# *Original Research Article*

# QUANTIFYING SOIL CARBON STOCKS AND SEQUESTRATION RATE UNDER TREE CANOPY LITTER IN SUDAN SAVANNAH

**ABSTRACT**

Soils of Sudan Savannah faces severe degradation that threaten the soil ability to store soil organic carbon. The impact of tree litter on soil carbon stock and carbon sequestration is essential for enhancing soil fertility, mitigating climate change effects, and sustaining agricultural productivity. Thus, on-farm field experiment was conducted near Biliya Sanda Gate, Usmanu Danfodiyo University, Sokoto, to investigate the contribution of tree canopy litter to soil carbon stock and carbon sequestration rate per year. The experiment was laid out in a Randomized Complete Block Design (RCBD) involving three treatments (*Vachellia nilotica, Azadirachta indica*, and open cultivated area). Soil samples were collected, prepared and analyzed for selected soil properties (Bulk density, pH and organic carbon) and soil carbon stocks and sequestration were computed using standard procedures. Data obtained was subjected to Analysis of Variance (ANOVA) and Least Significant Difference (LSD) test was used to separate significant means. Results showed that the treatments under the tree canopy significantly improved soil properties (Bulk density, pH and organic carbon), soil carbon stock and carbon sequestration rate than the open cultivated area. The soil carbon sequestration rate of the area in increasing order of the treatments was *A. indica* (29.03 t C ha-1 yr-1), followed by *V. nilotica* (20.19 t C ha-1 yr-1), and lastly the open area with the least carbon sequestration rate (11.10 t C ha-1 yr-1). The use of tree canopy in enhancing soil properties and carbon sequestration should be encouraged in the study area as the results reinforce the role of agroforestry systems in achieving Sustainable Development Goals (SDGs) related to climate action (SDG 13) and sustainable land use (SDG 15).

**Key word: *A. indica*, Carbon stock, Carbon sequestration, Tree litter, *V. nilotica***

**INTRODUCTION**

The rapid increase in atmospheric carbon dioxide (CO2) levels, mainly caused by fossil fuel burning, organic matter combustion, and unsustainable land use, has heightened global concerns about climate change (Singh et al., 2024), these could have devastating effects on agricultural production, soil and environmental quality. Murphy (2024) reported that, the industrial revolution has accelerated carbon dioxide (CO2) emissions, leading to increased concentrations and changes in agricultural soil's carbon sequestration capabilities. Deforestation, intensive agriculture, land degradation, and poor soil management have further exacerbated these emissions, depleting soil organic carbon and worsening climate change (Omotoso and Omotayo,2024). Soil degradation, intensive agriculture, deforestation and climate change are unprecedented threats to soil carbon content and amount of carbon sequestered which is a critical component of soil health (Garcia et al., 2018). These factors have continuously impacted the world food production system and food security (Rhodes, 2014; Telo-da-Gama, 2023).

The Food and Agriculture Organization (2020) reported that according to the Intergovernmental Panel on Climate Change (IPCC) special report, increased soil organic carbon (SOC) has been identified as one of the most cost-effective options for climate change adaptation and mitigation, as well as combating desertification, land degradation and food insecurity. Given this, the adoption of soil management practices that reduce soil disturbance and increase the input and stabilization of organic matter is important (Karlen and Cambardella, 2020). One of such practices is the use of forest tree litter for the improvement of soil carbon stock and carbon sequestration through agroforestry (Udawatta et al., 2017).

The United States Department of Agriculture USDA (2016) recognized Agroforestry practices as important strategies to combat climate change by addressing methane emissions and greenhouse gas concentrations. The impact of tree litter on soil carbon stock and carbon sequestration is essential for enhancing soil fertility, mitigating climate change effects, and sustaining agricultural productivity (Kassa et al*.,* 2017). Shivangi et al*.,* (2024) reported that the organic matter components present in the soil, particularly the soil organic carbon is crucial for maintaining soil health and fertility. However, the specific mechanisms of how tree litter influences soil carbon stock and the sequestration potential of most indigenous tree species are not well understood. Hence, the study was conducted to determine the impact of tree canopy litter on selected soil properties to quantify the soil carbon stock and carbon sequestration rate per year in the study area comprising two rows of linearly planted *Vachellia nilotica* and *Azadiracta indica* in order to know the best tree litter with higher sequestration potential.

