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Carbon Accumulation and Soil Organic Carbon Dynamics of *Cannabis sativa* in a Site-Specific Ecosystem, Abuja, Nigeria

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Abstract

The increasing need for nature-based climate mitigation strategies has renewed interest in plant species with high carbon sequestration potential. This study assessed the carbon accumulation of Cannabis sativa cultivated on a municipal dumpsite soil and an uncontaminated control soil under dry- and rainy-season conditions in Abuja, Nigeria. A controlled pot experiment was conducted using soils collected from a dumpsite (T1) and an adjacent uncontaminated site (T2). Soil physicochemical properties, growth performance, biomass production, soil organic carbon (SOC), and carbon content were evaluated using a two-way Analysis of Variance (ANOVA) and Tukey's HSD test at $p < 0.05$. The soils were moderately acidic to moderately alkaline, with pH ranging from 5.32 ± 0.42 to 8.50 ± 0.09, and were predominantly loam to clay-loam in texture, comprising 35% - 41% sand, 35% - 41% silt, and 21% - 26% clay. Growth performance varied significantly among treatments and seasons. Plant height increased progressively throughout the 18-week experimental period, reaching 110.0 ± 5.94 cm in T1 during the dry-season soil treatment, whereas the lowest final height (62.0 ± 4.44 cm) was recorded in T2 under the rainy-season soil treatment. Similarly, leaf production peaked at 130.0 ± 6.08 leaves plant^{-1} in T1 during the rainy season, significantly exceeding the 55.0 ± 4.58 leaves plant^{-1} observed in T2. Total biomass ranged from 8.60 ± 0.41 g to 15.20 ± 0.58 g, with T1 producing the highest biomass yield. Soil organic carbon increased after cultivation, reaching 0.97% ± 0.055% in T1 during the dry season. Plant carbon content ranged from 1.40% ± 0.039% in roots to 1.62% ± 0.064% in leaves, while carbon deposition was greatest in stems (0.150 ± 0.018 g). Significant differences among treatments and seasons were observed for most growth and carbon-related variables ($p < 0.05$). The findings demon-

strate short-term carbon accumulation in plant biomass together with increases in soil organic carbon concentration during the cultivation period. These observations indicate the potential of Cannabis sativa to contribute to carbon storage. Its rapid growth, high biomass productivity, and capacity to accumulate carbon in structural tissues highlight its suitability as a nature-based solution for climate change mitigation and ecosystem restoration in tropical environments.

Keywords

Cannabis sativa, Carbon Accumulation, Soil Organic Carbon, Biomass Accumulation, Climate Change Mitigation

1. Introduction

Open dumping of municipal solid waste is the primary cause of environmental degradation. These dumpsites contain unclassified waste and poisonous or radioactive materials that are hazardous to the environment. They may result in builds up of heavy metals, for example, arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg) and zinc (Zn). These overwhelming metals, when found in solid waste, have been known to deliver significant ecological effects [1]. Contamination by heavy metals poses many risks to the ecosystem and humans, raising public health concerns. Cancer, heart diseases and teratogenic abnormalities are attributed to groundwater pollution via leachate from the waste dumpsites [2]. They dissolve in the soil and move towards groundwater which in most cases are supplied for domestic and agricultural use. This way, they enter into the food chain and influence human wellbeing [3].

Hemp (*Cannabis sativa* L.) is a versatile crop that has attracted considerable attention due to its industrial, environmental, and phytoremediation applications. The species has been cultivated for thousands of years for fiber, food, medicine, and other utilitarian purposes, making it one of the oldest domesticated crops in human history [4] [5]. Industrial hemp is distinguished from psychoactive cannabis varieties by its low tetrahydrocannabinol (THC) content, typically not exceeding 0.3% on a dry-weight basis in many regulatory frameworks [6] [7]. In recent years, hemp has been widely investigated for phytoremediation because of its rapid growth, extensive root system, high biomass production, and ability to accumulate contaminants, including heavy metals, from polluted soils [8] [9]. Although research on hemp was historically constrained in many countries due to legal restrictions on cannabis cultivation, renewed interest has emerged following regulatory reforms and recognition of its economic and environmental value. Hemp provides numerous products, including food, pharmaceuticals, personal care products, textiles, paper, construction materials, biocomposites, and biofuels, thereby creating opportunities to offset cultivation and environmental remediation costs [10] [11]. Consequently, hemp is increasingly regarded as a promising

crop for sustainable agriculture, environmental restoration, and the development of a circular bioeconomy.

Industrial Hemp (*Cannabis sativa* L.) is a hardy, fast growing species of plant with fast growing roots that can be used to reach pollutants deep in the ground. This property makes hemp a potential choice for phytoremediation.

Carbon emission is one of the most challenging phenomena facing mankind in the 21st century because of its threats to climate change. Therefore, the use of biological methods to capture carbon from the soil and its conservation in the soil with the help of plants is increasingly becoming attractive in phytoremediation. This has been documented by Rovnov *et al.* [12].

Hemp (*Cannabis sativa* L.) is a multi-use crop that should be seriously investigated for its usefulness in the reduction of global atmospheric Carbon Dioxide. Ismagilov and Rusakov, 2024 [13] in their analysis of hemp as an effective carbon-depositing crop discovered that hemp crops capture a relatively large amount of Carbondioxide (14.78 t/ha) and, accordingly carbon (4.03 t/ha) from the atmosphere, making it an ideal carbon sink.

The Guardian [14] also reported that 1 hectare (2.5 acres) of hemp absorbs from 8 to 22 tons of CO_2 per year, more than any forest area, making hemp twice as efficient as trees at absorbing and retaining carbon.

Government around the world are encouraging widespread planting of hemp as a means of absorbing CO_2 and are issuing carbon credits to farmers growing the crop. Major producers include Canada, France, and China. In Australia, the Department of Primary Industry is encouraging the growth of Industrial hemp and is issuing licenses to companies and individuals that meet stringent criteria. In Italy, hemp is considered as an environmentally friendly crop capable of mitigating climate change and desertification [15].

In the Federal Capital Territory Abuja, the major source of carbon emission is waste dumps that arbitrarily spring up around the major city centers with Plethora's of human activities. These waste dumps constitute the major source of soil carbon which in most cases being transformed into the emission of Carbon into the atmosphere. Attempts to manage these waste dumps is challenging due to bureaucracy and policy inconsistency on the part of the Government.

