Pedological Characterization and Classification of Some Typical Soils in Three Agro-Ecological Settings of South-Eastern Tanzania

John J. Tenga, Balthazar M. Msanya, Johnson M. Semoka, Ernest Semu and Sibaway B. Mwango

Abstract— This study was carried out in South-Eastern Tanzania to establish representative experimental sites on the basis of agro-ecological settings and soils. Three pedons were characterized namely NWJ-P1 in Nawaje village, MKG-P1 in Mikangaula village and NNL-P1 in Nannala village. Soil moisture and temperature regimes in the study areas were, respectively, ustic and isohyperthermic. Fifteen soil samples from genetic soil horizons were analyzed for physico-chemical properties. Pedons NNL-P1 and MKG-P1 had loamy sand topsoils overlying sandy loam to sand clay loam subsoils. Pedon NWJ-P1 had sandy clay loam topsoil overlying clay subsoil with indications of eluviation-illuviation as dominant pedogenic process. Whereas pedons NWJ-P1 and MKG-P1 were medium acid to slightly acid (pH 5.91 - 6.35), pedon NNL-P1 was extremely to very strongly acid (pH 4.36 - 4.57). Topsoil OC contents of the soils were very low to medium (0.49 to 1.28%) while subsoil values were very low to low (0.16 - 0.66%). Total nitrogen in the pedons were very low (0.02 - 0.07%) while C/N ratios generally ranged from 7 to 18 indicating good to moderate quality of soil organic matter. All studied soils were low in available P (< 7 mg kg^{-1}) except topsoil of pedon NNL-P1 which had medium values (P range 7- 20 mg kg^{-1}). CEC values ranged from very low (< 6.0 $cmol_{(c)}$ kg^{-1}) to low (6.0 - 12.0 $cmol_{(c)}$ kg^{-1}). % base saturation of pedon NNL-P1 was medium (21 - 60) while pedons NWJ-P1 and MKG-P1 had high values (> 60%). Nutrient ratios Ca/TEB, Mg/K and %(K/TEB) indicated some degree of nutrient imbalance in the soils likely to impair nutrient availability to plants. According to USDA Soil Taxonomy the pedons classified as Typic Dystrustepts (pedon NNL-P1), Typic Argiustolls (pedon NWJ-P1) and Typic Haplustepts (pedon MKG-P1) which, according to WRB for Soil Resources, translated into Dystric Cambisols, Luvic Phaeozems, and Eutric Chromic Cambisols, respectively. In view of the study results, the studied pedons differed markedly in terms of pedological and physico-chemical properties, emphasizing the need to characterize soils before embarking on strategies and practices on soil fertility management for enhanced sustainable agriculture production. Sustainable cropping on the studied soils could be achieved with introduction of technologies suitable for rejuvenating soil fertility such as manuring, crop rotation, proper management of crop residues, fallow periods, introduction of leguminous cover crops in the farming system and use of fertilizers, particularly non-acidifying types of fertilizers.

Index Terms— Pedological characterization, soil chemical characteristics, soil classification, soil morphological characteristics, soil physical characteristics, South-Eastern, Tanzania.

1 Introduction

SOIL is a vital natural resource which plays an important role in plant growth and development for the livelihood of mankind. Pedological characterization as a systematic way of gathering soil information provides a clear understanding of soils in terms of their morphological, physical, chemical, biological and mineralogical properties; hence their potential and limitations for crop production [1], [2].

With increasing population and farming activities, nutrient depletion has become a common phenomenon in most soils, hindering agricultural production [3].

Low soil fertility is currently being reported as the major factor contributing to low crop productivity in Tanzania, including the South-eastern areas under current study [4]. The soils under study display remarkable variations in properties. According to [5], soil variations are influenced by many factors including nature of soil parent materials, climate and weathering trends over varying periods of time. Rajagopal et al. [5] emphasized that spatial and temporal variations of soils need to be well characterized and classified to allow transfer of generated agronomic technologies to other areas of similar soil series.

The combination of soil characterization and classification provides valuable information and understanding of the physical, chemical, mineralogical and biological properties of the soils that alleviate the adverse effect of soil diversity and aid precision agriculture [6], [7]. Soil characterization provides the basic information necessary to create functional soil classification schemes and to assess soil fertility in order to unravel some unique soil problems in an ecosystem. In many areas, including the current study area in Tanzania, the availability and acquisition of the information is a challenge due to the

- *John J. Tenga, Department of Soil and Geological Sciences, College of Agriculture, Naliendele Agricultural Research Institute, Mtwara, Tanzania. E-mail: johnmzungu@gmail.com*
- *Balthazar M. Msanya, Department of Soil and Geological Sciences, College of Agriculture, Sokoine University of Agriculture, Morogoro, Tanzania. E-mail: bmmsanya@gmail.com*
- *Johnson M.R. Semoka, Department of Soil and Geological Sciences, College of Agriculture, Sokoine University of Agriculture, Morogoro, Tanzania. E-mail: semoka@yahoo.com*
- *Ernest Semu, Department of Soil and Geological Sciences, College of Agriculture, Sokoine University of Agriculture, Morogoro, Tanzania. E-mail: semu@suanet.ac.tz*
- *Sibaway B. Mwango, Mlingano Agricultural Research Institute, Tanga, Tanzania. E-mail: sibawaymwango@gmail.com*

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fact that limited information has been generated relating to nutrient levels and their variations in the soils.

In the South-eastern Tanzania, two agro-ecological zones under study namely Makonde Plateau and the Inland Plains represent a very potential agricultural area. It is the largest producer of cashewnuts (the second largest crop contributing to the economy of the country), pigeon peas, sesame, cassava and Bambara nuts in Tanzania.

The early soil survey works carried by [4] in South-eastern Tanzania covered the Makonde plateau and the inland plains at a reconnaissance scale of 1:250,000. The nature of scale used in the above work is rather coarse and gives limited information for agricultural planning and experimentation purposes at farm level in the study area. A similar scenario was reported by [2] and [8], where in their study areas it was necessary to carry out site-specific soil characterization in order to establish prevailing heterogeneity of the soils, and to establish their potential and appropriate management practices.

