Research Article

# Density of Arbuscular Mycorrhizal Fungi and Nutrient Status of Soils in Selected Land Use Types and Soil Depths

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**Abstract** | Arbuscular mycorrhizal fungi (AMF) are one of the most beneficial components of the soil biota whose abundance in soil varies with land use type, soil depth and location. The study investigated the density of the AMF and nutrient status of soils in selected land use types and soil depths. Soil samples were collected from some fallow, cassava and pineapple fields in Ibadan and Ikwuano areas of Nigeria at 0-15, 15-30 and 30-45 cm depths and analyzed in the Laboratory. Spore densities of AMF varied significantly ($P > 0.05$) between the fallow and cultivated (cassava and pineapple) land use types in both locations. Across the soil depths, however, AMF spore density decreased significantly with depth in Ibadan, with mean values of 54±6, 45±3 and 39±5 spores 100 $g^{-1}$ soil at the 0–15, 15–30 and 30–45 cm, respectively. In Ikwuano, there was no significant differences among means, and mean spore densities were more abundant at the 15–30 cm depth (67±2 spores 100 $g^{-1}$ soil), followed concordantly by the 0–15 cm (66±4 spores 100 $g^{-1}$ soil) and lowest at 30–45 cm depth (64±3 spores 100 $g^{-1}$ soil). The status of soil nutrient elements (C, N, P, Ca, Mg, K and Na) were relatively higher in Ikwuano than in Ibadan soils. Spore density, essentially, correlated significantly positive ($r = 0.910^{*}$, $P > 0.05$) with the exchangeable $K^+$, but correlated significantly negative ($r = -0.834^{*}$, $P > 0.05$) with total N in the fallow field. The density of the AMF was higher in the fallow than the cultivated land use types, and more at the 0–15 cm depth relative to the subsoil depths.

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## Introduction

Interactions between soil microorganisms and plant roots at the soil-root interface result into various forms of associations (Barea *et al*., 2002), which could be either beneficial or detrimental to the interacting species. Mycorrhiza is a symbiotic association between fungi and plants in which a fungus lives within or outside the roots of plants, forming a mutualistic relationship that is usually beneficial to both partners

(Tedersoo *et al*., 2020). Arbuscular mycorrhizal fungi (AMF) are one of the commonest and beneficial soil microbial communities in both agricultural and natural ecosystems (Leal *et al*., 2009), which establish endomycorrhizal associations with over 85% of plant families (Smith and Read, 1997). In mycorrhizal association, the AMF protects the host plants against environmental stresses and enhances their uptake of inorganic minerals while the plants in turn, offer carbon compounds (photosynthates) to the AMF (Smith and Read, 2008). The association contributes to induced plant's resistance against pathogenic organisms in soil and tolerance to abiotic stresses such as drought (Smith and Read, 2008).

According to Kabir *et al*. (2003), soil fungi constitute a substantial part of the soil biomass having several vital roles in soil, including soil aggregation, organic matter decomposition, nutrient cycling and mycorrhizal symbioses. Symbiotic mycorrhizal fungi, in particular, form a major part of the microbes influencing plant growth and nutrient uptake (Johansson *et al*., 2004). Relative to non-mycorrhizal plants, plants participating in mycorrhizal symbioses usually have an increased nutrient uptake (Smith *et al*., 2010), greater tolerance to heavy metals toxicity (Rozpadek *et al*., 2014) and higher resistance to drought and salinity (Auge, 2001).

In addition, the AMF also enhances the growth rate and survival of seedlings of many tropical plant species (Janos, 1980). They enhance plant's uptake of water and nutrients, especially phosphorus (P), and improves their ability to fix nitrogen, thereby enabling them to survive in the tropical marginal environments (Requena *et al*., 2001). Mycorrhizal association also evidently enhances the uptake of micronutrients such as iron (Kim *et al*., 2009), Zn (Ryan *et al*., 2003) and Cu (Toler *et al*., 2005) in plants, among others (Ryan *et al*., 2004).

Traditionally, studies of the density and diversity of AMF has been based on the examination of relative abundances of the spores, which are distinguishable by their morphological characteristics (Muleta *et al*., 2008; Sale *et al*., 2015). This is mainly because the fungi involved in arbuscular mycorrhizal symbioses are obligate symbionts and reproduce essentially by soil-borne spores (Eun-Hwa *et al*., 2013). Although molecular methods are now available for the assessment of AMF populations and diversity, spores constitute one of the most important infective propagules of the AMF and they are vital in the isolation, quantification and identification of arbuscular mycorrhizal fungi (Smith and Read, 2008).

An understanding of the influence of land use systems and changes in land use types on the density of AMF is essential for harnessing the potentials of these important group of microbes in improving agricultural productivity, especially in impoverished soils. According to Soka and Ritchie (2015), studies of AMF populations and species diversity, and their roles in different land use types are vital for understanding the impact of land use changes on ecosystem functions. Many ecological studies of AMF indicate that the density and occurrence of AMF species decreases with intensification in land use (Oehl *et al*., 2003; Tchabi *et al*., 2008). Van-der-Heijden *et al*. (1998), had noted that developments in agricultural land use can change the whole range of AMF associations that are particularly suited to specific plants. Lower AMF species richness was reported in arable lands, while species-rich communities of AMF were observed under different perennial (forest) and natural ecosystems (Snoeck *et al*., 2010). Sanders *et al*. (1996) observed a variable response of different plant species to different species of AMF and a reduction in the abundance and diversity of indigenous AMF, particularly in disturbed arid and semi-arid environments, while Ndoye *et al*. (2012) noted a positive influence of land use systems (with Acasia plant species) on the diversity and spore abundance of AMF as well as on the functions of soil microbial communities.

The effect of depth on soil microbial populations, including the arbuscular mycorrhizal fungi, is also well known. Arbuscular mycorrhizal fungi are ubiquitous, occurring in virtually all climates and ecosystems (Barea *et al*., 1997) and at various depths of soil (Dalpe *et al*., 2000). Findings from independent researchers (Muleta *et al*., 2008; Oehl *et al*., 2005; Yang *et al*., 2010) indicate that AMF communities in subsoil layers differ from those of topsoils in terms of density, species diversity and community composition. In an arid habitat, Taniguchi *et al*. (2012), observed a decrease in AMF colonization with depth, which was maintained up to the 1 meter depth. In contrast, Gucwa-Przepióra *et al*. (2013) reported an increase in spore numbers of AMF and root colonization rate with depth, down to the 60 cm, in a heavy metal contaminated site.

While an appreciable number of research works are available on the density of AMF in specific land use types (Leal *et al*., 2009; Grantina *et al*., 2011; Ndoye *et al*., 2012; Dare *et al*., 2012; Zerihum *et al*., 2013), only a few took into cognizance the effects of soil depth on the population density of the AMF (Yang *et al*., 2010; Taniguchi *et al*., 2012; Gucwa-Przepióra *et al*., 2013). However, information on abundance of the AMF in relation to nutrient levels of soil is still scanty. This study therefore, investigated the density of arbuscular mycorrhizal fungi and nutrient status of soils in selected land use types and soil depths.

## Materials and Methods

*Description of study areas and sites*

The study was conducted on soils of Ibadan (IB) in Oyo State and Ikwuano (IK) in Abia State, both in the southern hemisphere of Nigeria.

The study sites in Ibadan (IB) are located within the University of Ibadan Teaching and Research Farm in Ibadan North Local Government Area of Oyo State, Nigeria and lie between latitudes 7°48'34" and 7°28'41" N and longitudes 3°36'46" and 3°54'39" E of the equator, with elevations of 204.5 m and 193.4 m, respectively. The geology of the soils are basement complex rocks. The annual rainfall of the area is about 1200 mm with rainy season occurring between April and November. The temperature is generally high with the average annual minimum temperature being 21.9°C and the maximum is 32.5°C. The mean monthly temperature ranges between 24°C and 28°C. Humidity is high in the early hours of the day but sharply decreases in the afternoon. The mean value at 6 a.m is 92.98%, while it is 61.4% at 4.00 pm (Akinbola *et al*., 2014).

In Ikwuano (IK), the study sites which lie between latitudes 5°29'42" and 5°28'58" N and longitudes 7°34'29" and 7°33'28" E of the equator with the elevations of 273 m and 296 m, respectively, are both located in Umuokwor, Oboro community in Ikwuano Local Government Area of Abia State, Nigeria. The soils are of coastal plain sands origin. The area is characterized by rainforest vegetation of the southeast geopolitical region of Nigeria, and is typical of the degraded humid forest ecology of the sub-Saharan Africa (IITA, 1996). The rate of precipitation in the area is high (over 2,000 mm per annum) with the peaks occurring between August and September. The ranges of air temperatures and relative humidity are $21^0$C to $31^0$C and 42% to 80%, respectively (Chukwu, 2013).

