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PHYSICO-CHEMISTRY AND MINERALOGY RELATED TO PRODUCTIVITY OF ARENOSOL, LUVISOL AND VERTISOL*

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Abstract – Soil productivity is generally associated with poor nutrient status and the physical condition of the soil, but the effect of soil mineralogy on soil productivity has received little attention. In this qualitative study, interactions between mineralogy and physico-chemistry and their role on the productivity of two luvisols, an arenosol and a vertisol are investigated. Minerals identified in the soils included smectites in the vertisol, kaolinite, quartz, hydromica, albite and biotite in the luvisols and arenosol. The presence of smectite in the vertisol has resulted in it having a higher organic matter content, higher cation exchange capacity, higher water holding capacity, and low bulk density than both luvisols and the arenosol. Both luvisols and the arenosol were dominated by quartz, feldspars and kaolinite, which are chemically inert compared to smectite and have fewer effects on soil cation exchange capacity, water holding capacity, and bulk density. The effect of soil mineralogy and physico-chemistry on the productivity of these soils is reflected in the yield of spinach (*Spinacia oleracea* variety Fordhook giant) grown on the different soils where spinach yield on the vertisol was the highest followed by that of the luvisols and then the arenosol.

Keywords – Cation exchange capacity, kaolinite, organic matter turnover, smectite, spinach yield, water holding capacity

1. INTRODUCTION

Arenosol, luvisol and vertisol are among the soil types which have been identified in arid and semi arid regions [1]. Agricultural productivity in these regions may therefore depend on how well these soils are managed. As a result of low rainfall and high rates of evapo-transpiration that usually prevail in these environments, the contents of organic matter, available nitrogen and phosphorus, and exchangeable bases which, according to Anikwe & Nwobodo [2] determine soil fertility, are usually low in these soils. Crop yields in semi arid regions are therefore relatively lower than in humid regions. Though fertilizers and organic manures have been used to improve the nutrient status and physical condition of these soils, variable levels of success have been obtained. These variations could be attributed to differences in the physical and mineralogical properties of the soils, and the interactions that may occur between the soil and the fertilizers or organic manure added.

The effects of interactions between fertilizers/manures and soil physico-chemical properties on soil productivity are well documented [3, 4, 5]. Secondary minerals constituting the clay fraction of soils govern most of the chemical processes including fixation, ion exchange and complexation which are the key interactions between any material added to the soil and the soil components [6]. These minerals also affect numerous microbial activities indirectly through their effect on the physico-chemical and chemical

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properties of the soil [7] and by so doing, soil minerals affect nutrient turn-over in the soil. Studies have attributed soil productivity in arid and semi arid climates to the nutrient status and moisture regime of the soil. In Botswana for example, poor productivity of the soils is blamed on the low phosphorus content and sandy texture that is characteristic of soils around the country [8].

The effect of interactions between the mineralogical and physico-chemical properties of these soils on their productivity has received little attention. This study was aimed at investigating how interactions between the mineralogy and physico-chemistry of two luvisols (from Barolong Farm and Tuli Block areas), a vertisol (from Pandamatenga) and an arenosol (from Mmamabula), all in Botswana, have affected their productivity. Whereas Barolong Farms (located between latitudes 25°30'S & 25°45'S and between longitudes 025°00'E and 025°45'E), Tuli Block (located between latitudes 22°12'S & 24°00'S and longitudes 027°00'E & 029°15'E) and Pandamatenga (located between latitudes 18° 25'S and 18° 40'S and between longitudes 025°05'E and 025°47'E) are the main agricultural regions of Botswana, Mmamabula (located at latitudes 28°34'S and longitude 026°34'E) lies along the Kgalagadi Sand Belt and is covered by arenosols which make up 71 % of the soils in Botswana. The findings of the study are likely to elucidate the agricultural productivity of these soils and help in their management, especially in desert environments. To assess the productivity of each of these soil types, *Spinacia oleracea* variety Fordhook giant was grown on each of them and the yields compared.