It is in an attempt to provide a biological solution to the soil carbon emission that this current research hinged on the carbon accumulation capacity or otherwise of *Cannabis Sativa* in carbon sequestration which has not been thoroughly examined and evaluated considering the strict regulation placed on the accessibility of *Cannabis Sativa* by the relevant authorities.

2. Study Area

The study was conducted in Apo District, located within the Abuja Municipal Area Council (AMAC) of the Federal Capital Territory (FCT), Nigeria. AMAC lies at the geographical center of Nigeria and serves as the administrative hub of the nation. The council is bordered by Kubwa and Karimu to the north, Kuje to

the south, Gwagwalada to the west, and Nyanya and Karu to the east.

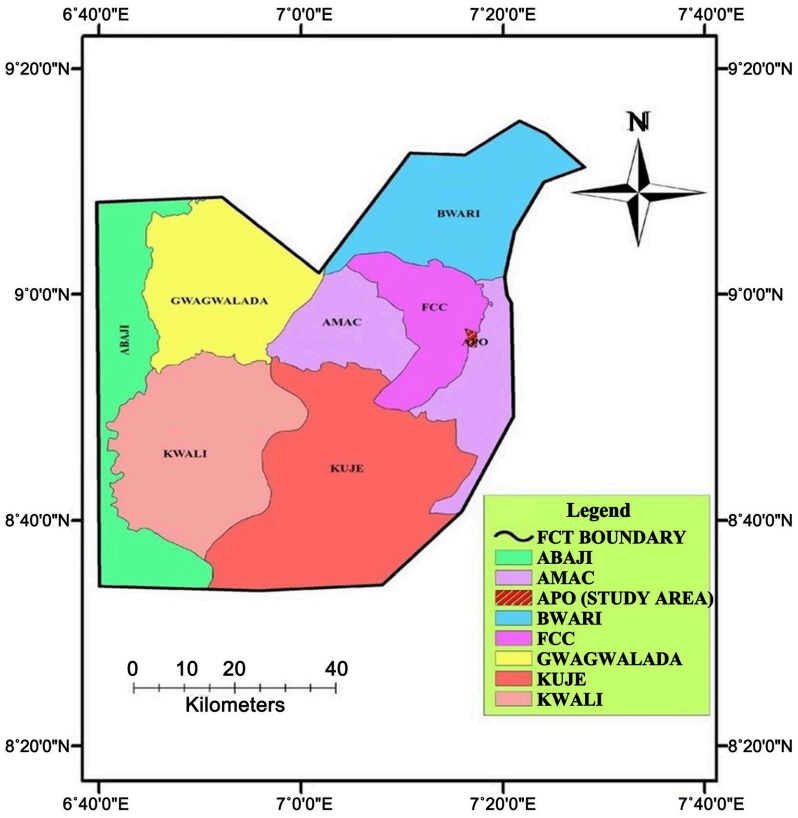


Figure 1. Map of Abuja showing the study area. Source: Urban and Regional Planning Department FCDA, Abuja (2016).

Apo District is bounded by Guzape (northeast), Lokogoma (southwest), Gaduwa (west), and Gudu (northwest). The area falls within latitude 9˚20'N-9˚25'N and longitude 7˚39'E-9˚45'E, with elevations ranging from approximately 495 m to 913 m above sea level.

The soils of the study area are basically Alluvial and Luvisols. Alluvial soils are soils that are deposited by the surface water. They are mostly found along the riversides, flood plains, and deltas. Alluvials are very fertile in nature. and mainly used for the production of vegetables. they range between dark brown to brown loamy sand and fine sandy loam with weak structure. Luvisols are moderately acidic, and are shallow to moderately deep and well drained. They have gravel to loamy sand surface horizons and organic matter content is moderately high.

The dominant land use in the study area includes commercial and automobile workshops (Figure 1).

2.1. Experimental Design

A controlled pot experiment was conducted to assess the growth performance and carbon accumulation of *Cannabis sativa* cultivated in dumpsite and control soils collected during different seasons. Soil samples were collected in March, repre-

senting the dry-season sampling period, and October, representing the rainy-season sampling period. In this study, season refers to the period of soil collection and is treated as a soil-sampling factor rather than as a separate cultivation environment. The experiment was therefore designed to evaluate whether soils collected during the two seasonal periods differed in their physicochemical properties and subsequent effects on plant growth and carbon-related measurements.

The experiment comprised 20 pots containing 2 kg of soil each, with the pots allocated among the dumpsite and control soil groups collected during the two seasonal periods. Growth parameters, including plant height and number of leaves, were recorded weekly throughout the 18-week cultivation period. At harvest, the plants were separated into roots, stems, and leaves for biomass determination and carbon-related analyses. Soil organic carbon was determined before planting and after harvest using the Walkley-Black chromic acid digestion method [16].

Composite topsoil samples (0 - 20 cm depth) were collected from a municipal dumpsite along Shafuyi Road, Apo District, Abuja, and from a nearby control site approximately 500 m upslope from the dumpsite. The dumpsite soil was designated Treatment 1 (T1), while the control soil was designated Treatment 2 (T2). Following collection, the soils were air-dried at room temperature, homogenized, and passed through a 2 mm sieve before being placed in labelled polyethylene bags for subsequent use.

Following soil preparation, the experimental pots were maintained under the cultivation conditions provided for the pot experiment, with routine watering and other standard intercultural practices. The dry- and rainy-season designations consequently identify the seasonal origins of the soil samples and should not be interpreted as evidence that plants were exposed to distinct seasonal climatic conditions. Air-drying and routine watering were not intended to reproduce the field moisture, temperature, or rainfall conditions associated with either season. Accordingly, differences observed between the seasonal soil groups are interpreted as differences associated with soil collection period and the properties of the collected soils, rather than as direct effects of seasonal cultivation environments.

For the purposes of the experimental design, five spatially separated soil composites were collected independently from each source area during each sampling season. This resulted in 20 soil composites in total, comprising five composites for each of the four treatment-season combinations: T1-dry, T1-rainy, T2-dry, and T2-rainy. Each composite represented a separate sampling unit and was collected from a distinct sampling location within its respective source area.

