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Soil Physicochemical Gradients Shape Arbuscular Mycorrhizal Fungal Communities and Root Colonization of Non-Reported Host Plants in Tropical Ecosystems

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Authors' contributions

This work was carried out in collaboration among all authors. Authors SSM, OOG and AUE designed the experimental concept and supervised the methodology. Authors UYI and UAM carried out the sampling and experimentation and wrote the manuscript, including the literature search. Author UAM provided the financial support. All authors read and approved the final manuscript.

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Abstract

Soil physicochemical properties and rhizosphere conditions are key determinants of arbuscular mycorrhizal fungi (AMF) diversity, spore production, and symbiotic functioning. This study investigated AMF diversity, spore abundance, and root colonization across six contrasting land-use systems in Southern Nigeria, with particular emphasis on previously unreported host plant species. Pronounced variations in soil physicochemical properties occurred among sites. All soils were

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coarse-textured and sand-dominated, with pH values ranging from strongly to moderately acidic (3.54 – 5.19) and clear nutrient gradients across ecosystems. Dumpsite soils contained the highest levels of total nitrogen (0.67), organic carbon (1.18) and available phosphorus (107.27), followed by cropland and mangrove soils. Electrical conductivity varied widely, from 29 mmho cm^{-1} in the derived savanna to 2,897 mmho cm^{-1} in mangrove soils, reflecting land-use intensity and tidal influence. Six AMF taxa were identified using spore morphology. *Acaulospora* spp. dominated all ecosystems, followed by *Rhizophagus* and *Glomus* spp., whereas *Gigaspora* and *Funneliformis* spp. were sparsely distributed. Total spore abundance peaked in cropland (384 spores 100 g^{-1} dry soil), mangrove (378), and dumpsite (368) soils, and was lowest in freshwater swamp soils (298). Root colonization was evaluated in 28 plant species across multiple families, revealing widespread AMF associations. Colonization levels were highest in dumpsite and lowland forest soils (28-30%), intermediate in derived savanna and mangrove ecosystems (24-27%), and lowest in freshwater swamp and cropland systems (10-24%). All values fell within ranges reported for tropical ecosystems (10 - 40%). Overall, this study provides a first integrated assessment of AMF patterns across land-use systems in Nigeria.

Keywords: AMF; physicochemical; Acaulospora; Rhizophagus; Glomus; Funneliformis; root colonization; tropical ecosystem; dumpsites.

1. Introduction

Arbuscular Mycorrhizal Fungi (AMF) are obligate biotrophic soil microorganisms belonging to the phylum Glomeromycota, forming mutualistic symbioses with the roots of most terrestrial plants (Smith and Read, 2008; Genre *et al*., 2020). Over 80% of land plant species depend on AMF at some stage of growth, including major food crops such as cereals and grasses (Poaceae), where they contribute significantly to nutrient acquisition and stress mitigation (Brundrett and Tedersoo, 2018; Rillig *et al*., 2019). AMF persist in soil as resistant spores and colonize plant roots through hyphal penetration, producing arbuscules and vesicles that facilitate nutrient transfer and carbon exchange within root cortical cells (Berruti *et al*., 2016).

Globally, more than 350 AMF species have been described, with Glomeraceae being one of the most widely distributed and functionally dominant families across agroecosystems (Yurkov *et al*., 2023). AMF improve plant growth through enhanced uptake of phosphorus, nitrogen, and micronutrients, and confer tolerance to abiotic stresses such as drought, salinity, and heavy metal toxicity (Begum *et al*., 2019; Batool *et al*., 2026). Their role in suppressing plant pathogens, improving soil aggregation, and reducing chemical fertilizer requirements positions them as key components of sustainable agriculture, particularly in the era of global demand for low-chemical, environmentally safe crop production systems (Huang *et al*., 2023; Kalamulla *et al*., 2022; Kumari *et al*., 2025).

Soil physicochemical properties; including pH, organic carbon, available phosphorus, and texture; strongly influence AMF diversity, community assembly, and symbiotic efficiency (Liu *et al*., 2018; Chen *et al*., 2019; Kumari *et al*., 2025). Likewise, land-use intensity, tillage regime, fertilization history, and vegetation type modify AMF spore density, root colonization, and host specificity patterns (Muneer *et al.,* 2021; Yan *et al*., 2024). While several studies have evaluated AMF responses under salinity, drought, heavy-metal stress, and agricultural disturbance worldwide (Plenchette *et al*., 2005; You *et al*., 2021), reports on AMF diversity and colonization among lesser-studied native plant hosts in Southern Nigeria remain limited. Knowledge gaps persist on how contrasting land-use systems, such as mangrove wetlands, freshwater swamps, dumpsites, croplands, and forested landscapes etc shape AMF interactions with indigenous vegetation.