**MATERIALS AND METHODS**

**Study Area**

The study was conducted on farmers’ farms near the Usmanu Danfodiyo University Sokoto gate (Biliya Sanda Gate) with coordinates of 13o6'N and 5o12'E in Wamakko Local Government Area of Sokoto State. Sokoto is located in the Sudan Savanna Ecological zone of Nigeria on Latitudes 11° 30’N and 14°00’N, Longitudes 4°00’E and 6° 40’ E and altitude 351 m ASL (SERC, 2015). The seasons vary year to year in terms of duration and also intensity, the duration of wet season is about three to five months which may start from May/June to August/September with maximum rainfall recorded in July and August, which is around 600-700 mm; significant plant growth takes place during this period, while the vegetation consisting of scattered, short trees and shrubs, with dominant green cover (Tsoho and Salau, 2012). The relative humidity ranges from 21 - 47 % in the dry season and 51-79 % during the rainy seasons and the minimum and maximum temperature of the area is 15 °C and 40 °C respectively (Musa et al., 2012). **Treatments and Experimental Design**

The experiment involved three treatments (*Vachellia nilotica*: *V. nilotica*; *Azadirachta indica*: *A. indica* and an open area; OA) blocked four times and were arranged in a Randomized Complete Block Design (RCBD). Measurements of all parameters were done at 0-15 cm (surface) and 15-30 cm (subsurface) soil depths.

**Soil Sample Collection and Preparation**

A half hectare (ha) of quadrat land containing well-developed *V. nilotica* and *A. indica* trees and an adjacent open area was selected for the study. A simple random sampling technique was used in soil sample collection, and samples were collected at 0–15 cm and 15–30 cm soil depths. Soil samples were collected randomly from four different locations within each treatment for all blocks and were thoroughly mixed to get composite samples. The composite samples were then air dried, crushed, sieved through a 2 mm sieve, and kept for analysis.

**Determination of Soil Parameters**

The particle size distribution was determined using the Bouyoucos hydrometer method as described by Gee and Bauder (1986). The values obtained were interpreted using the USDA textural triangle to determine the soil textural class.

Bulk density (BD) was determined using the core method as described by Blake and Hartge (1986). It involves taking undisturbed core samples, oven drying them at 105 °C to achieve constant weight and the mass of the oven dried soil was recorded as Md. The volume of core sampler is presented as VC and the Bulk density (BD) in g/cm³ was calculated using the formula: $Bulk density (g/cm³) = \frac{Md}{VC}$

Where: Md = Mass of oven dried soil (g); VC = Volume of core sampler $(π$r2h = cm3)

The soil pH was determined in 1:1 soil-water ratio using pH meter, following the method described by Page et al*.* (1982).

Soil organic carbon (OC) content of the treatments’ was determined using the wet oxidation method as described by Walkey and Black (1934).

**Soil carbon stock and soil carbon sequestration**

The soil organic carbon stock in each treatment and depth was estimated using the equation below as described by Han et al. (2018):

 $SOC stock (t C ha^{-1}) =SOC ×BD ×H ×0.1$;

Where: SOC = Soil Organic carbon content (g kg-1); BD = Bulk Density of soil (g cm-³); H = Depth of sampling/soil thickness (cm); 0.1 = A constant value to adjust the units.

Amounts of carbon sequestered in the soil for each treatment were estimated based on the soil carbon stock determined. Carbon sequestration rate per year was estimated as a difference in carbon stock between the initial soil carbon stock estimated in the same location in August, 2023 and the carbon stock that was estimated in August, 2024, as described by West and Post (2002) and Pramono et al. (2017).

Mathematically represented as:

 $CSEQ (t C ha yr) = \frac{[Final SOC stock (t C ha yr) -Initial SOC stock (t C ha yr)]}{ t (yr)}$

Where: CSEQ (t C ha yr) = Carbon sequestration rate; Final SOC stock (t C ha-1) = Final soil organic carbon stock in 2024 (for each treatments); Initial SOC stock (t C ha-1) = Initial soil organic carbon stock in 2023 (for each treatments); T (yr) = Time (1 year).

Both soil carbon stocks and carbon sequestration were evaluated at the depth of 0-30 cm.

**Data Analysis**

Data obtained were subjected to Analysis of Variance (ANOVA) using Statistix 10.0 analytical software at 5% level of probability and the means were separated using the Least Significant Difference (LSD) test where applicable.

**RESULTS**

**Influence of Tree Canopy Litter on Soil pH**

Soil pH as influence by tree canopies is presented in Table 1. The result shows that the effect of tree canopy litter on soil pH show significant (p≤0.05) difference at surface soil depth and shows no significant (p>0.05) difference in the subsurface soil depth. However, in the surface and subsurface depth, the open area, recorded the highest pH, while *Azadirachta indica* and *Vachellia nilotica* had the least pH values.

