
Pedological Characterization of Some Typical Alluvial Soils of Kilombero District, Tanzania

Asheri Mwamba Kalala^{1,2,*}, Balthazar Michael Msanya¹, Nyambilila Abdallah Amuri¹, Johnson Mashambo Semoka¹

¹Department of Soil and Geological Sciences, College of Agriculture, Sokoine University of Agriculture, Morogoro, Tanzania

²Tumbi Agricultural Research Institute (ARI-Tumbi), Tabora, Tanzania

Email address:

asherikalala@yahoo.com (A. M. Kalala), bmmsanya@gmail.com (B. M. Msanya), semoka@yahoo.com (J. M. Semoka), amurnyambilila@yahoo.com (N. A. Amuri)

*Corresponding author

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Abstract: This study was carried out in Kilombero District, Tanzania with the objective of characterizing the soils in terms of their morphology, genesis, physico-chemical properties and classification. Three pedons KISA-P1, MKU-P1 and MBA-P1 were identified within the Kilombero Valley, dug, described and sampled. Disturbed and undisturbed soil samples were taken from designated pedogenic horizons for physical and chemical analysis in the laboratory. Using both field and laboratory data soils were classified using both USDA Soil Taxonomy and World Reference Base for Soil Resources schemes of classification. Results show that the three pedons were developed under *Isohyperthermic* temperature and *Aquic* moisture regimes. All pedons were deep (100 - 120 cm). Whereas Pedons KISA-P1 and MBA-P1 had sandy clay loam topsoils overlying sandy clay subsoils, Pedon MKU-P1 had clayey texture throughout its profile depth. All pedons had low chromas of ≤ 3 and redoximorphic features in form of abundant mottles particularly in the subsoils. Topsoils of Pedons KISA-P1 and MBA-P1 had dominantly friable to very friable moist consistence while those of Pedon MKU-P1 had very firm moist consistence. Subsoil moist consistence varied from firm to extremely firm (Pedons KISA-P1 and MKU-P1) and from friable to very firm (Pedon MBA-P1). Structures were dominantly weak to moderate subangular blocky in all studied soils but some horizons were structureless single grained and massive. Soil reaction ranged from extremely acid (topsoil of MBA-P1) to mildly alkaline (subsoil of MKU-P1) with pH values of 4.44 and 6.73 respectively. Topsoil organic carbon and total nitrogen contents in the studied pedons were low (0.66 to 1.4%) and very low to low (0.08 to 0.19%) respectively. CEC_{soil} values were rated as low to medium ranging from 8.4 to 23.8 cmol (+)/kg respectively in Pedon KISA-P1 and Pedon MKU-P1. Percent BS values varied between and within studied pedons and ranged from low < 50% to high > 50%. Studied soils manifested nutrient imbalances in respect of basic cations. On the overall, fertility of the studied soils was rated as low to medium. According to USDA Keys to Soil Taxonomy, Pedons KISA-P1 and MKU-P1 classified as *Inceptisols*, equivalent to *Cambisols* in WRB for Soil Resources whereas Pedon MBA-P1 classified as *Entisols* equivalent to *Fluvisols*. All three sites were recommended for paddy production.

Keywords: Physico-Chemical Properties, USDA Soil Taxonomy, WRB, Pedons, Kilombero District, Tanzania

1. Introduction

Pedological characterization is very important in providing valuable information and knowledge on soil characteristics. It gives clear understanding of soil genesis, morphology, classification and spatial distribution of soils in an area [1, 2].

There are several soil forming factors, which influence the morphology of a given soil, including climate, parent material, biota, relief and time [1]. The study area Kilombero Valley is located in Ulanga and Kilombero Districts of Morogoro Region, Tanzania. The valley lies at the foot of the Great Escarpment of East Africa and has a total length of 250 km and a width of up to

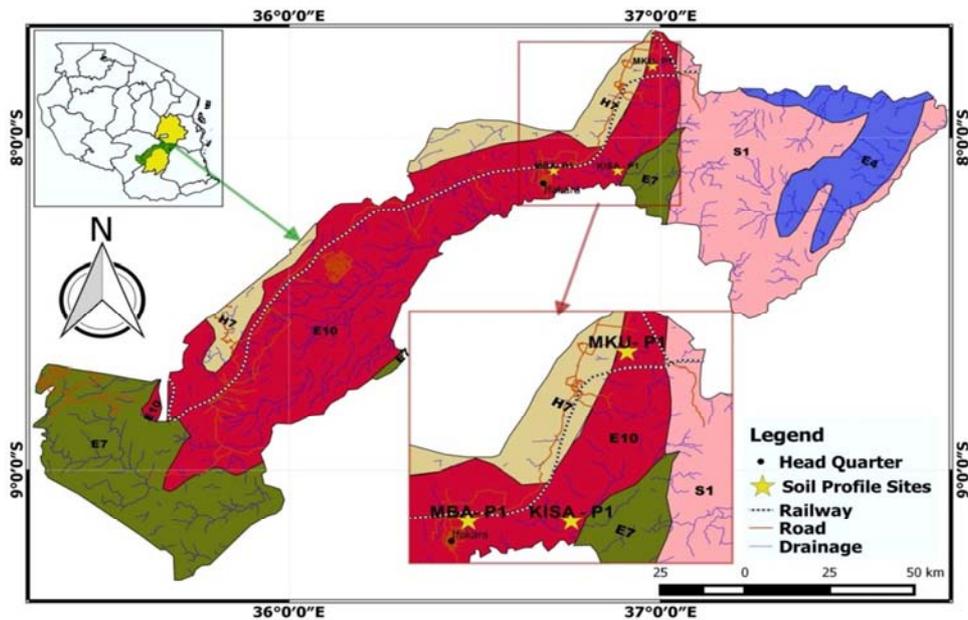
65 km, covering an area of about 11,600 km² [3, 4]. The soils of the valley comprise alluvial materials deposited by floods, which occur during rainy season. Declining soil and crop productivity is a major problem facing smallholder farmers (particularly rice producers) in Kilombero, Tanzania [5, 6] and this is contributed by continuous cropping without addition of adequate external soil fertility inputs [4, 7]. Recent studies have confirmed that deficiency of some macronutrients like nitrogen, potassium, phosphorus and sulphur is a major problem in many soils of Kilombero Valley [6, 8, 9]. In dealing with the deficiencies, understanding of soil genesis, morphology and other key properties is inevitable to allow sustainable use of the soil resources. Hence thorough knowledge about the soils is essential [10]. Most research works in Kilombero Valley were conducted on the basis of studying topsoils to about 20-30 cm depth and recommendations were made in respect of topsoil characteristics [6, 8, 9]. Yet, soil fertility specialists engaged in transferring agronomic technologies from one area to another require well characterized data of the entire pedon including the subsoil [2]. With regard to availability of such information in Tanzania, there is a big gap between need for pedological soil characterization and actual work that has already been done [2]. It was reported that only 3% of Tanzanian soils were mapped and characterized in sufficient detail [10]. The existing national soil-terrain (SOTER) inventory was produced at a scale of 1: 2 000 000 and this is mostly suitable for planning at national level and not practical for fertilizer and agronomic studies [11]. Efforts have been made by several researchers to map and classify soils in various ecologies in Tanzania [2]. However, not much is known about soils of Kilombero Valley in sufficient detail to allow ranking of their potential for various agricultural and non-agricultural uses and for transferring of technology to other areas with similar ecological conditions in Tanzania. Therefore, this study aimed at characterizing and classifying typical soils of Kilombero Valley according to Keys to Soil