In southern Nigeria, soils differ widely in salinity, organic matter status, and management history, ranging from pristine mangrove wetlands influenced by tidal saline inflow to highly disturbed dumpsites, cultivated farmlands, and lowland forests. These landscape variations provide a unique ecological gradient for examining AMF diversity and root colonization patterns. However, studies assessing AMF communities in relation to non-reported host species across these forest types are scarce, despite their importance for ecological restoration, soil fertility maintenance, and sustainable crop production. This study therefore investigates the diversity, spore abundance, and root colonization of arbuscular mycorrhizal fungi associated with selected non-previously reported host plant species across six distinct ecosystems in Southern Nigeria. Specifically, the study aims to: (i) characterize AMF spore abundance and community composition across mangrove, freshwater swamp, cropland, lowland forest, derived savanna, and dumpsite soils, (ii) assess root colonization levels of selected native and cultivated plant species within these ecosystems (iii) examine relationships between soil physicochemical properties and AMF diversity and colonization across land-use types and (iv) provide baseline ecological insights relevant for sustainable soil management and AMF-based biofertilizer development in tropical systems. We hypothesize that soil type, land-use intensity, and host identity significantly influence AMF abundance and colonization patterns, and that disturbed or nutrient-depleted soils will exhibit higher AMF dependency compared to undisturbed systems.

2. Materials and Methods

2.1 Study Area and Sampling Procedure

The study was conducted in Akwa Ibom State, Southern Nigeria, across six locations representing distinct land-use types and ecological settings. These sites encompassed contrasting forest and anthropogenically influenced ecosystems. The names and geographic coordinates of all sampling locations are presented in Table 1.

At each site, soil samples were collected using a soil auger from five randomly selected points within the sampling area. The individual samples were thoroughly homogenized to form a composite sample representative of each location. Composite samples were immediately transferred into sterile, labeled zip-lock polyethylene bags and transported to the laboratory for analysis. Soil samples were used for physicochemical characterization as well as isolation, identification, and enumeration of arbuscular mycorrhizal fungi (AMF) spores. All laboratory analyses were conducted at the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria.

In addition, root samples of dominant plant species occurring at each site were collected by carefully uprooting plants from the rhizosphere zone. Plant species were intentionally selected from non-Poaceae families that have not been widely reported as AMF hosts, in order to evaluate potential host–mycorrhizal associations. Collected roots were used for the assessment of AMF root colonization and related mycorrhizal parameters. Plant specimens were identified and authenticated at the Herbarium of the Department of Plant Science, Faculty of Biological Sciences, Akwa Ibom State University, Nigeria.

2.2 Soil Physicochemical Analysis

Soil physicochemical properties were determined from the six composite soil samples obtained across the different ecosystems. Samples were air-dried at room temperature, gently crushed, and sieved through a 2-mm mesh prior to laboratory analysis. The parameters analyzed included soil texture, pH, electrical conductivity (EC), Bray-1 extractable phosphorus, total nitrogen (N), organic carbon (OC), exchangeable cations, and selected micronutrients.

2.2.1 Soil pH and Electrical Conductivity

Soil pH was measured in a 1:2.5 soil-to-water suspension following the procedure described by Udoh et al. (2006). Briefly, 10 g of soil was mixed with 50 mL of deionized water, stirred for 10 minutes, allowed to stand for 30 minutes, and re-stirred for 2 minutes. Soil pH was then measured using a calibrated digital pH meter standardized with buffer solutions of pH 4.0, 7.0, and 9.2.

Table 1. Sampling locations and their coordinates

S/N	Sampling areas	Locations	GPS coordinate
1	Mangrove swamp	Iko, Eastern Obolo	4°31'7″N; 7°44'43″E
2	Freshwater Swamp	Akpaden, Mkpat-enin	4°37′22″ N; 7°46′1″E
3	Cropland/Bot. Garden	Akpaden, Mkpat-enin	4°32′21″ N; 7°46′1″E
4	Lowland Rainforest	Abak Usung-idim	4°57'2″, 7°47'45″E
5	Derived Savanna	Mmbarakom/Ibagwa	4°55'24″ N; 7°47′54″E
6	Dumpsite	Ikot Ntuen, Oruk Anam	4°52'3″ N; 7°46′26″E

Electrical conductivity of the supernatant was measured after the suspension had settled for 1 hour to assess soil salinity status. For samples with EC values exceeding 1.0 mS cm^{-1}, a saturated paste extract method was employed. Saturated paste extracts were prepared by gradually wetting 20 g of soil with distilled water until a glistening paste was formed that flowed freely from a spatula without releasing excess water. The paste was allowed to equilibrate for 4 hours and subsequently vacuum-filtered using a Buchner funnel fitted with high-retention filter paper. The EC of the filtrate was recorded and compared with potassium chloride (KCl) standards of known conductivity (1.412 and 12.90 mS cm^{-1} at 25°C), following Rhoades (1982) for salinity classification.

