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Pedological characterization and soil fertility assessment of the selected rice irrigation schemes, Tanzania

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Rice (*Oryza sativa* L.) is the second cereal food crop grown in Tanzania after maize (*Zea mays* L.) and covers approximately 18% of the agricultural land. Soil degradation due to intensive cultivation along with low organic matter input and nutrient imbalance has led to a decline in rice crop yields. This study was conducted to characterize, classify, and assess the fertility status of soils in two rice irrigation schemes of Morogoro region in Tanzania. The data obtained through this study will contribute significantly to land use planning and will facilitate the transfer of agro-technology and other development of the regions with similar ecological conditions. The studied pedons were named MKU-P1 and MKD-P1 for Mkula and Mkindo irrigation schemes, respectively. A total of seven composite soil samples (0–20 cm) were collected for soil fertility assessments. Landform, soil morphological features, parent material, natural vegetation, drainage, erosion, and laboratory data were used to classify the soils in their respective order as per the United States Department of Agriculture (USDA) Soil Taxonomy and the World Reference Base (WRB) soil classification systems. Results showed that the pedons were sandy clay loam in the topsoil and sandy clay to clay in the subsoil; soil reaction ranged from medium acid (pH 5.7) to strongly alkaline (pH 8.6). The topsoil and subsoil nutrients of the studied pedons including available K^+, total N, soil organic matter, and organic carbon are low. Based on the USDA Soil Taxonomy, MKU-P1 is classified as *Inceptisols cumulic humaquepts* and MKD-P1 as *Vertisols Fluvaquentic endoaquerts* corresponding to *Subaquatic fluvisols (loamic, oxyaquic)* and *Irragric vertisols (gleyic)* in the WRB, respectively. The pedons were ranked as suitable for rice production. However, the chemical fertility of the soil is ranked as low fertile associated with deficient in total N; available P, K^+, and Ca^{2+} with excessive iron and manganese; and likely to pose toxicity to crops. The application of organic and mineral amendments in recommended rates and timing for N and P is therefore essential to increase the nutrient content of these soils and minimize losses. Salinity in the subsurface pedon MKD-P1 needs to be taken into future consideration.

KEYWORDS

soil fertility, soil classification, paddy soils, pedons, soil health

1 Introduction

Soil classification and soil fertility assessments are fundamental disciplines and the basic features of modern agricultural technology (1, 2), and their vital purpose is to identify and quantify the soils and their ability to supply nutrients for plant growth and production (3). In comparison, land suitability assessment may be defined as an estimate of the land or soil to fit for specific crop production (4). It involves a wide range of criteria such as climatic factors, soil characteristics, and landforms to identify land use options and most suitable management solution for crop production (5, 6) and provides information related to the major factors of shortage in the production of a particular crop (7, 8). In quantitative approaches, several simulation modeling systems are used to evaluate land suitability and quantify the potential uses of land (9). FAO guidelines on land evaluation systems (10) and physical land assessment methods (11) are widely used for land suitability assessment and are adopted for the present study.

According to FAO (12), rice consumption in Africa is projected to reach 34.9 million tons by 2025. However, if the production trends continue to remain constant, the African countries will meet only two-thirds of the demand and more than 12 million tons will need to be imported annually corresponding to more than 5 billion USD (13). In Tanzania, productivity is estimated at 0.5–2.0 t ha^{-1} in the uplands rice production systems and at 4.5–6.0 t ha^{-1} in the lowland irrigated rice production system, which is far below the potential of 5 t ha^{-1} and 10–11 t ha^{-1} under proper resource endowment (14).

Previous studies carried out in some irrigated schemes of Tanzania showed that soil fertility degradation is one of the major threats facing rice production systems (15, 16), which is associated with the depletion of important nutrients such as nitrogen (N), phosphorus (P), potassium (K), sulfur (S), and zinc (Zn) (17, 18). The soils are also very low in organic carbon (OC), which is attributed to insufficient use of manure (19), topsoil erosion and leaching (20), and the deterioration of other physical soil properties (21). Therefore, the efficient management of soil is essential for ensuring proper rice production in the country (22).

Understanding soil characteristics and managing soil fertility are important to the sustainable use of soils (23), and they provide information on the soil type, fertility, and productivity (24–26), which are vital for livelihoods while maintaining food security and minimizing the risk of malnutrition (6, 19). Yet, in Tanzania, such information is still limited to specific zones of interest (27), and available information remains rather scanty relative to the large size of the country (28), particularly in lowland rice production systems (29). This makes farmers use inappropriate soil and water management options (1) and overdependence on agrochemicals as a key nutrient management option resulting in severe soil degradation and environmental pollution (30). Therefore, it is important to undertake various studies on soils to determine the appropriate management option for improved crop production (31). It is for this reason that the present study was conducted to characterize and classify the soils based on the USDA Soil Taxonomy and Tier-2 of the World Reference Base (WRB) for Soil Resources and assess the suitability and fertility status of the study areas for improved rice production.

2 Materials and methods

2.1 Description of the study areas

The study was carried out at Mkula and Mkindo irrigated schemes located in Kilombero and Mvomero districts, which lie between latitudes 8°14'28.93" S and 6°14'8.221" S and longitudes 36°20'5.71" E and 38°41'37.4928" E, respectively. The physiography and climate of the representative study sites are summarized in Table 1. Morogoro Region has a tropical savanna climate with a bimodal rainfall distribution pattern, having a dry spell separating the short rains between October and December and long rains between March and May (28). The mean annual rainfall and temperature in the Kilombero valley range from 1,200 to 1,400 mm and between 22°C and 23°C, respectively (32), and the mean annual rainfall and temperature in Mvomero range between 716.5 and 1,503.5 mm and 24°C–34°C, respectively (14). Both sites are characterized by a sandy clay loam topsoil, and clay contents increase toward the subsoil. Both sites are located within the agroecological zone E10 in the "*Eastern Plateaux and Mountain Blocks.*" The areas are mainly characterized by lowland irrigated rice production having two crop production patterns per year. The first pattern starts as long rains between February and June, and the second pattern is short rains between August and December. The sites receive sufficient water drained from the forest reservoir on the eastern side of Udzungwa Mountain for Mkula and the Wami basin for Mkindo. Figure 1 shows the location of the studied areas and representative sites of trials depicted on the generalized soil map of the Morogoro region of Tanzania and Figure 2 show the studied profile (MKU-P1 and MKD-P1).