2. MATERIALS AND METHODS

a) Soil sampling and preparation

Sixty soil samples each of luvisol1 (from Barolong Farms), luvisol2 (from Tuli Block), vertisol (from Pandamatenga), and arenosol (from Mmamabula) were collected at depths of between 0-50 cm and homogenised to form a composite sample that was representative of the specific soil type. Sampling was limited to a depth of 50 cm because this constitutes the rooting zone of most crops. Five sub-samples were then collected from each soil composite, air-dried, passed through a 2 mm sieve after which they were packaged for laboratory analyses. Each of the remaining samples from each soil type not used for analyses was passed through a sieve of 4 mm mesh size and then transferred into five separate 25 cm diameter plant pots. The pots were transferred into a greenhouse where they were watered and allowed to acclimatize for three days before spinach (*Spinacia oleracea* variety Fordhook giant) seeds were sown. The spinach was grown for nine weeks during which time the temperature in the green house was maintained at 20 °C and each plant pot received 0.5 litres of tap water every 48 hrs.

b) Minerals identification and determination of physico-chemical properties

For the identification of primary and secondary minerals in the soil samples, a Philips PW 3710 X-Ray diffractometer operated at 40 kV and 40 mA with a Cu anode radiation and a graphite monochromator was used. This system produces x-rays of wavelengths λ_1 = 1.54056Å (Cu–Kα) and λ_2 = 1.54439Å (Cu–Kα) with λ_2 stripped off. The bulk soils as well as the clay fraction of each soil type were scanned for minerals identification at different angles from 2^o 2 θ to 70^o 2 θ using a step size of 2 θ = 0.02 and time per step of 0.2 s [9]. Identification of minerals from data and diffractograms obtained after scanning was carried out using the 2001 Version of the Philips X'PERT Graphics and Identify Software package. The mineral peak list produced by the software package were compared with those in the Mineral Powder Data File ICDD 2002 [10] for identification.

The physico-chemical properties analysed for the different soil samples were particle size distribution, moisture content, water holding capacity (WHC), bulk density (D_b), pH, electrical conductivity (EC), cation exchange capacity (CEC) and organic matter content (OM). The principle of

Stoke's Law was applied to determine the particle size distribution of the samples as described by the United States Department of Agriculture (USDA) [11], whereas WHC was determined by the method described in Forster [12]. Moisture content of the different soils was gravimetrically determined [13]. The method for D_b determination of disturbed soil described by Tan [14] was used to determine the D_b of these soils. The pH of the samples was determined both in 1: 2.5 soil: H_2O and soil: KCl suspensions, and EC in a saturation paste extract of each soil sample as described by the USDA [11]. The modified Walkley Black procedure for organic carbon determination and the ammonium acetate procedure for CEC determination were employed in the determination of OM content and the CEC respectively of the different soil samples [11]. These analyses were performed for each of the five sub-samples from the composite sample of each soil type. All samples were analysed in duplicate. The values reported for each of these properties are therefore the means of 10 values obtained from the five sub-samples.

c) Determination of soil productivity

The productivity of each soil type was determined by comparing the yields of the spinach grown in each of the four soil composites. Spinach is a leafy vegetable and its yield can be measured by the number, size, and quality of leaves produced. In this study, the yield of spinach was determined by measuring the leaf area, leaf length, counting the number of leaves per spinach shoot, and determining the fresh and dry biomass of the spinach leaves. Before harvesting the spinach, the number of leaves per spinach shoot from each soil type was counted and the number of leaves per shoot from each soil type determined. After harvesting, the length of each spinach leaf was determined by measuring the length of each leaf blade. Three leaves were randomly sampled from each spinach shoot and used to determine the leaf area with a leaf area meter as described by Tei et al., [15]. Each spinach shoot from each pot was then weighed to determine the fresh biomass per shoot from the specific soil type. The weighed leaves were placed in pre-weighed paper sampling bags and dried in an oven at 70° C until a constant weight was obtained [16]. The dried residue was weighed and the value used to calculate the dry biomass per spinach shoot from the respective soil types.

Three spinach shoots were grown in each plant pot. Data obtained from 15 spinach shoots were then used to determine the yield of spinach from each soil type. Values reported for leaf area and leaf length were the means of at least three leaves for each of the 15 spinach shoots from the respective soil types. To determine whether the differences observed between the means of the leaf area, leaf length, leaf number, fresh biomass and dry biomass of spinach from the different soil types was significant, the data was subjected to the student *t*-test.