The soil samples were air-dried at room temperature, homogenized separately, and passed through a 2 mm sieve to remove stones, debris, and coarse materials. The prepared samples were stored in labelled polyethylene bags before potting. Care was taken to prevent cross-contamination during sample collection, preparation, and handling.

Certified *Cannabis sativa* seeds with low tetrahydrocannabinol (THC) content

were obtained through legally approved procedures. The seeds were initially sown in germination trays and watered regularly until emergence. Uniform and healthy seedlings were selected for transplanting into plastic pots perforated with three to four drainage holes at the base. Each pot received 2 kg of soil from one independently collected composite, and one seedling was transplanted into each pot.

The experiment comprised 20 pots, with five replicate pots allocated to each treatment-season combination. Each of the 20 independently collected soil composites was assigned to one pot, thereby linking each pot to a distinct soil sampling unit. The pots were arranged in a completely randomized design. Pot positions were assigned randomly within the experimental area, and the positions were periodically rotated to minimize potential effects of spatial differences in light exposure and other microenvironmental conditions. The five pots within each treatment-season combination constituted the within-source sampling and experimental replicates. However, the dumpsite and control soils originated from only one source area each; consequently, the experiment did not include independent replication of dumpsite or control sites, and the findings were interpreted as comparisons between the two sampled source areas rather than as generalizable effects of dumpsites and control sites as a whole.

Routine intercultural practices, including manual weeding and regular watering, were carried out throughout the experimental period. Growth parameters, including plant height and number of leaves, were recorded weekly from Week 1 to Week 18. At the end of the 18-week cultivation period, plants were harvested and separated into roots, stems, and leaves. Fresh biomass was determined using a digital weighing balance, while plant height was measured using a graduated ruler.

Soil samples from each experimental pot were collected before planting and after harvest for the determination of soil organic carbon (SOC). Plant tissues, comprising roots, stems, and leaves, were also analysed for carbon-related measurements. Soil organic carbon was determined using the Walkley-Black chromic acid digestion method [16], while soil organic matter was estimated by multiplying SOC values by a factor of 1.334. All laboratory analyses were conducted at the Chemistry Advanced Research Centre, Sheda Science and Technology Complex (SHESTCO), Kwali, Abuja.

Plant-tissue carbon analysis was conducted separately from soil organic carbon determination. At harvest, the plants were separated into roots, stems, and leaves, and each component was prepared for individual analysis. The tissues were cleaned to remove adhering soil and other extraneous materials, dried to constant mass, and ground into a homogeneous powder. Carbon concentration was determined using a wet-oxidation method adapted for plant material, as described by [17]. The method involves oxidation of the prepared sample with potassium dichromate in an acidic medium and determination of the carbon dioxide released during oxidation. Carbon concentration was expressed as a percentage of dry tissue mass. The carbon mass of each plant component was calculated by multiplying its

dry biomass by the measured carbon concentration and dividing the result by 100. This plant-tissue procedure was distinguished from the Walkley-Black method used for soil organic carbon determination. Because dichromate wet-oxidation methods may not recover all carbon present in plant tissues under every analytical condition, the reported tissue carbon concentrations (1.40% - 1.62% dry mass) represent the fraction of carbon recovered by the analytical procedure. These values are interpreted as estimates of tissue carbon content rather than absolute total tissue carbon unless complete analytical recovery has been independently validated [17].

In this study, carbon accumulation refers to the measured mass of carbon retained within harvested plant tissues, calculated as the product of tissue dry biomass and measured carbon concentration. Carbon storage refers to the observed increase in soil organic carbon concentration following cultivation together with carbon retained in plant biomass. The term "carbon deposition" is used operationally to describe the calculated carbon mass contained within each harvested plant component (roots, stems, or leaves) and does not imply direct measurement of carbon transfer into long-term soil storage. No carbon-sink efficiency index or carbon-use efficiency metric was calculated; accordingly, the measured outcomes are described throughout as carbon accumulation or carbon storage rather than carbon-sink efficiency.

2.2. Statistical Analysis

All measured variables were expressed as mean ± standard deviation (SD). Soil source (Treatment: dumpsite soil, T1; control soil, T2) and soil collection season (dry and rainy) were treated as fixed experimental factors throughout the analysis.

For growth variables (plant height and number of leaves), measurements were obtained repeatedly from the same experimental pots at weekly intervals over the 18-week cultivation period. To account for the non-independence of repeated observations from the same pot, growth data were analysed using repeated-measures analysis of variance, with treatment, soil collection season, sampling time, and their interactions specified as fixed effects, while pot identity was included as the repeated experimental unit. When significant main effects or interactions were detected, treatment means at individual observation times were separated using Tukey's Honestly Significant Difference (HSD) test at $p < 0.05$.

Harvest variables, including total biomass, root biomass, stem biomass, leaf biomass, tissue carbon concentration, carbon accumulation, and soil physicochemical characteristics measured once per pot, were analysed using two-way ANOVA with treatment and soil collection season as fixed factors.

Soil organic carbon (SOC) measurements obtained before planting and after harvest originated from the same experimental pot. These paired observations were analysed using a repeated-measures ANOVA in which sampling time (before planting versus after harvest) was treated as the within-pot factor, whereas

treatment and soil collection season were treated as between-pot factors. This approach accounted for the correlation between repeated measurements obtained from the same experimental unit.

Significant differences among means were determined using Tukey's HSD multiple comparison test at the 5% significance level ($p < 0.05$). Statistical analyses were performed using R version 4.4.2, and treatments sharing the same letter were considered statistically similar.

3. Discussion of Results

3.1. Soil Physicochemical Characteristics of the Study Site

The soils across the Cannabis sativa plots ranged from moderately acidic to moderately alkaline, with pH values varying among treatments and seasons (Figure 2). Soil pH ranged from 5.32 ± 0.42 to 8.50 ± 0.09, indicating substantial variation in soil chemical conditions among treatment-season combinations.