Table 1: Influence of tree canopy litter on pH, bulk density and organic carbon (OC) at 0-15 and 15-30 cm soil depths

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Treatments | pH | BD (g/cm3) | OC (g/kg) | pH | BD (g/cm3) | OC (g/kg) |
|   |   | 0 - 15cm |   |   | 15 - 30cm |   |
| AN | 6.29b | 1.14c | 15.05a | 6.32 | 1.19c | 11.35a |
| AI | 6.23b | 1.39b | 16.43a | 6.30 | 1.40b | 11.45a |
| OA | 6.42a | 1.61a | 3.85b | 6.42 | 1.65a | 3.80b |
| SE C:\Users\Shuaib\AppData\Local\Microsoft\Windows\Clipboard\HistoryData\{9CDC7694-23A7-413D-9E86-29420772A85A}\{FA794401-FA37-4175-991D-C60FEEB35BC6}\ResourceMap\{C33DE6D9-29C5-460C-B103-A1BF25BA083C} | 0.048 | 0.038 | 2.011 | 0.053 | 0.048 | 0.595 |
| LS | \*\* | \*\*\* | \*\*\* | Ns | \*\*\* | \*\*\* |

Means followed by the same letter (s) in the same column are not significant at p≤ 0.05 using LSD. ns- no significant OA- open area, AI- *Azadirachta indica*, AN- *Vachellia nilotica*, SE- standard error, LS- level of significance, \*- significant at p≤0.05, \*\*- significant at p≤0.01, \*\*\*- significant at p≤0.001

**Influence of Tree Canopy Litter on Bulk Density of Soil**

The effect of tree canopy litter on bulk density of the soil is presented in Table 1. The result shows that treatment effects were significant (p≤0.05) in both surface and subsurface soil depths. The open area recorded significantly higher bulk density than under the tree canopy treatments (*Azadirachta indica* and *Vachellia nilotica*) and bulk density values increased with soil depth in this study.

**Influence of Tree Canopy Litter on Organic Carbon (OC) Contents of the Soil**

The effect of tree canopy litter on organic carbon (OC) contents of the soil is presented in Table 1. The result shows that treatment effects were significant (p≤0.05) in both the surface (0–15) and the subsurface (15–30) soil depths in the two years. *Azadirachta indica* and *Vachellia nilotica* tree canopy treatments had significantly higher OC than open cultivated land across the two soil depths of the study area

**Influence of Tree Canopy on Soil Carbon Stock and Carbon Sequestration**

The effect of tree canopy litter on soil carbon stock and carbon sequestration is presented in Table 2. The result shows that treatment effects were significant at 0–30 cm soil depth. *Azadirachta indica* and *Vachellia nilotica* tree canopy treatments had significantly higher soil carbon stock than open cultivated land in the initial assessment (2023) and the final (2024) assessment. Even though both under tree treatments had higher soil carbon stock than the open area in the two years, *Azadirachta indica* recorded a higher value than the *Vachellia nilotica* in the two years, and the difference was significantly higher in 2024.

**Table 2: Influence of tree canopy litter on soil carbon stock, and carbon sequestration at 0 - 30 cm soil depth**

|  |  |  |  |
| --- | --- | --- | --- |
| Treatments | F-SCS(t C ha-1) | I-SCS (t C ha-1) | CSEQ (t C ha-1 yr-1) |
| C:\Users\Shuaib\AppData\Local\Microsoft\Windows\Clipboard\HistoryData\{9CDC7694-23A7-413D-9E86-29420772A85A}\{1DA622D1-8131-4244-BA1F-2D431655EEA6}\ResourceMap\{86F5A422-1D90-4747-BFE0-6504B09A5846}0 – 30 cm C:\Users\Shuaib\AppData\Local\Microsoft\Windows\Clipboard\HistoryData\{9CDC7694-23A7-413D-9E86-29420772A85A}\{1DA622D1-8131-4244-BA1F-2D431655EEA6}\ResourceMap\{E776096C-FF32-4E8F-B03F-7204C4924001} |
| VN | 46.00b | 25.81a | 20.19a |
| AI | 58.31a | 29.01a | 29.03a |
| OA | 18.70c | 7.59b | 11.10b |
| SE C:\Users\Shuaib\AppData\Local\Microsoft\Windows\Clipboard\HistoryData\{9CDC7694-23A7-413D-9E86-29420772A85A}\{1DA622D1-8131-4244-BA1F-2D431655EEA6}\ResourceMap\{A2F53DCF-7E9F-49DB-9829-9EDEA07F712B} | 4.4448 | 1.7439 | 3.8142 |
| LS | \*\*\* | \*\*\* | \*\* |

OA- open area, AI- *Azadirachta indica*, VN- *Vachellia nilotica*, SE- standard error, LS- level of significance, \*- significant at p≤0.05, \*\*- significant at p≤0.01, \*\*\*- significant at p≤0.001; Means having the same superscript alphabets are not significantly different from one another.