3. RESULTS AND DISCUSSION

a) Minerals identified in the different soil types

The mineralogical composition of the soil types varied as reflected in the X-ray diffractograms in Figs. 1-4. Quartz and hydromica were the main minerals identified in the bulk sample of both luvisols (Fig. 1a & 2a). Whereas the clay fraction of luvisol1 contained mainly quartz and kaolinite (Figure 1b), quartz, kaolinite and biotite were identified in the clay fraction of luvisol2 (Fig. 2b). Barolong Farm area is underlain by Gneisses and granitoids which are made up of quartz and K-feldspars [6]. In Tuli Block, veins of microcline-rich granite are ubiquitous [17]. The dominance of quartz and hydromica as the main primary minerals in both luvisols is therefore explained. Bulk soil samples of the arenosol were monomineralic; quartz being the identified primary soil mineral (Fig. 3a). Its clay fraction contained quartz and kaolinte (Fig. 3b). The Mmamabula area is geologically characterised by the Ecca Group of the Karoo Sediments, which are overlain by a variable thickness of Kalahari sands [17] accounting for the mineralogical composition. The vertisol consisted mainly of quartz, smectite and albite in the bulk soil (Fig. 4a) and only smectitic clay minerals in the clay fraction (Fig. 4b). Weathering of basaltic rocks under the moist conditions which prevailed in Pandamatenga in the past must have resulted in the formation of the smectite identified in the vertisol. The relative abundance of the different minerals identified in both the bulk soil and clay fraction of each sample were as indicated in Table 1.

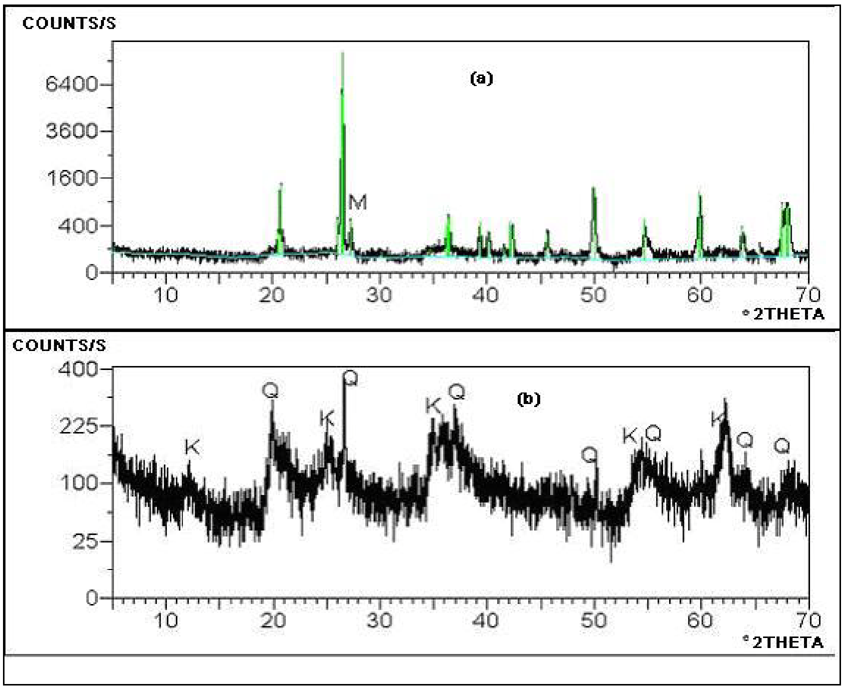

Fig. 1. X-ray diffractograms of the bulk soil (a) and clay fraction (b) of luvisol1.
K = kaolinite, M = hydromica, Q = quartz, all unlabelled peaks = quartz