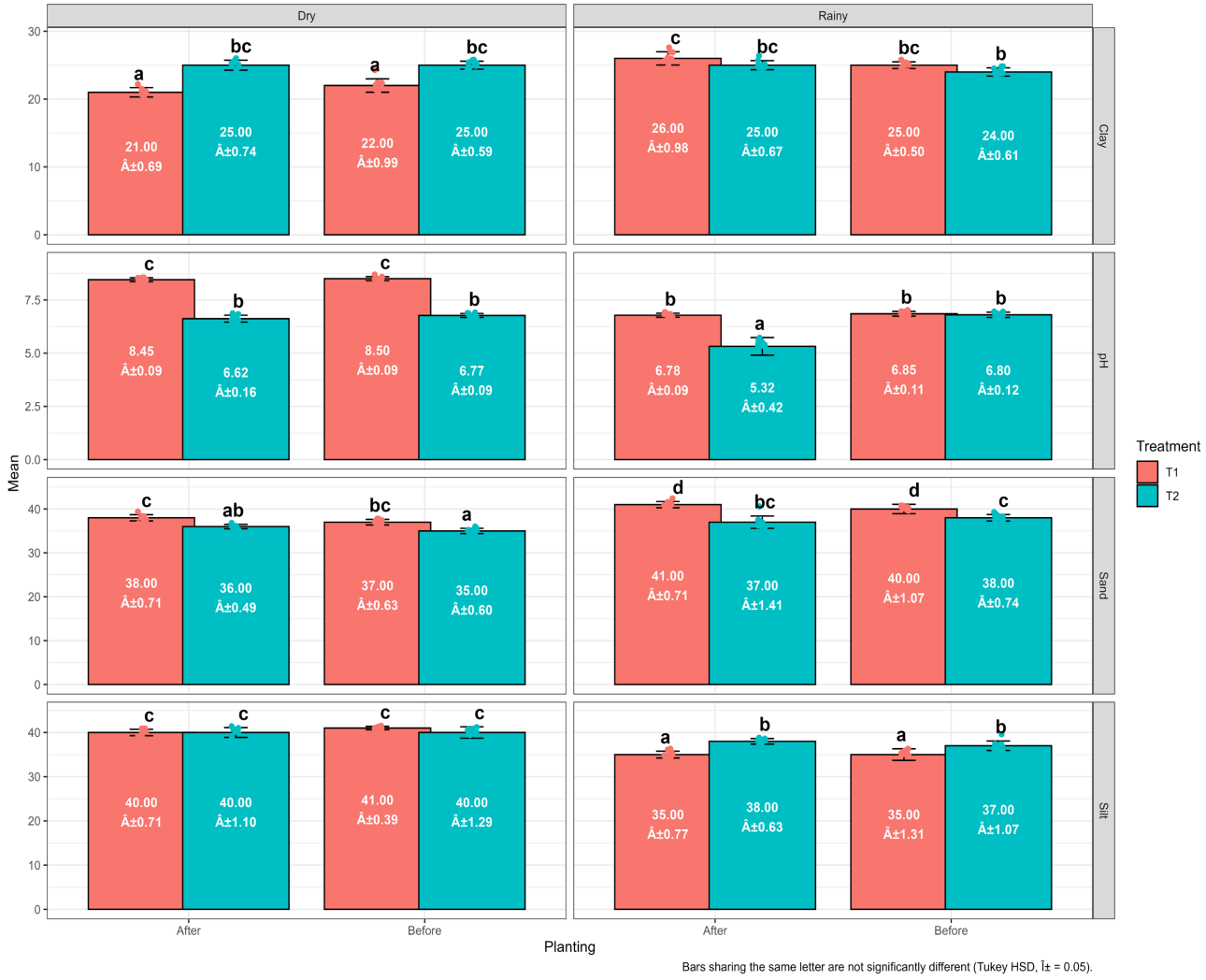


Figure 2. Soil physicochemical characteristics of the study site.

During the dry season, T1 exhibited alkaline pH values (8.45 ± 0.09 after planting and 8.50 ± 0.09 before planting), whereas T2 remained near neutral to slightly acidic (6.62 ± 0.16 after planting and 6.77 ± 0.09 before planting). The different Tukey grouping letters indicate that these differences were statistically significant ($p < 0.05$), reflecting contrasting soil chemical environments between the two sites. In contrast, treatments sharing the same letter were not significantly different from one another despite slight numerical differences in their mean values. A similar trend was evident during the rainy season, where pH remained within a narrow range, reflecting a relatively stable soil reaction despite seasonal changes in moisture conditions.

The observed pH range encompasses moderately acidic through moderately alkaline conditions. Although microbial activity and nutrient availability are often greatest under near-neutral conditions, both slightly acidic and moderately alkaline soils can support plant growth depending on nutrient availability and soil buffering capacity. Consequently, pH differences among the treatment-season combinations may have contributed to differences in nutrient dynamics and carbon accumulation observed during the experiment. Soils within slightly acidic to near-neutral conditions generally support greater microbial diversity and more efficient decomposition of organic residues, leading to enhanced incorporation of carbon into stable soil pools [18].

Soil texture was dominated by moderate proportions of sand, silt and clay, indicating a predominantly loam to clay-loam soil. Clay content ranged from 21.00% ± 0.69% to 26.00% ± 0.98%, while sand and silt contents varied from 35.00% ± 0.60% to 41.00% ± 0.71% and 35.00% ± 0.77% to 41.00% ± 1.29%, respectively. Although significant differences were detected among some treatments, the overall variation was relatively small. For example, the clay content of T2 during the dry season (25.00% ± 0.74%) was significantly higher than that of T1 (21.00% ± 0.69%), as reflected by the different Tukey groupings. However, the magnitude of this difference was insufficient to alter the overall textural classification of the soil.

An important feature of the study area is the dominance of fine particles, particularly the combined silt and clay fractions, which accounted for more than half of the soil matrix across all treatments. This characteristic is especially relevant to carbon sequestration because fine-textured soils are known to provide greater physical protection for organic matter. Clay minerals and silt particles can bind organic compounds, reducing their exposure to microbial decomposition and thereby enhancing long-term carbon storage [19] [20]. The slightly higher clay content observed in some treatments may therefore contribute to greater carbon stabilization capacity within those sites.

The pH and texture results indicate that the study sites possess favourable edaphic conditions for carbon storage. While statistically significant differences existed among treatments, the overall soil environment remained characterised by moderate acidity and substantial fine-particle content, both of which are widely recognised as important controls on soil carbon retention.