Taxonomy and the WRB for Soil Resources, to provide the needed data for land use planning and for making appropriate agronomic recommendations.

2. Materials and Methods

2.1. Description of the Study Area

The study was carried out in Kilombero District, Tanzania (Figure 1) with representative soil pedons KISA-P1, MKU-P1 and MBA-P1 in Kisawasawa, Mkula and Mbasa Wards, respectively. The three pedons are developed within the Kilombero Valley, which is a vast floodplain, between the Kilombero River in the south-east and the Udzungwa Mountains in the north-west. The valley is constituted by a series of flat alluvial plains with complex sedimentation pattern, subject to regular flood from braiding rivers originating from the Udzungwa Mountains [12]. The three sites are located in agro-ecological zone E10, within the “Eastern Plateaux and Mountain Blocks” physiographic unit with an area of about 6,253 km² [13]. Table 1 presents the salient features of the study sites. The soil parent materials of the area are dominantly alluvium derived from metamorphic rocks (mainly gneisses, quartzites and schists) of the Udzungwa Mountains. Whereas rainfall recorded at Kilombero Sugar Estate Weather Station for 20 years (between 1996 and 2015) for the sites at Mkula and Kisawasawa have an average total of 1378 mm with the peak (308.4 mm) in April (Figure 2). [4] Reported an average total rainfall value of 1200 mm for Kilombero District. The average minimum and maximum temperatures for 20 years were 20.5 and 31.6°C, respectively. All pedons have an isohyperthermic soil temperature regime (STR) and aquic soil moisture regime. Altitude across the study sites ranges from about 262 to 302 m a. s. l.



AEZ E10:1400 - 1600 mm rainfall, flat alluvial plains with complex sedimentation pattern, Altitude range 250 - 600 m a. s. l.

Figure 1. Kilombero District Map Showing Location of Studied Soil Profiles.

Table 1. Important characteristics of studied sites in Kilombero District, Tanzania.

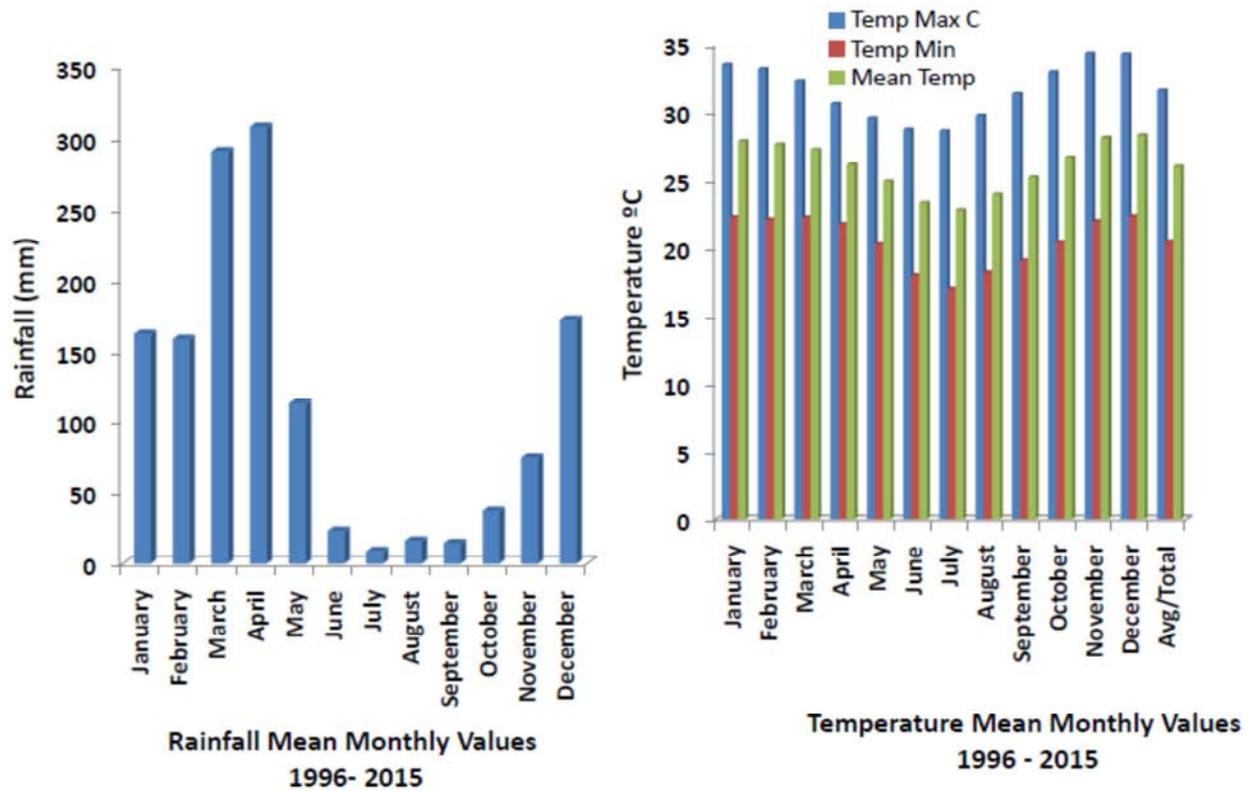
¹⁾ Pedon No.	Coordinates	Altitude m asl.	²⁾ MAR mm	Lithology/ parent materials	Land Use	³⁾ STR	⁴⁾ SMR
KISA-P1	036°53'31.6" E 07°53' 56.4" S	293	1378	Alluvium derived from metamorphic rocks	Mostly rain-fed paddy	Isohythermic	Aquic
MKU-P1	036°55' 08.1" E 07°47'41.4" S	302	Same as above	Same as above	Same as above	Same as above	Same as above
MBA-P1	036°42'42.8" E 08°05'46.0" S	262	Same as above	Same as above	Same as above	Same as above	Same as above