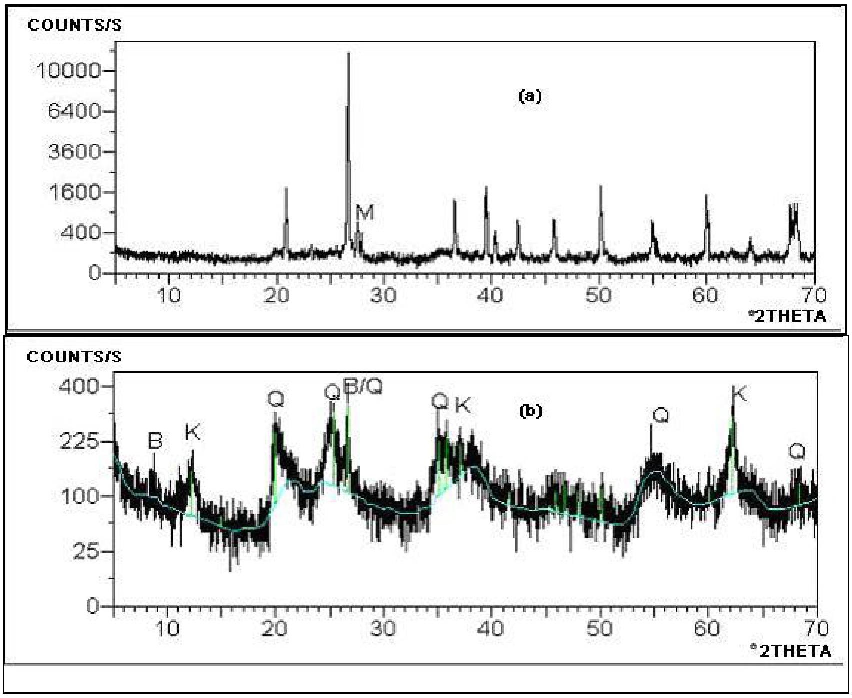

Fig. 2. X-ray diffractograms of the whole soil (a) and clay fraction (b) of luvisol2. B = biotite,
K = kaolinite, M = hydromica, Q = quartz, all unlabelled peaks = quartz

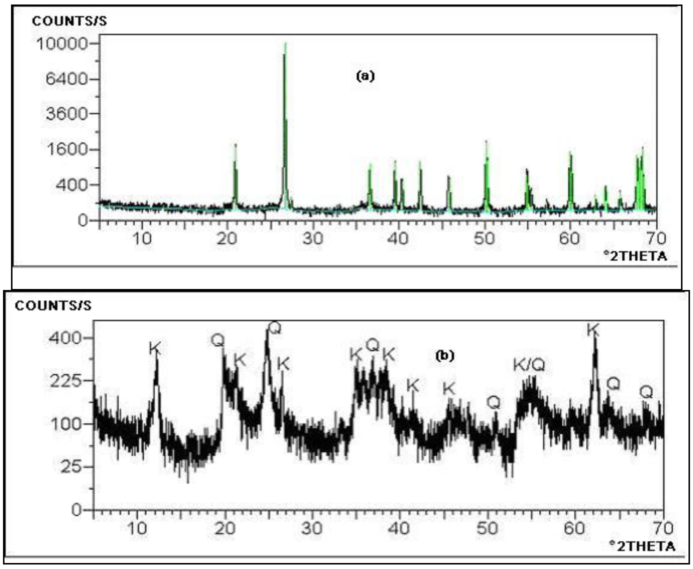

Fig. 3. X-ray diffractograms of the whole soil (a) and clay fraction (b) of the arenosol.
K = kaolinite, Q = quartz, unlabelled peaks in (a) = quartz,

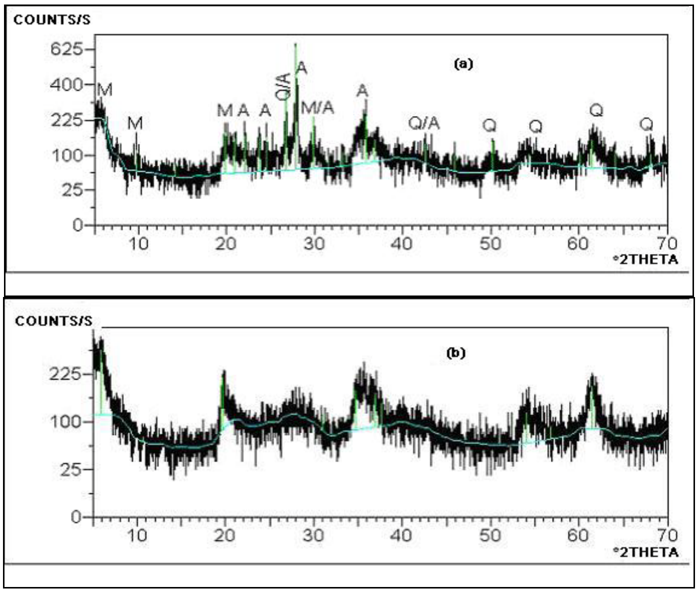

Fig. 4. X-ray diffractograms of the whole soil (a) and clay fraction (b) of the vertisol.
A = albite, M = smectite, Q = quartz, unlabelled peaks = smectite