2.2 Fieldwork and laboratory methods

A reconnaissance field survey using transect walks and an auger observation was done in both sites from July to August 2022 (Figure 3). Data on landform, soil morphological features (color, texture, consistency, structure, porosity, and depth), parent material, natural vegetation, drainage, slope gradient, elevation, erosion, and land use were recorded and filled in forms designed by the National Soil Service, Tanzania, adopted from the FAO Guidelines for Soil Description (33). The representative study sites were georeferenced by international coordinates using the Global Positioning System (GPS) (model GARMIN *etrex* 20), and, in each site, one representative soil profile pit was excavated to describe the characteristics of the soil. Soil color was determined using Munsell color charts (34). Disturbed soil samples were taken from designated pedogenic horizons, whereas undisturbed core soil samples were collected from three sections of the profile (0–5, 45–50, and 95–100 cm) for laboratory analysis. Using a soil auger, seven composite soil (0–20 cm depth) samples were collected from four sampling spots. The four subsamples collected from the sampling spots were mixed and quartered to obtain representative composite samples of 1 kg for laboratory analysis. In the Mkula irrigation scheme, the land was divided into three parts: the upper slope (MKU-U), middle slope (MKU-M), and lower slope (MKU-

TABLE 1 Physiography and climate of the representative study sites.

District	Kilombero District	Mvomero District
Village	Mkula Village	Mkindo Village
Date of survey	27/07/2022	10/08/2022
Location	Mkula irrigation scheme	Mkindo irrigation scheme
Pedon identification	MKU-P1	MKD-P1
Agro-ecological zone	*Eastern Plateaux and Mountain Blocks*	*Eastern Plateaux and Mountain Blocks*
Coordinates	7° 47' 57.084" S 36° 54' 47.592" E	6° 34' 11.64" S 37° 32' 29.112" E
Altitudes (m.a.s.l.)	296	361
Landform	Valley	Flat land
Slope gradient (%)	3%	2%
Cracks	Nd	Few cracks (1 cm)
Land use/Vegetation	Irrigated rice	Irrigated rice
Natural vegetation	55% grasses, 40% herbs, 3% bare ground, 1% trees, 1% shrubs	70% grass, 20% herbs, 10% bare ground
Natural drainage	Poorly drained	Moderately well drained
Flooding	Flooded approximately 3 months per year	Flooded approximately 3 months per year
Annual rainfall (mm)	1,200–1,400	716.5–1,503.5
Soil moisture regime (SMR)	Udic	Udic
Mean annual temperature (°C)	22–23°C	24–34°C
Soil temperature regime (STR)	Isohyperthermic	Isohyperthermic

L), while at the Mkindo irrigation scheme, the samples were taken at the upper slope (MKD-U), middle slope (MKD-M), lower slope (MKD-L), and at the valley (MKD-V).

Soil samples were collected and transported to the Sokoine University of Agriculture in Tanzania at Soil Laboratory for the determination of physical and chemical properties following standard procedures. Particle size analysis was done by the hydrometer method after dispersion with 5% sodium hexametaphosphate (35), Soil bulk density and moisture retention characteristics were done by drying undisturbed core soil samples at 105°C for 24 h (36). Soil pH

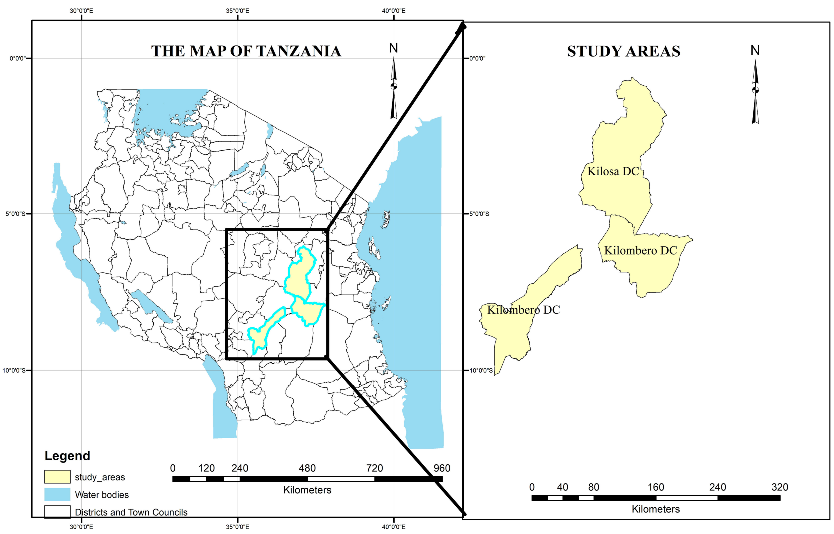

FIGURE 1
Location of the studied soil profile depicted on the generalized soil map of Mvomero and Kilombero districts—Tanzania (Source: Tanzania Government Printer).

FIGURE 2
Soil profiles excavated at Mkula (MKU-P1) and Mkindo (MKD-P1) villages in Kilombero and Mvomero districts—Tanzania.

and electrical conductivity were determined potentiometrically in soil-to-water suspension (1:2.5) and 1 N KCL (37). Soil OC was determined by the Walkley and Black wet oxidation method (38, 39). Extractable P was determined by a spectrophotometer (40). Total nitrogen was analyzed by the micro-Kjeldahl distillation method (37). Cation exchange capacity (CEC) was determined by the neutral ammonium acetate saturation method (NH4-Ac, pH 7.0) followed by Kjeldahl distillation (41). Exchangeable bases (K^+, Mg^{2+}, Ca^{2+}, and Na^+) were determined by the 1N NH4-Ac (pH 7.0) method. Mg and Ca were read by the UV-Vis spectrophotometer and K and Na by flame (42). Extractable micronutrients (Fe, Cu, Zn, and Mn) were extracted by diethylenetriamine pentaacetic acid (DTPA) and determined using atomic absorption spectroscopy (AAS) (43).

2.3 Soil classification and land suitability assessments

The first step in delineating land suitability for crop production was to identify the relevant climate, soil, and landscape of the areas (4, 5). In this study, field and laboratory data were used to classify and assess the suitability of the soils for rice production. The soils in each pedon were classified into their appropriate order, suborder, great group, and subgroup following the guideline of the USDA Soil Taxonomy (44) and tier-2 of the FAO World Reference Base for Soil Resources (45). The suitability assessments of the studied pedons were done by using simple limitation methods (46). The land diagnostic property was selected, and the corresponding levels of generalization were established related to the suitability classes through gradation matrices (47). Each pedon was assigned to a suitability class by matching the ecological and soil nutrient requirements for rice production (Table 2) (46). The group of land qualities considered for evaluation includes climate (c), topography (t), drainage characteristics (w), soil physical characteristics (s), and soil chemical fertility (f). The land suitability was ranked as S11 (96–100)—no limitation; S12 (86–95)—slight limitation; S2 (61–85)—moderate limitation; S3 (41–60)—severe limitation; N1 (20–40)—Very severe limitation that can be corrected; N2 (0–19)—very severe limitation that cannot be corrected. The overall soil suitability for rice production was assessed through the maximum limitation method where suitability is taken from the most limiting factor of soil characteristics (4, 47). The requirements of each kind of land use are obtained from Osinuga et al. (46) and Sys et al. (11). Table 3 show factor rating and rating values of soils.