3.2. Growth Performance and Tolerance of *Cannabis Sativa*

The growth response of *Cannabis sativa* varied significantly among treatments and seasons, as evidenced by differences in seedling height, leaf production, and biomass accumulation (Figures 3-5). Across the growth cycle, plants generally exhibited progressive increases in height and leaf production, although the magnitude of growth differed between treatments and seasons. The Tukey HSD groupings indicate that several of these differences were statistically significant ($p < 0.05$), suggesting that environmental conditions influenced plant performance at different developmental stages.

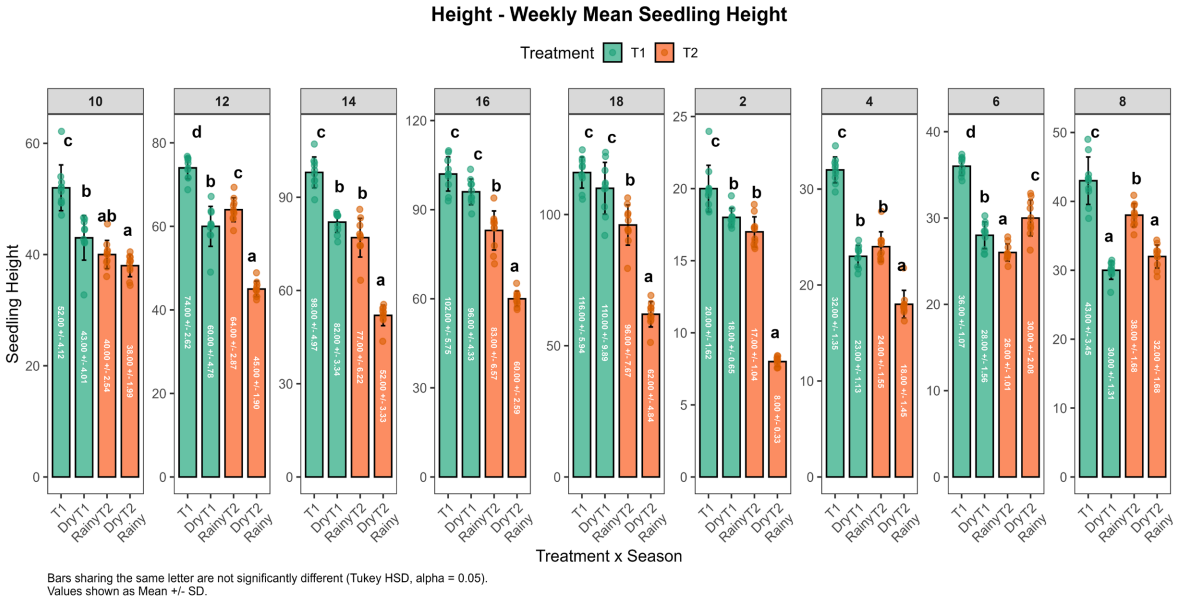


Figure 3. Weekly mean values of seedling height.

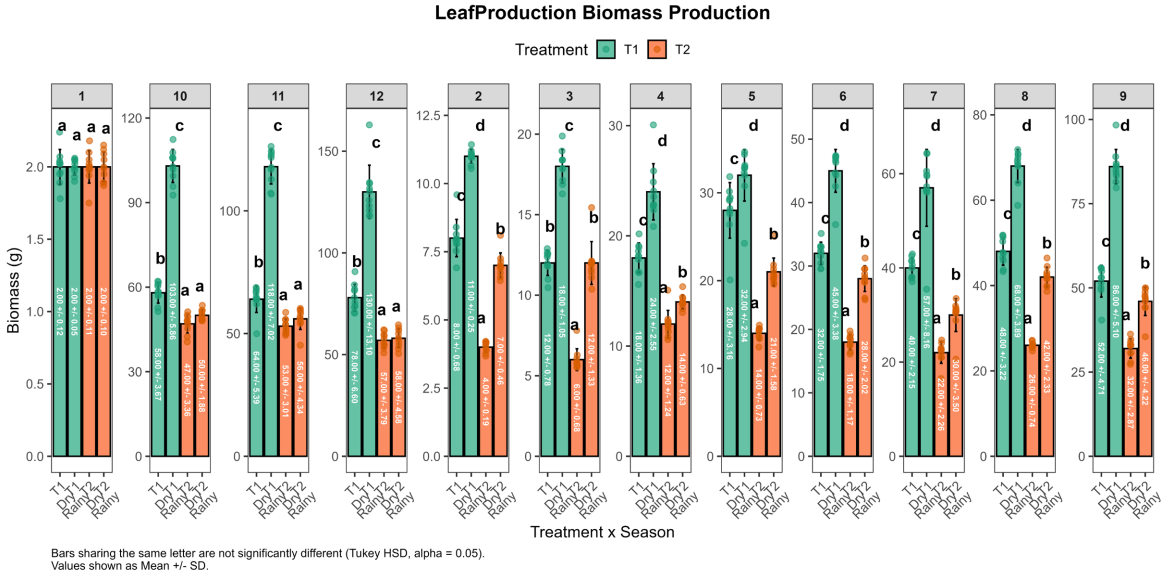


Figure 4. Weekly mean values of leaf production.