Table 1. Relative abundance of minerals in the whole soil and clay fraction of the different soil types

Soil Type		Quartz	Kaolinite	Biotite	Albite	Hydromica	Smectite
Luvisol1	Whole soil	+++	nd	nd	nd	++	nd
	Clay fraction	+++	++	nd	nd	nd	nd
Luvisol2	Whole soil	+++	nd	nd	nd	++	nd
	Clay fraction	+++	+++	++	nd	nd	nd
Arenosol	Whole soil	+++	nd	nd	nd	nd	nd
	Clay fraction	+++	+++	nd	nd	nd	nd
Vertisol	Whole soil	+++	nd	nd	+++	nd	+++
	Clay fraction	nd	nd	nd	nd	nd	+++

+++ = Major, ++ = Minor, nd = not detectable,

b) Physico-chemical properties of the different soil types

All four soil types varied in their physico-chemical properties as indicated in Table 2. The vertisol had the highest value for moisture content and WHC and the arenosol the lowest with values of both luvisols lying in between (Table 2). Smetitic clay, which is the dominant clay mineral in both the bulk soil and clay fraction of the vertisol, absorbs water between its interlayer spaces whereas kaolinitic clays (dominant in both luvisols and the arenosol) do not [3].

Table 2. Physico-chemical properties of the different soil types

Properties		**Soil types**			
		Luvisol1 (SE)	**Luvisol2 (SE)**	**Arenosol (SE)**	**Vertisol (SE)**
PSD (wt %)	Sand	82.3 (3.12)	83.3 (2.96)	96.0 (2.11)	34.1 (1.69)
	Silt	12.0 (1.21)	11.9 (1.32)	2.3 (1.12)	37.3 (2.11)
	Clay	5.8	4.8 (1.11)	1.8 (0.31)	28.6 (1.21)
Texture		Loamy sand	Loamy sand	Sand	clayey loam
Structure		Blocky	Blocky	Crumb	Prismatic
Moisture content (%)		2.3 (0.01)	2.4 (0.04)	1.0 (0.01)	21.9 (0.11)
Water holding capacity (%)		43.8 (3.41)	32.8 (3.22)	20.7 (2.11)	51.1 (4.51)
Bulk density (g/cm^3)		1.5 (0.01)	1.5 (0.02)	1.6 (0.01)	0.6 (0.04)
pH – H_2O		6.8 (0.12)	6.5 (0.02)	5.0 (0.14)	7.1 (0.21)
pH – KCl		4.5 (0.10)	5.0 (0.12)	3.8 (0.11)	5.0 (0.14)
Electrical conductivity (μS/cm)		211.0 (14.00)	310.2 (13.00)	221.0 (15.12)	270.5 (14.21)
Organic matter content (%)		1.9 (0.02)	1.8 (0.11)	0.8 (0.03)	2.3 (0.17)
Cation exchange capacity($cmol_c$/kg soil)		7.7 (1.12)	5.1 (1.23)	0.3 (0.01)	72.7 (4.21)

SE = Standard error

Dantsova et al. [18] also observed that more water is needed to prepare a saturation paste extract of montmorillonite clay (smectitic clay) than kaolinite clay, indicating that smectitic soils are able to retain more water than kaolinitic soils. The absorption of water by smectites results in hydration of the interlayer cations, and consequently, an increase in basal spacing that result in swelling of the soils. This swelling is likely to block air- and water- conducting pores in the soil, resulting in a decrease in infiltration and hydraulic conductivity and a consequent increase in the water holding capacity of the soil. The higher WHC and moisture content of the vertisol relative to the arenosol and luvisols are thus explained.