2.4 Soil fertility assessments

Soil fertility was assessed using the soil fertility index (SFI) model (48–50). This procedure uses a numerical scale ranging between the highest value of 100 and the lowest value of 0 assigned to a particular characteristic of soil. If a characteristic was quite good for the intended crop, the highest rate of 100 was assigned to it, and, when it met some limitations, a lesser rate was assigned. The rating values were classified as per Saglam and Dengiz (49) (Table 4).

2.5 Correlation analysis

The relationship between the soil parameters was evaluated through correlation analyses using SPSS software.

3 Results and discussion

3.1 Soil morphological characteristics

Field survey involves soil observations (auguring and profiles) including topography; slope; and the nature of the parent materials, soil horizon depths, color, texture, vegetations, mottles, and soil biological activities. The key morphological properties of the profiles are shown in Table 1. The studied pedons show slight

TABLE 2 Soil suitability assessments classes for rice production.

Land qualities		S11 96-100	S12 86-95	S2 61-85	S3 41-60	N1 21-40	N2 0-20
Climate (C)	Annual rainfall (mm)	1,200–1,500	1,000–1,200	800–1,000	800	<800	<800
	No. of dry months	0–2	2–3	4–5	6–7	>7	>7
	Mean annual temp. (°C)	>25	22–25	20–22	18–20	<18	<18
	Relative humidity (%)	>75	70–75	65–70	60–65	<60	<60
Topography (T)	Slope gradient (%)	0–2	3–6	7–16	16–25	>25	>25
Wetness (W)	Drainage	Wd	Id	Md	Pd	Vpd	Vpd
	Flooding	F0	F0	F1	F1	F2	F2
Soil physical properties (S)	Soil depth (cm)	>100	75–100	60–75	50–60	<50	<50
	Surface texture	C, SCL	CL	SC, CL	SL, L	LS	S
	Gravel at 0–20 cm (%)	<2	2–4	5–15	16–30	30–35	>35
Chemical fertility (F)	pH (H_2O)	7.5–8.0	7.0–7.5	5.5–7.0	5.0–5.5	4.0–5.0	<4.0
	OC(%)	>5	3–5	2–3	1–2	<1	-
	TN (%)	>0.5	0.4–0.5	0.2–0.4	0.1–0.2	<0.1	<0.1
	Available P (mg/kg)	>10	7-10	4–6	2–4	<2	<2
	Exchange K (cmol/kg)	>0.6	0.4-0.6	0.2–0.4	0.1–0.2	0.05–0.1	<0.05
	CEC (cmol/kg)	>16	12-16	8–12	5–8	<5	-
	BS (%)	>75	75	50–75	35–50	<35	<35

Classes: S11 (96-100)—no limitation; S12 (86-95)—Slight limitation; S2 (61-85)—moderate limitation; S3 (41-60)—severe limitation; N1 (20-40)—very severe limitation that can be corrected; N2 (0-19)—very severe limitation that cannot be corrected (11, 46).

TABLE 3 Factor ratings and rating values of soil parameters.

Soil parameter	Factor rating				
	100	80	50	20	10
pH (1:2.5; soil: water)	6.5-7.5	7.6-8.5	5.5-6.4	4.5-5.4	<4.4->8.5
EC (dS m^{-1})	0-2	2.1-4	4.1-6	6.1-8	>8
SOM (g kg^{-1})	>30	20.1-30	10.1-20	5.1-10	0-5
TN (g kg^{-1})	>3.20	1.71-3.20	0.91-1.70	0.45-0.90	<0.45
P (mg kg^{-1})	>80	25.1-80	8.1-25	2.4-8.0	<2.5
Ca (cmol (+) kg^{-1})	17.6-50	5.76-17.5	1.19-5.75	>50	<1.19
Mg (cmol (+) kg^{-1})	>12.5	4.1-12.5	1.34-4.0	0.42-1.33	<0.42
K (cmol (+) kg^{-1})	0.29-0.74	0.75-2.56	0.13-0.28	>2.56	<0.13
Na (cmol (+) kg^{-1})	0-0.20	0.21-0.30	0.31-0.70	0.71-2.0	>2.0
Zn (mg kg^{-1})	0.71-2.41	2.4-8.0	0.2-0.7	>8	<0.2
Fe (mg kg^{-1})	2.1-4.5	1.1-2.0	0.2-1.0	>4.5	<0.2
Mn (mg kg^{-1})	15-50	4-14	50-170	>170	<4
Cu (mg kg^{-1})	>0.2				<0.2
Soil textural class	CL, SCL, SiCL	vfSL, L, SiL, Si	C, SC, SiC	SL, fSL	S, LS

Chemical property: EC, electric conductivity; SOM, soil organic matter; TN, total nitrogen; C:N, carbon-to-nitrogen ratio; P, phosphorus; SO_4-S, sulfate sulfur; Ca, calcium, Mg, magnesium; K, potassium; Na, sodium, CEC, cation exchange capacity; ESP, exchangeable sodium percentage; BS, base saturation; Zn, zinc; Fe, iron; Mn, manganese; Cu, copper.' Textural class: CL, clay loam; SCL, sandy clay loam; SiCL, silty clay loam; vfSL, very fine sandy loam; L, loam; SiL, silty loam; Si, silt; C, clay; SC, sandy clay; SiC, silty clay; SL, sandy loam; fSL, fine sandy loam; S, sand; LS, loamy sand. Source: (48–50).

TABLE 4 Classes and values of soil fertility index.

Class	Soil fertility index	Description
S1	>80	Good fertility
S2	80-51	Moderate fertility
S3	50-20	Marginal fertility
N	<20	Poor fertility

Source: (Saglam and Dengiz, 2014).

variation in drainage patterns, but the MKU-P1 pedon is poorly drained and very shallow (20 cm), while MKD-P1 is well drained and very deep (>160 cm). The soils are of friable moist consistency and are slightly hard to very hard when dry. Soil horizons were quite distinct in both pedons ranging from smooth clear, smooth diffused to gradual wavy with smooth horizon topography without any evidence of the rock outcrop and surface crusting throughout the profiles. However, few fine cracks were observed in the topsoil (1–10 cm) of the pedon MKD-P1. The topsoil color of the pedon MKU-P1 varies from gray (2.5Y5/1) when moist to dark gray (7.5YR4/1) when dried, and the subsoil color varies from light yellowish brown (2.5Y6/4) when moist to yellowish brown (10YR5/6) when dried with a predominance of a few fine to medium-yellowish mottles indicating the presence of reduced iron-oxide minerals probably due to the elluviation–illuviation process as a result of waterlogged conditions (51, 52). In MKD-P1, the topsoil color varies from dark brown (7.5YR3/2) when moist to very dark grayish brown (10YR3/2) when dried, and the subsoil varies from dark gray (5YR4/1) when moist to very dark-grayish brown (10YR3/2) when dried with very few faint to brownish-gray fine mottle characteristics of the vertisol soils that dry very rapidly when water saturation is minimized in the areas. Several researchers also observed the same trends of a distinct pattern of mottling associated with alternating conditions of the reduction and oxidation of sesquioxides of Al and Fe caused by seasonal waterlogging conditions (18, 23, 53). However, the observed waterlogging condition and soil structure of the pedons are favorable for the growth of the rice crops (46). Plant roots and a few earthworms were found in the studied pedons ranging from numerous fine roots and few earthworms in the topsoil and few fine roots in the subsoil.