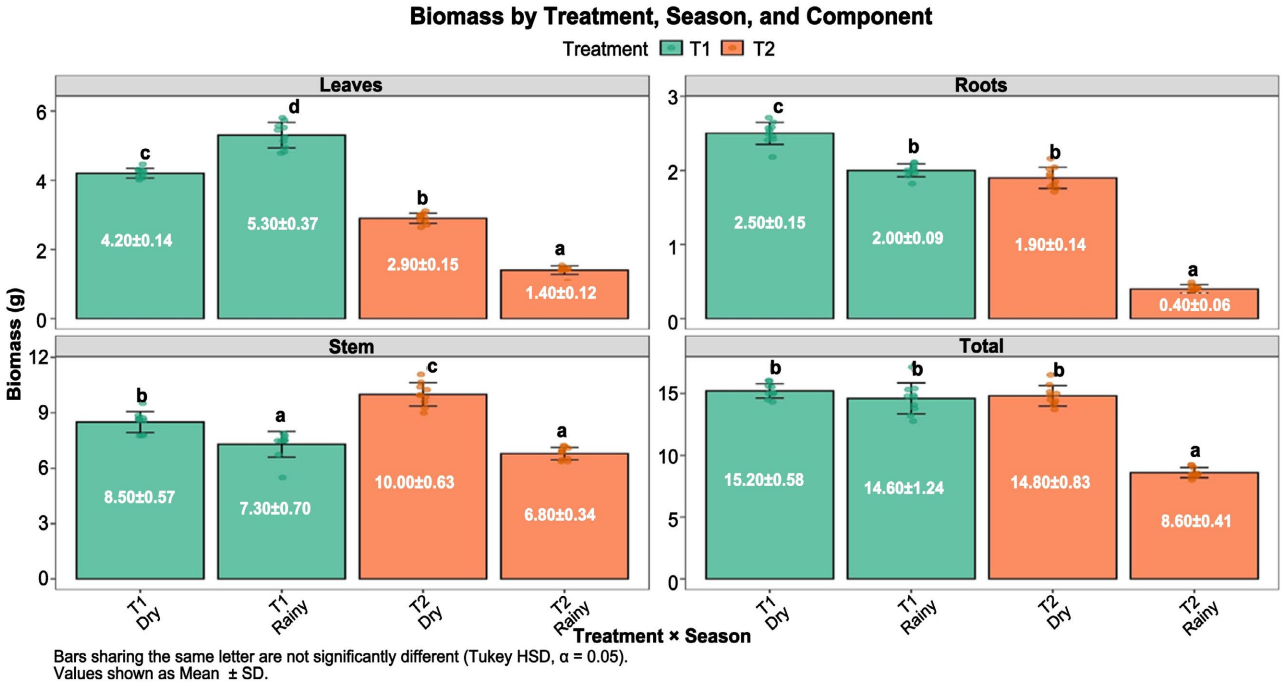


Figure 5. Average plant biomass.

Seedling height increased steadily throughout the experimental period in both treatments, reflecting the rapid growth habit that characterizes *Cannabis sativa*. During the early growth stage (week 2), T1 under dry-season conditions attained a mean height of 20.0 ± 1.62 cm, significantly exceeding T2 during the rainy season (8.0 ± 0.53 cm). This trend persisted throughout the study period. By week 18, plants in T1 reached 110.0 ± 5.94 cm (dry season) and 105.0 ± 5.21 cm (rainy season), whereas T2 attained 95.0 ± 3.67 cm and 62.0 ± 4.44 cm, respectively. Although T1 under dry and rainy conditions shared similar statistical groupings at several growth stages, T2 during the rainy season consistently produced the lowest heights, indicating reduced growth vigour under those conditions. The maintenance of substantial height growth in T1 across seasons suggests a greater capacity to tolerate environmental variability and sustain biomass production.

Leaf production followed a similar pattern. During the first week, leaf numbers were relatively uniform across treatments, ranging from 2.00 ± 0.12 to 2.10 ± 0.08 leaves plant^{-1}, with no significant differences observed. However, treatment effects became increasingly pronounced as plants matured. By week 12, T1 under rainy-season conditions produced the highest number of leaves (130.0 ± 6.08 leaves plant^{-1}), significantly exceeding T2 under rainy-season conditions (55.0 ± 4.58 leaves plant^{-1}). Similar trends were observed throughout weeks 6 - 11, where T1 consistently maintained greater leaf production than T2. Since leaf area and leaf abundance directly determine photosynthetic capacity, the larger canopy developed under T1 likely enhanced carbon assimilation and contributed to greater biomass accumulation. Previous studies have reported that the high productivity

of *Cannabis sativa* is closely linked to its ability to rapidly develop an extensive photosynthetic canopy, thereby maximizing carbon capture during the growing season [11].

The differences observed in height and leaf production were reflected in biomass allocation patterns. Total biomass ranged from 8.60 ± 0.41 g in T2 during the rainy season to 15.20 ± 0.58 g in T1 during the dry season. Interestingly, T1 during both seasons (15.20 ± 0.58 g and 14.60 ± 1.24 g) and T2 during the dry season (14.80 ± 0.83 g) belonged to the same Tukey grouping, indicating statistically comparable overall biomass production despite differences in growth attributes. In contrast, T2 during the rainy season produced significantly lower biomass (8.60 ± 0.41 g), largely due to reductions in leaf biomass (1.40 ± 0.12 g) and root biomass (0.40 ± 0.06 g). These reductions indicate that the treatment constrained both photosynthetic development and belowground resource acquisition.

Biomass partitioning further revealed that stems represented the largest carbon pool within the plant. Stem biomass reached 10.00 ± 0.63 g in T2 during the dry season and 8.50 ± 0.57 g in T1 during the dry season, substantially exceeding root biomass in all treatments. This allocation pattern is consistent with the growth strategy of *Cannabis sativa*, which invests heavily in structural tissues that support rapid vertical growth and carbon storage. The strong contribution of stem biomass is particularly important from a carbon-sink perspective because lignified tissues retain carbon for longer periods than metabolically active leaves.

Taken together, the height, leaf production, and biomass data demonstrate that *Cannabis sativa* possesses considerable ecological tolerance and maintains high productivity across contrasting environmental conditions. While growth reductions were evident in T2 during the rainy season, plants under the remaining treatment-season combinations consistently produced substantial aboveground and belowground biomass. The ability to sustain rapid height growth, develop extensive foliage, and accumulate significant structural biomass highlights the adaptability of the species and reinforces its potential as an effective carbon-sequestering crop. Similar findings have been reported by [5] and [11], who identified rapid biomass accumulation, vigorous canopy development, and high carbon uptake efficiency as key characteristics underpinning the environmental value of industrial hemp.

3.3. Carbon Sequestration Potential of *Cannabis sativa*

The carbon sequestration potential of *Cannabis sativa* was evaluated using soil organic carbon (SOC), plant carbon content, carbon deposition, and biomass weight as indicators of carbon capture and storage. The results revealed significant differences among treatments, seasons, and plant components, indicating that the capacity of *Cannabis sativa* to sequester carbon is influenced by both environmental conditions and biomass allocation patterns (**Figure 6** and **Figure 7**).