For appropriate decision making on sustainable use and management of soils and for improving agricultural production, there is need for characterization and classification of soils of the study areas in a manner that will facilitate communication and transfer of knowledge to all end users of soil information, including farmers, extension staff and decision makers.

The main objective of the current study was to characterize the soils of the study areas in terms of their pedological, morphological and physico-chemical properties, and classify them using the USDA Soil Taxonomy [9] and the World Reference Base for Soil Resources [10].

2 MATERIALS AND METHODS

2.1 Description of the Study Area

The study was conducted in two Agro-ecological Zones (AEZs) defined on the basis of climate, soil type and elevation. The selected AEZs cover three villages including Nannala (Tandahimba district), Mikangaula and Nawaje (Nanyumbu district) with representative soil profiles designated as NNL-P1, MKG-P1 and NWJ-P1, respectively. The area is located approximately between 38° 03′ and 40° 30′ E and latitude 10° 05′ and 11° 25′ S with altitude ranging from 200 - 600 m.a.s.l. Figure 1 is a location map of the area showing among other features, positions of the studied soil profiles. Table 1 gives detailed salient characteristics of the study areas.

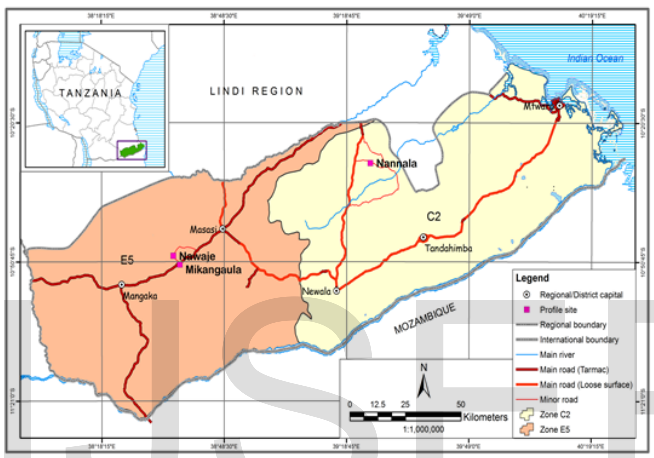

Fig.1. Base map showing the location of soil pedon sites in the study area

2.1.1 Soils and physiography

The Nannala site is found in AEZ designated as Coastal zones (C2) in the Makonde plateau, and is characterized by nearly level to gently rolling plains and plateaux at an altitude below 500 m. The soils in this AEZ are well drained sands and

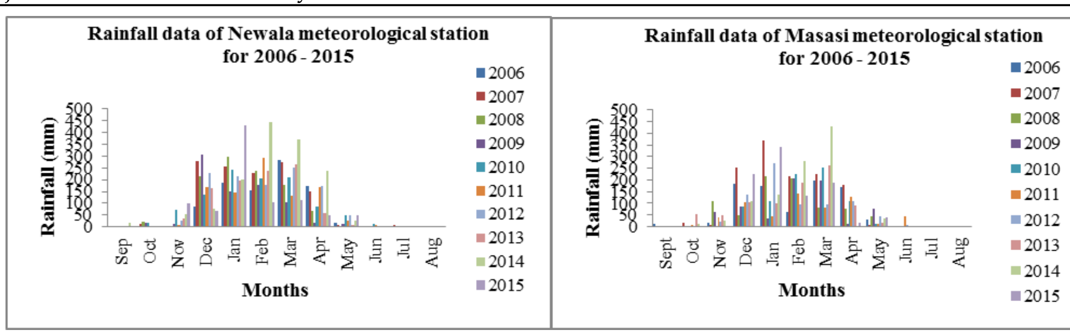

Fig. 2. Rainfall data collected at Newala Meteorological Station (AEZ C2) and Masasi Meteorological Station (AEZ E5)

TABLE 1
SITE CHARACTERISTICS OF THE STUDIED PEDONS AT NANNALA, NAWAJE AND MIKANGAULA

Attributes	**Description**		
	Nannala (NNL-P1)	**Nawaje (NWJ-P1)**	**Mikangaula (MKG-P1)**
Coordinates	10° 29′ 15.7″ S, 039° 24′ 36.5″ E	10° 48′ 11.8″ S, 038° 36′ 32.8″ E	10° 52′ 39.1″ S, 038° 36′ 20.2″ E
AEZ#	CH1	CPh8	CPh4
Altitude (m.a.s.l)	525	359	335
Landform	Gently undulating to rolling plain	Level to rolling plain	Level to rolling plain
Geology/ Lithology	Neogene sandstones	Intermediate metamorphic rocks	Acid metamorphic rocks
Slope %	2	1	2
Land use / Vegetation	Agriculture (groundnuts, cassava, pigeon peas, maize, Bambara groundnuts, cowpeas)	Agriculture (cowpeas, green gram, groundnuts, cassava, maize, Bambara groundnuts)	Agriculture (pigeon peas, groundnuts, maize, Bambara groundnuts, cassava)
Mean annual rainfall (mm)	800 - 1284 mm	600 - 1200 mm	600 - 1200 mm
SMR*	Ustic	Ustic	Ustic
Mean annual temperature °C	26° C	24° C	24° C
STR	Isohyperthermic	Isohyperthermic	Isohyperthermic

#AEZ = Agro-Ecological Zone description:
CH1: Coastal zone (coastal hinterland plain and plateaux)
CPh8: Eastern plateaux and mountain block (semi humid plains on acidic metamorphic rock)
CPh4: Eastern plateaux and mountain block (semi humid plains on intermediate metamorphic rock)
*SMR = soil moisture regime, STR = soil temperature regime

sand loams developed on Neogene sandy clays, sandstone and other terrestrial sediments [11]. Nawaje and Mikangaula sites are found in AEZ designated as Eastern plateaux and mountain block (E5) in the Inland Plains, characterised by level to rolling plains at an altitude 200 - 500 m.a.s.l. with well drained soils developed on acidic and intermediate metamorphic rocks [11].

