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# Using Urea Intercalated Biochar and Organic Fertilizer as Soil Management Option Part 2: Its interactive Effects with Soil Moisture and Compaction on Soil Properties and Carbon Emission

*Tijani, F. O., Adewumi, T. M., Abdulraman, O. A., Oyebola, O. K., Adebayo, A. A., Amosun, E. O., and Oyedele, D. J.

*Department of Soil Science and Land Resources Management, Obafemi Awolowo University, Ile-Ife, Nigeria*

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Corresponding Author's E-mail Address:

email: **daptij@yahoo.com**

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**ABSTRACT**

Soil response including carbon dioxide emission under the combination of compaction, fertilizer and soil moisture were investigated in a screenhouse. The factorial experiment consisted of two levels of moisture contents (50% and 70% field capacity, FC), three levels of compaction (0, 2 and 4 kg weights) and fertilizer treatments consisted of control, biochar, organic fertilizer + urea (FertC), urea intercalated biochar + organic fertilizer (FertD). Carbon dioxide ($C0_2$) evolution was determined using static chamber approach. Saturated hydraulic conductivity ($K_{sat}$), unsaturated hydraulic conductivity at 2 cm suction ($K_{2cm}$), bulk density, total porosity, soil mean weight diameter, geometric weight diameter and organic carbon were determined using standard methods and the data was subjected to analysis of variance at 5% probability level. FertC in soil compacted under 2 kg and at 50% FC significantly enhanced (P<0.05) $K_{2cm}$ (3.87 x $10^{-4}$ m/s) in the sandy loam soil while the least was observed in the uncompacted soil amended with FertD. Biochar in uncompacted soil significantly increased (P<0.05) $K_{sat}$ (2.77 x $10^{-3}$ m/s) while the two biochar-based amendments increased porosity (46.30 - 48.03%) and improved bulk density (1.32 - 1.33 g/cm$^3$). Furthermore, FertD plus uncompacted soil kept between 50% - 70% field capacity significantly increased $CO_2$ emission (21.68 g/m$^2$/day) and this decreased as soil was compacted under 4 kg load. Organic carbon was highest in soil compacted at 2 kg but soil aggregates were unaffected by the combinations of the treatments. Thus, combinations of the treatments impact soil differently which can be explored further on the field depending on soil management focus.

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## 1.0 Introduction

Achieving sustainable land use involves the deployment of adequate soil management techniques to maintain and/or improve diverse soil properties. Soil hydraulic conductivity is a soil property that describes the ease of movement of liquid, often water, through soil pores. It depends on the intrinsic attributes of the soil matrix and the properties of the liquid moving through it. Hydraulic conductivity is essential in agriculture, construction industries (e.g. water distribution in embankment; Chen *et al*. 2016 etc.) and in maintenance of healthy environment. Hydraulic conductivity and infiltrability are affected by texture or particle size distribution. For instance, the sand content influences saturated hydraulic conductivity (Ks). Soil organic carbon (SOC) also affects Ks through its influence on soil structure (Falk et al., 2024). In coarse soils in particular, Ks is affected by compaction, often indexed by high soil bulk density, and fine (silt and clay) content (Chen *et al*., 2016), and any process leading to compaction or accumulation of fine materials such as tillage and slope, respectively (Singh *et al*., 2023, Woldeyohannis, *et al*., 2024). Despite all its demerits, compaction is advantageous in improving the root environments for anchorage against rainy and windy settings (Woldeyohannis, *et al*., 2024) and therefore deserves a serious consideration in scientific investigation. Generally, hydraulic conductivity decreases as suction increases but may be relatively higher in soils with higher concentration of narrow pores under unsaturated conditions. In addition to suction, unsaturated hydraulic conductivity (Kh) depends on soil water content and pore system (Gallage *et al*., 2024), a component of soil structure, that has been linked to SOC. The dynamics of SOC yield mixed results in response to water input or irrigation (Kochsiek *et al*. 2009; Zhou *et al*., 2016; Dal Ferro *et al*., 2023) underscoring the importance of moisture management in this study. Apart from management techniques, Talukder *et al*. (2023) also noted measurement scales as one of the determinant factors in the spatio-temporal dynamics of soil hydraulic properties. Soil amendments that include inorganic fertilizer, manure, biochar etc. are invaluable materials in the improvement of soil productivity. Inorganic fertilizer represents a quick source of nutrients to soil solution for plant uptake while organic amendments not only improve the soil nutrient and chemical status, they also enhance soil physical and biological properties. Biochar is produced from the thermochemical processing of biomass in the absence or limited supply of oxygen (Lehmann and Joseph, 2009, Lehmann *et al*. 2011). Its intercalation with urea occurs when biochar is added to a heated urea solution in the presence of adhesive polymer and the resulting compound is oven-dried (Manikandan and Subramanian, 2013). Biochar has been found to improve bulk density, fertility, soil hydraulic properties such as field moisture capacity or field capacity (FMC or FC), permanent wilting point and crop yields (Jeffery *et al*. 2011; Razzaghi et al. 2020). The effectiveness of biochar depends on both soil and biochar properties (Edeh and Buss, 2020). Increase in soil moisture content leads to reduction in soil strength, establishing the consideration for moisture content in compaction study. Soil compaction associated with soil bulk density in the region of 1.7 g/cm$^3$, reduced root length whereas moisture content at 70% FC improved root length over soil at 100% FC in sandy soil and sandy clay loam soil (Yu *et al*. 2024). Soil properties respond to soil compaction differently (Romero-Ruiz *et al*., 2023). Increase in compaction mainly affect large or macropores (Feng *et al*. 2023) which collapse to smaller pores and consequently leads to alteration in soil pore distribution. Addition of manure, plant residue and biochar enhance SOC (Dal Ferro *et al*. 2012) which in turn also improves soil bulk density and porosity (Johannes *et al*., 2017). Increase in SOC in soils can increase soil porosity and permeability but decrease soil density and compaction strength (Ojo *et al*., 2022). Various investigations have revealed two-way benefits between soil aggregates and SOC (Six and Paustian, 2014, Dal Ferro *et al*., 2023). Soil aggregates get formed and cemented by SOC while the aggregate formed also protect SOC from decomposition. Mean weight diameter, water stable aggregates etc. are indicators of aggregation (Abad *et al*. 2023) and are used as aggregation metrics in many studies; aggregation being a key component of soil structure which is an essential soil quality indicator.