*Soil samples collection and analysis*

Two sites were sampled in each of the two locations (Ibadan and Ikwuano). Within each site, three land use types namely cassava, pineapple and fallow fields were identified. Guided by simple random sampling technique, 3 core soil samples were collected in each of the 3 land use types from 0–15, 15–30 and 30–45 cm depths using a soil auger. Thus a total of 9 core soil samples were collected per land use type. For each land use type in one location, samples collected from the same soil depth were bulked together to obtain composite samples of the respective soil depths. Soil samples were air dried at room temperature in preparation for laboratory analyses. Each composite sample was divided into two subsets: to determine the physical and chemical properties of the soils and for the estimation of AMF population.

Particle size distribution was determined by hydrometer method of Gee and Or (2002), Soil pH was determined in a 1:2.5 soil to liquid suspension (20 g soil and 50 ml distilled water) using the glass electrode pH meter (Hendershot *et al*., 1993), Soil organic carbon was estimated by the Walkley and Black wet oxidation method of Mclean (1982) and total nitrogen by the micro kjedahl method of Bremner as modified by Udo *et al*. (2009). Available phosphorus was determined calorimetrically by Mehlich III method (Mehlich, 1984) using UV spectrophotometer set at the wavelength of 882 nm, while exchangeable cations were extracted in Mehlich III solution and determined instrumentally by Atomic Absorption Spectrophotometry (AAS) method (Spark, 1996). Effective cation exchange capacity (ECEC) was calculated by the summation of the total exchangeable bases and exchangeable acidity.

*Extraction and enumeration of AMF spores*

The population of arbuscular mycorrhizal fungi (AMF) spores in the soils was estimated using the wet sieving and decanting method as described by Gerdemann and Nilcoson (1963). A 100 g of each soil sample was mixed with a convenient volume of water in a large beaker (500 Ml) and stirred thoroughly with a glass rod to obtain a uniform suspension. The suspension was allowed to settle for 30 s and the supernatant was decanted through sieves of

**Table 1:** *Soil properties of selected land use types in two locations of southern Nigeria.*

| | Ibadan | | | Ikwuano | | |
|---|---|---|---|---|---|---|
| **Soil property** | **Fallow** | **Cassava** | **Pineapple** | **Fallow** | **Cassava** | **Pineapple** |
| pH ($H_2O$) | 6.00 ±0.44 | 6.22±0.16 | 6.27±0.04 | 4.50±0.14 | 4.15±0.07 | 4.54±0.12 |
| Organic C (g $kg^{-1}$) | 11.67±1.35 | 9.24±2.18 | 10.92±2.38 | 17.57±5.49 | 20.30±4.51 | 14.56±2.53 |
| Total N (g $kg^{-1}$) | 1.67±0.19 | 2.59±0.41 | 1.91±0.46 | 1.87±0.43 | 2.38±0.20 | 2.19±0.13 |
| C/N | 7.83±1.66 | 3.94±0.88 | 5.88±0.77 | 9.29±1.88 | 8.31±1.80 | 6.83±1.32 |
| Avail. P (mg $kg^{-1}$) | 15.50±0.29 | 16.17±0.24 | 18.17±0.28 | 29.67±0.25 | 21.83±0.23 | 13.00±2.17 |
| TEA (cmol $kg^{-1}$) | 5.33±2.61 | 5.71±2.62 | 5.21±4.32 | 5.68±8.97 | 5.92±6.46 | 6.05±0.25 |
| $Ca^{2+}$ (cmol $kg^{-1}$) | 1.33±0.10 | 1.45±0.19 | 1.65±0.38 | 3.99±1.60 | 5.51±2.05 | 1.75±0.66 |
| $Mg^{2+}$ (cmol $kg^{-1}$) | 1.67±0.13 | 1.73±0.11 | 1.52±0.38 | 1.92±0.42 | 1.96±0.30 | 1.42±0.16 |
| $K^+$ (cmol $kg^{-1}$) | 0.17±0.04 | 0.35±0.05 | 0.28±0.02 | 0.38±0.05 | 0.43±0.04 | 0.44±0.03 |
| $Na^+$ (cmol $kg^{-1}$) | 1.00±0.02 | 1.27±0.14 | 1.02±0.07 | 0.13±0.03 | 1.21±0.09 | 1.18±0.07 |
| TEB (cmol $kg^{-1}$) | 4.34±0.23 | 4.80±0.42 | 4.47±1.14 | 7.43±2.08 | 9.11±2.46 | 4.79±0.86 |
| ECEC (cmol $kg^{-1}$) | 9.68±0.42 | 10.51±0.50 | 9.67±1.63 | 13.11±1.98 | 15.02±2.36 | 10.84±0.81 |
| Sand (g $kg^{-1}$) | 864.83±16.31 | 824.00±15.66 | 884.67±18.77 | 840.00±30.11 | 845.00±28.13 | 841.00±28.04 |
| Silt (g $kg^{-1}$) | 65.56±12.21 | 61.83±10.71 | 28.50±13.73 | 41.33±14.35 | 35.00±12.03 | 32.33±10.25 |
| Clay (g $kg^{-1}$) | 129.67±7.01 | 114.17±9.93 | 86.83±6.88 | 121.00±15.42 | 120.00±17.65 | 126.67±19.42 |

Data were reported as means ± standard errors. TEA = Total exchangeable acidity, TEB = Total exchangeable bases, ECEC = Effective cation exchange capacity

diameter 500, 212, 106 and 53 - µm, arranged in that sequence. The process was repeated three times for each sample. Particles in the 106 and 53-µm mesh sizes were collected and centrifuged at 1800 rpm for 2 min. The sediment was resuspended in 40% sucrose solution and centrifuged again at 1800 rpm for 1.5 min to allow for flotation of spores. The spores in suspension were filtered and quantified by direct counting under a compound microscope using the X40 objective. The density of AMF spores in the soil was expressed as number of AMF spores in 100 g of soil.

*Statistical analysis*

Measured variables were analyzed using descriptive statistics with the aid of the GenStat discovery edition 4.0. Means were subjected to analysis of variance (ANOVA) to test for their statistical differences and significant means were separated using the Duncan's multiple range test. Relationships between AMF spore density and selected soil properties (nutrient parameters) were determined using the Pearson correlation analysis at 0.05 level of probability.

## Results and Discussion

*Soil properties of three land use types in Ibadan and Ikwuano, southern Nigeria*

The pH of Ibadan (IB) soils ranged from an average of 6.00±0.44 in IB-fallow to 6.27±0.04 in IB-pineapple (Table 1). These range of pH (6.00 - 6.27) of soils of Ibadan area indicates slightly acidic soil reactions. Similarly, Ikwuano (IK) soil pH ranged from 4.15±0.07 in IK-Cassava to 4.54±0.12 in IK-Pineapple (Table 1), showing a very strong to strong acid reactions (Adebayo *et al*., 2009).

The status of the soil nutrient elements (C, N, P, Ca, Mg, K and Na) were relatively lower in Ibadan soils in comparison to the soils of Ikwuano area (Table 1). Organic carbon occurred in low to moderate amounts (9.24±2.18 – 11.67±1.35 g $kg^{-1}$) in Ibadan soils, but in moderate to high amounts (14.56±2.53 – 20.30±4.51 g $kg^{-1}$) in soils of Ikwuano area. This is with reference to Greg (2004) who placed the preferred values of organic carbon in soils at values above 20 g $kg^{-1}$ and not lower than 10 g $kg^{-1}$. The concentrations of total nitrogen vary from medium to high amounts, ranging from 1.67±0.19 – 2.59±0.41 g $kg^{-1}$ in Ibadan and from 1.87±0.43 to 2.39±0.13 g $kg^{-1}$ in Ikwuano. In their ratings of fertility classes of Nigerian soils for fertilizer use and management practices, Chude *et al.* (2012) reported the ranges of 0.6–1.0, 1.1–1.5, 1.6–2.0 and 2. –2.4 g $kg^{-1}$ as low, moderately low, medium and high, respectively, for total nitrogen. Specifically, organic carbon and total nitrogen contents in Ikwuano were highest at the cassava field (C = 20.30±4.51

g $kg^{-1}$, N = 2.38±0.20 g $kg^{-1}$) compared to the two other land use types. In Ibadan, however, total nitrogen was also highest at the cassava field (2.59±0.41 g $kg^{-1}$), whereas the highest content of organic carbon (11.67±1.35 g $kg^{-1}$) occurred at the fallow field. The effect of fallow on organic matter build-up has been widely reported by different authors (Tian *et al*., 2005; Aguilera *et al*., 2013; Ahukaemere *et al*., 2020). The C:N ratio, an index of the degree of biological activities in soils was low in soils of both locations. This must have resulted from the very high levels of total N in the studied soils. According to Watson *et al*. (2002), nitrogen is more rapidly released into the soil at low C:N ratios. In general, a good balance of C:N ratio ranging from 25-35 is necessary to maintain microbial activity (Kutsanedzie *et al*., 2015). Results showed that, in both locations, the C:N ratio was highest at the fallow fields (IB-fallow = 7.83±1.66, IK-fallow = 9.29±1.88) compared to those cultivated to cassava and pineapple (Table 1). This is in tandem with Fantaw-Yimer *et al*. (2007), who reported lower C:N ratios for arable soils relative to soils under forest field. However, the result disagrees with studies by Eyayu and Mamo (2018) who observed higher C:N ratio in cultivated land than forest land, and Abbasi *et al*. (2007) who noted lower ratios of carbon to nitrogen in the soils of natural vegetation than that of arable lands.