2.1.2 Climate

The study area is influenced by the south-eastern trade winds in midyear and the north-eastern trade winds during the turn of the year. The study sites characteristically experience low, erratic and poorly distributed rainfall. The rainfall pattern is mono-modal. The rains start from December to April with a 2 - 3 weeks dry spell between the end of January and February of the year. The mean annual rainfall varies with altitude from 820 mm at around 100 m.a.s.l to 1245 mm at 870 m.a.s.l. The lowest mean monthly temperature is 24.3° C occurring in July and the highest annual mean temperature is 27.5° C in December. The mean annual temperature is 26° C in the coastal area and 24° C in the inland area [12].

2.2 Field methods

Transect walks, auger observations and descriptions to establish representative experimental sites were carried out. FAO guidelines for soil description [13] were used to describe landforms, elevation, slope gradient, parent material (lithology), vegetation and land use/crops of the selected sites. Soil morphology characteristics such as colour, texture, consistence, structure, porosity and effective soil depths were described according to FAO guidelines for soil description [13]. Three representative soil profile pits of 2.5 m by 1.5 m for each selected site were excavated to the depth of 2 m and geo referenced using Global Positioning System model GARMIN (etrex 20). Disturbed soil samples were collected from each of the exposed genetic soil horizons whereas undisturbed soil samples (core samples) were collected at depths of 0 - 5 cm, 45 - 50, and 95 - 100 cm, for laboratory analysis. Soil colours were determined by the use of soil colour chart [14].

2.3 Laboratory methods

Undisturbed core samples were used for determination of bulk density (BD) and soil moisture retention characteristics. Bulk density was determined by weighing soil cores after drying overnight at 105°C [15]. Soil moisture retention characteristics were studied using sand kaolin box for low suction values and pressure plate apparatus for higher suction values [16], [17]. Available water capacity of soil was calculated as the difference in water retention between -33kPa and -1500 kPa [18]. Disturbed soil samples from delineated horizons were used after air-drying, gently grinding and sieving through a 2 mm sieve for determination of physical and chemical properties. Texture was determined by the Bouyoucos hydrometer method after dispersing soil with 5% sodium hexametaphosphate [19]. Textural classes were determined using USDA textural triangle [13]. Soil pH was measured potentiometrically in water and in 1M KCl at the ratio of 1:2.5 soil:water and soil:KCl [20], respectively. Electrical conductivity (EC) was measured using an EC meter on 1:2.5 soil-water extracts. Organic carbon (OC) was determined by the Walkley and Black wet oxidation method [21], and the OC values converted to OM by multiplying with a factor of 1.724 [22]. Total nitrogen was determined by micro-Kjedahl digestion-distillation method as described by [23]. Available P was determined by the Bray and Kurtz-1 method [21]. Cation exchange capacity of the soil (CECsoil) was determined from the same 1 M neutral NH_4OAc (ammonium acetate) extracts [24]. The CECclay was calculated by dividing CECsoil by percentage clay (x 100). The exchangeable bases (Ca^{2+}, Mg^{2+}, Na^+ and K^+), were determined by atomic absorption spectrophotometer (AAS) [25]. The total exchangeable bases (TEB) was calculated as the sum of the four bases (Ca^{2+}, Mg^{2+}, Na^+ and K^+). Percent base saturation (PBS) values were obtained by dividing TEB by CECsoil and multiplying by 100.

2.4 Classification of the soils at the selected sites

Using field and laboratory analytical data, the soil pedons were classified to family level of the Soil Taxonomy [9] and to Tier-2 of the World Reference Base for Soil Resources [10].

3 RESULTS AND DISCUSSION

3.1 Selected soil morphological characteristics

Some morphological characteristics of the studied pedons are shown in Table 2. All the pedons are very deep (> 150 cm) and somewhat excessively drained. The topsoils of the three studied soils have loamy sand topsoils overlying subsoils of varied textures. Whereas the subsoil of pedon NNL-P1 has sandy loam and clay textures, pedons NWJ-P1 and MKG-P1 have dominantly clay and sandy clay loam textures respectively. On the overall, pedons NNL-P1 and MKG-P1 have comparable textures as they have formed from same parent materials under similar ecological conditions. The friable to very friable dark brown to brownish black topsoils of the three pedons indicates no restriction to root or water movement. The firm consistence in the subsoils of the three pedons may cause some restrictions to root growth particularly for deep rooted crops. The structures of the studied soils are subangular blocky throughout their depths, with grades ranging dominantly from weak (Pedon NNL-P1) to moderate (Pedon MKG-P1) and to strong (Pedon NWL-P1). The strong structure in the subsoil of pedon NWJ-P1 could be attributed to the high clay content in that soil. The observed structures of the studied soils suggest no restrictions to root growth, and water movement will normally not be impeded. According to [26], the subangular blocky structures of the studied soils would promote drainage, aeration and root penetration. Common clay cutans were observed in the subsoil of Pedon NWJ-P1 suggesting that eluviation-illuviation is an important pedogenic process in this pedon. Pedon NNL-P1 has gradual wavy soil boundaries whereas pedon NWJ-P1 has gradual smooth horizon boundaries.