**DISCUSSION**

The surface and sub-surface soil pH for the two years are slightly acidic based on Esu (1991) soil pH rating.The decreased pH under tree canopy (*Azadirachta indica:*(AI) and *Vachellia nilotica*: (VN) could be linked to increased organic carbon as shown in the Table 1, which can result in higher organic matter which upon decomposition produces acids that lowers the soil pH (Sarwar et al*.*, 2008). Nevertheless, the pH values observed in this study irrespective of treatments tested are within the range of 5.5-7.0 which is considered good for agricultural crop production according to Landon (1991). Additionally, the results are in line with the findings of Kumar and Singh (2019).The result obtained for the bulk density of the soil could be due to the effect of the tree canopy litter accumulation under tree canopies resulting in decreased soil bulk density. The results corroborated with Zeng et al*.* (2014), who reported that bulk density of the soil decreased in afforested area treatments. Similarly, the primary source of organic carbon (OC) in soils is plant residues and in a mineral matrix, their inputs undergo partial transformation into soil organic matter (SOM) through microbial decomposition (Xu et al., 2022); soil bulk density decreases with an increase in organic matter (Keller and Håkansson, 2009; Chaudhari et al., 2013). The significant differences observed between open areas and under-tree treatments can be attributed to the physical and biological interactions facilitated by tree canopies. Canopy cover helps to reduce soil erosion and enhances moisture retention. Soil moisture contributes to lower bulk density (Enkova and Urík 2012); this agrees with Kokilia et al*.* (2024), who reported that soils beneath tree canopies had higher moisture levels due to reduced evaporation and improved soil structure from accumulated litter. The slightly higher value of bulk density recorded in subsurface is an evidence that bulk density tends to increase with depth in the soil profile and this result align with Hosea et al. (2018). For the soil organic carbon, the values of the organic carbon obtained (11.35-16.43 g/kg) in the under tree treatments in both surface and sub-surface is between medium to high based on Esu (1991) rating while that of open cultivated area in both surface (3.80 and 3.85 g/kg) is classified as low (<10 g/kg) based on Esu (1991). The relationship between tree canopy litter and soil organic carbon (OC) contents is critical for understanding ecosystem health and functionality. The findings indicate that tree canopy treatments, specifically from *Azadirachta indica* and *Vachellia nilotica,* significantly enhance OC levels compared to open cultivated land across both surface (0-15 cm) and subsurface (15-30 cm) soil depths. This observation aligns with various studies that have explored the influence of tree canopy on soil properties. Bhardwaj et al. (2022) highlighted that litter fall from different tree species, including *Azadirachta indica*, contributes significantly to improvement of soil organic carbon level as well as microbial biomass carbon compared to open area without tree canopy. The accumulation of leaf litter under tree canopies also enhances microbial activity (Kara et al., 2008). Microbial population and activity contribute to the carbon pool in the soil (Lange et al., 2015; Liang et al., 2017). Moreover, studies have shown that areas beneath tree canopies exhibit higher OC concentrations than those in open fields. Pardon et al. (2017) and Adekiya et al. (2023) revealed that the establishment of trees increased litter inputs and subsequently enhanced soil carbon stock. The impact of different canopy types on soil properties further supports these findings. *Vachellia nilotica* has been reported to significantly improve soil organic carbon (Arora and Chaudhry, 2017). The results are also in with the findings of Pandey et al. (2022) that *Azadirachta indica* litter has a significant effect on increasing soil organic carbon contents. This finding further supports the position of Chen et al*.* (2016) thatintegrating agroforestry practices could leverage the benefits of tree canopies to improve soil health. The results also indicated an increase in soil organic carbon stock in the final year, and the resulting increase indicated that the carbon content in the soil increased over the one-year period and thus enhanced the carbon sequestration potential. The increase in soil organic carbon over the one-year period indicates a positive trend in carbon accumulation, which aligns with previous studies of Gupta et al. (2014) and Wang et al. (2022). Increases in soil carbon stock indicate positive carbon sequestration (Sleutel et al., 2003; Friggens et al., 2020; Feng et al., 2023). The findings reveal significant potentials for carbon sequestration due to tree canopy effects. The result indicates that both tree species have a notable capacity to enhance soil carbon stock compared to open cultivated land. The comparative analysis shows that *Azadirachta indica* consistently exhibits higher carbon sequestration rates than *Vachellia nilotica*. This trend is supported by existing literature that emphasizes the superior biomass production and litter quality of *Azadirachta indica*, which contributes to more significant organic matter accumulation in the soil. Nooret al*.* (2016) highlighted that *Azadirachta indica* can sequester substantial amounts of carbon. The result indicated that *Azadirachta indica* have sequestration potential of 29.30 t C ha-1 yr-1 of carbon and the soil carbon stock range from 29.01 – 58.31 t C ha-1 of carbon in the previous and final year respectively. This result is closer to the findings of Mohamed et al. (2020) that neem plantation of 10 years old showed a carbon sequestration potential of 49.78 t C ha-1 in the below ground biomass. This capacity is crucial for enhancing soil fertility and promoting sustainable agricultural production. In contrast, while *Vachellia nilotica* also contributes positively to soil carbon stock, its performance is generally lower than that of *Azadirachta indica* in this study. The result indicated that *V. nilotica* treatments sequesteration potential of 20.19 t C ha-1 yr-1 and the soil carbon stock range from 46.00 – 25.81 t C ha-1 of carbon in the previous and final year respectively, the result is similar to that of Yasin et al. (2020) in that, the amount of soil carbon sequestration rate tended to be lower with depth but increased with tree age and that ecosystem carbon stock (soil+plant) in space of two years is about from 37.23 t ha-1. *V. nilotica* can sequester a significant amount of soil carbon per year (Arora and Chaudhry, 2017; Devi et al., 2021). The differences in sequestration potential between these two species may be attributed to their growth characteristics and the nature of their litter. Litter from *Azadirachta indica* tends to decompose more slowly (Devender et al., 2022); this can result in a more stable form of organic matter that enhances long-term carbon storage. This distinction can also be attributed to differences in biomass production, litter quality, and decomposition rates, with *A. indica* producing more stable organic matter conducive to long-term carbon storage. Such findings provide new insights into species-specific contributions to soil carbon dynamics, advancing agroforestry practices for sustainable soil management. The implications of this study extend beyond local ecosystems, offering valuable insights into global carbon sequestration strategies, similar studies in dry Afromontane forests (Desa’a forest, Ethiopia) have highlighted the influence of canopy cover on SOC stocks (92.89 Mg ha) across various pools, including aboveground biomass and litter carbon. This comparison demonstrates the universal importance of tree canopy in mitigating climate change through enhanced carbon storage. The findings also align with research on old-growth forest canopies in Costa Rica, where treetop soils store three times more carbon than ground soils. Such studies emphasize the untapped potential of canopy-driven carbon sinks globally. Likewise, the observed increase in SOC stocks over one year suggests a positive trend in carbon accumulation, consistent with Sleutel et al. (2003) and Friggens et al. (2020). These results reinforce the role of agroforestry systems in achieving Sustainable Development Goals related to climate action (SDG13) and sustainable land use (SDG15).