3.2 Soil physical and chemical characteristics

Soil texture is an important characteristic that influences agricultural production, affecting crop selection, crop growth, soil moisture availability, erodibility, root penetration, and the movement of nutrients and water (54). Generally, the topsoil of both studied pedons had sandy clay loams and the sand contents decrease down the profiles, which may be due to the leaching of the finer particles as a result of an elluviation–illuviation process or washing out of the surface soil through erosion. The silt contents of the studied pedons did not show any regularity with depth and are low in all profiles compared to sand and clay. The pedon MKU-P1 has higher sand contents compared to MKD-P1. This result is consistent with observations by Kalala (18) that pedons were characterized by higher sand contents and an increase of clay with depth in the Kilombero valley. However, the subsoil of the pedon MKD-P1 has higher clay contents compared to MKU-P1. The silt–clay ratio is an indication of the susceptibility of the soils to detachment and transport that also depends on other properties like bulk density, soil organic matter, and climate (54). The silt–clay ratio of both studied pedons is higher (0.4) in top soils, which falls within the threshold level of 0.4 implying moderate resistance to erosion (54). The subsoil levels in all studied pedons fall below the threshold level of 0.4 (Table 5) indicating more susceptibility to weathering compared to the topsoil, probably due to the illuviation of clay contents that increases with depth (1, 23).

Soil bulk density describes the quality of the soils, and its information is crucial in the determination of soil compaction and root penetration (55). According to Landon (54), surface soils with bulk densities ranging from 1.1 to 1.4 Mg m^{-3} indicate that the soils are less compact and suitable for agricultural production. The pedon MKU-P1 has a lower bulk density value in the topsoil (0.8 Mg m^{-3}) and varies from 1.36 to 1.39 Mg m^{-3} in the subsoil. Also, the pedon MKD-P1 has lower bulk in the topsoil (1.14 Mg m^{-3}) and varies from 1.35 to 1.60 Mg m^{-3} in the subsoil. In both pedons, bulk density increases with depth (Table 6) and the values of the topsoil fall below the critical level of sandy loam for root restriction (1.8 Mg m^{-3}) indicating that the soils are favorable for rice growth (56). Similar trends of increasing bulk density with depth were observed by Lufega and Msanya (57) working on the soil units of Morogoro District and Msanya et al. (3) working on the soil of Dodoma City, Tanzania. The lower bulk density in the topsoil might be due to the tillage and decomposed organic materials in the areas. The topsoil total porosity of the study areas ranged from 5.95% to 68.24%. According to Landon (54), the topsoil with a total porosity of more than 40% is favorable for root penetration. In both pedons, total porosity decreases with depth, which is inversely correlated with bulk density. This indicates less compaction in the surface soils compared to the subsoil, which may be attributed to higher organic matter contents and tillage. According to Lipiec and Hatano (58), soil porosity and pore size distributions are important determinants of water, nutrients, and gaseous exchanges within and throughout the root zone.

Soil reaction (pH) is a very important chemical characteristic that may be used as a guide in assessing the suitability of soils for various stages of crop production (56). The pH of the study areas ranged from moderately acidic (5.75) to moderately alkaline (8.69). The MKU-P1 pedon has moderate acidity (5.7) in the topsoil, which increases the profile to slightly acidic (6.1–6.2). On the other hand, the topsoil of MKD-P1 has slight acidity (6.0), which also increases on moving the subsoil to moderately alkaline (8.1–8.6). The low pH (acidic) in the topsoil might be due to the leaching of some basic cations toward the subsoil leaving H^+ in the topsoil or the nature of the parent materials and the contribution of Fe^{3+} oxide reduction to H^+ consumption, which is far greater than the reduction of Mn^{4+}-Mn^{3+} oxides and $SO4^{2-}$ during the submerging (59). Guo et al. (60) reported that soil pH in paddy soil undergoes periodic changes during submergence, which is mainly attributed to the soil redox reactions. In each pedon, the value of $pH_{(H2O)}$ is higher than that of $pH_{(KCl)}$ (Table 5), an indication of a net negative charge in the soils (3).

TABLE 5 Selected physical properties of the studied pedons.

Pedons	Horizon	Depth (cm)	Sand (%)	Clay (%)	Silt (%)	Textural class	Bulk density (Mg m^{-3})	Porosity (%)	Silt-clay ratio	pH (H2O)	pH (KCl)	EC (dS/m)	OC (%)	TN (%)	C:N ratio	Bray-1. P (mg kg^{-1})	Oslen P (mg kg^{-1})
MKU-P1	Ap	0 – 23/28	61.68	27.04	11.28	SCL	0.84	68.24	0.40	5.75	4.89	0.07	2.60	0.31	8.6	7.85	nd
	Bg-1	28-51/58	55.68	33.04	11.28	SCL	1.36	48.63	0.34	6.21	5.03	0.07	1.94	0.18	10.7	1.42	nd
	Bg-2	58-89	47.68	39.04	13.28	SC	nd	nd	0.34	5.99	5.02	0.06	0.88	0.07	12.5	2.11	nd
	Cg	89-100+	55.68	37.04	7.28	SC	1.39	47.54	0.19	6.13	4.94	0.05	0.53	0.06	8.8	0.95	nd
MKD-P1	Ap	0-30	62.4	26.68	10.92	SCL	1.14	56.90	0.41	6.03	4.98	0.11	1.73	0.15	11.5	1.00	nd
	BssA	30-46/54	50.4	44.68	4.92	SC	1.35	48.90	0.10	8.10	7.01	0.6	1.25	0.06	20.8	nd	4.87
	Bss	54-110/120	38.4	56.68	4.92	C	1.60	39.62	0.08	8.69	7.09	0.9	0.91	0.09	10.1	nd	2.51
	Bg	160+	38.4	50.68	10.92	C	nd	nd	0.21	8.64	7.03	0.8	1.31	0.05	13.1	nd	2.80

S, sand; C, clay; L, loam; nd, not determined.