Protection of carbon dioxide in the soil and adequate transport of gases, especially oxygen in and out of soil are essential soil quality concern with respect to agricultural production and ecosystem services. Diffusivity and advective gas transport in soil are affected by properties of the migrating gas, soil pore characteristics, moisture content or air-filled porosity and texture. The pore characteristics or space geometry is influenced by texture and compaction (van Verseveld and Gebert, 2020). Soil air-filled porosity and diffusivity are also influenced by application of organic amendments. For instance, it has been found to increase with the addition of fir-wood biochar (Yi *et al*., 2024)

Verseveld and Gebert (2020) observed that air-filled porosity that played important role in gas permeability in soil vary among soils and can even vary in the same soil in response to different combinations of compaction and moisture. For instance, compaction play a more significant role than moisture in loamy sand soil and coarser soils but may be reversed in fine textured soils such as silty or clayey soils with pores that are already small and therefore permeability may be less dependent on compaction compared to soil moisture. High frequency monitoring of soil properties shortly after compaction and under different climate condition can be valuable to predicting soil quality indices especially, soil structure recovery among others (Romero-Ruiz, *et al*., 2023). There are divergent observations in the response of some soil properties to tillage, a compaction inducing farm operation. For instance, Villarreal *et al*. (2020) observed that intensive tillage had higher hydraulic conductivity and effective macropores compared with no tillage whereas Singh *et al*. (2023) rated zero tillage to be better in not only hydrophysical properties including near saturated hydraulic conductivity (1 cm and 3 cm suctions) but also in aggregate mean weight diameter and SOC, necessitating the need for site and soil specific studies. Thus, this study targets the effects of the application of biochar intercalated with urea and organic fertilizer, particularly their interactions with moisture and compaction on some soil properties, and associated carbon dioxide emission at different time scales.

## 2.0. Materials and Methods

### *2.1. Study site*

The soil used for the experiment was sampled from the Fertility Section of the Obafemi Awolowo University Teaching and Research Farm and the experiment was conducted in the screenhouse; both within the University's estate which is located in the Southwestern Nigeria between Latitudes 7° 31' 308'' N and 7° 33'267'' N and Longitudes 4° 33'466'' E and 4° 34'446'' E with an altitude of about 244 m above mean sea level. The annual precipitation is between 1200 mm and 1500 mm while the maximum daily temperature is between 27°C and 35°C and the minimum is in the range of 18.9°C and 23.3°C. The soil was derived from coarse granite and gneiss (Okusami and Oyediran, 1985); an Ultisol, that is locally classified as Iwo Series (Smyth and Montgomery, 1962). It is classified as Typic Isohyperthermic Paleustults (USDA system) or Chromic Lixisol (FAO/UNESCO system) (Ojetade *et al*., 2021).