2.2.2 Total Nitrogen and Bray-1 Phosphorus

Total nitrogen was determined using the Kjeldahl digestion method as described by Bremner (1996). Oven-dried (70°C) and finely ground soil samples were digested using a selenium–salicylic acid–sulfuric acid mixture. Digest tubes were heated at 110°C for 1 hour, cooled, and treated with hydrogen peroxide. Digestion was continued at 330°C until the solutions became clear, after which they were allowed to cool and diluted to 50 mL with distilled water. Nitrogen concentration was quantified colorimetrically using the sodium salicylate–hypochlorite method, with absorbance measured against prepared standards.

Available phosphorus was extracted using the Bray-1 ammonium fluoride–hydrochloric acid extractant and quantified colorimetrically following standard procedures.

2.2.3 Soil Organic Carbon

Soil organic carbon was estimated using the wet oxidation method, in which oxidizable carbon was converted using acidified dichromate followed by titration or colorimetric determination. Results were expressed as percentage organic carbon and converted to organic matter using the Van Bemmelen factor (1.724).

2.2.4 Exchangeable Cations, Micro-nutrients and Soil Texture

Exchangeable cations (Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}) were extracted using 1 M ammonium acetate (pH 7.0) and quantified using atomic absorption spectrophotometry and flame photometry, depending on the element. Micronutrients (Fe, Zn, Cu, and Mn) were extracted using diethylenetriaminepentaacetic acid (DTPA) and measured following standard spectrophotometric methods described by Lindsay and Norvell (1978). Soil texture was determined using the hydrometer/pipette method to quantify sand, silt, and clay fractions, Mwendwa (2022).

2.3 Isolation, Identification, and Enumeration of Arbuscular Mycorrhizal Fungi (AMF) Spores

AMF spores were isolated from soil samples using the wet sieving and sucrose flotation technique. For each sample, 100 g of soil was thoroughly moistened and homogenized with distilled water, then passed through a 710-μm sieve to remove coarse debris, followed by filtration through 45–53 μm mesh sieves to retain spores. The filtrate was centrifuged at 1,800 rpm for 5 minutes, after which the supernatant was discarded and the pellet resuspended in 440 g L^{-1} sucrose solution. The suspension was centrifuged again under the same conditions, and the supernatant containing viable spores was rapidly sieved and washed thoroughly with distilled water for 1 minute to remove sucrose and prevent osmotic damage.

Recovered spores were transferred into gridded Petri dishes and counted under a stereomicroscope at 40× magnification. Spore abundance was expressed as the total number of spores per 100 g dry soil. For identification, spores were mounted on permanent slides using polyvinyl alcohol–lactic acid–glycerol (PVLG) and PVLG mixed with Melzer's reagent. Identification to genus level was based on spore morphology, including size, wall structure, subtending hyphae characteristics, color reaction, and presence of germination shields, using taxonomic keys described by Morton et al. (1995). Where necessary, spores were gently crushed to expose internal structures. Representative spores were photographed and archived as permanent slide vouchers.

2.4 Assessment of Root Colonization and Mycorrhizal Parameters

AMF root colonization was assessed using the modified grid-line intersect method of Phillips and Hayman (1970) and quantified using the mycorrhizal rating scale proposed by Derkowska et al. (2008). Fresh root samples were thoroughly washed under running water, cut into 1–2 cm segments, and cleared in 10% KOH at 90°C for 45 minutes to remove cytoplasmic contents and pigments. Cleared roots were rinsed five times with sterile distilled water, bleached with hydrogen peroxide (H_2O_2) for 3 minutes, acidified in 1% HCl for 2 minutes, and stained with Trypan Blue in lactoglycerol following Koske and Gemma (1989). Roots were destained overnight to enhance visualization of fungal structures.

Twenty-two root fragments per plant species were mounted on slides in lactoglycerol and examined under a compound microscope at 400× magnification. The presence of AMF structures (hyphae, arbuscules, vesicles, and entry points) was recorded at 20 intersections per sample. Root colonization percentage was calculated as:

$$\text{Root colonization (\%)} = \frac{Number\ of\ AMF-positive\ segments}{Total\ number\ of\ segments\ examined} \times 100$$

Mycorrhizal intensity was scored on a scale of 0–5, where 0 indicates no colonization and 5 represents very high colonization intensity. Spore density and colonization data were integrated to assess the degree of symbiotic association.

2.5 Data Presentation

Data obtained from soil physicochemical analyses, AMF spore abundance, and root colonization assessments were summarized using descriptive statistics. Results were presented in tabular form to facilitate comparisons among sampling sites. Representative photomicrographs of AMF spores were included to illustrate morphological features and support taxonomic identification.

3. Results

3.1 Physicochemical Characteristics of Forest Soils

The physicochemical properties of soils differed markedly among the six forest types, reflecting contrasting ecological pressures and land-use histories (Table 1). Soil reaction ranged from strongly to moderately acidic (pH 3.54–5.19), with the highest pH recorded in the dumpsite soil (5.19) and the lowest in cropland soil (3.54).