Electrical conductivity is a measure of water-soluble salts in the soil suspension such as Na^+, Ca^{2+}, and Mg^{2+}, which may be chlorides, sulfates, or carbonates; it is an indication of soil salinity (54). The values of EC in the topsoil of the study areas are very low and ranged between 0.1 and 0.07 dS/m. The topsoil values of exchangeable sodium percentage ranged between 2.5% and 6.1%, which falls below the range of sodic soils (less than 15%) (54). In MKU-P1, all values are below 15% indicating that the salinity effects of the area are negligible. However, in MKD-P1, the value increases toward the subsoil and ranges from 20.5% to 21.1%, which is sodic (56). According to Wakeel (61), soils with ESP ≥ 13 at the exchange sites but with low concentrations of total soluble salts (EC < 4 dS m^{-1}) are described as sodic soils, and those with highly soluble salt concentrations of EC ≥ 4 dS m^{-1} and ESP ≥ 13 are termed saline-sodic soils. Hence the subsoil of the pedon MKD-P1 is sodic. However, since the topsoil is not sodic, the soil is suitable for rice production. Conversely, care must be taken to reduce the amount of sodium in the subsoil that in the future might rise and dominate the topsoil or form a hard layer and cause poor infiltrations and drainage in the subsoil (27).

Soil OC is one part of the larger global carbon cycle that involves carbon cycling in the soils and atmosphere. It affects the physical, chemical, and biological properties of the soil such as water infiltration, water-holding capacity, nutrient availability, soil structure, bulk density, and the activity of soil microorganisms (62). Generally, soil OC in the study areas ranged from very low (0.53%) to high (2.60%) (54). The low to high OC could be due to the limited use of organic manure and the burning of rice straws, which is a vital organic source of nutrients in the rice cropping systems. The studied pedon MKU-P1 has higher (2.6%) topsoil OC compared to MKD-P1, which decreases to very low (0.53%) in the subsoil. In contrast, the pedon MKD-P1 was moderate (1.73%) in OC in the topsoil and decreases to low (0.91%) in the subsoil. It was observed that OC decreased the profile possibly due to the influence of fresh organic matter such as dead roots on the topsoil. However, the trend of decrease is not regular in MKDP-1 resulting in higher OC in the Bg horizon (1.3%) than that of the BssA horizon (1.2%). This may be due to the clay texture of the lower subsoil compared to the sandy clay texture, indicating that clay plays an important role in OC stabilization, particularly in the subsoil (63).

The total nitrogen of the studied pedons ranged from medium (0.31%) to very low (0.06%) (54, 56). The pedon MKUP-1 is higher in the total nitrogen of the topsoil compared to MKDP-1, which varies from medium (0.31%) to very low (0.06%) whereas that of MKD-P1 varies from low (0.15%) to very low (0.05%). The low observed nitrogen levels may be attributed to erosion, leaching, and continued nutrient mining by plants. According to Fageria et al. (53), in an anaerobic soil environment, the major part of N is lost through leaching and denitrification. However, the N loss can be supplemented by the N fertilizer and or manure application. The C:N ratio is a measure of the relative nitrogen contents of organic materials, and it is a good indicator of the quality of organic materials that are very useful tools in the prediction of organic matter mineralization (26, 64). The topsoil C:N ratio of the study areas ranged between 8.6 and 11.7, which are below and close to the guideline value of 10:1 indicating that soils have good-quality organic matter (54).

TABLE 6 Some exchangeable bases, micronutrients, and other related properties and the nutrient balance of the studied pedons.

Pedons	Horizon	Depth (cm)	Exchangeable bases (Cmol (+)/kg)						BSP	ESP	Nutrient balance				Micronutrients (Mg/kg)			
			Ca	Mg	Na	K	CECsoil	TEB	%		Ca/Mg	Ca/TEB	K/Mg	% (K/TEB)	Zn	Fe	Cu	Mn
MKU-P1	Ap	0 - 23/28	0.26	0.95	0.06	0.15	2.38	1.42	59.6	2.52	0.27	0.18	0.15	10.5	0.54	380.09	5.71	58.88
	Bg-1	28-51/58	0.32	1.20	0.06	0.17	2.98	1.75	58.7	2.01	0.26	0.18	0.14	9.71	0.41	117.25	4.55	29.79
	Bg-2	58-89	0.33	1.29	0.06	0.2	3.24	1.9	58.6	1.85	0.25	0.17	0.15	11.5	0.88	82.36	6.16	38.87
	Cg	89-100+	0.22	0.88	0.06	0.1	2.2	1.27	57.7	2.72	0.25	0.17	0.11	8.66	0.19	65.11	1.31	90.20
MKD-P1	Ap	0-30	3.01	1.06	0.70	0.26	11.4	5.0	44.1	6.1	2.82	0.59	0.24	5.14	0.62	241.06	2.39	95.26
	BssA	30-46/54	4.13	2.71	3.25	0.08	15.82	10.1	64.3	20.5	1.52	0.40	0.02	0.79	nd	20.32	1.33	10.71
	Bss	54-1010/120	3.83	3.64	5.23	0.06	24.80	12.7	51.4	21.1	1.05	0.30	0.01	0.43	nd	14.28	1.56	22.41
	Bg	160+	3.81	3.71	5.36	0.21	28.64	13.0	44.2	18.1	1.02	0.29	0.05	1.59	nd	2.75	1.15	14.05

TEB, total exchangeable bases; CEC, cation exchange capacity; ESP, exchangeable sodium percentage; BSP, base saturation percentage; nd, not determined.

The available P of the study areas ranged from very low (0.95 mg P/kg) to low 7.8 mg P/kg and falls within S3 and N1 classes indicating that soils have limited soil P that needs to be corrected for effective rice production (46). In MKU-P1, the P content of the topsoil is low (7.8 mg P/kg) and varies to very low (1.4–0.9 mg P kg^{-1}) in the subsoil. The pedon MKD-P1 has very low P throughout the profile (Table 7). According to Landon (54), P-values ranging from 5 to 7 mg P kg^{-1} are problematic for rice production. The low available P in the soils of the study areas may be due to low-phosphorus parent materials or P fixation and the formation of insoluble compounds of Ca^{2+} as a result of alkaline soils in the case of the MKD-P1 subsoil or Al and Fe compounds in acid condition for MKU-P1 and the topsoil of MKD-P1(65, 66). Uwitonze (24) and Haryuni et al. (67) reported that P availability to plants is strongly influenced by the pH of the soils and maximized when the soil pH is between 5.5 and 7.5.

The CEC is a measure of the ability of the soil to hold positively charged ions and is an important property in overall assessments of soil fertility (56). According to a rating by Landon (54) the CEC in the topsoil of the study areas ranged from very low (2.38 $cmol_{(+)}$ kg^{-1}) to low (11.4 $cmol_{(+)}$ kg^{-1}) (Table 8), an indication of poor fertility and being unsuitable for irrigated agriculture. The values of CEC in MKU-P1 are very low throughout the profile, while that of MKD-P1 varies from low in the topsoil (11.4 $cmol_{(+)}$ kg^{-1}) through a medium (15.82 $cmol_{(+)}$ kg^{-1}) to high 28.64 $cmol_{(+)}$ kg^{-1} in the subsoil. Generally, the CEC increases with depth in pedon MKD-P1, whereas in MKU-P1, the increase is less pronounced; this may be due to higher clay contents in the subsoil of MKD-P1 and higher pH values (68). The low CEC values, in MKU-P1, may be due to the leaching of some basic cations. According to McLean (69), leaching leads to higher H^+ in the soils; the H^+ replaces the basic cations from the exchange complex of the soils and built-up exchangeable acidity that begins to attack the mineral crystal releasing Al^{3+}. As some of the H^+ degenerate into the minerals increasing the pH, as a result, hydroxyl-Al ions are formed, which are chelated by organic matter or polymerized on the cation exchange sites of the soil minerals. Additionally, Landon (54) reported that CEC is lowest at the soil pH of 3.5–4.0 and increases as the pH is increased by liming; the positive charges retain anions (negatively charged ions) such as chloride (Cl^-) and sulfate (SO_4^{2-}).