¹⁾ Soil pedons: KISA-P1 (Kisawasawa Ward) Pedon MKU- P1 (Mkula Ward) Pedon MBA-P1 (Mbasa Ward)

²⁾ MAR: Mean Annual Rainfall for 20 years

³⁾ STR: Soil Temperature Regime

⁴⁾ SMR: Soil Moisture Regime



Source: Kilombero Sugar Weather Station

Figure 2. Mean Monthly Rainfall and Temperature for the 20 Years.

2.2. Field Work

Reconnaissance field survey was carried out using transect walks, auger observations and descriptions to establish three representative study sites. Three representative soil profiles, one for each site, were identified, excavated and described according to FAO Guidelines for Soil Description [14]. Data on landforms, soil morphological characteristics, elevation, slope gradient, parent material (lithology), vegetation and land use/crops were collected from the three observation sites. The data were filled on field description forms designed based on Guidelines for Soil Description by FAO [14]. Soil profile pits were geo-referenced using Global Positioning System (GPS) Model OREGON 400t. Soil colours were determined by Munsell soil colour charts [15]. In each profile pit, undisturbed (core) soil samples at depths of 0-5 cm, 45-50 cm and 95-100 cm) were taken. Disturbed samples

(weighing about 1 kg) were taken from each of the designated genetic soil horizons of soil profiles for laboratory physical, chemical and mineralogical analyses.

2.3. Laboratory Methods

Undisturbed (core ring) samples were used for determination of bulk density and moisture retention characteristics. Bulk density was determined by the core method [16]. Pressure (plate/pressure) membrane apparatus [11] was used to determined soil water-holding characteristics. Disturbed soil samples were air-dried, ground and passed through a 2-mm sieve for physical and chemical soil properties determination. Particle size distribution was determined by hydrometer method [17] after dispersing soil with sodium hexametaphosphate and textural classes determined using the USDA textural triangle [18]. Soil pH in water and in 1M KCl was measured potentiometrically using a soil:water/KCl ratio of

1:2.5 weight to volume basis [19]. Potentiometric method also was used to determine electrical conductivity. Organic carbon was determined by Walkey-Black wet oxidation method [20] and total nitrogen (TN) was determined by micro-Kjeldahl digestion method [21]. Basic cations (Ca, Mg, K and Na) extracted by ammonium acetate (NH₄OAc) method [22] were determined using atomic absorption spectrophotometer [23]. The total exchangeable bases (TEB) were calculated arithmetically as the sum of the four exchangeable bases (Ca²⁺, Mg²⁺, K⁺ and Na⁺) for a given soil sample. Other parameters including C/N ratio, exchangeable sodium percentage (ESP), Chemical Index of Alteration (CIA), Silt clay ratio (SCR) and base saturation percentage (BS %) were calculated. Determination of multi-element oxides for selected soil horizons was done as follows: 200 g of fine earth soil samples were weighed and open air-dried by using Infrared lamps for two hours. Samples were then ground to particle size $\leq 177 \mu\text{m}$ (80 Mesh) using swing mill pulverizer. An AAS machine version 208FS was used to quantify Mg and Na, while other elemental oxides were measured using PANalytical, Minipal 4 Energy Dispersive X-Ray Fluorescence Spectrometer (ED-XRF) Model PW4030/45B.

2.4. Classification of Soils

Using field and laboratory data, soil pedons were classified to family level of USDA Soil Taxonomy [18] and to Tier-2 of World Reference Base (WRB) for Soil Resources [24].

3. Results and Discussion

3.1. Soil Morphology and Genesis of the Studied Soils in Kilombero Valley

Salient morphological characteristics of the studied profiles are given in Table 2. All studied pedons were deep to very deep and had shallow water tables. Pedons KISA-P1 and MBA-P1 had sandy clay loam topsoils overlying sandy clay subsoils whereas Pedon MKU-P1 had dominantly heavy clay horizons alternating with sandy clay and clay horizons. Topsoil of Pedon KISA-P1 was black while Pedons MKU-P1 and MBA-P1 had respectively grayish brown and very dark grayish brown topsoils. Pedon MKU-P1 had extremely hard dry consistence throughout its depth, being attributed to the heavy clay texture of soil. The other pedons had relatively lower dry consistence but ranging from slightly hard to very hard in Pedon KISA-P1 and from soft to very hard in Pedon MBA-P1. Pedon MBA-P1 was typically structureless single-grained while Pedons KISA-P1 and MKU-P1 had horizons with weak to moderate subangular blocky structure alternating with structureless single grained and structureless massive clods. All the pedons had abundant redoximorphic features in form of strong brown (iron) mottles due to the reducing/waterlogged soil conditions. Researchers [25, 26, 27] observed similar mottles respectively in subsoils of floodplains in Nigeria and in surface-water grey soils in Bangladesh. Horizon boundary attributes varied among and within pedons, whereby distinctness ranged from abrupt to gradual, but topography was dominantly smooth. On the overall, morphology and genesis of the studied soils were typical of alluvial soil formation.