Substantial variability was observed in soil nutrient status across locations. Total Nitrogen and Organic Carbon were highest in the dumpsite soil (0.67% and 1.18%, respectively), while extremely low Nitrogen was recorded in the freshwater swamp (0.06%), and Organic Carbon was comparatively low in the lowland rainforest (0.38%). Bray-1 extractable phosphorus exhibited the greatest spatial heterogeneity, ranging from 0.09 mg kg^{-1} in freshwater swamp soils to 107.27 mg kg^{-1} in both cropland and dumpsite soils. All soils were coarse-textured and sand-dominated (86–92% sand), with minimal silt and clay fractions.

Exchangeable cations were most enriched in the dumpsite soil, where Ca (4.62 cmol kg^{-1}), Mg (1.64 cmol kg^{-1}), and K (0.65 cmol kg^{-1}) markedly exceeded values in other ecosystems. In contrast, the freshwater forest recorded the lowest concentrations of these cations (Ca 1.11, Mg 0.68, K 0.07 cmol kg^{-1}). Micronutrient distribution also varied, with Fe concentrations highest in mangrove soils (242.10 ppm), while Mn peaked in the dumpsite soil (24.10 ppm). Zinc and Copper were generally low across sites but showed slight enrichment in the dumpsite and lowland rainforest soils. Electrical conductivity varied widely, ranging from 29 mmho cm^{-1} in the derived savanna to 2897 mmho cm^{-1} in mangrove soils, with moderately elevated salinity observed in the dumpsite (519 mmho cm^{-1}).

3.2 AMF Species Composition and Spore Abundance

Six arbuscular mycorrhizal fungal (AMF) taxa were isolated and identified across all sampled soils, with pronounced variation in species composition and spore abundance among forest types (Table 2). *Acaulospora* spp. consistently dominated all ecosystems, exhibiting the highest spore densities, followed by *Rhizophagus* spp. and *Glomus* spp. In contrast, *Gigaspora* spp. and *Funneliformis* spp. were sparsely represented, while *Scutellospora* spp. was not detected in any of the sampled soils.

Total spore abundance differed across land-use types, with cropland soils recording the highest density (384 spores 100 g^{-1} dry weight), closely followed by mangrove (378 spores 100 g^{-1}) and dumpsite soils (368 spores 100 g^{-1}). Lower total spore counts were observed in lowland rainforest (351 spores 100 g^{-1}), derived savanna (312 spores 100 g^{-1}), and freshwater swamp soils, which exhibited the lowest overall abundance (298 spores 100 g^{-1}). These distribution patterns highlight strong habitat-specific structuring of

AMF communities, likely driven by differences in soil properties, disturbance intensity, and host plant availability.

Representative spores of the different AMF taxa isolated and identified in this study are presented in Fig. 1. Identification was based on diagnostic morphological features, including spore size, wall layer organization, characteristics of the subtending hyphae, colour reactions, and the presence or absence of germination shields, following the criteria described by Morton et al. (1994).

3.3 Plant Species Diversity and Percentage Root Colonization by AMF

Table 3 summarizes the diversity of sampled plant species and their corresponding levels of root colonization by arbuscular mycorrhizal fungi (AMF) across the different forest and land-use types. AMF colonization was detected in all examined plant roots, although the extent of infection varied markedly among habitats and host species.

Overall, higher levels of AMF root colonization were recorded in plants from the dumpsite, lowland forest, derived savanna, and mangrove ecosystems, where colonization percentages generally ranged from 20% to 29%. In contrast, plant species sampled from cropland and freshwater swamp environments exhibited comparatively lower colonization levels, typically between 11% and 19%.

A pronounced habitat-dependent variation was observed for *Millettia aboensis* (Aboen bean tree), which exhibited substantially higher root colonization in dumpsite soils (28.57%) compared with cropland soils (14.28%). This difference highlights the strong influence of local soil conditions and land-use history on AMF-host plant interactions.

Fig. 2 provides direct anatomical evidence of AMF symbiosis, illustrating the presence of characteristic arbuscules and vesicles within the cortical cells of colonized roots. These structures confirm functional mycorrhizal associations and indicate active nutrient exchange between the host plants and AMF.

In terms of plant species composition, members of the families Asteraceae, Fabaceae, and Euphorbiaceae were the most frequently encountered across the sampling areas, followed by Acanthaceae, Arecaceae, and Apocynaceae. The successful colonization of these diverse, largely non-Poaceae hosts further underscores the broad host range and ecological adaptability of AMF in tropical ecosystems of Southern Nigeria.