3.2 Soil physical characteristics

TABLE 2
MORPHOLOGICAL FEATURES OF REPRESENTATIVE SOIL PEDONS OF THE STUDY AREAS AT NANNALA, NAWAJE AND MIKANGAULA

Profile	Horizon	Depth (cm)	Texture1)	Moist colour2)	Consistence3)	Structure4)	Cutans5)	Horizon boundary6)
NNL-P1	Ap	0 - 25/30	LS	db (10 YR 3/3)	vfr, ns&np	w-f&m, sbk	-	gw
	AB	25/30 - 50/55	LS	dyb (10 YR 5/4)	fr, ns&np	w-f&m, sbk	-	gw
	Bw1	50/55 - 85/88	SL	dyb (10 YR 5/4)	fr, ns&np	w-f&m, sbk	-	gw
	Bw2	85/88 - 112/115	C	yb (10 YR 5/6)	fi, s&p	w-f&m, sbk	-	gw
	Bw3	115 - 160+	SL	yb (10 YR 5/6)	fr, ns&np	w-f&m, sbk	-	-
NWJ-P1	Ap	0 - 22/30	SCL	bb (5 YR 2/1)	fr, ss&sp	m-f&m, sbk	-	gs
	BA	22/30 - 52/60	SCL	drb (5 YR 3/4)	fi, ss&sp	m-f&m, sbk	-	gs
	Bt1	52/60 - 80/100	C	drb (5 YR 3/6)	fi, s&p	s-m&c, sbk	c,d,c	gs
	Bt2	80/100 – 140	C	rb (2.5 YR 4/6)	fi, s&p	s-m&c, sbk	c,d,c	gs
	Bt3	140 - 200+	C	rb (2.5 YR 4/6)	fi, s&p	s-m&c, sbk	c,d,c	-
MKG-P1	Ap	0 - 16/24	LS	drb (2.5 YR 3/2)	vfr, ns&np	w-f&m, sbk	-	cw
	AB	16/24 - 45/49	SL	drb (2.5 YR 3/4)	fr, ns&np	w-f&m, sbk	-	cw
	Bw1	45/49 – 103	SCL	rb (2.5 YR 4/6)	fi, ss&sp	m-m&c, sbk	-	gw
	Bw2	103 – 156	SCL	b (10 YR 4/6)	fi, ss&sp	m-f&m, sbk	-	gs
	Bwc	156 - 200+	SL	b (10 YR 4/6)	fr, ns&np	w-m&c, sbk	-	-

1) Texture: SL = sandy loam, LS = loamy sand, SCL = sandy clay loam, C = clay
2) Colour: db = dark brown, dyb = dull yellowish brown, yb = yellowish brown, bb = brownish black, drb = dark reddish brown, rb = reddish brown, b = brown
3) Consistence: vfr = very friable, fr = friable, fi = firm, s = sticky, p= plastic, ss = slightly sticky, sp = slightly plastic, ns = non-sticky, np = non-plastic
4) Structure: w-f&m = weak fine and medium, m-f&m = moderate fine and medium, s-m&c = strong medium and coarse, m-m&c = moderate medium and coarse, sbk = subangular blocky;
5) Cutans: c=common; d=distinct; c=clay
6) Horizon boundary: g = gradual; c = clear; s =smooth; w = wavy

3.2.1 Soil particle distribution (texture), silt/clay ratio and bulk density (BD)

Table 3 presents the soil physical properties of the studied soil pedons obtained from laboratory analysis. Texture is the most stable physical property which influences other soil properties like soil structure, consistence, soil moisture regime and infiltration rate, runoff rate, erodibility, workability, permeability, root penetrability and fertility of the soil [27].

Results in this study reveal that particle size distribution of the studied pedons are variable, but pedons NNP-P1 and MKG-P1 have similar textural classes, dominantly loamy sand and sandy loam. The similarities of the two pedons are attributed to the fact that the two profiles have developed under the same soil forming factors and have attained comparable degree of soil development. Shelukindo [28] also found similar results for some typical soils of Miombo woodlands. Pedon NWJ-P1, unlike the other pedons, has sandy clay loam topsoil overlying dominantly clay subsoil. The silt/clay ratios of 0.33 to 0.50, 0.10 to 0.40 and 0.36 to 0.65 were observed in pedons NNL-P1, NWJ-P1 and MKG-P1 respectively. The subsoil silt/clay ratios of pedon NWJ-P1 are lower than those of the other pedons indicating that pedon NWJ-P1 is more weathered than the other pedons. The decrease of silt/clay ratio values with depth indicates that subsoils are more weathered than topsoils. Karuma et al. [29] reported similar results for soils of Busia County in Kenya.

TABLE 3

SELECTED PHYSICAL PROPERTIES OF THE STUDIED PEDONS AT NANNALA, NAWAJE AND MIKANGAULA

Pedon	Horizon	Depth (cm)	Sand	Clay	Silt	Textural class	Silt/clay ratio	BD Mg m^{-3}
			%					
NNL-P1	Ap	0 - 25/30	82	12	6	LS	0.50	1.48
	AB	25/30 - 50/55	82	12	6	LS	0.50	1.56
	Bw1	50/55 - 85/88	82	14	4	SL	0.29	nd
	Bw2	85/88 - 112/115	36	50	14	C	0.28	1.39
	Bw3	115 - 160+	76	18	6	SL	0.33	nd
NWJ-P1	Ap	0 - 22/30	72	20	8	SCL	0.40	1.38
	BA	22/30 - 52/60	48	46	6	SCL	0.13	1.51
	Bt1	52/60 - 80 /100	34	60	6	C	0.10	1.38
	Bt2	80/100 – 140	30	62	8	C	0.13	nd
	Bt3	140 - 200+	34	60	6	C	0.10	nd
MKG-P1	Ap	0 - 16/24	82	12	6	LS	0.50	1.35
	AB	16/24 - 45/49	74	18	8	SL	0.40	1.37
	Bw1	45/49 – 103	70	22	8	SCL	0.36	1.34
	Bw2	103 – 156	72	20	8	SCL	0.40	nd
	Bwc	156 - 200+	76	16	8	SL	0.50	nd

nd = not determined

TABLE 4

MOISTURE CONTENT HELD AT VARIOUS SUCTION PRESSURES FOR THE STUDIED PEDONS AT NANNALA, NAWAJE AND MIKANGAULA

Profile	Horizon	Depth (cm)	0 kPa (SAT.)	10 kPa (FC)	25 kPa	100 kPa	1500 kPa (P.W.P.)	P.A.W. = (FC - P.W.P.)
NNL-P1	Ap	0 – 5	39.7	9.9	8.5	7	6.5	3.4
	AB	45 – 50	36	10.3	9.4	6.6	6.4	3.9
	Bw2	95 – 100	40.9	11.3	9.6	7.5	6.2	5.1
NWJ-P1	Ap	0 – 5	41.4	18.6	18.2	17.1	16.5	2.1
	BA	45 – 50	37.4	32.4	28.1	23.6	23	9.4
	Bt1	95 – 100	40.9	36.4	34.1	31.6	30.7	5.7
MKG- P1	Ap	0 – 5	46.7	12.8	9.7	7.1	6.6	6.2
	AB	45 – 50	37	13.7	11	9.5	9.1	4.6
	Bw1	95 - 100	31.5	15.8	12.5	11	10.6	5.2