Values of available phosphorus was generally moderate (15.50±0.29 – 18.17±0.28 mg $kg^{-1}$) in Ibadan soils, but moderate to high (13.0±2.17 to 26.6±0.25 mg $kg^{-1}$) in soils of Ikwuano area. According to Chude *et al*. (2012), soil available P value is low at 3–7 mg $kg^{-1}$, moderate at 7-20 mg $kg^{-1}$ and high at >20 mg $kg^{-1}$. The higher concentrations of available P in Ikwuano than Ibadan soils, may be a function of the relatively higher content of organic carbon, since most of the P available in soil derives from the soil organic matter pool. In Ikwuano, the concentrations of available P within the three land use types, occurred in the order of fallow > cassava > pineapple fields, whereas the reverse was the case in Ibadan (Table 1). This contrasting results of soil available P across the land use types between the studied locations could be attributed to the differences in environment (Cao *et al*., 2012; Blake *et al*., 2000), cropping systems (Ohno *et al*., 2005) and/or soil type (Zhang *et al*., 2009). The findings in the available P content of Ikwuano land uses, where the fallow field had higher P values relative to the cultivated land use types, tally with that of Eyayu (2018), who observed significantly higher concentrations of available P in the forest soils of Ethiopia than in the cultivated land use types.

Considering the land use types in Ibadan, the highest value (10.51±0.50 cmol $kg^{-1}$) and lowest value (9.67±1.63 cmol $kg^{-1}$) of the effective cation exchange capacity (ECEC) was detected under the cassava and pineapple land uses, respectively. A similar trend also occurred in Ikwuano, where the cassava and pineapple land uses had the highest and lowest ECEC values of 15.02±2.36 and 10.84±0.81 cmol $kg^{-1}$, respectively. In general, the soil ECEC of both locations when placed side by side, was higher in Ikwuano than in Ibadan area across the three land use types. This can be attributed to the corresponding higher contents of organic carbon in the soils of Ikwuano area than that of Ibadan, in all the three land use types (Table 1). Although the colloidal particles (clay and humus) together constitute the seat of ion exchange in soils, the soil organic matter (SOM) particularly play a vital role in soil cation exchange reactions, since it offers more negatively charged surfaces relative to clay particles (Brady and Weil, 2002). Thus, as the organic matter content of soils increases, the cation exchange capacity (CEC) also increases.

*Soil properties of three soil depths in Ibadan and Ikwuano, southern Nigeria*

The average range of pH of Ibadan (IB) soils was 6.13±0.11 in IB-15–30 cm depth to 6.33±0.08 in IB-0–15 cm; a range of pH classified also as slightly acidic soils. In Ikwuano (IK), the pH values ranged from 4.42±0.13 in IK-15–30 cm depth to 4.48±0.16 in IK-0–15 cm (Table 2), which equally qualify the Ikwuano soils as very strong acid to strong acid soils. The pH ranges in each of the locations which fall within the same classes of soil pH, irrespective of land use types and soil depths, reflects strong influence of the parent materials from which the soils were derived.

In Ikwuano, organic carbon and total nitrogen contents were highest at the 15–30 cm depth (C = 18.06±4.33 g $kg^{-1}$, N = 2.28±0.33 g $kg^{-1}$) in comparison with the two other soil depths (0-15 cm and 30-45 cm). Similarly, in Ibadan, the highest contents of organic carbon and total nitrogen were recorded at the 15-30 cm (11.62±1.79 g $kg^{-1}$) and 30-45 cm (2.24±0.50 g $kg^{-1}$) depths, respectively. These findings of higher concentrations of organic carbon and nitrogen contents in a subsoil depth than the topmost depth of soil

**Table 2:** *Soil properties of three soil depths in two locations of southern Nigeria.*

| | Ibadan | | | Ikwuano | | |
|---|---|---|---|---|---|---|
| **Soil property** | **0 – 15cm** | **15 – 30cm** | **30 – 45cm** | **0 – 15cm** | **15 – 30cm** | **30 – 45cm** |
| pH ($H_2O$) | 6.33±0.08 | 6.13±0.11 | 6.24±0.75 | 4.48±0.16 | 4.42±0.13 | 4.29±0.11 |
| Organic C (g $kg^{-1}$) | 11.50±1.77 | 11.62±1.79 | 8.68±2.35 | 17.36±5.34 | 18.06±4.33 | 17.01±3.68 |
| Total N (g $kg^{-1}$) | 1.84±0.44 | 2.10±0.21 | 2.24±0.50 | 2.05±0.31 | 2.28±0.33 | 2.10±0.23 |
| C/N | 7.18±1.54 | 5.62±0.79 | 4.74±1.40 | 8.97±2.30 | 7.71±1.19 | 7.75±1.48 |
| Avail. P (mg $kg^{-1}$) | 13.00±0.30 | 23.67±0.23 | 13.17±0.26 | 27.83±0.18 | 19.33±0.26 | 17.33±0.11 |
| TEA (cmol $kg^{-1}$) | 5.33±0.80 | 5.35±3.65 | 5.25±1.74 | 5.37±9.56 | 6.05±5.67 | 6.21±4.33 |
| $Ca^{2+}$ (cmol $kg^{-1}$) | 1.76±0.28 | 1.40±0.14 | 1.30±0.18 | 3.59±1.64 | 3.59±1.59 | 4.06±1.83 |
| $Mg^{2+}$ (cmol $kg^{-1}$) | 1.70±0.07 | 1.60±0.14 | 1.49±0.17 | 1.93±0.37 | 1.79±0.33 | 1.58±0.59 |
| $K^+$ (cmol $kg^{-1}$) | 0.33±0.03 | 0.27±0.02 | 0.32±0.06 | 0.47±0.04 | 0.38±0.04 | 0.38±0.04 |
| $Na^+$ (cmol $kg^{-1}$) | 1.11±0.02 | 1.07±0.04 | 1.18±0.15 | 1.21±0.20 | 1.17±0.06 | 1.14±2.15 |
| TEB (cmol $kg^{-1}$) | 4.91±0.77 | 4.35±0.30 | 4.30±0.51 | 7.20±2.07 | 6.94±2.02 | 7.17±2.02 |
| ECEC (cmol $kg^{-1}$) | 10.71±0.32 | 9.71±0.47 | 9.55±0.68 | 12.58±1.92 | 13.00±1.94 | 13.39±2.10 |
| Sand (g $kg^{-1}$) | 853.50±17.12 | 819.83±21.95 | 840.17±19.36 | 851.67±29.37 | 842.67±28.66 | 831.67±27.11 |
| Silt (g $kg^{-1}$) | 45.33±10.51 | 65.00±16.18 | 45.50±6.16 | 30.67±11.55 | 39.67±12.82 | 38.33±12.81 |
| Clay (g $kg^{-1}$) | 101.17±8.91 | 115.17±12.64 | 114.33±15.07 | 120.00±20.01 | 117.67±16.07 | 130.00±15.99 |

Data were reported as means ± standard errors. TEA = Total exchangeable acidity, TEB = Total exchangeable bases, ECEC = Effective cation exchange capacity

occurred as a shift from that of Kunlanit et al. (2020), who reported the abundance of soil organic matter at the top 0–20 cm of the soil profile relative to the 20–100 cm depth. Eyayu and Mamo (2018) have also reported higher mean values of organic carbon and total N in the 0–20 cm depth of soil. The accumulation of organic matter in topsoil has been attributed to its position in the soil profile, which allows for direct input of organic litter (Sahrawat, 2004). Values of the C:N ratio were highest at the 0-15 cm depth in both locations compared to the subsoil depths (Table 2). This concurs with common knowledge as soil C:N ratio tends to decrease with soil depth.