Table 2. Physicochemical characteristics of forest soils

S/N	Parameters	Forest types					
		Mangrove	**Fresh water swamp**	**Cropland**	**Lowland forest**	**Derived savanna**	**Dumpsite**
1	pH	3.73	4.04	3.54	3.65	3.69	5.19
2	Nitrogen (%)	0.22	0.06	0.14	0.25	0.11	0.67
3	Org. Carbon	0.46	0.57	0.87	0.38	0.73	1.18
4	Bray Phosphorus	1.61	0.09	107.27	31.82	89.92	107.27
5	Sand %	92.00	86.00	88.00	88.00	86.00	88.00
6	Clay %	8.00	10.00	10.00	8.00	10.00	10.00
7	Silt %	4.00	4.00	4.00	4.00	4.00	4.00
8	Ca (cmol/kg)	2.87	1.11	1.43	1.57	1.22	4.62
9	Mg (cmol/kg)	2.13	0.68	0.82	0.98	0.66	1.64
10	K (cmol/kg)	0.51	0.07	0.12	0.07	0.08	0.65
11	Na (cmol/kg)	0.05	0.04	0.05	0.03	0.03	0.04
12	Min (ppm)	6.60	4.50	4.50	15.30	10.90	24.10
13	Fe (ppm)	242.10	125.70	108.60	177.70	194.30	161.10
14	Cu (ppm)	1.93	1.92	1.93	3.92	1.92	3.93
15	Zn (ppm)	5.13	7.62	5.12	5.14	5.11	7.64
16	EC (mmho/cm)	2897.00	47.00	74.00	99.00	29.00	519.00

Table 3. Spore count of arbuscular mycorrhiza fungi found in the sampled soils

Forest types	**AMF Species**						
	***Acaulospora* spp**	***Rhizophagus* spp**	***Scutelospora* spp**	***Gigaspora* spp**	***Glomus* spp**	***Funneliformis* spp**	**Spore/ 100gdwt)**
Mangrove	241	61	0	6	44	26	378
Freshwater Swamp	191	51	0	9	35	12	298
Cropland	222	72	0	4	55	31	384
Lowland Rainforest	201	68	0	5	48	29	351
Derived Savanna	176	74	0	7	36	19	312
Dumpsite	198	79	0	8	58	25	368

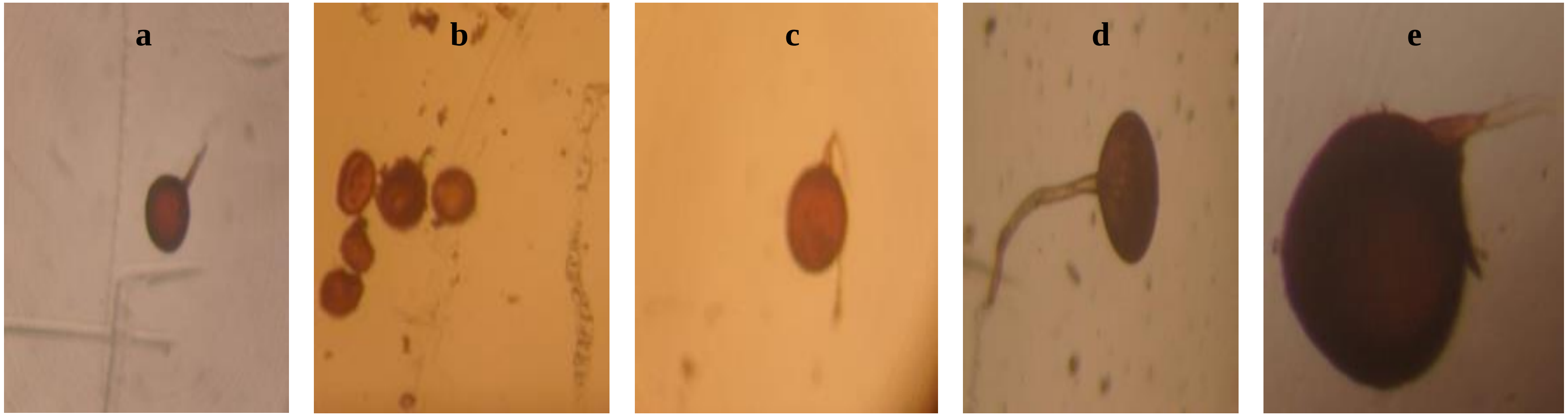

Fig. 1. Show the arbuscles of AMF spp identified in this study; (a: *Acaulospora* spp), (b: *Rhizophagus* spp), (c: *Gigaspora* spp), (d: *Glomus* spp) and (e: *Funneliformis* spp)

Table 4. showing percentage colonization by AMF on the roots of some plant species