SAT= Saturation , FC = Field Capacity, P.W.P. = Permanent Wilting Point
P.A.W. = Plant Available Water, kPa=kilopascal

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Bulk density (BD) is an important parameter for the description of soil quality and ecosystem functions [30]. Topsoil bulk densities of the studied soils ranged from 1.35 to 1.48 Mg m^{-3} while subsoil bulk densities ranged from 1.34 to 1.56 Mg m^{-3} for all soil profiles (Table 3). Generally, BD increased with depth in the studied pedons. The lower topsoil BD may be attributed to higher organic matter content [31]. According to [26], bulk density increases with depth since the subsoils are compacted, with less organic matter, aggregates and pore space, hence minimal numbers of roots compared to topsoils. The relatively higher subsoil BD values for pedons NNL-P1 and NWJ-P1 may pose a slight limitation to root penetration and water movement in these soils.

3.2.2 Soil moisture characteristics of the studied pedons

Table 4 presents results on soil moisture retention characteristics of the studied pedons. Soil water content in the three pedons decreases with increasing suction from saturation point to permanent wilting point. According to [32], soil particle size distribution, organic matter and soil type influence the variation of available moisture content in the soil. Plant available water for pedons NNL-P1, NWJ-P1 and MKG-1 ranged from 3.4 - 5.1%, 2.1 - 9.4%, and 4.6 - 6.2%, respectively. Plant available water increases with depth in pedon NNL-P1 and to some extent in pedon NWJ-P1, but there is no clear trend in pedon MKG-P1. However, higher water retention appears to be associated with higher clay and OM contents (horizon BA of pedon NWJ-P1) and higher amount of OM (horizon Ap of pedon MKG-P1).

Figure 3 presents the moisture retention curves of the studied soils. The moisture retention curves of pedon NWJ-P1 indicate that at all soil matric suctions, the soil holds much more moisture than the other two pedons. The higher moisture retention capacity of pedon NWJ-P1 is attributed to the higher clay content of the soil as compared to the other two pedons. According to [33], high ability of retaining water related to high clay content enables soils to hold more water, thereby contributing to moisture reserve for plants during the dry period. Although pedons NNL-P1 and MKG-P1 have comparable moisture retention behavior because of their similarity in texture, pedon NNL-P1 has the least moisture retention capacity of all the studied pedons.

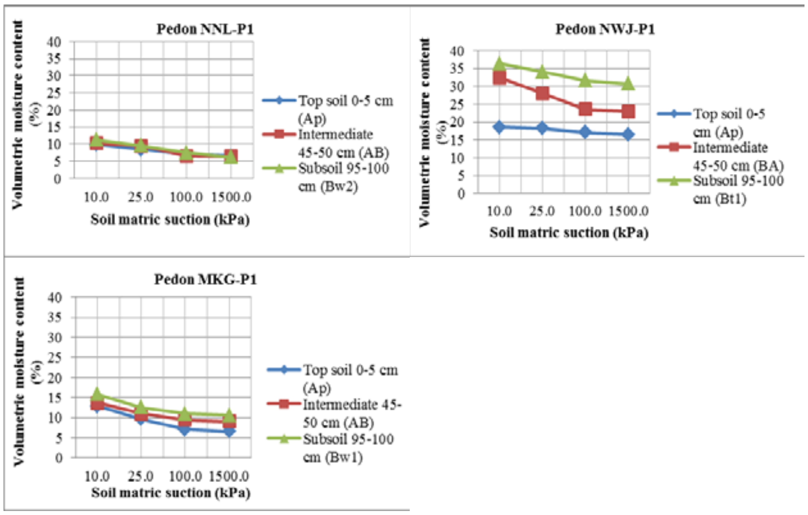

Fig. 3 Soil moisture characteristic curves of the studied pedons at Nannala, Nawaje and Mikangaula

3.3 Soil chemical characteristics

Some selected soil chemical characteristics of the studied pedons are presented in Table 5.

3.3.1 Soil pH and electrical conductivity (EC)

Soil pH plays an important role in determining the solubility and reactivity of soil elements such as Al, Mn and Cd [34]. According to [35] and [36], pedons NWJ-P1 and MKG-P1 are rated as being medium acid to slightly acid with pH ranging between 5.91 and 6.35. This pH range being > 5.5 is favourable for the growth of a wide range of crops. The pH values of pedon NNL-P1 range between 4.36 and 4.57 and are rated as extremely acid to very strongly acid [37]. Such low pH values are not favourable for plant growth. Landon [27] reported that acidic soils with low pH (< 5.5) have a great potential to cause Al toxicity, deficiencies of some essential nutrients to plant growth and retardation of bacterial activity and decomposition of organic matter. The low pH in this pedon may be attributed to leaching of exchangeable bases from surface to subsurface soils, continuous removal of crop residues and burning during farming practices.

Electrical conductivity (EC) is a measure of salinity in the soil. The EC values all the studied soils are very low (< 1.7 dS/m). The low EC values throughout the pedons do not pose any problem of crop yield reduction [37], [38].