Values for both OM content and CEC of the four soil types followed the order vertisol > luvisol1 > luvisol2 > arenosol (Table 2). Sorptive processes which occur on the surface of soil minerals, especially the secondary minerals, play an important role in organic carbon and consequently OM sequestration [19].

Results from a study by Wattel-Koekkoek and Buurmann, [20] indicated that OM turn-over in kaolinite-rich soils is faster (360 yrs) than in smectitic soils (1100 yrs), implying that soils with smectitic clays like the vertisol accumulate more OM than the luvisols and arenosol which are kaolinitic. This can be explained by the fact that kaolinite-associated soil organic matter is enriched in polysaccharide products which are more easily broken down than the aromatic compounds which dominate the smectite-associated organic matter [21].

Bulk density values for the different soil types followed the order arenosol > luvisol1 – luvisol2 > vertisol. Accumulation of OM in soil results in a reduction in D_b due to an increase in porosity and dilution of the denser soil mineral fraction with the less dense OM [22]. A higher content of OM in the vertisol compared to luvisol1, luvisol2, and the arenosol may explain the observed values of D_b of these soils. Values obtained for pH indicated that the arenosol was acidic, whereas the vertisol and both luvisols had circumneutral pH values (Table 2). The pH values of the different samples in the soil-KCl suspension were lower than that in the soil-H_2O suspension (Table 2), reflecting that these soils have an overall negative charge. Electrical conductivity (EC) values ranged from 211 μS/cm for luvisol1 to 310 μS/cm for luvisol2. These results were indicative of low concentration of total dissolved salts (TDS) in the different soils. The role played by soil mineralogy, clay content and OM content in soil CEC has been widely studied and findings of these studies indicate that smetitic soils and soils with high organic matter content have a higher CEC than vice versa [23]. The higher values obtained for the CEC of the vertisol compared to those obtained for the arenosol and luvisols is therefore justified.

c) Spinach Yield in the four soil types

Values for fresh biomass (MFB) of spinach grown on the different soil types followed the order spinach from vertisol > spinach from luvisol2 > spinach from luviso1 > spinach from arenosol. The mean dry biomass (MDB) of spinach grown on the vertisol were significantly higher than those grown on luvisol2, arenosol and luvisol1 respectively (Table 3). Whereas the spinach grown on the arenosol had the smallest, shortest and least number of leaves, those grown on the vertisol had the largest, longest and most number of leaves per shoot (Table 3). Except for the differences observed between the fresh biomass of spinach from luvisol1 and luvisol2 (t = 0.05), and luvisol2 and vertisol (t = 1.5), the differences observed in the means of the fresh biomass, leaf area, leaf number, dry biomass and leaf length were statistically significant as the value obtained for the student *t*-test were all higher than the critical value of t at 0.05 confidence limit (1.7).

d) Effects of interactions of soil mineralogy and physico-chemistry on spinach yield

The mineralogical composition of the vertisol enables it to have high CEC and OM content which guarantees higher retention of plant nutrients. In addition, it also has low bulk density that enhances root penetration exposing the root system to a larger area from where nutrients could be absorbed. Higher clay content implies more stable aggregates and consequently lower rates of erosion. The opposite was true for the arenosol where the spinach yield was lowest. Spinach yields on both luvisols were lower than that on the vertisol, but higher than that of the arenosol. This is also a reflection of their mineralogical and physico-chemical properties, both of which lie between those of the vertisol and the arenosol. According to Ben-Hue et al., [24] the clay content of luvisols usually results in soil which encourages sheet erosion. As a result, there is a gradual washing away of the top soil, which is usually richer in plant nutrients.