S/N	Sampling areas	Plant species			
		Common names	**Scientific name**	**Family**	**AMF col. (%)**
1	Mangrove	Colic wood	*Myrsine seguinii*	Primulaceae	24.762
2		Golden leather fern	*Acrostichum aureum*	Pteridaceae	27.619
3		Blistery macaranga	*Macaranga denticulata*	Euphorbiaceae	25.714
4		Nipa palm	*Nypa fruticans*	Arecaceae	24.762
5		Date palm	*Phoenix dactylifera*	Arecaceae	23.810
6		Black mangrove	*Avicennia africana*	Acanthaceae	20.952
7		Toxic goosebery	*Cleistanthus collinus*	Phyllanthaceae	26.667
8	Fresh water swamp	Girdlepod	*Mitracarpus villosus*	Rubiaceae	12.38
9		Red tassel flower	*Emilia sonchifolia*	Asteraceae	17.14
10		Dragons’s blood tree	*Harungana madagascariensis*	Hypericaceae	14.28
11		Wild sunflower	*Aspilia africana*	Asteraceae	18.09
12		Caesarweed	*Urena lobata*	Malvaceae	24.76
13	Cropland	Custard apple	*Xylopia aethiopica*	Annonaceae	11.42
14		Aboen bean tree	*Millettia aboensis*	Fabaceae	14.28
15		Blood root	*Justicia secunda*	Acanthaceae	19.04
16		Small-fruited voacanga	*Voacanga africana*	Apocynaceae	15.23
17		Bush buck	*Gongronema latifolium*	Apocynaceae	18.09
18		Fireball plant	*Eremomastax speciosa*	Acanthaceae	16.19
19		Camwood	*Baphia nitida*	Fabaceae	13.33
20		Christmas bush	*Alchornea cordifolia*	Euphorbiaceae	15.24
21		Bush cane	*Costus afer*	Costaceae	16.19
22	Lowland forest	Bush marigold	*Aspilia africana*	Asteraceae	29.52
23		Hairy croton	*Crotum hirtus*	Euphorbiaceae	20.95
24		False yam	*Icacina manni*	Icacinasceae	29.91
25	Derive savanah	Centro	*Centrosema pubescens*	Fabaceae	24.76
26		Siam weed	*Chromolaena odorata*	Asteraceae	26.67
27	Dumpsite	Kamala plant	*Mallotus oppositifolius*	Euphorbiaceae	29.52
28		Aboen bean tree	*Milettia aboensis*	Fabaceae	28.57

4. Discussion

4.1 Physicochemical Characteristics of the Sampled Soils

The soil textural and chemical analyses from the six sampling sites revealed a predominance of coarse-textured, sand-dominated soils with low clay and silt fractions, a pattern consistent with highly weathered tropical substrates subjected to intense pedogenesis and strong leaching (Hamarashid *et al.,* 2010; Chen *et al*., 2025). Such textural properties promote rapid drainage and aeration but limit water and nutrient retention, conditions known to influence microbial community composition and nutrient cycling Fierer, (2017). The observed strong to moderately acidic pH levels are typical of humid tropical forest soils and may further contribute to the solubility of certain nutrients and metals, thereby shaping microbial ecologies, including those of arbuscular mycorrhizal fungi (AMF) (Ebrahimi and Ojani, 2024; Pena and Tibbett, 2024; Kumari *et al*., 2025).

Notably, the higher soil pH measured in the dumpsite likely reflects organic waste buffering effects and anthropogenic nutrient inputs, a pattern reported in similar disturbed landscapes (Hue, 2022; Asare and Száková, 2023). Decomposing organic materials increase soil base cations, elevating pH relative to adjacent undisturbed soils. The elevated nitrogen (N) and organic carbon (OC) contents in dumpsite soil similarly point to enhanced organic matter accumulation and active mineralization, processes commonly associated with high organic inputs and microbial decomposition (Hossain *et al.,* 2017). Conversely, the low N in freshwater swamp soils likely results from persistent waterlogging and anaerobic conditions, which restrict N retention by promoting denitrification and leaching (Van Cleemput *et al*., 2007). The reduced OC in lowland soils also aligns with rapid decomposition under aerobic conditions and limited litter accumulation, consistent with previous findings from tropical forest ecosystems (Chakravarty *et al*., 2020).

Variability in available phosphorus (P) and exchangeable cations (Ca, Mg, K) across the ecosystems was marked. The extremely high P values in cropland and dumpsite soils suggest inputs from agricultural fertilization and waste deposition, which contribute to mobile P pools (Tian *et al*., 2017; Khan *et al*., 2023). Soil P availability is widely recognized as a principal driver of AMF colonization and sporulation, since AMF function primarily to enhance host P uptake (Smith *et al*, 2011; Kumari *et al*., 2025).