In Ibadan, available P content was highest at the 15–30 cm depth (23.67±0.23 mg $kg^{-1}$) but lowest at the 0–15 cm (13.00±0.30 mg $kg^{-1}$), whereas in Ikwuano, the concentrations of available P occurred in the order of 0-15 cm > 15-30 cm > 30-45 cm depths (Table 2). The effective cation exchange capacity (ECEC) of the soils decreased with soil depth in Ibadan (*i.e.* 0–15 cm > 15–30 cm > 30–45 cm), but in a reverse (increasing) order in Ikwuano (*i.e.* 0–15 cm < 15–30 cm < 30–45 cm). The ECEC results of Ikwuano soils where the deeper 30–45 cm depth had the highest value relative to the upper soil depths, contradicts the view of Brady and Weil (2002) that cations are mostly found abundant in the organic matter rich top-soils that are mixed with different organic materials at variable stages of decomposition which continuously release cations. However, the result in Ibadan, where ECEC was highest at the 0–15 cm depth, followed by the 15–30 cm and lowest at the 30–45 cm depth, conforms to expectations and is in tandem with the findings of Oladoye (2015) and Oyodele *et al*. (2008) who attributed decrease in ECEC values with depth to a corresponding decrease in organic matter levels.

*Density of arbuscular mycorrhizal fungi in three land use types at Ibadan and Ikwuano areas of southern Nigeria*

Soils of the fallow field in Ibadan (IB-fallow) had the highest density of AMF spores (54±7 spores 100 g $^{-1}$ soil) compared to soils of the cultivated land use types (cassava and pineapple fields) in the area (Table 3). In contrast, the highest spore numbers in Ikwuano was detected from soils cultivated to pineapple (71±2 spores 100 g $^{-1}$ soil), followed by the cassava land use type (6 8±2 spores 100 g $^{-1}$ soil) while the lowest AMF spore density (57±3 spores 100 g $^{-1}$ soil) was observed in soils of the fallow field (Table 3). Overall, soils of Ikwuano area, harboured higher numbers of AMF spores than soils of Ibadan area, in all the three land use types (Table 3). The results, therefore, showed a variation in spore numbers of the AMF with respect to both the land use types and locations, concurring with Dare *et al*. (2013) who stated that the population and composition of the AMF may be affected by various factors which includes the land use or cropping systems practiced on the soil. Variations in spore density could arise as a result of the varying sporulation ability of AMF species under different land uses (Schenck and Kinloch, 1980), differences in agroecosystems and environmental conditions (Nandjui *et al*., 2013), or with differences in soil types (Marschner *et al*., 2001; Wieland *et al*., 2001). The higher spore densities observed in the Ikwuano land uses relative to those of Ibadan, irrespective of the high levels of acidity and available soil P in the Ikwuano area, contradicts a few studies (Gavito and Varela, 1995; Xavier and Germida, 1997; Redecker *et al*., 2013), who noted lower AMF spore densities with increased acidity and soil available P; but supports other similar works which reported positive influence of available P (Neumann and George, 2004; Subramanian *et al*., 2006; Muleta, 2007) and soil pH (Johnson *et al*., 1991; Mohammad *et al*., 2013; Tchabi *et al*., 2008) on the spore density of AMF.

Generally, the spore numbers of AMF detected across the three land use types in both locations, which ranged from 39±4 spores 100 $g^{-1}$ soil in IB-cassava to 71±2 spores 100 $g^{-1}$ soil in IK-pineapple (Table 3) vary from low to moderate when compared with the results of similar studies under different land use types. Zerihum *et al*. (2013) observed mean spore numbers (100 $g^{-1}$ soil) ranging from 307 to 1506 from acasia tree species in Ethiopia. In a tropical forest and pasture, Picone (2000) reported a range of 110 to 2600 spores 100 $g^{-1}$ soil, while Tao *et al*. (2004) noted 5 to 6400 spores 100 $g^{-1}$ soil under a valley savanna of the dry tropics. Dare *et al*. (2013) reported spore numbers ranging from 189 to 529 100 $g^{-1}$ soil from soils of yam cropping systems at four locations in Nigeria. However, in Northern Ethiopia, Birhane *et al*. (2010) detected low spore densities of 11 to 32 spores 100 $g^{-1}$ soil in dry deciduous woodlands under different acacia species.

Significant differences (P > 0.05) in spore density were observed between fallow and the cultivated (cassava and pineapple) land use types within each location. However, spore numbers of the cultivated land uses (cassava and pineapple fields) were not significantly different from one another in each of the locations (Table 3). Between the locations, there was no significant difference (P > 0.05) between spore densities obtained from IB-fallow (54±7 spores 100 $g^{-1}$ soil) and IK-fallow (57±3 spores 100 $g^{-1}$ soil). However, spore numbers obtained under IB-cassava (39±4 spores 100 $g^{-1}$ soil) and IK-cassava (68±2 spores 100 $g^{-1}$ soil) differed significantly (P > 0.05) from each other. Similarly, spore number obtained under pineapple land use in Ibadan (43±5 spores 100 $g^{-1}$ soil) was also significantly different from spore number detected under the same land use type (pineapple field) in Ikwuano (71±2 spores 100 $g^{-1}$ soil). The higher AMF spore density in the fallow field of Ibadan relative to those of the cassava and pineapple fields (cultivated land uses) is consistent with the report of Plenchette *et al*. (2005), who maintained that uncontrolled weeds (fallow fields) may positively influence the population and infectivity rate of the AMF. In intensive agricultural systems, the primary roles of mycorrhizosphere organisms may be marginalized, because microbial populations in conventional farming systems are easily altered by tillage operations and high use of mineral fertilizers and other agrochemicals (Gianinazzi *et al*., 2002). Again, the realization that the cultivated pineapple field harboured more spore numbers than the uncultivated fallow field in Ikwuano, corroborated the findings of Janos (1992) and Picone (2000) who reported that disturbed habitats induced the ability of AMF to sporulate due to grazing, disturbance and reduced decomposition rate than natural ecosystems. Similarly, Shi *et al*. (2007) noted that the sporulation of AMF is more likely to occur when the host plant is perturbed or stressed.

**Table 3:** *Spore density of AMF in three land use types and soil depths at two locations of southern Nigeria.*

| Location | Land use type | Mean spore number (100 $g^{-1}$ soil) | Soil depth | Mean spore number (100 $g^{-1}$ soil) |
|---|---|---|---|---|
| Ibadan | Fallow | 54 ± 7b | 0 – 15cm | 54 ± 6a |
| | Cassava | 39 ± 4a | 15 – 30cm | 45 ± 3ac |
| | Pineapple | 43 ± 5a | 30 – 45cm | 39 ± 5c |
| Ikwuano | Fallow | 57 ± 3b | 0 – 15cm | 66 ± 4b |
| | Cassava | 68 ± 2c | 15 – 30cm | 67 ± 2b |
| | Pineapple | 71 ± 2c | 30 – 45cm | 64 ± 3b |

*Data were reported as means ± standard errors. Means followed by the same letters are not significantly different at 0.05 alpha level*

*Spore density of arbuscular mycorrhizal fungi at three soil depths in Ibadan and Ikwuano areas of southern Nigeria*
Across the soil depth in Ibadan, the ability of soil to support AMF populations decreased significantly (P > 0.05) with increasing soil depth, with mean values of 54±6, 45±3 and 39±5 spores of AMF 100 $g^{-1}$ soil at the 0–15, 15–30 and 30–45 cm depths, re-

spectively (Table 3). Similar results of a decrease in AMF spore density with increasing soil depth have been reported by Shukla *et al.* (2013) and Becerra *et al.* (2014). In Ikwuano, however, AMF spore density was highest at the 15–30 cm depth (67±2 spores 100 $g^{-1}$ soil), followed concordantly by the 0–15 cm (66±4 spores 100 $g^{-1}$ soil) while the 30–45 cm depth also had the lowest number of AMF spores (64±3 spores 100 $g^{-1}$ soil). The findings in Ikwuano where the highest spore density was recovered from the middle 15–30 cm soil layer, corroborated that of Muleta *et al.* (2008) who observed a peak in spore numbers at the middle depth (20–30 cm) of a coffee plantation relative to the uppermost layer. Similarly, Gucwa-Przepióra *et al.* (2013) had reported an increase in spore density of AMF and root colonization rate to the depth of 60 cm, in a heavy metal contaminated site. In the contrary, the reduction in spore density of AMF with increasing soil depth, as was observed in Ibadan area, can be attributed to the fewer density of roots in lower depths of soil (Cuenca and Lovera, 2010). Other researchers had explained this on the basis of less organic carbon content (Oehl *et al.*, 2005) and low levels of oxygen in deeper soil layers (Verma *et al.*, 2010), since fungi are sensitive to low oxygen pressure which intensifies with depth (Brady and Weil, 2002).