Table 2. Main morphological features of the studied soil profiles in Kilombero District, Tanzania

Pedon	Horizon	Depth (cm)	¹⁾ Texture	²⁾ Moist colour	³⁾ Consistence	⁴⁾ Structure	⁵⁾ Mottles	⁶⁾ Horizon boundary
KISA-P1	Ap	0 - 12	SCL	bl(10YR2/1)	sh; fr, & ss & sp	m;m;cr	-	cs
	BA	12 - 23	SCL	bl(10YR2/1)	vh; fr; ss & sp	stl-mas	-	as
	Bwg1	23 - 45	SCL	vdg(7.5YR3/1)	vh; fr; s & p	stl-mas	f-c; fi; sb; Fe	cs
	Bwg21	45 - 74	SC	g(7.5YR5/1)	vh; fi; s & p	w; c; sbk	f-c; fi; sb; Fe	gs
	Bwg22	74 - 120+	SC	g(7.5YR5/1)	vh; fi; s & p	w; c; sbk	f-c; fi; sb; Fe	-
MKU-P1	Apg	0 - 14/22	hC	gb(10YR6/1)	eh; vfi; s & p	m;f & m; sbk	f; fi; rb; Fe	aw
	Cg	11/22 - 29	SC	vdgb(10YR3/2)	eh; vfi; s & p	stl-sg	c; m; br; Fe	as
	Abg	29 - 43/47	hC	br(7.5YR2.5/1)	eh; efi; vs & vp	m; m; ab & sbk	c; m; bg; Fe	as
	ABg	43/47 - 65/83	hC	vdg(10YR3/1)	eh; efi; vs & vp	w-m; m & c; sbk	c; vfi+fi; yb; Fe	aw
	Bwg	65/83 - 116+	C	yb(10YR5/6)	eh; efi; vs & vp	m; m; sbk	c; fi; (50% yb + 50% gb)	-
MBA-P1	Apg	0 - 28/35	SCL	vdgb(10YR3/2)	so; vfr; ns & np	stl-sg	vf; fi; rb; Fe	aw
	C11g	28/35 - 74	SC	br(10YR5/3)	sh; fr; ss & sp	stl-sg	c; vf; bg; Fe	as
	C12g	74 - 120+	SC	pb(10YR6/3)	vh; vfi; ss & sp	stl-sg	c; vf; bg; Fe	-

¹⁾ Texture: SC = sandy clay; SCL= sandy clay loam; C = clay

²⁾ Colour: g = gray; gb = grayish brown; vdgb = very dark grayish brown; vdg = very dark gray; bl = black; yb = yellowish brown; br = brown; pb = pale brown

³⁾ Consistence: Dry: so = soft; sh = slightly hard; h = hard; vh = very hard; eh = extremely hard. Moist: fr = friable; fi = firm; vfi = very firm; efi = extremely firm. Wet: ns = non-sticky; ss = slightly sticky; vs = vs. np = non-plastic; sp = slightly plastic; p = plastic; vp = very plastic

⁴⁾ Structure: Grade: m = moderate; w = weak; = structureless single grained; stl-mas = structureless massive. Size: f = fine; m = medium; c = coarse. Type: cr = crumbs; ab = angular blocky; sbk = subangular blocky; mas = massive

⁵⁾ Mottles: Abundance: f = few; c = common; a = abundant. Size: vf = very fine; fi = fine; medium. Colour: sb = strong brown; bg = bluish gray; yb = yellowish brown. Type: Fe = iron

⁶⁾ Horizon boundary: Distinctness: a = abrupt; c = clear; g = gradual. Topography: s = smooth; w = wavy.

3.2. Physical Properties of the Studied Soils in Kilombero Valley

3.2.1. Soil Moisture Retention Characteristics

Figure 3 presents results on soil moisture characteristics of two of the studied pedons. The soil moisture release curves clearly indicate that Pedon MKU-P1 held more moisture than Pedon MBA-P1 at any suction level for all the three pedon sections. Moreover, Pedon MKU-P1 released soil moisture more gradually with increasing pressure than Pedon MBA-P1. The difference in behaviour of the two pedons was attributed to the fine texture of the former pedon vis-à-vis the relatively coarser texture of the latter. The results on

volumetric moisture content complied with the heavy clayey texture in Pedon MKU-P1 as opposed to dominance of sand particles in Pedon MBA-P1 (Table 2). [28] reported a pedon with high clay content to have higher moisture retention capacity with a gradual moisture decrease as suction potential increased, compared to one dominated by sand with a rapid decrease in moisture content as the suction potential increased. This phenomenon suggests an effect of drastic dryness of field crops whenever there is a dry spell during the rainy season in the case of Pedon MBA-P1 (28, 29). Average rainfall data (Figure 2) show December to May rainfall is above 100 mm/month allowing farmers to practice both rainfed and irrigated rice production in the district.

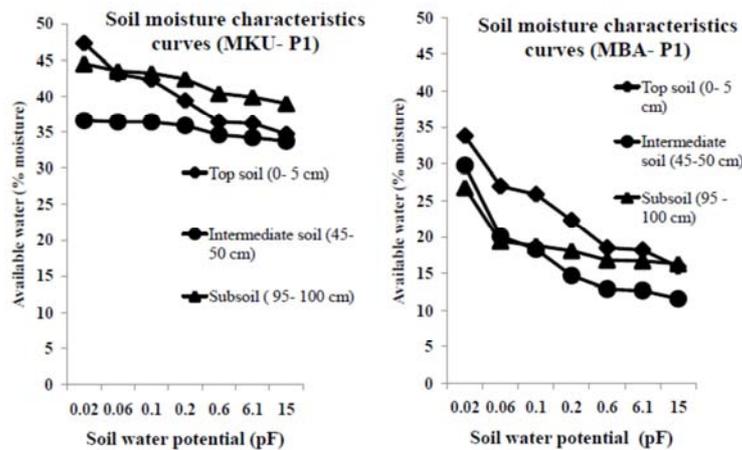


Figure 3. Soil moisture characteristic curves for Mkula and Mbasa Sites, Kilombero District, Tanzania.