**CONCLUSION**

This study provides compelling evidence that integrating tree canopy systems into land management practices can significantly enhance SOC stocks and carbon sequestration potential. It offers actionable insights for agroforestry development aimed at combating climate change and promoting sustainable agriculture globally. From the results obtained, it can be concluded that *Vachellia nilotica* and *Azadirachta indica* tree canopy litter significantly improved soil properties and increased soil carbon stock and soil carbon sequestration than the open cultivated areas. Also, the *Azadirachta indica* tree canopy litter offers best carbon sequestration potential. Thus, the utilization of *Vachellia* niloticaand *Azadirachta indica* in agroforestry systems in semi-arid regions should be promoted as they enhance carbon accumulation in the soil which improves soil organic carbon. Likewise, the impact of *Valanites aegyptiaca* and *Faidherbia albida* which are commonly encountered tree species around the area on soil characteristics and carbon sequestration should be explored.

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**APPENDIX**

Appendix I: Textural composition of the soil

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Treatments | Sand (%) | Silt (%) | Clay( % ) | Sand (%) | Silt (%) | Clay( % ) |
|  | 0-15 cm | 15-30 cm |
| OA | 91.36 | 5.91 | 2.73 | 90.40 | 3.91 | 5.69 |
| AI | 92.34 | 6.33 | 1.33 | 92.35 | 3.92 | 3.73 |
| VN | 90.87 | 4.42 | 4.71 | 86.97 | 6.36 | 6.67 |

OA- Open area, AI- *Azadirachtaindica*, VN- *Vachellia nilotica* Textural class- sandy soil