Within the locations, spore numbers obtained from the three soil depths in Ikwuano area were not significantly different ($P > 0.05$) from one another (Table 3). However, in Ibadan, significant difference ($P > 0.05$) was observed between the 0–15 cm (54±6 spores 100 $g^{-1}$ soil) and 30–45 cm (39±5 spores 100 $g^{-1}$ soil) depths, with each of the two depths having no significant differences with the 15–30 cm depth (45±3 spores 100 $g^{-1}$ soil). Between the locations, there were significant differences ($P > 0.05$) in AMF populations obtained from each of the three soil depths (Table 3), indicating influence of the differences in soil type and environmental conditions.

Similar to the results of the land use types considered in this study, spore densities recovered from Ikwuano area also outweighed those of Ibadan soils in all the three soil depths. Even the highest spore density of 54±6 spores 100 $g^{-1}$ soil in Ibadan recovered from the 0-15 cm depth was less than the number realized from the least abundant depth (30–45 cm) in Ikwuano (with 64±3 spores of AMF 100 $g^{-1}$ soil) (Table 3). In generally, the mean spore density obtained from the three soil depths of the present study, which ranged from 39±5 spores 100 $g^{-1}$ soil at IB-0–30 cm to 67±2 spores 100 $g^{-1}$ soil at IK-15–30 cm, were comparable with the numbers reported by Shukla *et al.* (2013) at four different depths of soil (0-10, 10-20, 20-30 and 30-40 cm) in Sagar, India; but lower than that of Becerra *et al.* (2014) who reported the range of 122 to 210 mean spores of AMF per 100 g soil at five soil depths (0-10, 10-20, 20-30, 30-40 and 40-50 cm) in saline soils of central Argentina.

*Arbuscular mycorrhizal fungi populations and soil nutrient levels*

**Land use types:** Considering the land use types, there were both positive and negative correlations between AMF spore density and nutrient levels of soil in both locations.

In Ibadan, organic carbon and available phosphorus had a non significant ($p > 0.05$) positive correlations with spore density at the fallow and cassava land uses, but negative correlations at the pineapple field (Table 4), whereas total nitrogen correlated negatively with spore density in all the three land use types and this was significant at the fallow field ($r = -0.834^*$, $p < 0.05$). Many studies have reported negative correlations between spore numbers and soil properties, particularly with phosphorus (Kahiluoyo *et al.*, 2001; Emmanuel *et al.*, 2010; Oehl *et al.*, 2010; Dare *et al.*, 2013; Nandjui *et al.*, 2013). The negative relationships suggest a reduction in spore density of the AMF as levels of such soil properties increase in soil. However, in other similar studies, it was shown that soil parameters such as organic carbon (Tchabi, 2008; Hu *et al.*, 2013), available P (Neumann and George, 2004; Subramanian *et al.*, 2006; Muleta, 2007), and pH (Johnson *et al.*, 1991; Mohammad *et al.*, 2013; Tchabi *et al.*, 2008), could affect AMF spore abundance positively. Muzakir (2011) observed increased AMF spore numbers and species diversity as the organic matter and soil pH increases. He thus, inferred that the amount and type of mycorrhizal spores was affected by the soil chemistry. With only a few exceptions, the exchangeable base cations showed positive correlations with spore density at the fallow field, but negative correlations at the cultivated land use types (cassava and pineapple fields). Specifically, there was a strong significant positive correlation with the exchangeable $K^+$ at the fallow field ($r = 0.910^*$, $p < 0.05$, Table 4).

In Ikwuano, however, there was a non significant positive correlation at the fallow field between spore

**Table 4:** *Pearson correlation showing the relationships between AMF spore density and soil nutrients of three land use types in two locations of southern Nigeria.*

| Coefficient of correlation (r) | | | | | | |
|---|---|---|---|---|---|---|
| | Ibadan | | | Ikwuano | | |
| Soil nutrient element | Fallow | Cassava | Pineapple | Fallow | Cassava | Pineapple |
| Organic carbon (g $kg^{-1}$) | 0.769 | 0.009 | -0.082 | 0.710 | 0.043 | -0.077 |
| Total Nitrogen (g $kg^{-1}$) | -0.834* | -0.634 | -0.045 | 0.640 | -0.477 | 0.129 |
| Available P (mg $kg^{-1}$) | 0.116 | 0.059 | -0.476 | 0.650 | 0.536 | -0.280 |
| Exchangeable $Ca^{2+}$ | -0.266 | -0.515 | -0.765 | 0.714 | 0.029 | -0.294 |
| Exchangeable $Mg^{2+}$ | 0.236 | 0.131 | -0.642 | 0.708 | 0.021 | -0.207 |
| Exchangeable $K^{+}$ | 0.910* | -0.277 | -0.555 | 0.615 | 0.445 | 0.334 |
| Exchangeable $Na^{+}$ | 0.256 | -0.409 | 0.121 | 0.720 | 0.153 | -0.256 |

* *Significant at 0.05 (5%) level of probability*

**Table 5:** *Pearson correlation showing the relationships between AMF spore density and nutrient levels of three soil depths in two locations of southern Nigeria.*

| Coefficient of correlation (r) | | | | | | |
|---|---|---|---|---|---|---|
| | Ibadan | | | Ikwuano | | |
| **Soil nutrient element** | **0 – 15cm** | **15 – 30cm** | **30 – 45cm** | **0 – 15cm** | **15 – 30cm** | **30 – 45cm** |
| Organic carbon (g $kg^{-1}$) | 0.134 | 0.120 | 0.310 | 0.299 | 0.093 | 0.201 |
| Total Nitrogen (g $kg^{-1}$) | -0.379 | -0.351 | -0.565 | 0.661 | 0.242 | 0.131 |
| Available P (mg $kg^{-1}$) | 0.080 | -0.391 | 0.046 | 0.238 | -0.121 | -0.172 |
| Exchangeable $Ca^{2+}$ | -0.237 | -0.542 | -0.211 | 0.433 | -0.107 | -0.097 |
| Exchangeable $Mg^{2+}$ | 0.138 | -0.237 | 0.300 | 0.378 | 0.040 | -0.015 |
| Exchangeable $K^{+}$ | 0.756 | 0.234 | -0.203 | 0.593 | 0.277 | 0.803 |
| Exchangeable $Na^{+}$ | 0.065 | -0.426 | -0.283 | 0.046 | 0.246 | -0.094 |

density and each of the seven nutrient elements considered in this study (Table 4). A similar trend also occurred at the cassava land use, except in total N where correlation was rather negative, but also non significant ($r = -0.477$, $p > 0.05$). Positive correlations of spore numbers with nutrient elements suggest the tendency of the AMF spore to increase as the soil nutrient levels increases. However, over 98% of such results of positive correlation between AMF spores and soil nutrient elements from the results of the present study were non significant, stalling further inferences in that direction. Conversely, apart from the total N and exchangeable $K^+$, all other nutrient elements evaluated in this study had a non significant negative correlation with spore density at the pineapple land use type (Table 4).

**Soil depths:** Across the soil depths in Ibadan, there was a non significant positive correlation between soil nutrients and spore density at the 0–15 cm depth, except in total N and exchangeable $Ca^{2+}$ where correlations were negative. At IB-15–30 cm, the result was in the contrast, as correlations were negative with the exception of organic C and exchangeable $K^+$, in which cases the relationships were rather positive. At IB-30–45 cm, however, organic C, available P and exchangeable $Mg^{2+}$ showed a non significant positive correlations with spore density whereas total N, exchangeable $Ca^{2+}$, $K^+$ and $Na^+$, all had non significant negative correlations with spore density (Table 5).

In Ikwuano, there was a non significant positive correlation at the 0–15 cm depth between spore density and each of the seven nutrient elements investigated in the present study (Table 5). These positive relationships tend to suggest an increase in AMF spore density as the soil nutrient levels increases. The result (of positive correlations) was also similar at the 15–30 cm depth, except in available P and exchangeable $Ca^{2+}$ where correlations were rather negative (Table 5). Isobe *et al*. (2007) had also reported a negative correlation between soil available P and AMF spore density in upper soil layers. At the 30–45 cm depth, however, organic C, total N and exchangeable $K^+$ had positive correlations with the spore density whereas the relationship was rather negative with the four other nutrient elements (Table 5).

Essentially, results of the correlation analysis between AMF spore populations and the soil nutrient levels at the three soil depths were all non-significant in both locations. This limits further inferences in the present study on the relationships between AMF spore density and soil nutrients across the soil depths. Similar inference was drawn by Shukla *et al.* (2013) who maintained that it is equivocal to establish direct cause and effect relationships between soil properties and the sporulation of AMF.

## Conclusions and Recommendations

Arbuscular mycorrhizal fungi (AMF) spores were more abundant at the fallow field relative to the cultivated (cassava and pineapple) land use types, and was higher at the upper 0-15 cm depth of soil compared to the subsoil (15-30 and 30-45 cm) depths. Although the findings of this research to a large extent, showed no definite pattern of relationship between AMF spore density and soil nutrients, significant ($P < 0.05$) positive and negative correlations were observed with exchangeable $K^+$ and total N, respectively, in the fallow land.