TABLE 5
SELECTED CHEMICAL PROPERTIES OF THE STUDIED PEDONS AT NANNALA, NAWAJE AND MIKANGAULA

Pedon	Horizon	pH		EC	OC	OM	TN	C/N	Available P
		H_2O	KCl	dS/m	%			ratio	mg kg^{-1}
	Ap	4.57	3.75	0.03	0.49	0.84	0.04	12	8.71
	AB	4.52	3.75	0.03	0.39	0.67	0.03	13	1.98
NNL-P1	Bw1	4.43	3.75	0.03	0.27	0.47	0.03	9	1.86
	Bw2	4.40	3.79	0.03	0.31	0.53	0.05	6	1.50
	Bw3	4.36	3.74	0.03	0.20	0.34	0.02	10	1.56
	Ap	6.12	5.37	0.04	1.28	2.21	0.05	26	2.70
	BA	5.95	4.63	0.02	1.26	2.17	0.07	18	1.26
NWJ-P1	Bt1	5.88	4.71	0.02	0.66	1.14	0.06	11	0.36
	Bt2	5.93	5.13	0.02	0.45	0.78	0.04	11	0.72
	Bt3	5.97	5.49	0.02	0.49	0.84	0.05	10	0.36
	Ap	6.34	5.44	0.02	0.53	0.91	0.03	18	6.13
	AB	6.35	5.19	0.02	0.20	0.34	0.03	7	3.30
MKG-P1	Bw1	6.18	5.38	0.02	0.22	0.38	0.02	11	2.28
	Bw2	5.91	4.97	0.02	0.31	0.53	0.03	10	1.92
	Bwc	5.98	4.47	0.02	0.16	0.28	0.02	8	1.08

3.3.2 Organic carbon (OC), organic matter (OM) total nitrogen (TN) and C/N ratio

Organic carbon (OC) contents in topsoils of the studied soils range from very low to medium [37] with values of 0.49 to 1.28%, corresponding to 0.84 to 2.21% organic matter (OM) (Table 5). Subsoil OC contents range from very low to low (0.16 - 0.66%), corresponding to 0.28 - 1.14% OM. Generally the OC content decreases with depth for the three studied soils. According to [39] and [26], OC is a major component of OM and plays a vital role in the plant nutrients phosphorus and sulphur, and is the primary source of nitrogen for plant growth.

The values of total nitrogen in the studied pedons range from 0.02 - 0.07 (Table 5), while the C/N ratios range from 7 to 18. This range indicates that the studied surface and subsurface horizons though with a very low N content (< 0.10%), had C/N ratios indicating good to moderate quality of soil organic matter (SOM) for pedons NNL-P1 and MKG-P1. However, topsoil C/N ratio of pedon NWJ-P1 is exceptionally high (>20) indicating poor quality [35], which implies slowdown of decomposition rate by soil microbes; hence low N content in the soil [40]. According to [1], low N content in the soil requires N fertilizer application for optimal plant growth.

3.3.3 Available P

Available phosphorus in the studied pedons ranges from 0.36 mg/kg to 8.71 mg kg^{-1}, with values decreasing as depth increases (Table 5). According to [35] and [37], all the studied soils are rated as low in P content except for topsoil of pedon NNL-P1 which is rated as medium. Available P of 7.0 mg P kg^{-1} and above is considered optimum below which P-deficiency symptoms are likely to occur in most crops [27], [35]. Landon [27] reported that when P is < 15 mg kg^{-1}, response of most crops to P is expected. The low values of P observed in the studied soils could be attributed to the nature of soil parent material, leaching, or low soil pH <5.8 (particularly for pedon NNL-P1) which would favour reaction with iron (Fe) and aluminium (Al) to inhibit availability of P to plants. Similar P trends were reported in studies by [41], [42], [43].

3.3.4 Exchangeable bases, cation exchange capacity (CEC) and base saturation (BS)

The amounts of exchangeable cations namely Ca, Mg, K and Na of the studied soils are presented in Table 6. Ca levels vary among and within pedons with a general tendency of increasing with soil depth. According to [37] topsoil Ca levels are rated as high for both pedons NNL-P1 (2.75 $cmol_{(c)}$ kg^{-1} soil) and NWJ-P1 (5.54 $cmol_{(c)}$ kg^{-1} soil) and as medium for pedon MKG-P1 (1.96 $cmol_{(c)}$ kg^{-1} soil). Subsoil Ca levels range from 0.65 $cmol_{(c)}$ kg^{-1} soil (low) to 1.86 cmol(c) kg^{-1} soil (high) for pedon NNL-P1; 1.65 $cmol_{(c)}$ kg^{-1} soil (very low) to 2.85 $cmol_{(c)}$ kg^{-1} soil (medium) for pedon NWJ-P1; and from 0.25 $cmol_{(c)}$ kg^{-1} soil (very low) to 2.25 $cmol_{(c)}$ kg^{-1} soil (medium) for pedon MKG-P1.

Topsoil exchangeable Mg levels are low in pedon NNL-P1 while they are medium in pedons NWJ-P1 and MKG-P1. Subsoil Mg levels are rated as ranging from medium to high for pedon NWJ-P1 and low to medium for pedon MKG-P1. Exchangeable Mg in pedon NNL-P1 decreases with depth. The relatively higher values of exchangeable Mg in the topsoils of this pedon may be due to low leaching losses, washing by runoff, and mining by cropping systems [30], [44]. In the case of pedons NWJ-P1 and MKG-P1 exchangeable Mg increases with depth most probably due to leaching of this cation down the pedon.

Topsoil exchangeable K values are rated as low in pedons NNL-P1 and MKG-P1 (respectively 0.05 and 0.20 $cmol_{(c)}$ kg^{-1} soil) and medium for pedon NWJ-P1 (0.49 $cmol_{(c)}$ kg^{-1} soil). Subsoil exchangeable K values for pedon NNL-P1 are very low (0.02 to 0.07 $cmol_{(c)}$ kg^{-1} soil), medium for pedon NWJ-P1 (0.39 to 0.62 $cmol_{(c)}$ kg^{-1} soil) and low to medium for pedon MKG-P1 (0.22 to 0.52 $cmol_{(c)}$ kg^{-1} soil).

Exchangeable Na values range from 0.02 - 0.10 $cmol_{(c)}$ kg^{-1} soil with most of the horizons having < 0.1 $cmol_{(c)}$ kg^{-1} soil which is ranked as very low. This indicates there is no sodicity problem in the three studied soils [35].

Cation exchange capacity (CEC) data are presented in Table 6. CEC determines the ability tof soil to bind or hold exchangeable cations against leaching [37], [45]. The CEC values of the studied pedons range from 3.9 to 10.9 $cmol_{(c)}$ kg^{-1} for topsoils and from 2.24 to 8.86 $cmol_{(c)}$ kg^{-1} for subsoils, respectively. According to [27], the topsoil and subsoil CEC values are rated as ranging from very low (< 6.0 $cmol_{(c)}$ kg^{-1}) to low (6.0 - 12.0 $cmol_{(c)}$ kg^{-1}).