The exchangeable cations of the studied pedons ranged from very low (0.22 cmol $_{(+)}$ kg^{-1}) to medium (4.13 $cmol_{(+)}$ kg^{-1}) (Table 8). The pedon MKU-P1 is low in Ca^{2+} throughout the profile compared to MKD-P1 (56). Exchangeable Mg^{2+} in both pedons is high ranging from 0.88 to 3.64 $cmol_{(+)}$ kg^{-1} (54). The soil K^+ reserve and its availability to plants are vital in determining the K-supplying capacity of soils (70). The concentration of K^+ in both topsoils and subsoils was low and ranged from 0.06 to 0.26 $cmol_{(+)}$ kg^{-1} in the two pedons (54). Wakeel (61) reported that K^+ concentration in soils depends on clay minerals and other exchangeable cations, especially Ca^{2+}, Mg^{2+}, and Na^+. High concentrations of these cations in irrigated soils lead to K^+ desorption, leaching, and even loss from the soil profile. Low K^+ in soils might be due to low K^+ inherent parent materials and/or excessive use of N and P fertilizers with insufficient K^+ application.

The base saturation percentage (BSP) is defined as the sum of basic cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+) over the total cation

TABLE 7 Summary of morphological and diagnostic features of the studied pedons.

Pedons	Diagnostic horizons USDA	Other features: USDA Soil Taxonomy (Soil Survey Staff, 2006)	Diagnostic horizons, properties and materials (WRB, 2006)
MKU-P1	Mollic epipedon; Cambic horizon	Valley, very shallow, sandy clay loam, slightly to medium acid, udic SMR, redoximorphic features, many fine mottles, isohyperthemic STR	Mollic horizon, glayic, redoximorphic.
MKD-P1	Mollic epipedon, vertic horizon	Almost flat, very deep, sandy clay loam to clay, medium acidic to medium basic, isohyperthemic, and many fine surface cracks, and slickensides.	Vertic, irragric horizon, shrink-swell cracks, very hard dry consistency.

exchange capacity (71). It is an important chemical property in soil classification and soil fertility assessments that influences soil structure stability, nutrient availability, soil pH and soil response to fertilizers, and other soil amendments (25, 72). The values of the BSP in the topsoil of the study areas are moderate and ranged between 44.1% and 59.6% (54). According to Hazelton and Murphy (56), the soils with base saturation below 30% indicated strongly leached soils and the ones with BSP above 70% indicated very weakly leached soils. The individual pedon has the following BSP: The pedon MKU-P1 has a medium BSP throughout the profile that varies from 59.6% in the topsoil and decreases the profile to 57.7% (Table 6). Munsell Color (Firm), (2019) (34) reported that soils with low base saturation levels of <60% may result in very acidic soils and potentially toxic cations such as Al and Mn. The BSP in the topsoil of the pedon MKD-P1 is moderate (44.1%) but varies from high (64.3%) to moderate (44.2%) in the subsoils. The moderate BSP in both pedons might be due to poor cultivation practices, poor soil and water conservation, and an inadequate supply of fertilizer. The higher BSP in the subsoil of the pedon MKD-P1 might be due to the higher level of sodium concentration since, according to Landon (54), the base saturation percentage does not distinguish between different bases and imbalance may cause nutrition problems. However, based on descriptions picked from Osinuga et al. (46), all values of the BSP in the studied pedons are classified as suitable for rice production.

In assessing the soil requirement for plant nutrients, the relationship that exists between certain ions (Ca^{2+}, Mg^{2+}, and K^{+}) and their balanced ratio must be determined to ensure proper plant growth (18). The exchangeable cations in the study areas have different trends of bases. In MKU-P1, the basic cations follow this trend of Mg > Ca > K > Na, while the trend in MKD-P1 is $K^{+} > Ca^{2+} > Mg^{2+} > Na^{+}$ (Table 8). The result of the pedon MKU-P1 is consistent with Kalala (18), working on the soils of the Kilombero valley, who also observed higher Mg^{2+} in the soils. In both pedons, the Ca/TEB ratio is below 0.5 throughout the profiles indicating that Ca^{2+} has no effects on the uptake of other cations such as K^{+} and Mg^{2+} (31). The Ca/Mg ratio in the studied pedons ranges from 0.25 to 2.82, and all are within favorable levels (1.2–5.2) for crop production (1, 23). The Mg^{2+}/K^{+} ratios in pedons MKU-P1 and MKD-P1 vary from 0.11 to 0.15 and 2.1 to 5.09, respectively. Based on the rating by Landon (54), all Mg^{2+}/K^{+} ratios of the pedon MKU-P1 are within the favorable level for rice production. However, the topsoil of the pedon MKD-P1 and the last subsoil is above the critical level (1–4), implying potential nutrient imbalance and toxicity, hence causing Mg^{2+} deficiency due to a higher K level. According to Landon (54), the minimum level of the K/TEB ratio is 2% to avoid K^{+} deficiency and above 25%, which is rare to occur; the soils will have similar effects to high Na. The K/TEB ratio of the studied pedons ranges from favorable (9.71%) to unfavorable (55.4%). All values of K/TEB in MKU-P1 fall within the favorable levels, and those of MKD-P1 fall within the unfavorable levels (Table 10). This finding indicated that the levels of K in the pedon MKD-P1 have nutrient imbalance and the K^{+} level may induce the deficiency of other cations such as Ca^{2+} and Mg^{2+}.

The value of Cu of the studied pedons ranged from 1.15 to 5.7 mg kg^{-1} which is under the sufficient level of 0.2 mg kg^{-1} for optimum plant growth (54, 73). The topsoil Zn levels ranged from 0.5 to 0.6 mg kg^{-1}. Based on categorization by Landon (54), both Zn levels fall within the sufficient range of 0.5 mg kg^{-1} for rice growth. However, the studied pedon MKD-P1 has a low level of Cu

TABLE 8 Classification of the studied pedons.

