Practices and Physiology* (p. 22). Saurabh singh.

Silva Neto, E. C. da, Pereira, M. G., Frade Júnior, E. F., Silva, S. B. da, Carvalho Júnior, J. A., & Santos, J. C. Dos. (2019). Temporal evaluation of soil chemical attributes after slash-and-burn agriculture in the Western Brazilian Amazon. *Acta Scientiarum. Agronomy*, *41*(1), 42609. https://doi.org/10.4025/actasciagron.v41i1.42609

Stewart, Z. P., Pierzynski, G. M., Middendorf, B. J., & Prasad, P. V. V. (2020). Approaches to improve soil fertility in sub-Saharan Africa. *Journal of Experimental Botany*, *71*(2), 632–641. https://doi.org/10.1093/jxb/erz4

46

Syed, A., Sarwar, G., Shah, S. H., & Muhammad, S. (2021). Soil Salinity Research in 21 st Century in Pakistan: Its Impact on Availability of Plant Nutrients, Growth and Yield of Crops. *Communications in Soil Science and Plant Analysis*, *52*(3), 183–200. https://doi.org/10.1080/00103624.2020.1854294

Tanji, K. K. (2012). Agricultural salinity assessment and management. *Scientific Publishers, (No. 71)*.

Tas, I., Yildirim, Y. E., & Gokalp, Z. (2022). *THE EFFECT OF EXCESSIVE SODIUM-CONTAINING IRRIGATION*. *11*(22), 19–28.

Tessema, N., Yadeta, D., Kebede, A., & Ayele, G. T. (2023). Soil and Irrigation Water Salinity, and Its Consequences for Agriculture in Ethiopia: A Systematic Review. *Agriculture (Switzerland)*, *13*(1), 1–19. https://doi.org/10.3390/agriculture13010109

Udo, E.J., Ibia, T.O., Ogunwale, J.A., Ano, A.A. and Esu, I. E. (2009). Manual of Soil, Plant and Water Analyses. In *Sibon Books Limited*.

USSL. (1954). *Diagnosis and improvement of saline and alkali soils. US Salinity Laboratory Staff, Hand Book 60.* United States Department of Agriculture.

USSL Staff. (1954). *Diagnosis and improvement of saline and alkali soils. USDA Handbook No 60 Washington DC, USA, 160 pp*.

Wali, S. U., Gada, M. A., Umar, K. J., Abba, A., & Umar, A. (2021). Understanding the causes, effects, and remediation of salinity in irrigated fields: A review. *International Journal of Agriculture and Animal Production*, *11*, 9–42. https://doi.org/10.55529/ijaap.11.9.42

Wali, S. U., Umar, K. J., Abubakar, S. D., Ifabiyi, I. P., Dankani, I. M., Shera, I. M., & Yauri, S. G. (2019). Hydrochemical characterization of shallow and deep groundwater in Basement Complex areas of southern Kebbi State, Sokoto Basin, Nigeria. *Applied Water Science*, *9*(8), 169. https://doi.org/10.1007/s13201-019-1042-5

Wantasen, S., Luntungan, J. N., Tarore, A. E., Lumingkewas, A., & Ogie, T. B. (2021). Study on the quality of irrigation water in the talawaan irrigation channel using the Sodium Adsorption Ratio (SAR) Method. *Journal of Physics: Conference Series*, *1918*(3), 032018. https://doi.org/10.1088/1742-6596/1918/3/032018

Wolka, K., Mulder, J., & Biazin, B. (2018). Effects of soil and water conservation techniques on crop yield, runoff and soil loss in Sub-Saharan Africa: A review. *Agricultural Water Management*, *207*, 67–79. https://doi.org/10.1016/j.agwat.2018.05.016

Zhang, Y.-Y., Wu, W., & Liu, H. (2019). Factors affecting variations of soil pH in different horizons in hilly regions. *PLOS ONE*, *14*(6), e0218563. https://doi.org/10.1371/journal.pone.0218563