Base saturation (BS) values of the studied pedons range from 43.0 to 73.0 % and from 31.0 to 74.0 % in topsoils and subsoils, respectively (Table 6). According to [27], BS of < 20% is low, 21 to 60% medium and > 60% high. On the basis of this categorization, pedon NNL-P1 has medium BS while pedons NWJ-P1 and MKG-P1 have high BS. According to FAO (2006), soils having BS<50% are considered as less favourable soils whereas those with BS≥50% are more favourable soils.

TABLE 6
EXCHANGEABLE BASES AND RELATED PROPERTIES OF THE STUDIED PEDONS AT NANNALA, NAWAJE AND MIKANGAULA

Pedons	Horizon	Depth (cm)	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	TEB	CEC_{soil}	BS
			cmol(c) kg-1						%
NNL-P1	Ap	0 - 25/30	2.75	0.35	0.05	0.03	3.18	7.41	43
	AB	25/30 - 50/55	1.85	0.26	0.06	0.02	2.19	7.18	31
	Bw1	50/55 - 85/88	1.75	0.28	0.02	0.02	2.07	5.39	38
	Bw2	85/88 - 112/115	3.45	0.26	0.07	0.08	3.86	8.86	44
	Bw3	115 - 160+	0.65	0.26	0.02	0.02	0.95	2.24	42
NWJ-P1	Ap	0 - 22/30	5.54	1.88	0.49	0.07	7.98	10.9	73
	BA	22/30 - 52/60	2.85	2.45	0.39	0.08	5.77	8.02	72
	Bt1	52/60 - 80 /100	2.35	2.62	0.56	0.07	5.60	7.60	74
	Bt2	80/100 - 140	1.75	2.85	0.62	0.08	5.30	8.13	65
	Bt3	140 - 200+	1.65	2.60	0.52	0.10	4.87	7.18	68
MKG-P1	Ap	0 - 16/24	1.95	0.51	0.20	0.03	2.69	3.90	69
	AB	16/24 - 45/49	2.25	0.56	0.28	0.03	3.12	4.59	68
	Bw1	45/49 - 103	0.45	1.56	0.22	0.05	2.28	3.42	67
	Bw2	103 - 156	0.25	1.33	0.43	0.05	2.06	3.04	68
	Bwc	156 - 200+	0.45	1.09	0.52	0.05	2.11	3.15	67

3.3.5 Cation ratios and nutrient balance in the studied pedons

TABLE 7
CATION RATIOS AND NUTRIENT BALANCE IN THE STUDIED PEDONS AT NANNALA, NAWAJE AND MIKANGAULA

Profile	Horizons	Depth (cm)	Ca/Mg	Ca/TEB	Mg/K	%(K/TEB)
NNL-P1	Ap	0 - 25/30	7.86	0.86	7.00	1.57
	AB	25/30 - 50/55	7.12	0.84	4.33	2.74
	Bw1	50/55 - 85/88	6.25	0.85	14.00	0.97
	Bw2	85/88 - 112/115	13.27	0.77	0.37	15.59
	Bw3	115 - 160+	2.50	0.68	13.00	2.11
NWJ-P1	Ap	0 - 22/30	2.95	0.69	3.84	6.14
	BA	22/30 - 52/60	1.16	0.49	6.28	6.76
	Bt1	52/60 - 80/100	0.90	0.42	4.68	10.00
	Bt2	80/100 – 140	0.61	0.33	4.60	11.70
	Bt3	140 - 200+	0.63	0.34	5.00	10.68
MKG-P1	Ap	0 - 16/24	3.82	0.72	2.55	7.43
	AB	16/24 - 45/49	4.02	0.72	2.00	8.97
	Bw1	45/49 - 103	0.29	0.20	7.09	9.65
	Bw2	103 -156	0.19	0.12	3.09	20.87
	Bwc	156 - 200+	0.41	0.21	2.10	24.64

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The availability of nutrients for plant uptake does not depend only on their absolute amounts but also on cation ratios / balance [46]. In most cases, a good trend is with calcium higher than magnesium, and magnesium higher than potassium [35]. Cation ratios in the studied pedons are presented in Table 7. The trend Ca>Mg>K (see also Table 6) which prevails in the three studied pedons generally indicates a good balance among the cations. The Ca/Mg ratios range from 2.50 to 13.27, 0.61 to 2.95 and 0.19 to 4.02 in pedons NNL-P1, NWJ-P1, and MKG-P, respectively. According to [37], optimum Ca/Mg ratios favourable for most crops range from 2 to 4. The Ca/Mg ratios observed in topsoils of the studied pedons are within the optimum range except for pedon NNL-P1 in which they are higher than the favourable level. This high Ca/Mg ratio may limit the uptake of Mg by plants. Landon [27] reported that availability of Mg and P to plant becomes less as the Ca/Mg ratio exceeds 5:1. The Ca/TEB ratios in the studied pedons ranged from 0.12 to 0.86 (Table 7). According to [27], Ca/TEB ratio which is more than 0.5 may affect the uptake of other bases particularly Mg and /or K. Hence, the topsoil Ca/TEB ratios of the studied pedons are unfavourable.

The Mg/K ratios observed in pedons NNL-P1, NWJ-P1 and MKG-P range from 0.37 to 14, 3.84 to 6.28 and 2.10 to 7.09, respectively. Whereas the topsoil Mg/K ratios of pedons NWJ-P1 and MKG-P1 are within the optimum range of 1 to 4 for nutrient uptake by plants [27], [37], those of pedon NNL-P1 are rated as unfavourable. The percentage (K/TEB) ratios of pedons NWJ-P1 and MKG-P1 are rated as favourable while those of pedon NNL-P1 are unfavourable for nutrient uptake. According to [27] and [29], %(K/TEB) ratios above 2% are favourable for most tropical crops.