3.2.2. Texture, Silt/Clay Ratio, Bulk Density and Porosity

Table 3 presents data on other soil physical properties including texture, silt/clay ratio, bulk density and porosity of the soils. Pedons KISA-P1 and MBA-P1 had sandy clay loam topsoils overlying sandy clay subsoils while Pedon MKU-P1 had sandy clay to clay topsoil overlying clay subsoils. Pedon MKU-P1 had much heavier texture throughout profile depth when compared with the other two pedons, implying it would behave differently from these two in terms of physical and chemical properties. For example, clayey texture is

associated with high water retention capacity and high nutrient supply [25]. Pedon MKU-P1 would offer more favourable conditions for paddy than the other two pedons. Clay content increased somewhat with depth in all pedons providing some indication of clay eluviation-illuviation, although there was no clear evidence of clay illuviation features (clay cutans) in the subsoils. Some researchers [27, 28] observed consistent clay increase with depth as an indication of clay migration in studies done in Bangladesh and Western-Kenya.

Table 3. Some physical properties of the studied soil profiles of Kilombero District, Tanzania.

Pedon No.	Horizons	Depth (cm)	Sand %	Clay %	Silt %	Textural class	Silt / clay ratio	BD Mg/m ³	Porosity %	Penetration resistance kg/cm ²
KISA-P1	Ap	0 -12	62	32	6	SCL	0.19	nd	nd	nd
	BA	12 - 23	62	30	8	SCL	0.27	nd	nd	nd
	Bwg1	23 - 45	58	34	8	SCL	0.24	nd	nd	nd
	Bwg21	45 - 74	54	40	6	SC	0.15	nd	nd	nd
	Bwg22	74 - 120+	50	44	6	SC	0.12	nd	nd	nd
MKU-P1	Ap	0 - 14/22	54	43	3	C	0.07	1.15	53.5	2.3
	Cg	11/22 - 29	53	42	5	SC	0.12	nd	nd	nd
	Ab	29 - 43/47	33	64	3	C	0.05	1.64	37.3	16.5
	AB	43/47 - 65/83	37	58	5	C	0.09	nd	nd	nd
	Bw	65/83 -116+	41	56	3	C	0.05	1.47	45.6	6.6
MBA-P1	Apg	0 - 28/35	71	27	2	SCL	0.03	1.54	38.1	1.83
	C11g	28/35 - 74	51	48	1	SC	0.02	1.59	36.0	17.2
	C12g	74 - 120+	45	52	3	SC	0.07	1.67	33.7	14.5

nd= not determined BD = bulk density

Silt/clay ratio, an indicator of soil susceptibility to detachment and transport, was less than the threshold of 0.4 [30], implying moderate resistance to erosion. Silt/clay ratios in the three pedons showed irregular patterns and were lower in Pedons MKU-P1 and MBA-P1 than in Pedon KISA-P1. The pedons differed in bulk density, whereby Pedon MKU-P1 had a BD of 1.15 Mg/m³ while pedon MBA-P1 had BD of 1.5 Mg/m³ in topsoils. Bulk density affects infiltration, rooting depth, available water capacity, soil porosity, plant nutrient availability, and soil microbial activity, which influence key soil processes and productivity [1, 31, 32]. Bulk density normally increases with soil depth since subsurface layers are more compacted and have less organic matter, aggregation, and root penetration compared to surface layers, hence less pore space [1]. Among other factors, tillage practices done prior to planting temporarily decrease bulk density on the surface but increases at the depth of tillage [32]. Several researchers have observed similar trends of bulk density increasing with depth [26, 33] in rice fields. BD values > 1.65 Mg/m³ are unfavorable to root growth in sandy clay loams and clay loams [32]. Thus, the observed BD values in Pedons MKU-P1 and MBA-P1 are favorable in that regard. Table 3 also presents the penetration resistance of the studied pedons. Topsoil penetration resistance values of the pedons ranged from 1.83 - 2.3 kg/cm² while those of subsoils ranged from 6.6 - 17.2 kg/cm². This indicates lower soil compaction in topsoils than in subsoils, which corresponds to the observed low BD values in topsoils. The penetration resistance increased with increasing depth signaling the presence of reduced water movement and creation of water table. Some researchers [28, 29, 30] observed similar trend of low penetration resistance in topsoils than in subsoils. According to [28], penetration resistance of < 30 kg/cm² infers a compaction that cannot impair growth and development of crops in the studied profiles.

3.3. Chemical Properties of the Studied Pedons in Kilombero Valley

3.3.1. Soil Reaction (PH), Organic C, Total N, Organic Matter (OM) and C/N Ratio

Some chemical properties of the studied pedons are presented in Table 4. Soil pH is the most important chemical characteristic of soil solution. pH_{H2O} levels in topsoils of the three pedons ranged between 4.44 and 5.78 (very low to medium), whereas in subsoils they ranged between 5.71 and 6.73 (medium). [31] rated pH_{H2O} values of 4.6 - 4.9 as very low, < 5.5 as low and 5.5 to 7.0 as medium. The low pH in topsoils may be attributed to low amounts of bases caused by leaching during fluctuations of water table and percolation of water during flooding periods, removal of bases through crop harvests and farming practices. [27] Observed similar trend of pH increasing with depth in annually flooded soils of Bangladesh. Likewise, [34] reported a similar trend of soil pH increasing with depth in paddy soils of Kilombero Valley. Electrical conductivity (EC) is a measure of relative salt concentration or salinity, and too much salt in the soil can interfere with root function and nutrient uptake [35, 36]. EC values ranged between 0.01 and 0.05 (dS/m) in all pedon horizons implying that all the soils were non-saline. According to [30, 36], the topsoil organic carbon (OC) and total nitrogen (TN) contents of the studied soils were low (ranging from 0.66 to 1.4% OC) and very low to low (TN ranging from 0.08 to 0.19%). The low values of OC and TN may be attributed to burning of crop residues, which decreases the amount of organic matter in the surface soil [4]. The C/N ratios of topsoils ranged between 2.95 in MKU-P1 to 12.75 at MBA-P1. Although OC and TN decreased with depth as expected, C/N ratios did not show a consistent pattern. According to [31, 36], C: N ratio of 10:1 indicates good quality organic material, although they cautioned that C: N ratio might not be a good indicator of soil fertility, and thus encouraged use of individual C and N values instead.