Pedons	USDA Soil Taxonomy					FAO-WRB Soil Classification	
	Order	Suborder	Great group	Subgroup	Family	Reference Group- Tier 1	Tier-2 WRB Soil name
MKU-P1	Inceptisols	Aquerts	Humaquepts	Cumulic Humaquepts	*Flat, very shallow, sandy clay loam, slightly to medium acid, udic SMR, isohyperthemic STR,* Cumulic Humaquepts	Fluvisols	Subaquatic Fluvisols (loamic, oxyaquic)
MKD-P1	Vertisols	Aquerts	Endoaquerts	Fluvaquentic endoaquerts	Very deep, moderately alkaline, sodic, udic, isohyperthemic, Fluvaquentic endoaquerts	Vertisols	Irragric vertisols (glayic)

throughout the subsoil that was below the detection limit. All values of Fe (2.75–380.09 mg kg^{-1}) and Mn (10.71–95.26 mg kg^{-1}) were within the sufficient range for plant growth (23, 54).

3.3 Soil classification

Based on field and laboratory data, the pedons were classified according to the family level of the USDA Soil Taxonomy and Tier-2 of the WRB (44, 45). The diagnostic horizons, diagnostic properties, and other diagnostic materials are shown in Table 7. The soil of the pedons of MKU-P1 is classified as *Inceptisols* per the USDA and *Fluvisols* in FAO-WRB soil classifications with *Mollic epipedon* having redoximorphic features and *glayic properties* as a result of frequent irrigation and flooding. The soil of the pedon MKD-P1 is classified as *Vertisols* in both USDA and FAO-WRB soil classifications having *vertic horizons* with shrink–swell cracks in the upper horizon and very hard consistency. The details of classifications are shown in Table 8.

3.4 Soil-site suitability for rice production

The suitability of land for rice crop production was assessed based on climatic and physiochemical properties that represent the fertility states of the soil (Table 9). The slopes and climatic conditions of the study areas are rated as highly suitable for rice production (S11) in terms of rainfall, and temperature while drainage is rated S3 for MKU-P1 and N for MKD-P1. The textural classes of the topsoil are sandy clay loam and sandy clay, or clay in the subsurface horizons is rated as S11 in both pedons. The base saturation is rated as S11 for the pedon MKD-P1 and S2 for MKU-P1. The pedon MKU-P1 is low in CEC ($cmol_{(+)}$ kg^{-1}) and low exchangeable K^+ that is rated within N1 and S3, while the pedon MKD-P1 is rated within S12 for both CEC ($cmol_{(+)}$ kg^{-1}) and exchangeable K^+. The land included in these classes of CEC has certain fertility limitations that reduce crop performances unless appropriate nutrient management is taken into consideration (47). Using the FAO land suitability evaluation based on climate and topography the areas were potentially suitable for rice production (11, 46) with soil fertility limitation factors such as total N and available P, K^+, and Ca^{2+} that might be due to poor agricultural practices associated with low organic matter application, nutrient imbalance, inappropriate water management, and increased carbon release (6, 74). These results were consistent with other studies carried out in some rice irrigation schemes in Tanzania (17, 75, 76). The areas can be ameliorated through the management strategies of applying inorganic and organic fertilizers with good agricultural practices (77–79).

3.5 Soil fertility status of the study areas

The textural classes of the studied pedons ranged from sandy clay for MKU-S1 and MKU-S3, sandy loam for MKU-S2 and MKD-S1, and sandy clay loam for MKD-S2, MKD-S3, and MKD-S4. Based on rice requirements, all textural classes are favorable for rice production (46). The pH of the surface soils of the pedon MKU-P1 is very

TABLE 9 Soil suitability classes of the studied pedons.

Land Qualities		MKU-P1	MKD-P1
Climate (C)	Annual rainfall (mm)	(S11)	(S11)
	No. of dry months	(S2)	(S2)
	Mean annual temp. (°C)	(S11)	(S11)
	Relative humidity (%)	(S11)	(S11)
Topography (T)	Slope gradient (%)	(S11)	(S11)
Wetness (W)	Drainage	(S3)	(N1)
	Flooding	(F0)	(F0)
Soil physical properties (S)	Soil depth (cm)	(S12)	(S11)
	Surface texture	(S11)	(S11)
	Gravel at 0–20 cm (%)	(S11)	(S11)
Chemical fertility (F)	pH (H_2O)	(S2)	(S11)
	OM (%)	(S3)	(S2)
	TN (%)	(S2)	(S3)
	Available P (mg kg^{-1})	(S12)	(N1)
	Exchange K ($cmol_{(+)}$ kg^{-1})	(S3)	(S12)
	CEC ($cmol_{(+)}$ kg^{-1})	(N1)	(S12)
	BS (%)	(S2)	(S11)

S11 (96–100)—no limitation; S12 (86–95)—slight limitation; S2 (61–85)—moderate limitation; S3 (41–60)—severe limitation; N1 (20–40)—very severe limitation that can be corrected; N2 (0–19)—very severe limitation that cannot be corrected.

TABLE 10 Chemical and physical properties of the surface soils of the study areas.

Pedons	MKU-P1			MKD-P1			
Sampling sites	MKU-U	MKU-M	MKU-L	MKD-U	MKD-M	MKD-L	MKD-V
Sand %	37.04	19.04	35.04	80.4	60.4	56.4	72.4
Silt %	17.28	9.28	13.28	2.92	6.92	8.92	4.92
Clay%	37.04	19.04	35.04	16.68	32.68	34.68	22.68
Texture class	SC	SL	SC	SL	SCL	SCL	SCL
$pH_{(H2O)}$	4.83	4.80	4.62	4.78	6.92	6.03	5.35
$pH_{(KCl)}$	4.52	4.48	4.50	4.10	5.79	4.94	4.49
EC	0.06	0.06	0.09	0.057	0.18	0.076	0.364
OC %	1.79	1.35	1.93	1.89	1.28	1.69	2.17
TN%	0.07	0.33	0.24	0.07	0.19	0.19	0.22
Avail. P (mg/kg)	2.45	7.74	0.68	8.38	1.26	2.05	8.80
Na^+	0.08	0.06	0.07	0.01	1.28	0.77	1.21
K^+	0.18	0.15	0.18	0.23	0.13	0.06	0.06
Ca2+	0.34	0.19	0.34	1.09	3.21	3.30	2.52
Mg^{2+}	1.25	0.55	1.07	0.41	1.35	1.31	0.77
CEC(cmol/kg)	3.22	1.6	2.76	5.78	10.84	12.78	10.22
BS (%)	57.45	59.37	60.14	99.25	97.95	99.56	93.35
ESP	2.484	3.75	2.536	1.11	11.8	6.004	11.89
Ca/Mg	0.27	0.34	0.31	2.65	2.37	2.52	3.26
Zn	0.95	1.06	0.38	1.03	0.37	0.12	2.37
Cu	6.92	5.86	4.28	0.97	2.62	2.81	1.40
Mn	21.45	49.66	11.56	30.83	56.96	73.29	37.23
Fe	234.05	333.86	251.23	156.16	138.85	180.27	254.92

U, upper; M, middle; L, lower; V, valley.