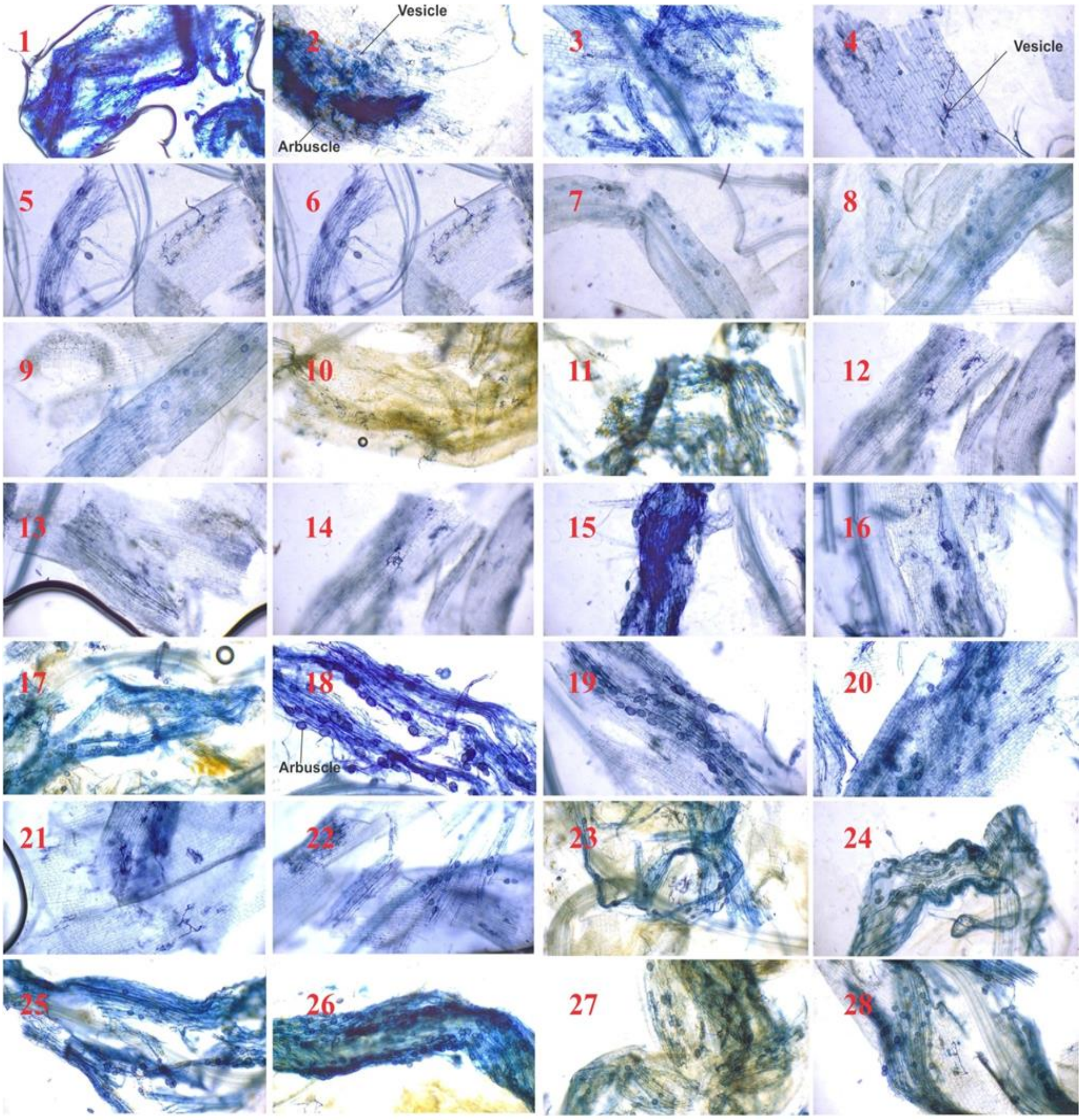

Fig. 2. Show the spores of AMF in the roots of 28 sampled plants across the study areas

In contrast, the low P in swamp soils may reflect P fixation under acidic, anoxic conditions, where Fe and Al oxides bind phosphate, rendering it unavailable to biota (Osayande *et al*., 2017; Ebrahimi and Ojani, 2024). Despite the proximity to coastal influence, low sodium (Na) levels across sites indicate minimal salinity stress, suggesting that salinity was not a dominant factor in shaping AMF activity within these soils. However, the very high electrical conductivity (EC) in mangrove soils underscores localized salt accumulation, likely driven by tidal influence, which can impose physiological stress on plant roots and soil microbes (Chen *et al*., 2016; Devaney *et al*., 2021).

Micronutrient distributions were also heterogeneous. Iron (Fe) peaked in mangrove soils, possibly due to reductive mobilization under fluctuating redox conditions (Ruiz *et al*., 2024), while manganese (Mn) was highest in dumpsite soils, reflecting complex interactions between waste inputs and soil redox dynamics (Alimi *et al*., 2025). Copper (Cu) and zinc (Zn) concentrations were elevated in dumpsite and lowland forest soils, likely due to localized accumulation from organic inputs and plant litter decomposition (Singh *et al*., 2025). These nutrient patterns provide a contextual framework for interpreting AMF community responses, as micronutrient availability can modulate symbiotic efficiency and fungal metabolism Harrison (2005).

4.2 Spore Abundance and Community Patterns

The total and mean AMF spore counts were highest in cropland, mangrove, and dumpsite soils, relative to freshwater swamp, lowland forest, and derived savanna systems. This pattern may reflect microhabitat stability, enhanced P availability, and moderate pH conditions, which collectively favor AMF sporulation (Mukhongo *et al*., 2023). Indeed, while AMF are often considered sensitive to disturbance, some taxa demonstrate resilience and even increased sporulation under moderate soil perturbation (van der Heyde *et al*., 2017), particularly in phosphorus-rich soils; dumpsite and cropland, where host plants allocate greater carbon to mycorrhizal partners.