Table 4. Some chemical properties of the studied soil profiles of Kilombero District, Tanzania.

Pedon No.	Horizon	Depth (cm)	pH		EC (dS/m)	OC (%)	TN	C/N Ratio
			H ₂ O	KCl				
KISA-P1	Ap	0 - 12	5.78	4.38	0.04	1.40	0.13	10.77
	BA	12 - 23	6.24	4.58	0.03	0.80	0.02	40.00
	Bwg1	23 - 45	6.32	4.83	0.03	0.60	0.04	15.00
	Bwg21	45 - 74	6.34	5.36	0.05	0.31	0.03	10.33
	Bwg22	74 - 120+	6.54	5.58	0.05	0.19	0.04	4.75
MKU-P1	Ap	0 - 14/22	5.60	4.2	0.03	0.66	0.19	2.95
	Cg	11/22 - 29	6.00	4.33	0.02	0.56	0.08	8.25
	Ab	29 - 43/47	6.37	4.83	0.01	0.42	0.07	6.00
	AB	43/47 - 65/83	6.04	5.00	0.03	0.42	0.11	3.18
	Bw	65/83 - 116+	6.73	5.18	0.03	0.29	0.08	28.9
MBA-P1	Apg	0 - 28/35	4.44	4.15	0.01	1.02	0.08	12.75
	C11g	28/35 - 74	5.71	4.44	0.01	1.78	0.15	11.87
	C12g	74 - 120+	6.35	4.60	0.01	1.00	0.09	11.11

3.3.2. Exchangeable Cations and Related Properties

Table 5 presents data on exchangeable cations and related

parameters of the studied soils. Exchangeable K ranged between 0.11 and 0.24 cmol (+)/kg in topsoils. According to [36], K levels are rated as low (< 0.2 cmol (+)/kg) and as

medium (0.2 to 0.4 cmol (+)/kg). Hence Pedon KISA-P1 had medium K while Pedons MKU-P1 and MBA-P1 had low levels of K. Exchangeable K critical level for rice was established by [9] as 0.2 cmol (+)/kg, below which rice response to K application is observed. The soils of MBA-P1 might need application of K at a recommended rate. The

subsoils of the studied pedons had relatively high values of K indicating leaching of the nutrient from topsoils. Exchangeable Mg levels ranged between 0.73 and 3.96 cmol (+)/kg and were rated as low to medium. Like for K, the values of Mg were higher in the underlying horizons showing there might have been leaching of the nutrient to the subsoil.

Table 5. Exchangeable cations and allied properties of the studied pedons of Kilombero District, Tanzania.

Pedon No.	Horizons	Depth (cm)	Exchangeable bases				CEC _{soil}	TEB	CEC _{clay}	BS %	ESP
			cmol(+)/kg								
			K	Mg	Ca	Na					
KISA-P1	Ap	0 -12	0.25	0.73	2.15	0.24	8.4	3.37	26.3	40.1	0.9
	BA	12 - 23	0.07	1.80	6.27	0.25	10.6	8.39	35.3	79.2	0.7
	Bwg1	23 - 45	0.07	1.92	5.86	0.30	11.0	8.15	32.4	74.1	0.9
	Bwg21	45 - 74	0.05	0.66	2.56	0.21	8.8	3.48	22.0	39.6	1.0
	Bwg22	74 - 120+	0.11	1.97	5.45	0.36	10.4	7.89	23.6	75.9	1.5
MKU-P1	Ap	0 - 14/22	0.16	3.96	5.56	0.12	18.0	9.80	33.3	54.3	0.4
	Cg	11/22 - 29	0.24	7.90	6.45	0.07	23.8	14.66	56.7	61.2	0.1
	Ab	29 - 43/47	0.12	6.42	2.36	0.09	20.0	8.99	31.3	44.9	0.3
	AB	43/47 - 65/83	0.11	2.23	2.25	0.04	13.2	4.63	22.8	34.8	0.2
	Bw	65/83 - 116+	0.11	3.29	1.16	0.09	12.0	4.65	21.4	38.5	0.4
MBA-P1	Apg	0 - 28/35	0.11	2.19	1.85	0.05	12.4	4.20	45.9	33.8	0.1
	C11g	28/35 - 74	0.18	6.01	3.46	0.18	17.6	9.83	36.7	55.8	0.5
	C12g	74 - 120+	0.12	6.42	0.16	0.10	10.6	6.80	20.4	63.7	0.5

Exchangeable Ca levels varied irregularly with depth and ranged between 1.85 and 5.56 cmol (+)/kg in the topsoils of all pedons. According to [36] topsoil exchangeable Ca levels in Pedon MBA-P1 with loamy texture were rated as low to medium while in Pedons MKU-P1 and KISA-P1 with clayey texture, were rated as medium to high. Sodium levels ranged between 0.04 and 0.30 cmol (+)/kg in all the three pedons and were rated as very low to low [36]. The values of Na in the studied pedons were less than 1 cmol (+)/kg which is the highest level for sodium to be detrimental to plant roots [30]. Exchangeable sodium percentage (ESP) ranged from 0.1 to 1.5% in all horizons of the studied pedons, hence the soils can be said to be non-sodic as the ESP values are < 6 [30, 36]. The cation exchange capacity (CEC) in topsoils ranged from 8.4 in Pedon KISA-P1 to 18.0 cmol (+)/kg in Pedon MKU-P1. [30] Categorized CEC of < 5 as very low, 5-15 as low and 15 - 25 cmol (+)/kg as medium. These values suggest that CEC in Pedons KISA-P1 and MBA-P1 was low while it was medium in Pedon MKU-P1. Percent base saturation (BS) varied within and among pedons with no clear trend but with relatively higher topsoil values in Pedons KISA-P1 and MKU-P1 than in Pedon MBA-P1. [36] suggested that soils with BS > 50% are fertile soils and vice versa although the following classes were recognized: BS < 20% as low, 20-60 as medium, and above 60% as high.