strongly acidic and varies from pH 4.62–4.83 while the pH of MKD-P1 ranged from very strongly acidic (4.78) to neutral (6.9). Results indicated that 100% of the surface soils in pedon MKU-P1 and 25% for MKD-P1 were low in pH falling within the N class indicating low fertility. The low pH might be due to the leaching of basic cations, resulting in a high concentration of hydrogen ions, manganese, and aluminum on soil colloids (80). Soils with low pH (<5.5) are potentially great for Mn, Al, and Fe toxicity and the deficiency of some essential nutrients, hence poor soil fertility (53). The OC of the surface soils ranged from moderate (1.28%) in the MKD-S2 pedon to

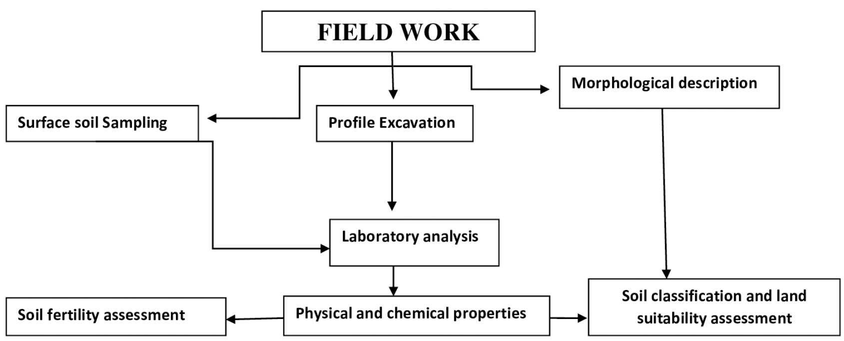

FIGURE 3
Flowchart of the methodological approach used in the study.

high (2.17%) in the MKD-S4 pedon (57). In both pedons, OC increases down the slope, and this may be associated with the erosion of organic materials from the upper to lower slope. The low OC in the studied areas might have resulted from poor management techniques of organic matter by poor farming practices (81). Kalala (18) observed similar trends of low OC in the Kilombero valley and related this with increasing soil CEC and activity of soil microbes. Integrating organic materials can contribute to replenish fertility levels, thereby enhancing mineralization and the release of essential plant nutrients (48–50). Merumba et al. (23) reported that the critical level of N that would support the growth of the majority of crops in Tanzanian soils is 2.0 g kg^{-1}. The low nitrogen in the studied pedons could be associated with low N fertilizer input, erosion, and volatilization due to the anaerobic environments of the soils (82, 83). The phosphorus of the surface soils varies from very low (0.68 mg kg^{-1}) in MKU-S3 to low (8.8 mg kg^{-1}) in MKD-S4. Based on P requirements, 66.6% and 50% of the soils were classified as poor in fertility (N), and 33.3%–50% were classified as marginal in fertility (S3) in MKU-P1 and MKD-P1 pedons, respectively. The low P content in the studied soils might be due to the low inherent P of the parent rocks and P fixations with Al and Fe as a result of the low pH of the soils (84). According to Landon (54), the low P level in soils can be corrected by the application of both inorganic and organic fertilizers. However, organic matter improves soil pH and enhances P availability (23). Based on cation exchange capacity, 100% of the surface soils in both pedons have Mg^{2+} concentration below the required level for fertile soils that fall within the N class indicating poor fertility (48–50). The concentrations of Ca^{2+} in all soils of the pedons MKU-P1 and only 25% of the MKD-P1 soils ranked within the N class, indicating poor fertility. The remaining 75% of the soils in MKD-P1 are within the S3 class, suggesting a marginal fertile status. In both pedons, the exchangeable sodium percentage of the surface soils is less than 13, indicating that the soils are not sodic (61).

Extractable Zn contents in the soils of the pedon MKU-P1 varied from 0.38 mg kg^{-1} in MKU-S3 to 1.06 mg kg^{-1} in MKU-S2, while that of MKD-P1 soil varies from 0.12 mg kg^{-1} in MKD-S3 to 2.37 mg kg^{-1} in MKD-S4 (Table 15). The critical level for Zn deficiency in the soil is 0.4–0.6 mg kg^{-1}, and values higher than 10–20 mg kg^{-1} are regarded as excess (85). The results show that 66.6% and 50% of soils are ranked as S1, while 33.3% and 50% are ranked as N in MKU-P1 and MKD-P1 pedons, respectively, indicating adequate and deficient Zn levels. The surface soils in both sites are high in extractable Fe (>4.5 mg kg^{-1}), falling within the N classes (80). The high extractable Fe may be due to the nature of the parent materials, which are siliceous and ferruginous with low Mg and K contents (23). According to Hazelton and Murphy (56), Fe concentration (>400 mg kg^{-1}) is associated with toxicity and its management is vital to minimize nutrient loss. Management techniques include the use of organic matter, inorganic fertilizer, and liming of soils with $CaCO_3$ and or $MgCO_3$ or $CaMg(CO_3)$ to increase pH (23). The extractable Cu of the surface soils ranges from 4.28 to 6.92 mg kg^{-1} and 0.97 to 2.81 mg kg^{-1} for MKU-P1 and MKD-P1, respectively. The concentration of Cu is 0.2 mg kg^{-1}, which is above the required amount for plant growth (54). Extractable Mn ranges from 11.56 to 73.29 mg kg^{-1}; according to the rating by Saglam and Dengiz (49), with exception of MKD-S3, all other soils are sufficient in Mn (15–50 mg kg^{-1}), falling within S1 class of fertile soils. These results are in agreement with Bissah et al. (86); Dai and Dong (87), and Kouadio et al. (71) who demonstrated a rapid decline in soil chemical fertility following intensive cultivation with inappropriate use of organic matter and suggested that for effective soil fertility improvement plans, the sole application of a mineral fertilizer is unlikely to succeed.

4 Conclusions and recommendations

The objective of this study was to classify and investigate the suitability and fertility of two lowland rice irrigation schemes in Morogoro region, Tanzania. The results of the study revealed that both studied pedons were ranked as suitable for rice production. However, some chemical fertility such as total N, available P, OC, and exchangeable bases were in a state of degradation and less favorable for rice production. The areas will benefit if proper soil fertility management practices will be employed with the following recommendations:

i. The application of the nitrogen fertilizer such as urea in 100 kg N ha^{-1} in split application to avoid severe nitrogen loss.
ii. The application of the P fertilizer such as diammonium phosphate, and triple super phosphate at a rate of 30 kg P ha^{-1} at a time of rice transplanting.
iii. Avoid burning straws and incorporate them into the soils together with the application of organic manure to improve soil OC, which will aid in improving CEC and soil health.
iv. iv. Improving drainage systems in the areas enhances the removal of irrigated water and minimizes the salinity stress that may develop from the subsoil.
v. Crop rotation with legumes improves soil fertility by nitrogen fixation and minimizes rice diseases.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

This work was carried out in collaboration among all authors. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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