## Novelty Statement

The novelty of this research is to ascertain how soil nutrients affect the density of indigenous arbuscular mycorrhizal fungal communities in soil.

## Authors' Contribution

**Nzube Thaddeus Egboka:** Conducted the research and wrote the manuscript.
**Olajire Fagbola:** Supervised the research.
**Ugochukwu Nnamdi Nkwopara and Nnaemeka Henry Okoli:** Proofe read the manuscript and performed the statistical analyses, respectively.
**Akaninyene Isaiah Afangide and Tochukwu Victor Nwosu:** Helped in the Laboratory analyses and preparation of tables and figure.

*Conflict of interest*
The authors have declared no conflict of interest

## References

Abbasi, M.K., Zafar, M. and Khan, S.R. 2007. Influence of different land-cover types on the changes of selected soil properties in the mountain region of Rawalakot Azad Jammu and Kashmir. Nutr. Cyc. Agroecosyst., 78: 97-110. https://doi.org/10.1007/s10705-006-9077-z

Adebayo, M.K.A., Osunde, A.O., Ezenwa, M.I.S., Dofin, A.J. and Bala, A. 2009. Evaluation of the status and suitability of some soils for arable cropping in the southern Guinea savanna of Nigeria. Nigerian J. Soil Sci., 19(2): 115 – 120.

Aguilere, J., Motavalli, P. Valdivia, C. and Gonzalesi, M.A. 2013. Impacts of cultivation and fallow length on soil carbon and nitrogen availability in the Bolvian Andean Highland Region. Mount. Res. Dev., 33(4): 391 - 403. https://doi.org/10.1659/MRD-JOURNAL-D-12-00077.1

Ahukaemere, C.M., Okoli, N.H., Aririguzo, B.N. and Onwudike, S.U. 2020. Tropical soil carbon stocks in relation to fallow age and soil depth. Malaysian J. Sustain. Agric., 4(1): 37 - 41. https://doi.org/10.26480/mjsa.01.2020.05.09

Andrea, B., Erica, L., Raffaella, B. and Valeira, B. 2015. Arbuscular mycorrhizal fungi as natural biofertilizers: let's benefit from past successes. Front. Microbiol., 6: 1-20. https://doi.org/10.3389/fmicb.2015.01559

Auge, R.M. 2001. Water relations, drought and vesicular arbuscular mycorrhizal symbiosis. Mycorrhiza, 1: 3-42. https://doi.org/10.1007/s005720100097

Barea, J. M. and Jeffries, P. 1995. Arbuscular mycorrhizas in sustainable soil plant systems. In Mycorrhiza structure, function, molecular biology and biotechnology, Hock B.,Varma, A. eds. Springer-Verlag, Heidelberg, Germany, pp. 521–559. https://doi.org/10.1007/978-3-662-08897-5_23

Barea, J.M., Gryndler, M., Lemanceau, P.H., Schuepp, H. and Azcon, R. 2002. The rhizosphere of mycorrhizal plants. In: Gianinazzi S, Schu¨epp H, Barea JM, Haselwandter K, eds. Mycorrhiza technology in agriculture: from genes to bioproducts. Basel, Switzerland: Birkha¨user Verlag, 1–18. https://doi.org/10.1007/978-3-0348-8117-3_1

Barea, J.M., Azcon-Aguilar, C. and Azcon, R. 1997. Interactions between mycorrhizal fungi and rhizosphere microorganisms within the context of sustainable soil-plant systems. In Multitrophic Interactions in Terrestrial Systems, Gange, A.C., Brown, B.K. eds. CambridgeUniversity Press, Cambridge, pp. 65-77.

Becerra, A., Bartoloni, N., Cofre, F.S. and Cabello, M. 2014. Arbuscular mycorrhizal fungi in saline soils: Vertical distribution at different soil depth. Brazilian J. Microbiol., 45(2): 585-594. https://doi.org/10.1590/S1517-83822014000200029

Birhane, E., Kuyper, T.W., Sterck, F.J. and Bongers, F. 2010. Arbuscular mycorrhizal associations in Boswellia papyrifera (frankincense-tree) dominated dry deciduous woodlands of Northern Ethiopia. For. Ecol. Manage., 260: 2160 - 2169. https://doi.org/10.1016/j.foreco.2010.09.010

Blake, L., Mercik, S., Koerschens, M., Moskal, S., Poulton, P.R., Goulding, K.W.T., Weigel A. and Powlson, D.S. 2000. Phosphorus content in soil, uptake by plants and balance in three European long-term field experiments. Nutr. Cyc. Agroecosyst., 56:263 – 275. https://doi.org/10.1023/A:1009841603931

Brady, N.C. and Wail, R.R. 2002. Elements of the nature and properties of soils. In The Nature and Properties of Soils. 13th Edition.

Brust, G.E. 2019. Management strategies for organic vegetable fertility. Saf. Pract. Org. Food, 193 – 212. https://doi.org/10.1016/B978-0-12-812060-6.00009-X

Cao, N., Chen, X., Cui, Z. and Zhang, F. 2012. Change in soil available phosphorus in relation to the phosphorus budget in China. Nut. Cycling Agroecoyst., 94:161 – 170. https://doi.org/10.1007/s10705-012-9530-0

Chude, V.O., Olayiwola, S.O., Daudu, C. and Ekeoma, A. 2012. Fertilizer Use and Management Practice for Crops in Nigeria. 4th Edition, Produced by Federal Fertilizer Department, Federal Ministry of Agriculture and Rural Development, Abuja, pg. 41.

Cuenca, G. and Lovera, M. 2010. Seasonal variation and distribution at different soil depths of arbuscular mycorrhizal fungi spores in a tropical sclerophyllous shrubland. Botany, 88:54-64. https://doi.org/10.1139/B09-100.

Dalpe, Y., Diop, T.A., Plenchette, C. and Gueye, M. 2000. Glomales species associacted with surface and deep rhizosphereof faidherbia albda in Senegal. Mycorrhiza, 10: 125-129. https://doi.org/10.1007/s005720000069

Dare, M.O., Abaidoo, R.C., Fagbola, O. and Asiedu, R. 2012. Diversity of arbuscular mycorrhizal fungi in soils of yam (*Dioscorea* spp.) cropping system in four agroecologies of Nigeria. Arch. Agron. Soil Sci., 1-11.

Emmanuel, B., Fagbola, O. and Osonubi, O. 2012. Influence of fertilizer application on the occurrence and colonisation of arbuscular mycorrhizal fungi (AMF) under maize/Centrosema and sole maize systems. Soil Res., 50(1):76–81. https://doi.org/10.1071/SR11254

Emmanuel, B., Fagbola, O., Abaidoo, R. and Osonubi, O. 2009. Abundance and distribution of arbuscular mycorrhizal fungi species in long-term soil fertility management systems in northern Nigeria. J. Plant Nutr., 33: 1264-1275. https://doi.org/10.1080/01904167.2010.484088

Eyayu, M.F. and Mamo, Y.A. 2018. The effects of land use and soil depth on soil properties of watershed, Northwest, Ethiopia. Ethiopia J. Sci. Technol., 11(1): 39-56. https://doi.org/10.4314/ejst.v11i1.4

Fantaw Yimer, Ledin, S. and Abdu, A. 2007. Changes in soil organic carbon and total nitrogen contents in three adjacent land use types in the Bale Mountains, south eastern highlands of Ethiopia. Forest Ecol. Manage., 242: 337-342. https://doi.org/10.1016/j.foreco.2007.01.087

Gavito, M.E. and Varela, L. 1995. Response of criollo maize to single and mixed-species inocula of arbuscular mycorrhizal fungi. Plant Soil, 176: 101–105. https://doi.org/10.1007/BF00017680

Gee, G.N. and Or, D. 2002. Particle size analysis: In Methods of soil analysis, Dan, D.I. and Topps, G.C. (eds), part 4, physical methods. Soil science society of America book series, No 5 ASA and SSA Madison, W.I. pp 225 – 295.

Gerdemann, J.W. and Nicolson, T.H. 1963. Spores of mycorrhizal Endogone species extracted from soil by wet sieving and decanting. Trans. Br. Mycol. Soc., 46: 235-244. https://doi.org/10.1016/S0007-1536(63)80079-0

Grantina, L., Seile, E., Kenigsvalde, K., Kasparinskis, R., Tabora, G., Nikolajeva, V., Jungerius, P. nad Muiznieks, I. 2011. The influence of land use on abundance and diversity of soil: comparison of conventional and molecular methods of analysis. Envron. Exp. Biol., 9: 9-21.

Greg, R. 2004. Soil advisory office with contributions from John Diron, horticultural office. Soil sense leaflet, 4: 99 – 533.