4 SOIL CLASSIFICATION IN THE STUDIED

TABLE 8
DIAGNOSTIC FEATURES AND CLASSIFICATION OF THE STUDIED PEDONS ACCORDING TO USDA SOIL TAXONOMY (SOIL SURVEY STAFF, 2014)

Pedon	**Diagnostic horizon(s)**	**Other diagnostic features**	**Order**	**Suborder**	**Great group**	**Subgroup**	**Family**
NNL-P1	Ochric epipedon; Cambic horizon	Gently undulating to rolling, very deep, sandy over clayey, extremely to strongly acid, ustic SMR≠, isohyperthermic STR#	Inceptisols	Ustepts	Dystrustepts	Typic Dystrustepts	***Gently undulating to rolling, very deep, sandy over clayey, extremely to strongly acid, isohyperthermic, Typic Dystrustepts***
NWJ-P1	Mollic epipedon; Argillic horizon	Level to rolling, very deep, loamy over clayey, medium acid to slightly acid, ustic SMR, isohyperthermic STR	Mollisols	Ustolls	Argiustolls	Typic Argiustolls	***Level to rolling, very deep, loamy over clayey, medium acid to slightly acid, isohyperthermic, Typic Argiustolls***
MKG-P1	Ochic epipedon; Cambic horizon	Level to rolling, very deep, loamy, medium acid to slightly acid, ustic SMR, isohyperthermic STR	Inceptisols	Ustepts	Haplustepts	Typic Haplustepts	***Level to rolling,, very deep, loamy, medium acid to slightly acid, isohyperthermic, Typic Haplustepts***

≠SMR = Soil moisture regime, #STR = Soil temperature regime

TABLE 9
DIAGNOSTIC HORIZONS AND FEATURES, AND CLASSIFICATION OF THE STUDIED SOILS ACCORDING TO WRB FOR SOIL RESOURCES (IUSS WORKING GROUP WRB, 2015)

Pedon No.	Diagnostic horizons	Reference Soil Group (RSG) - TIER1	Principal Qualifiers	Supplementary Qualifiers	WRB soil name - TIER 2
NNL-P1	Cambic horizon	Cambisols	Dystric	Arenic, Ochric,	Dystric Cambisols (Arenic, Ochric)
NWJ-P1	Mollic horizon; Argic horizon	Phaeozems	Luvic	Abruptic, Clayic, Chromic	Luvic Phaeozems (Abruptic, Clayic, Chromic)
MKG-P1	Cambic horizon	Cambisols	Chromic, Eutric	Loamic, Ochric	Eutric Chromic Cambisols (Loamic, Ochric)

AREAS

Field description and laboratory analytical data were used to classify the soils of the study areas according to the USDA Soil Taxonomy [9] and the World Reference Base for Soil Resources [10]. Soil diagnostic horizons, properties and materials used in soil classification are presented in Table 8, while Table 9 presents the soil names according to the USDA Soil Taxonomy [9] and the FAO World Reference Base for Soil Resources [10]. According to the USDA Soil Taxonomy the main soils of the studied areas are *"Gently undulating to rolling, very deep, sandy over clayey, extremely to strongly acid, isohyperthermic, Typic Dystrustepts" (*pedon NNL-P1*), "Level to rolling, very deep, loamy over clayey, medium acid to slightly acid, isohyperthermic, Typic Argiustolls" (*pedon NWJ-P1*)* and "*Level to rolling,, very deep, loamy, medium acid to slightly acid, isohyperthermic, Typic Haplustepts (*pedon MKG-P1*)* corresponding respectively with *"Dystric Cambisols (Arenic, Ochric)", "Luvic Phaeozems (Abruptic, Clayic, Chromic)"* and *"Eutric Chromic Cambisols (Loamic, Ochric)"* in the WRB.

5 CONCLUSIONS AND RECOMMENDATIONS

The studied pedons display varying morphological, physical and chemical properties and are likely to behave differently in terms of their use and management. This emphasizes the need to characterize soils before fertilizer recommendations are made. Pedons NNL-P1 (developed from Neogene sandstones) and MKG-P1 (developed from acid metamorphic rocks) have distinctly coarser texture (LS-SCL) than pedon NWJ-P1) (SCL-C) developed from intermediate metamorphic rocks. In view of its finer texture, Pedon NWJ-P1 displays much more favourable moisture retention characteristics than pedons NNL-P1 and MKG-P1. On the basis of their silt/clay ratios, pedons NNL-P1 and MKG-P1 show lower degree of pedogenic development than pedon NWJ-P1. The former pedons have silt/clay ratios >0.2 while the latter has silt/clay ratios <0.2 and pedogenic features notably clay cutans in the subsoil manifesting higher degree of pedogenic development. In terms of OC, the three studied pedons have very low to medium levels while TN levels remain low. Pedon NNL-P1 is strongly acid while pedons NWJ-P1 and MKG-P1 are slightly acid. Available P levels of the studied pedons range from low to medium. Pedons NWJ-P1 and MKG-P1 have high BS values and pedon NNL-P1 medium values. Yet, the CEC values are rated as very low to low for the three pedons. Although there seems to be some degree of nutrient balance in the studied pedons, there are also indications of nutrient imbalance e.g. the Ca/TEB ratios of the three studied pedons are unfavourable for plant nutrient uptake; and Mg/K and %(K/TEB) ratios are unfavourable for pedon NNL-P1 in respect of nutrient uptake. Generally, the soils are of low to medium fertility on the basis of levels of N, OM, pH and available P. According to the USDA Soil Taxonomy, pedons NNL-P1 and MKG-P1 classified as Inceptisols while pedon NWJ-P1 classified as Mollisols, corresponding respectively to Cambisols and Phaeozems in the World reference Base for Soil Resources.

Sustainable cropping on the studied soils can be achieved with introduction of technologies suitable for rejuvenating soil fertility such as manuring, crop rotation, proper management of crops residues, fallow periods, introduction of leguminous cover crops in the farming system and use of fertilizers, particularly non-acidifying types of fertilizers [33], [47]. Aluminum toxicity may be a serious problem in pedon NNL-P1 which is strongly acid. This should be corrected by liming the soils to pH >5.5. In addition, or alternatively, OM application can be used to reduce Al toxicity by binding the Al ions into OM complexes.

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