Among individual taxa, *Acaulospora, Rhizophagus*, and *Glomus* spp. were the most abundant. These genera are widely reported as dominant AMF in tropical soils, attributable to their high sporulation rates, adaptability to variable nutrient conditions, and broad host ranges (Zhang *et al*., 2021; Mukhongo *et al.*, 2023). The pronounced presence of *Acaulospora* spp. in mangrove, dumpsite, and cropland soils aligns with previous studies showing this genus’ affinity for environments with moderate acidity and available P (Muchane *et al.*, 2012; Nopphakat *et al.*, 2022). Even in freshwater swamp and lowland forest soils, where overall spore densities were lower, *Acaulospora* remained the most frequent spore producer, indicating its ecological tolerance across edaphic gradients.

Although *Scutellospora* spp. have been documented in both wetland and non-flooded ecosystems (Muchane *et al.,* 2012), they were notably absent in this study, suggesting potential regional biogeographic constraints or competitive exclusion by more ecologically dominant genera. Differences in spore morphology, dormancy dynamics, and host specificity likely contribute to these distribution patterns, but further investigation is needed to understand the functional implications of these community structures.

4.3 Root Colonization Patterns and Habitat Effects

Root colonization by AMF was evident in all sampled plant species, demonstrating that symbiotic associations extend beyond traditional Poaceae hosts to a diverse suite of indigenous and non-reported plant taxa within these tropical forests. Reported AMF colonization ranged from approximately 10% to nearly 30%, a range that aligns with previously documented root infection levels in tropical systems (Nopphakat *et al*., 2022). These findings support the growing consensus that AMF are highly versatile symbionts that colonize a broad range of plant families, including woody perennials and herbaceous species, with colonization intensity modulated by soil nutrient status and plant functional traits (Bauer *et al*., 2003; Enebe and Erasmus, 2023).

Sites characterized by higher soil P and moderate pH, such as the dumpsite, lowland forest, and mangrove, also exhibited the highest root colonization percentages (20–29%). These conditions are favorable for AMF establishment and suggest that soil fertility gradients, rather than solely disturbance intensity, may more strongly influence symbiotic engagement. The comparison between *Millettia aboensis* roots sampled from the dumpsite and cropland soils further illustrates this point: the higher colonization in the dumpsite likely reflects both greater phosphorus availability and possibly greater carbon allocation by the host under organic-rich conditions, enhancing AMF assimilation and arbuscule development.

Conversely, lower colonization levels observed in roots from cropland and freshwater swamp sites (10–18%) may reflect a combination of reduced P accessibility, greater soil compaction, or anaerobic stress conditions that inhibit extensive hyphal penetration (Van Cleemput *et al*., 2007; Torppa *et al*., 2023). Such variability underscores that AMF-host interactions are context dependent, responding not only to the presence of spores but also to root physiology, soil chemistry, and environmental stress gradients.

Collectively, the observed patterns of spore abundance and root colonization affirm that AMF establishment and proliferation in tropical forest soils are shaped by an interplay of edaphic factors, host identity, and habitat disturbance history, reinforcing the concept that soil microbial ecology is tightly linked to land-use dynamics (van der Heyde *et al*., 2017; Zhang, *et al*., 2025). These insights provide a foundation for targeted soil fertility and conservation strategies in Southern Nigeria, where AMF function could be harnessed to enhance crop productivity and ecosystem resilience.

5. Conclusion

This study demonstrates that arbuscular mycorrhizal fungi (AMF) are widely distributed across contrasting land-use systems in southern Nigeria, and that their diversity, spore abundance, and root colonization intensity are strongly regulated by soil physicochemical conditions. Variations in soil nutrient status, acidity, and electrical conductivity across ecosystems were shown to shape distinct AMF community patterns, with nutrient-enriched environments-particularly cropland, mangrove, and dumpsite soils-supporting comparatively higher spore densities.

The consistent dominance of *Acaulospora*, *Rhizophagus*, and *Glomus* spp. across all sampling locations highlights their ecological adaptability and functional relevance in tropical soil environments. Notably, the occurrence of measurable AMF colonization in a wide range of previously unreported host plant species confirms the broad host range of AMF and extends current understanding of their ecological associations in both forested and anthropogenically influenced ecosystems within the study region.

Collectively, these findings underscore the importance of heterogeneous forest and land-use systems as reservoirs of beneficial soil microbial diversity such as AMF. By integrating assessments of AMF species composition, spore abundance, and root colonization in non-reported host plants, this study provides a robust scientific basis for the incorporation of mycorrhizal fungi into sustainable land management, soil fertility enhancement, and ecosystem restoration strategies in tropical environments.

Future research should explore seasonal dynamics of AMF communities across additional forest types and land-use systems within the region. Furthermore, detailed evaluations of symbiotic strength, integrating spore density and root colonization metrics, will be essential for optimizing AMF-based interventions aimed at improving plant health, ecosystem resilience, and long-term sustainability in the study area.

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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Competing Interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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