Gucwa-Przepióra, E., Błaszkowski, J., Kurtyka, R., Małkowski, Ł. and Małkowski, E. 2013. Arbuscular mycorrhiza of Deschampsia cespitosa (Poaceae) at different soil depths in highly metal-contaminated site in southern Poland. Acta Soc. Bot. Pol., 82: 251–258. https://doi.org/10.5586/asbp.2013.033

Hendershot, W.H., Lalande, H. and Duqyette, M. 1993. Soil reaction and exchangeable acidity.In Soil sampling and methods of analysis. Canadian Soc. Soil Sci., 141: 141 – 145.

Hu, Y., Rillig, M.C., Xiang, D., Hao, Z. and Chen, B. 2013. Changes of AM fungal abundance along environmental gradients in the arid and semi-arid grasslands of northern China. PLoS ONE, 8.2: 57593. https://doi.org/10.1371/journal.pone.0057593

Isobe, K., Aizawa, E., Iguchi, Y. and Ishii, R. 2007. Distribution of arbuscular mycorrhizal fungi in upland field soil of Japan: (1) relationship between spore density and soil environmental factor. Plant Prod. Sci., 10: 122 – 8. https://doi.org/10.1626/pps.10.122

Janos, D.P. 1980. Mycorrhizae influence tropical succession. Biotropica, 12: 56-64. https://doi.org/10.2307/2388157

Janos, D.P. 1992. Heterogeneity and scale in tropical vesicular-arbuscular mycorrhiza formation. In: Read DH, Lewis DH, Fitter AH, Alexander IJ (Eds) Mycorrhizas in ecosystems: CAB International, Wallingford, England, pp 276 - 282.

Johansson, J.F., Paul, L.R. and Finlay, R.D. 2004. Microbial interactions in the mycorrhizosphere and their significance for sustainable agriculture. FEMS Microbiol. Ecol., 48: 1-13. https://doi.org/10.1016/j.femsec.2003.11.012

Kabir, S., Rajendran, N., Amemiya, T. and Itoh K. 2003. Quantitative measurement of fungal DNA extracted by three different methods using real-time PCR. J. Gen. Appl. Microbiol., 49: 101–109. https://doi.org/10.2323/jgam.49.101

Kahiluoto, H., Ketoja, E., Vestberg, M. and Saarela, I. 2001. Promotion of AM utilization through reduced P fertilization. Plant and Soil, 231: 65 - 79. https://doi.org/10.1023/A:1010366400009

Kunlanit, B., Khwanchum, L. and Vityakon, P. 2020. Land Use Changes Affecting Soil Organic Matter Accumulation in Topsoil and Subsoil in Northeast Thailand. Appl. Environ. Soil Sci., 2020: 15. https://doi.org/10.1155/2020/8241739

Kutsanedzie, F., Ofori, V. and Diaba, K.S. 2015. Maturity and safety of compost processed in HV and TW composting systems. Sci. Technol. Soc., 3(4): 202–209. https://doi.org/10.11648/j.ijsts.20150304.24

Leal, P.L., Sturmer, S.L. and Siqueira, J.O. 2009. Occurrence and diversity of arbuscular mycorrhizal fungi in trap cultures from soils under different land use systems in the amazon, Brazil. Brazilian J. Microbiol., 40: 111-124. https://doi.org/10.1590/S1517-83822009000100019

Marschner P., Yang C.H., Lieberei R., Crowley D.E. 2001. Soil and plant specific effects on bacterial community composition in the rhizosphere. Soil Biol. Biochem., 33: 1437–1445. https://doi.org/10.1016/S0038-0717(01)00052-9

Mclean, E.O. 1982. Soil pH and lime requirement. pp.199-224. In A.L. Page *et al.* (ed.) Methods of soil analysis. Part 2.2nd ed. Agron. Monogr.9.ASA, Madison, WI. https://doi.org/10.2134/agronmonogr9.2.2ed.c12

Mehlich, A. 1984. Mehlich 3 Soil Test Extractant. A Modification of the Mehlich 2 Extractant. Commun. Soil Sci. Plant Anal., 15: 1409-1416. https://doi.org/10.1080/00103628409367568

Mohammad, M.J., Hamad, S.R and Malkawi, H.I. 2003. Population of arbuscular mycorrhizal fungi in semi-arid environment of Jordan. J. Arid Environ., 53: 409-417. https://doi.org/10.1006/jare.2002.1046

Muleta, D., Assefa, F., Nemomissa, S. and Granhall, U. 2008. Distribution of arbuscular mycorrhizal fungi in soils of small holder agroforestrymonocultural coffee systems in southwestern Ethiopia. Biol. Fertil. Soils, 44: 653 – 659. https://doi.org/10.1007/s00374-007-0261-3

Muleta, D., Assefa, F., Nemomissa, S. and Granhall, U. 2007. Composition of coffee shade tree species and density of indigenous arbuscular mycorrhizal fungi (AMF) spores in Bonga natural coffee forest, southwestern Ethiopia. Forest Ecol. Manage., 241: 145-154. https://doi.org/10.1016/j.foreco.2007.01.021

Muzakir, H.A. and Cendawan, M. 2011. Arbuskula Indigeneous dan Sifat Kimia Tanah di Lahan Kritis Tanjung Alai, Sumatera Barat. J. Soil Land Util. Manage. 201:8: 53-57. https://doi.org/10.25077/js.8.2.53-57.2011

Nandjui, J., Don, R.R., Niangoran, M.K., Beaulys, F., Yao, T. and Adolphe, Z. 2013. Assessment of the occurrence and abundance of mycorrhizal fungal communities in soils from yam (*Dioscorea* Spp.) cropping fields in Dabakala, North Côte D'ivoire. Afr. J. Agric. Res., 8.44: 5572-5584.

Ndoye, F., Kane, A., Ngonkeu, E.L., Bakhoum, N., Sanon, A., Diouf, D., Ourèye, S.M, Baudoin, E., Noba, K. and Prin, Y. 2012. Changes in land use system and environmental factors affect arbuscular mycorrhizal fungal density and diversity, and enzyme activities in rhizospheric soils of *Acacia senegal* (L.) Wild. Ecology, Article ID 563191, 13 pages. https://doi.org/10.5402/2012/563191

Neumann, E. and George, E. 2004. Colonisation with the arbuscular mycorrhizal fungus Glomus mosseae (Nicol. & Gerd.). Plant Soil, 231: 245 – 255. https://doi.org/10.1023/B:PLSO.0000035573.94425.60

Oehl, F., Laczko, E., Bogenrieder, A., Stahr, K., Bösch, R., Van der Heijden M. and Sieverding, E. 2010. Soil type and land use intensity determine the composition of arbuscular mycorrhizal fungal communities. Soil Biol. Biochem., 4(25): 724 - 738. https://doi.org/10.1016/j.soilbio.2010.01.006

Oehl, F., Sieverding, E., Ineichen, K., Mader, P., Boller, T. and Wiemken, A. 2003. Impact of land use intensity on the species diversity of arbuscular mycorrhizal fungi in agroecosystem of Central Europe. Appl. Environ. Microbiol., 69: 2816 - 2824. https://doi.org/10.1128/AEM.69.5.2816-2824.2003

Oehl, F., Sieverding, E., Ineichen, K., Ris, E.A., Boller, T. and Wiemken, A. 2005. Community structure of arbuscular mycorrhizal fungi at different soil depths in extensively and intensively managed agroecosystems. New Phytol. 165: 273-283. https://doi.org/10.1111/j.1469-8137.2004.01235.x

Ohno, T., Griffin, T.S., Liebman, M. and Porter, G.A. 2005. Chemical characterization of soil phosphorus and organic matter in different cropping systems in Maine, U.S.A. Agric. Ecosyst. Environ., 105:625–634. https://doi.org/10.1016/j.agee.2004.08.001

Oladoye, A.O. 2015. Physico-chemical properties of soil under two different depths in atropical forest of International Institute of Tropical Agriculture, Ibadan, Nigeria. J. Res. For. Wildlife Environ., 7(1): 40 -54.

Oyedele, D.J. Gasu, M. B and Awotoye, O.O. 2008. Changes in soil properties and plant uptake of heavy metals on selected municipal solid waste dump sites in Ile-Ife, Nigeria. African Journal of Environmental Science and Technology, 3 (5): 107 - 115.