3.3.3. Nutrient Balance

The availability of nutrients for plant uptake does not depend only on their absolute levels in soils but it also depends on nutrient balance. In most cases, the good trend is with calcium higher than magnesium, and magnesium higher than potassium [35]. The exchangeable cations in the study areas followed almost that trend: Ca>Mg>K>Na at MKU-P1 and KISA-P1. A similar trend was observed in soils of other parts of Tanzania [10, 37, 38, 39]. The pedon MBA-P1 had high Mg and followed a trend Mg>Ca>K>Na. Other than the absolute amount, the cations availability to plants is sometimes influenced by several ratios including Ca:Mg, Mg:K and K:TEB (where TEB is total exchangeable bases). The Ca/TEB ratios in the topsoil for studied pedons ranged from 0.44 to 0.64 (Table 6) and decreased down the profile. According to [30] Ca/TEB ratios of more than 0.5 may affect the uptake of other bases, particularly Mg and/or K, as calcium induced deficiency of Mg and/or K may become visible. Thus, Ca may influence uptake and induce deficiency of K at Kisawasawa (KISA-P1) and Mkula (MKU-P1). The Ca/TEB at Mbasaa (MBA-P1) was almost optimal. Ca/Mg ratios ranged from 0.84 to 2.95 generally decreasing with depth in all the pedons showing that Ca content was higher in topsoils than in subsoils.

Table 6. Nutrient ratios in the studied pedons of Kilombero District, Tanzania.

Pedon No.	Horizons	Depth (cm)	Ratios of Nutrients			% (K/TEB)
			Ca/TEB	Ca/Mg	Mg/K	
KISA-P1	Ap	0 -12	0.64	2.95	2.92	7.42
	BA	12 - 23	0.75	3.48	25.71	0.83
	Bwg1	23 - 45	0.72	3.05	27.43	0.86
	Bwg21	45 - 74	0.74	3.88	13.20	1.44
	Bwg22	74 - 120+	0.69	2.77	17.91	1.39
MKU-P1	Ap	0 - 14/22	0.57	1.40	24.75	1.64
	Cg	11/22 - 29	0.44	0.82	32.92	1.65

Pedon No.	Horizons	Depth (cm)	Ratios of Nutrients			% (K/TEB)
			Ca/TEB	Ca/Mg	Mg/K	
MBA-P1	Ab	29 - 43/47	0.26	0.37	53.50	1.33
	AB	43/47 - 65/83	0.49	1.01	20.27	2.39
	Bw	65/83 - 116+	0.25	0.35	29.91	2.38
	Apg	0 - 28/35	0.44	0.84	20.86	2.51
	C11g	28/35 - 74	0.35	0.58	33.39	1.83
	C12g	74 - 120+	0.02	0.02	53.50	1.78

[30] Ranked Ca/Mg range between 2 and 4 as optimal indicating all studied pedons to have optimal Ca/Mg ratios. Topsoils of pedons had Mg/K ratios of 2.95 to 24.8 and showed irregular pattern whereby pedon KISA-P1 had an optimal ratio falling between the recommended 1 and 4 for optimal nutrient uptake by plants [30]. In general, there was imbalance between Mg and K indicating Mg was relatively high and would influence negatively uptake of K by plants. The percentage K/TEB ratios ranged between 1.64 to 7.2% and decreased down the profile. For MKU-P1, the ratio was low but in Pedons KISA-P1 and MBA-P1 they were above 2% (Table 5), which is considered favorable for most tropical crops [30].

3.3.4. Total Elemental Composition

The total elemental oxides of topsoils and subsoils of studied pedons are presented in Table 7. The most abundant oxide was SiO₂, which ranged from 51.8 to 77.1% in

topsoils, and from 44.4 to 71.1% in subsoils. The high SiO₂ content is an indication of existence of amorphous silica. Contents of Al₂O₃ ranged between 0.0 and 14.0% in topsoils and from 11.5 to 17.5 in subsoils. The contents of topsoil Fe₂O₃ ranged between 4.69 and 24.92% and from 5.37 to 30.61% in subsoils. The K₂O contents ranged between 2.77 to 11.5 in topsoils and between 2.61 to 3.25 in subsoils. The total K₂O in Pedon MBA-P1 was low in topsoil and high in subsoils. This may be attributed to the coarse texture of the soil and hence easy leaching of the element. The other elemental oxides MnO, Na₂O, CaO, MgO and TiO₂ of the studied pedons were in low concentrations (below 3.0%). According to [39], low levels of these element oxides in the studied soils are associated with leaching during weathering process and due to low concentrations of these elements in parent rocks/minerals.

Table 7. Total elemental composition of the studied soil pedons of Kilombero Valley, Tanzania.