Table 3. Yield parameters of spinach grown on the different soil types

Sample No.	Fresh biomass (gm)				Dry biomass (gm)				Leaf area (cm^2)				Leaf length (cm)				Number of leaves			
	LV1	LV2	ARE	VER	LV1	LV2	ARE	VER	LV1	LV2	ARE	VER	LV1	LV2	ARE	VER	LV1	LV2	ARE	VER
1	18.5	21.5	25.3	33.2	4.6	8.3	8.3	16.5	135.0	102.0	59.0	109.0	21.4	22.6	10.2	31.9	9.0	10.0	7.0	12.0
2	27.6	34.6	21.7	29.0	5.8	9.7	7.9	15.3	132.0	98.0	71.0	149.0	19.6	25.0	9.5	28.3	11.0	10.0	6.0	10.0
3	26.3	40.3	23.4	32.1	5.6	10.6	7.2	18.2	116.0	119.0	62.0	132.5	20.0	23.2	9.4	32.2	10.0	10.0	7.0	12.0
4	28.9	21.0	21.3	32.3	5.2	8.1	7.6	16.5	86.0	78.0	85.0	130.2	20.7	21.4	8.5	20.6	9.0	11.0	6.0	13.0
5	17.3	23.8	8.1	29.2	4.2	8.7	2.3	17.3	98.0	132.0	89.0	162.0	18.3	22.7	10.4	21.4	8.0	6.0	5.0	14.0
6	25.4	23.6	9.1	31.3	4.6	8.1	3.2	16.8	101.0	93.0	72.0	103.0	18.5	26.0	10.9	21.2	12.0	8.0	5.0	13.0
7	19.3	18.5	21.7	33.5	4.4	7.7	7.7	18.3	79.0	109.0	98.0	153.0	21.0	23.9	8.2	29.2	11.0	10.0	4.0	11.0
8	28.3	35.2	31.3	30.5	5.3	10.1	8.6	17.1	89.0	128.0	93.0	157.0	18.3	21.1	10.0	29.0	13.0	9.0	5.0	13.0
9	26.5	22.1	19.5	27.6	5.1	8.6	7.2	15.3	111.0	75.0	92.0	148.3	20.0	21.4	9.0	32.5	9.0	9.0	5.0	11.0
10	32.1	31.0	17.2	29.5	5.9	9.3	6.5	16.1	85.0	63.0	65.0	151.7	22.0	21.4	9.3	32.6	9.0	8.0	5.0	13.0
11	29.3	28.4	16.3	27.2	5.6	8.3	6.3	14.7	126.0	72.0	73.0	166.7	21.0	22.9	9.6	27.6	10.0	10.0	4.0	12.0
12	25.6	18.0	21.1	26.3	4.8	6.9	8.1	14.7	137.0	81.0	89.0	155.7	21.7	23.6	8.4	23.0	11.0	9.0	6.0	12.0
13	27.1	19.2	20.1	26.5	5.3	7.3	7.3	15.3	94.0	77.0	65.0	142.0	20.4	21.1	8.1	24.8	11.0	10.0	6.0	11.0
14	25.3	32.2	19.1	26.7	5.2	9.6	6.9	15.1	124.0	106.0	87.0	101.0	19.2	23.0	9.9	27.3	10.0	8.0	5.0	13.0
15	36.1	26.0	18.4	24.9	6.3	7.5	6.5	13.7	152.0	126.0	65.0	144.0	23.3	23.8	8.8	28.2	10.0	8.0	5.0	11.0
Mean (SD)	26.2 (5.0)	26.4 (7.0)	19.6 (5.7)	29.3 (2.7)	5.6 (0.6)	8.6 (1.1)	6.8 (1.8)	16.1 (1.3)	111.0 (22.6)	97.3 (22.5)	77.7 (13.2)	140.3 (21.0)	20.4 (1.4)	22.9 (1.5)	9.4 (0.8)	27.3 (4.2)	10.0 (1.3)	9.0 (1.3)	5.0 (0.9)	12.0 (1.1)

LV1= Luvisol1, LV2 = Luvisol2, ARE = Arenosol, VER = Vertisol, SD = Standard deviation

4. CONCLUSION

This study has observed that productivity of the vertisol is higher than both the luvisol and arenosol studied as the mineralogical composition of the vertisol (smectite) enhances its productivity in terms of improved CEC, WHC, OM content, and porosity (as measured by bulk density) compared to the arenosol and luvisols, where the dominant minerals were quartz, feldspars and kaolinite. These results are confirmed by the yield of spinach grown on the different soils. Yield of spinach as measured by fresh and dry biomass, leaf area, length, and number per shoot followed the order vertisol > luvisol1=luvisol2 > arenosol. Previous related work by Ngole et al. [25] support the findings of this study.

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