Picone, C. 2000. Diversity and abundance of arbuscular mycorrhizal fungus spores in tropical forest and pasture. Biotropica, 32: 734 - 750. https://doi.org/10.1646/0006-3606(2000)032[0734:DAAOAM]2.0.CO;2

Plenchette, C., Clermont-Dauphin, C., Meynard, J.M. and Fortin, J.A. 2005. Managing arbuscular mycorrhizal fungi in cropping systems. Canadian J. Plant Sci., 85: 31 – 40. https://doi.org/10.4141/P03-159

Redecker, D., Arthur, S., Herbert, S., Sidney, L.S., Joseph, B.M. and Christopher, W. 2013. An evidence-based consensus for the classification of arbuscular mycorrhizal fungi (Glomeromycota). Mycorrhiza, 23: 515 – 531. https://doi.org/10.1007/s00572-013-0486-y

Requena, N., Perez-Solis, E., Azcon-Aguilar, C., Jeffries, P. and Barea, J.M. 2001. Management of indigenous plant-microbe symbioses aids restoration of desertified ecosystems. Appl. Environ. Microbiol., 67: 495 - 498. https://doi.org/10.1128/AEM.67.2.495-498.2001

Rozpadek, P., Wezowicz, K., Stojakowska, A., Malarz, J., Surówka, E., Sobczyk, Ł., Anielska, T., Wazny, R., Miszalski, Z. and Turnau, K. 2014. Mycorrhizal fungi modulate phytochemical production and antioxidante activity of Cichorium intybus L. (Asteraceae) under metal toxicity. Chemosphere, 112: 217 - 224. https://doi.org/10.1016/j.chemosphere.2014.04.023

Ryan, M., Derrick, J. and Dann, P. 2004. Grain mineral concentrations and yield of wheat grown under organic and conventional management. J. Sci. Food Agric., 84: 207– 216. https://doi.org/10.1002/jsfa.1634

Ryan, M.H. and Angus, J.F. 2003. Arbuscular mycorrhizae in wheat and field pea crops on a low P soil: increased Zn-uptake but no increase in P-uptake or yield. Plant and Soil, 250: 225 – 239. https://doi.org/10.1023/A:1022839930134

Sahrawat, K.L. 2004. Organic matter accumulation in submerged soils. Adv. Agron., 81: 169–201. https://doi.org/10.1016/S0065-

2113(03)81004-0

Säle, V., Aguilera, P., Laczko, E., Mäder, P., Berner,A., Zihlman, V., Van der Heijden, M.G.A. and Oehl, F. 2015. Impact of conservation tillage and organicfarming on the diversity of arbuscular mycorrhizalfungi. Soil Biol. Biochem., 84: 38 - 52. https://doi.org/10.1016/j.soilbio.2015.02.005

Sanders, I.R., Alt, M., Groppe, K., Boller, T. and Wiemken, A. 1995. Identification of ribosomal DNA polymorphisms among and within spores of the Glomales: application to studies on the genetic diversity of arbuscular mycorrhizal fungal communities. New Phytol., 130: 419 – 427. https://doi.org/10.1111/j.1469-8137.1995.tb01836.x

Schenck, N.C., Kinloch, R.A. 1980. Incidence of mycorrhizal fungi on six field crops in monoculture on a newly cleared woodland site. Mycologia, 72: 445 - 455. https://doi.org/10.2307/3759518

Shi, Y., Zhang, L.Y., Li, X., Feng, G., Tian, C.Y. and Christie, P. 2007. Diversity of arbuscular mycorrhizal fungi associated with desert ephemeral in plant communities of Junggar Basin, North-West China. J. Appl. Soil Ecol., 35: 10 - 20. https://doi.org/10.1016/j.apsoil.2006.06.002

Shukla, A., Vyas, D. and Jha, A. 2013. Soil depths: an overriding factor for distribution of arbuscular mycorrhizal fungi. J. Soil Sci. Plant Nutr., 13(1): 23-33. https://doi.org/10.4067/S0718-95162013005000003

Smith, S.E., Facelli, E., Pupe, S. and Smith, F.A. 2010. Plant Performance In Stressfull Enviroment: Interpreting New and Established Knowledge of The Roles of Arbuscular Mychorrizhas. Plant Soil: 326: 3 – 20. https://doi.org/10.1007/s11104-009-9981-5

Smith, S.E. and Read, D.J. 1997. Mycorrhizal Symbiosis, 2nd edition. Academic Press, London, 605.

Smith, S.E. and Read, D.J. 2008. Mycorrhizal Symbiosis, third edition. Academic Press, New York.

Snoeck, D., Abolo, D. and Jagoret, P. 2010. Temporal changes in VAM fungi in the cocoa agroforestry systems of Central Cameroon. Agrofor. Syst., 78: 323 - 328. https://doi.org/10.1007/s10457-009-9254-6

Soka, G. and Ritchie, M. 2015. Arbuscular mycorrhizal symbiosis, ecosystem processes and environmental changes in tropical soils. Appl. Ecol. Environ. Res., 13: 229 - 245. https://doi.org/10.15666/aeer/1301_229245

Spark, D.L. 1996. Methods of soil analysis. Part 3. Chemical methods. SSSA and ASA. Madison, W.I.P 551-571.

Subramanian, K.S., Santhanakrishnan, P., Balasubramanian, P. 2006. Responses of field grown tomato plants to arbuscular mycorrhizal fungal colonization under varying intensities of drought stress. Sci. Horti., 107: 245 - 253. https://doi.org/10.1016/j.scienta.2005.07.006

Tao, L., Jianping, L. and Zhiwei, Z. 2004. Arbuscular mycorrhizas in a valley-type savanna in southwest China. Mycorrhiza, 14: 323 - 327. https://doi.org/10.1007/s00572-003-0277-y

Tchabi, A. 2008. Arbuscular mycorrhizal fungi in the sub-Saharan savannas of Benin and their aassociation with Yam (Dioscorea spp.): Potential of Yam Growth Promotion and Reduction of Nematode Infestation. PhD. Basel University, Switzerland. http://edoc.unibas.ch/diss/DissB_8413

Tedersoo, L., Bahram, M. and Zobel, M. 2020. How mycorrhizal associations drive plant population and community biology. Science, 367 (6480): 1 – 9. https://doi.org/10.1126/science.aba1223

Tian, G., Kang, B.T. and Kolawole, G.O. 2005. Long-term effects of fallow systems and lengths on crop production and soil fertility maintenance in West Africa. Nutr. Cycling Agroecosyst., 71: 139–150. https://doi.org/10.1007/s10705-004-1927-y

Toler H.D., Morton J.B. and Cumming J.R. 2005. Growth and metal accumulation of mycorrhizal sorghum exposed to elevated copper and zinc. Plant and Soil, 164: 155 – 172. https://doi.org/10.1007/s11270-005-2718-z

Udo, E.J., Ibia, T.O., Ogunwale, J.A., Ano, A.O., Umeugochukwu, O.P., Ezaku, P.I., Chude, V.O. and Esu, I.E. 2009. Manual of soils, plant and water analysis. Sibon books Limited, Flat 15, Block 6, Fourth Avenue Festac, Lagos.

Van der Heijden, M.G.A., Klironomos, J.N., Ursic, M., Moutoglis, P., Streitwolf-Engel, R., Boller, T., Wiemken, A. and Sanders, I.R. 1998. Mycorrhizal fungal diversity determines plant biodiversity, ecosystem variability and productivity. Nature, 396: 69 - 72. https://doi.org/10.1038/23932

Watson, C.A., Bengtsson, H., Løes, A.K., Myrbeck, A., Salomon, E., Schroder, J. and Stockdale, E.A. 2002. A review of farm-scale nutrient budgets for organic farms in temperate regions. Soil Use Manage., 18: 239-247. https://doi.org/10.1079/SUM2002127

Wieland, G., Neumann, R. and Backhaus, H. 2001. Variation of microbial communities in soil, rhizosphere and rhizoplane in response to crop species, soil type, and crop development. Appl. Environ. Microbiol., 67: 5849 – 5854. https://doi.org/10.1128/AEM.67.12.5849-5854.2001

Xavier, L.J.C. and Germida, J.J. 1997. Growth response of lentil and heatto Glomus clarum NT4 over a range of P levels in a Saskatchewan soil containing indigenous AM fungi. Mycorrhiza, 7: 3 – 8. https://doi.org/10.1007/s005720050156

Yang, F.Y., Li, G.Z., Zhang, D.E., Christie, P., Li, X.L. and Gai, J.P. 2010. Geographical and plant genotype effects on the formation of arbuscular mycorrhiza in Avena sativa and Avena nuda at different soil depths. Biol. Fertil. Soils, 46: 435 - 443. https://doi.org/10.1007/s00374-010-0450-3

Zerihum, B., Mauritz, Y. and Fassil, A. 2013. Diversity and abundance of arbuscular mycorrhizal fungi associated with acasia from different land use systems in Ethiopia. Afr. J. Microbiol. Res., 7(48): 5503 – 5515. https://doi.org/10.5897/AJMR2013.6115

Zhang, H.M., Wang, B.R., Xu, M.G. and Fan, T.L. 2009. Crop yield and soil responses to long-term fertilization on a red soil in Southern China. Pedosphere, 19(2):199 – 207. https://doi.org/10.1016/S1002-0160(09)60109-0