Pedon	Pedon section	Percentage											Total	CIA
		SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	K ₂ O	CaO	TiO ₂	MnO	MgO	Na ₂ O	CuO			
KISA-P1	Topsoil	77.40	0.00	4.69	11.5	1.54	2.10	0.11	0.003	0.008	0.090	97.44	0.0	
	Subsoil	50.45	17.50	21.43	3.25	2.11	2.84	0.11	0.010	0.010	0.120	97.83	76.5	
MKU-P1	Topsoil	51.80	14.00	24.92	2.77	2.90	2.10	0.14	0.043	0.008	0.130	98.81	71.1	
	Subsoil	44.35	15.50	30.61	2.61	2.51	2.51	0.21	0.027	0.006	0.125	98.45	75.2	
MBA-P1	Topsoil	51.80	14.00	24.92	2.77	2.90	2.10	0.14	0.043	0.008	0.130	98.81	71.1	
	Subsoil	71.10	11.50	5.37	7.61	1.05	1.39	0.04	0.003	0.001	0.080	98.14	57.1	

The current study also involved determination of weathering index referred to “*Chemical Index of Alteration*” (CIA) using the total elemental composition data to estimate the degree of weathering of studied pedons. The CIA is used and reported by some researchers [2, 40, 41] as a quantitative indicator of degree of weathering of silicates since feldspars are said to be the most abundant reactive minerals in the earth’s crust and that calcium, sodium and potassium are removed from feldspars during weathering process. The authors hypothesized that during weathering, proportion of alumina to alkalis would typically increase in the weathered product and that a good measure of degree of weathering could be obtained by the “*Chemical Index of Alteration*”, defined as:

$$CIA = \{Al_2O_3 / (Al_2O_3 + K_2O + Na_2O + CaO)\} * 100.$$

On the basis of subsoil CIA values the studied soils are young in terms of pedogenic development with weathering indices of 76.5, 75.2 and 57.1% for Pedons KISA-P1, MKU-P1 and MBA-P1 respectively. According to [41] the trend shown here suggests that degree of weathering of the soils followed the trend Pedon KISA-P1>Pedon MKU-P1>Pedon MBA-P1. The smaller the CIA value, the younger the soils

are in terms of degree of weathering and age of formation [30]. In practical terms, Pedons KISA-P1 and MKU-P1 can be said to display almost the same degree of weathering as their CIA values were almost the same. Pedon MBA-P1 with the smallest CIA value was the least weathered something that may be attributed to more frequent deposition of fresh materials to the site and/or nature and degree of weathering of the transported materials from which the soils have formed.

3.3.5. Soil Classification

Table 8 presents a summary of the classification of the studied pedons. Soil morphological and laboratory analytical data used to define diagnostic horizons and classifying the soils. Referring the Keys to Soil Taxonomy [18], Pedons KISA-P1 and MKU-P1 were classified as *Inceptisols* with Greatgroup *Endoaquepts* correlating to *Cambisols* of WRB [24]. The soils are less developed with A horizon resting on C material with shallow water table in most time of the year forming Mollic epipedon and Cambic subsurface horizon. Pedon MBA-P1 was classified as *Entisols* of Great group *Fluvaquents* corresponding to a very low developed Fluvisols

with water saturation during most of the time in the year. In general, these pedons are related with less developed soils probably due to annual floods bringing the new materials. The findings are close to those of [42] who reported 23 *Inceptisols* and 8 *Entisols* out of 42 map units mapped in Kilombero Valley. The *Entisols* and *Inceptisols* are mostly reported to be used for rice production. In the Philippines,

Inceptisols and *Entisols* form respectively 13.7 and 2.5% of the country's soil and are used mainly for rice production [43]. The results indicate that the *Entisols* and *Inceptisols* developed under similar conditions to those reported above (aquic SMR and isohyperthermic STR) can be used for rice production.

Table 8. Classification of the studied soil pedons of Kilombero District, Tanzania.

Diagnostic horizons	Other diagnostic features	KEYS TO SOIL TAXONOMY [24]				WRB FOR SOIL RESOURCES [25]			
		Order	Suborder	Great group	Subgroup	Family	Reference Soil Group (Tier-1)	WRB soil name (Tier-2)	
KISA-P1									
Mollic epipedon; cambic horizon	Flat, very deep, loamy over clayey, slightly to medium acid, aquic SMR - redoximorphic, stratification, Isohyperthermic STR	Inceptisols	Aquepts	Endoaquepts	Humic Endoaquepts	<i>Flat, very deep, loamy over clayey, slightly to medium acid, aquic, isohyperthermic, Humic Endoaquepts</i>	Cambisols	<i>Gleyic Cambisols (Loamic)</i>	
MKU-P1									
Mollic epipedon; Cambic horizon	Flat, very deep, clayey, slightly to medium acid, aquic SMR - redoximorphic, stratification, isohyperthermic STR	Inceptisols	Aquepts	Endoaquepts	Humic Endoaquepts	<i>Flat, very deep, loamy over clayey, slightly to medium acid, aquic, isohyperthermic, Humic Endoaquepts</i>	Cambisols	<i>Dystric Gleyic Cambisols (Clayic)</i>	
MBA-P1									
Ochric epipedon	Flat, very deep, clayey, medium to very strongly acid, aquic SMR - redoximorphic, stratification, isohyperthermic STR	Entisols	Aquepts	Fluvaquepts	Typic Fluvaquepts	<i>Flat, very deep, clayey, medium to very strongly acid, aquic, isohyperthermic, TypicFluvaquepts</i>	Fluvisols	<i>Eutric Gleyic Fluvisols (Clayic, Humic)</i>	

KISA-P1 = Kisawasawa profile MKU-P1 = Mkula profile MBA-P1 = Mbasa profile
SMR = Soil Moisture Regime STR = Soil Temperature Regime

4. Conclusions and Recommendations

The studied pedons were deep and had somewhat similar morphological characteristics emanating from similar ecological conditions and mode of formation. The pedons developed under *Isohyperthermic soil temperature regime* and *Aquic soil moisture regime*. All pedons had low chromas and abundant mottles (redoximorphic features) due to waterlogging conditions. On the basis of pH, CEC, BS, SOM and TN, the fertility of the studied soils was generally rated only as medium. Although the studied pedons had all features of recent formation, Pedons KISA-P1 and MKU-P1 (Cambisols) appeared to be relatively more developed than Pedon MBA-P1 (Fluvisol). The soils had optimal nutrient ratios except for Mg/K ratios which indicated that plant uptake of K might be slightly impaired. Based on landform features and soil physico-chemical properties, the soils represented by the three studied profiles were recommended for paddy rice production. Care should be taken though to address possible deficiency of some nutrient elements through judicious use of fertilizers e.g. urea and NPK formulations.

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