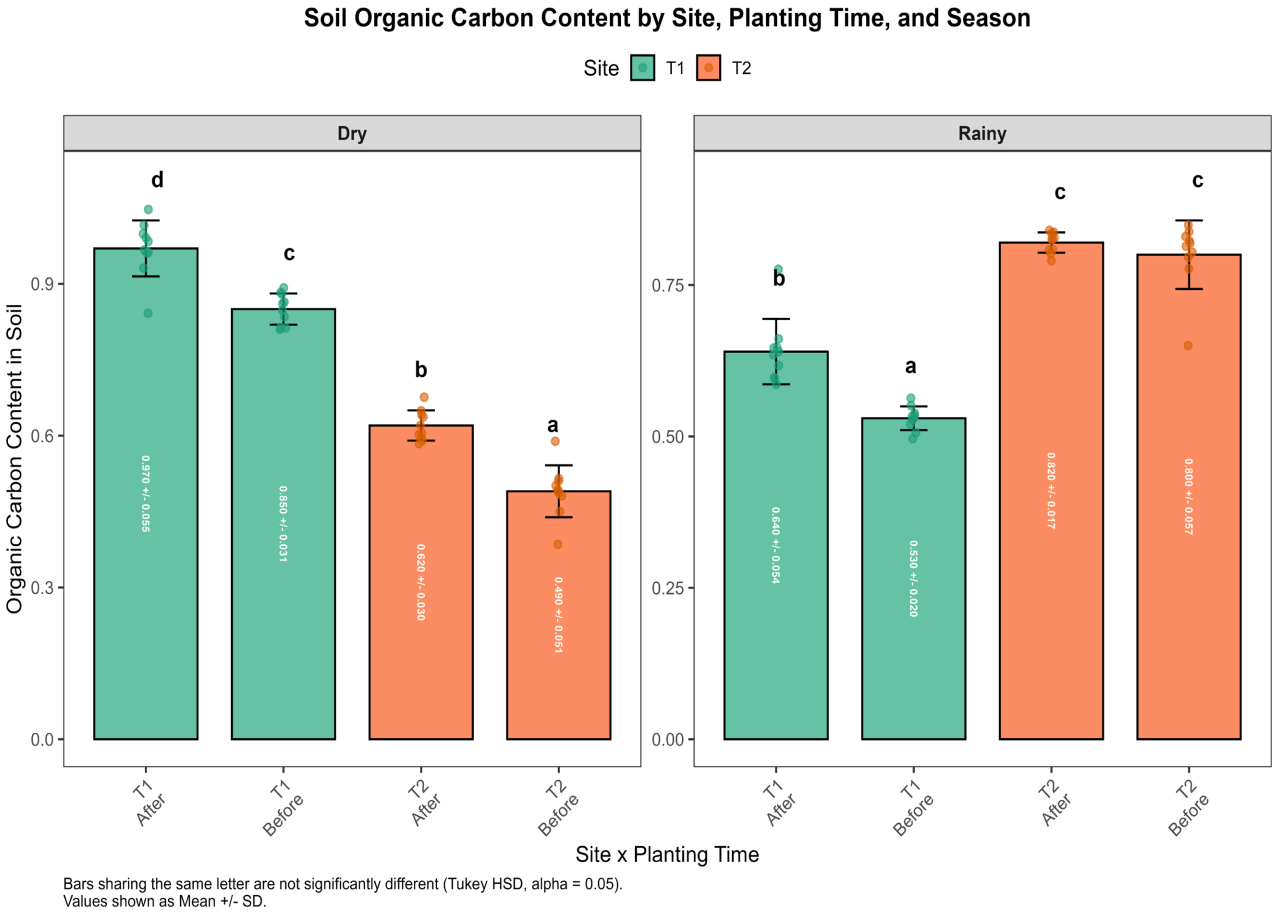


Figure 6. Organic carbon content in soil.

Soil organic carbon content varied significantly among sites and seasons (**Figure 6**). During the dry season, SOC values were consistently higher in T1 than in T2. The highest SOC was recorded in T1 after planting (0.97% ± 0.055%; group *d*), followed by T1 before planting (0.85% ± 0.031%; group *c*), whereas T2 after planting (0.62% ± 0.030%; group *b*) and T2 before planting (0.49% ± 0.051%; group *a*) recorded comparatively lower values. The increase observed in T1 after planting relative to before planting suggests a net accumulation of organic carbon within the soil during the cultivation period. In contrast, the rainy season exhibited a different pattern, with T2 recording the highest SOC values both after planting (0.82% ± 0.017%) and before planting (0.80% ± 0.067%), and both treatments belonging to the same statistical group (*c*). T1 recorded lower values of 0.64% ± 0.054% after planting and 0.53% ± 0.020% before planting. The higher SOC observed after planting in most cases indicates that *Cannabis sativa* contributed organic residues to the soil through root development, litter deposition, and rhizosphere processes. Such increases in SOC are widely regarded as evidence of short-term increases in soil organic carbon concentration during cultivation because soil organic matter represents one of the largest and most stable terrestrial carbon reservoirs [21].

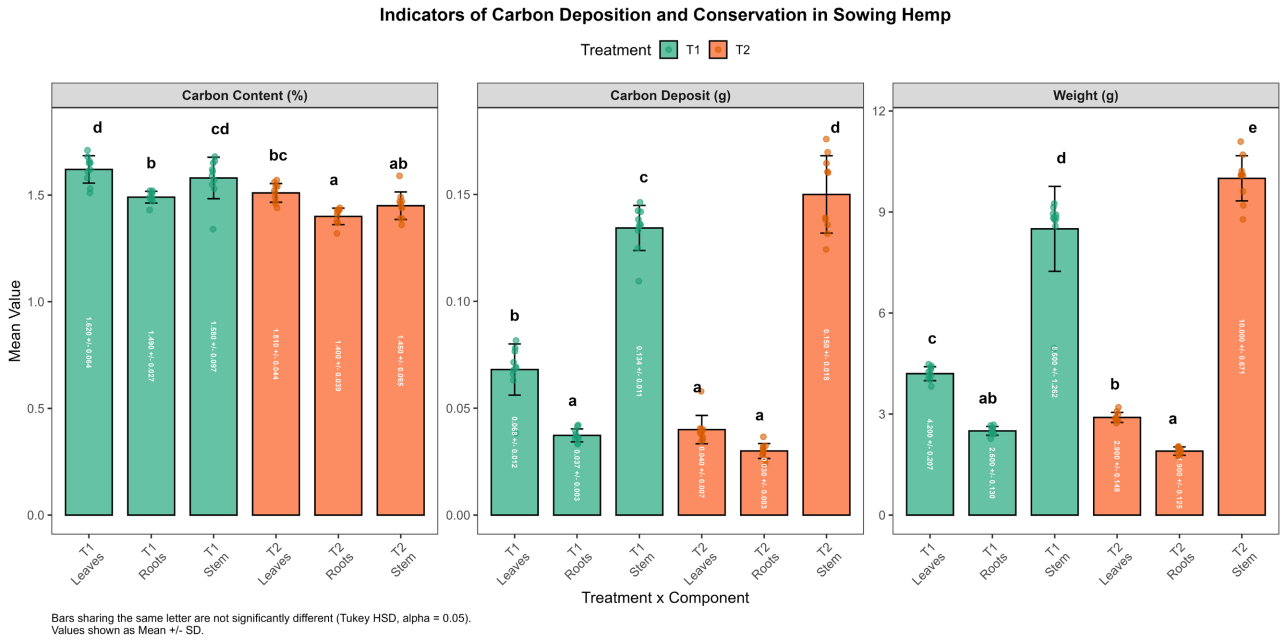


Figure 7. Indicators of carbon deposition and conservation in sowing hemp.

The distribution of carbon within plant tissues further demonstrated the sequestration capacity of the species (Figure 7). Carbon content ranged from 1.40% ± 0.039% in T2 roots to 1.62% ± 0.064% in T1 leaves. Leaves in T1 recorded the highest carbon concentration (1.62% ± 0.064%; group *d*), significantly exceeding all other plant components, while roots in T2 exhibited the lowest concentration (1.40% ± 0.039%; group *a*). Stems maintained relatively high carbon contents in both treatments (1.58% ± 0.097% in T1 and 1.46% ± 0.065% in T2), reflecting the importance of structural tissues as carbon storage pools. Although leaves exhibited higher carbon concentrations, the stem component accounted for the largest share of total carbon storage because of its substantially greater biomass.

This pattern becomes clearer when carbon deposition is considered. Carbon deposition ranged from 0.030 ± 0.003 g in T2 roots to 0.150 ± 0.018 g in T2 stems. Stem tissues recorded significantly greater carbon deposition than either leaves or roots in both treatments, with values of 0.134 ± 0.011 g and 0.150 ± 0.018 g in T1 and T2, respectively. In contrast, roots contributed the least carbon deposition, recording 0.037 ± 0.003 g in T1 and 0.030 ± 0.003 g in T2. The higher carbon deposition observed in stems reflects the substantial allocation of assimilated carbon to lignified tissues, which generally decompose more slowly than foliage and therefore contribute more effectively to potential longer-term carbon storage if retained following harvest. This finding is consistent with previous studies showing that the carbon sequestration potential of hemp is strongly linked to its rapid accumulation of structural biomass [5].

Biomass weight showed a similar trend. Stem biomass reached 8.50 ± 1.28 g in T1 and 10.00 ± 0.67 g in T2, values that were significantly higher than those recorded for leaves and roots. Root biomass remained comparatively low, ranging

from 1.90 ± 0.26 g to 2.50 ± 0.13 g, while leaf biomass varied from 2.90 ± 0.18 g to 4.20 ± 0.27 g. The close correspondence between biomass weight and carbon deposition indicates that carbon storage in *Cannabis sativa* is primarily driven by biomass accumulation. Treatments that produced larger structural biomass consequently retained greater amounts of carbon within plant tissues.

Taken together, the soil and plant data provide strong evidence of the carbon-sink capacity of *Cannabis sativa*. The increase in soil organic carbon after planting, combined with substantial carbon accumulation within aboveground biomass, demonstrates that the species accumulated substantial carbon in plant biomass during the cultivation period. While leaves contained the highest carbon concentration, stems emerged as the dominant carbon reservoir because of their greater biomass and carbon deposition. This distinction is important because long-term carbon sequestration depends not only on carbon concentration but also on the quantity of biomass produced and retained within the ecosystem.

The results further suggest that the carbon sequestration potential of *Cannabis sativa* in Abuja is driven by two complementary pathways: the incorporation of carbon into soil organic matter and the accumulation of carbon in persistent structural tissues. The consistently high stem biomass, coupled with significant gains in soil organic carbon following cultivation, indicates that the species possesses considerable potential as a nature-based climate mitigation crop. Similar observations have been reported by [21], who emphasized the role of plant biomass and soil organic matter as the principal mechanisms of terrestrial carbon sequestration, and by [11], who identified industrial hemp as a high-biomass crop capable of capturing substantial amounts of atmospheric carbon over relatively short growing periods.

4. Conclusions

This study demonstrated that *Cannabis sativa* exhibited rapid biomass production and accumulated measurable quantities of carbon in plant tissues during 18-week pot experiment. Soil organic carbon concentrations also increased in several treatment combinations following cultivation, indicating short-term carbon accumulation under the experimental conditions.

The findings indicate that *Cannabis sativa* contributes to carbon storage through dual pathways: the accumulation of carbon in plant biomass and the enhancement of soil organic carbon. The species' ability to produce substantial structural biomass while improving soil carbon status underscores its potential as a nature-based solution for climate change mitigation and ecosystem restoration. Consequently, *Cannabis sativa* may serve as a valuable component of sustainable land management strategies aimed at enhancing carbon capture and promoting environmental resilience in tropical ecosystems.

Although these findings suggest that *Cannabis sativa* may contribute to carbon storage within managed ecosystems, additional field studies incorporating unplanted controls, soil carbon stock measurements, greenhouse-gas flux monitor-

ing, and postharvest assessments are required before conclusions regarding net long-term carbon sequestration can be made.

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Author Contributions

Enoh, Ndifreke Esther conceived the study, designed the experiment, conducted the field and laboratory investigations, collected the data, interpreted the results, and prepared the original manuscript draft. S.M. Hassan supervised the research, contributed to the study design, provided academic guidance throughout the investigation, critically reviewed the manuscript, and approved the final version for publication. J.A. Edicha co-supervised the research, contributed to the experimental design and interpretation of results, critically revised the manuscript for important intellectual content, and approved the final manuscript. M. Rabiu performed the statistical analyses, assisted with data interpretation, verified the analytical results, and contributed to the preparation and revision of the manuscript. S. Yahaya assisted with field and laboratory activities, contributed to data organization, manuscript editing, language refinement, formatting, and proofreading of the final manuscript. All authors read and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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