### 2.2. *Screen house experiment*

The experiment, described in more details in Tijani *et al*. (2023), was a 2 x 3 x 4 factorial experiment involving two (2) levels of moisture contents, three (3) levels of compaction and four (4) different rates of fertilizer-related amendments, giving a total of 24 treatments combinations laid out in a Completely Randomized Design and replicated three (3) times. The fertilizer treatments consisted of Control, Biochar (10 tons/ha), Organic Fertilizer 5 ton/ha + Urea 40 kg/ha, and urea (40 kg/ha) intercalated Biochar (10 ton/ha) + organic fertilizer (5 ton/ha) (See Tijani *et al*. (2023) for more details). The soils in the containers were kept at different moisture levels (50% and 70% field moisture capacity) an approach also used by Yu *et al*. (2024) and compacted under 0 kg, 2 kg and 4 kg weights. The highest weight is close to the weight used by van Verseveld and Gebert, (2020) who used weights of 4.936 kg which in their case they allowed to fall multiple times on a base plate consisting the column containing the soil, until the soil reached a desired height within the column.

**2.3. Soil physical and chemical analyses**

The unsaturated hydraulic conductivity at 2 cm suction ($K_{2cm}$) and carbon dioxide emission were monitored daily while the measurements of bulk density, porosity, aggregate assessment (mean weight diameter, MWD, and geometric mean diameter, GMD), saturated hydraulic conductivity ($K_{sat}$) and organic carbon (OC) was conducted at the end of the experiment (six weeks).

Particle size distribution of the soils was determined using the hydrometer method (Gee and Or, 2002), bulk density by the core method, total porosity as water content at saturation (Flint and Flint, 2002), $K_{sat}$ by the modified permeameter method (Klute and Dirksen, 1986 and van Verseveld and Gebert, 2020), and $K_{2cm}$ by the disc infiltrometer technique. The mean weight diameter (MWD) and geometric mean diameter (GMD) were then determined according to Kemper and Rosenau (1986). Soil organic Carbon was determined by chromic acid digestion method (Nelson and Sommers, 1996). Carbon dioxide emission from the soil was measured using the static chamber method.

***2.4. Data analyses***

Data were subjected to analysis of variance (ANOVA) and treatment means were compared using least significant difference at 5% level of probability using the Statistical Analysis System software (9.0)

**3.0. Results and Discussion**

*3.1. Soil properties*

The soil properties before imposing treatments showed that the soil was sandy loam in texture, the bulk density was 1.4 g/cc and the organic matter content was 1.52%. More information can be found in the companion paper (Tijani *et al*. 2023) while only statistically significant ($P<0.05$) data are presented and discussed in the sub-sections below.

*3.2. Unsaturated hydraulic conductivity of soil subjected to varying moisture, compaction and their interactions with fertilizers*

It can be seen in Table 1 and 2 that soil moisture and compaction, when considered alone, had limited impact on hydraulic conductivity at 2 cm suction ($K_{2cm}$). This is in line with Singh *et al*. (2023) who also did not observe significant difference in near hydraulic conductivity (3 cm suction) under conventional tillage, with potential to compact the soil, across all slopes and at 10 cm suction between intensive and no tilled soil under irrigated crop sequences (Talukder *et al*. 2023). Soil moisture at 50% field capacity (FC) only increased unsaturated hydraulic conductivity compared with when it was at 70% FC on the second day of the experiment. It was not until the fifth day of the experiment that soil compacted under 2 kg load increased in unsaturated hydraulic conductivity more than the soil compacted under 4 kg load. However, the rate of water flow at 2 cm suction for a soil compacted under 2 kg load was not different from soil that was not subjected to any compaction. The minimal influence of compaction on hydraulic conductivity may be down to minor increase (1.4 – 2.1%) in bulk density due to the load used in this study. Limited impact of compaction on hydraulic conductivity when the bulk density increase was not more than 20% has been reported on a non-homogenous field soil from Loess Plateau (Zhang *et al*., 2006).

Table 3 highlights days in which interaction effects on $K_{2cm}$ was significant when combined effects of compaction (soil under load) and moisture were considered. It was significantly highest ($P<0.05$) in experimental day 3 when 2 kg load interacted with 50% FC ($2.39 \times 10^{-4}$ m/s) and when 4 kg load was imposed at 75% FC ($2.40 \times 10^{-4}$ m/s). Similarly, on the sixth day, combination of compaction due to 4 kg load and moisture content at 75% FC gave the highest $K_{2cm}$ ($2.49 \times 10^{-4}$ m/s). On day 9, the highest water movement occurred in soil under 2 kg load with 75% FC ($2.19 \times 10^{-4}$ m/s). The final significant interaction was on the 18th day of the experiment when soil without load and at 75% FC recorded the fastest water transport ($2.28 \times 10^{-4}$ m/s) followed by soil compacted under 2 kg load and at 50% FC ($2.19 \times 10^{-4}$ m/s) and soil under 4 kg load and at 75% FC ($2.16 \times 10^{-4}$ m/s). Generally, soils subjected to higher load and are moister predominantly conducted water faster than others while the soils tend to have higher $K_{2cm}$ in earlier days of the experiment than afterward. This may be down to the fact that under unsaturated soil condition or drier soil, there is a clear drop in unsaturated hydraulic conductivity in the coarse pore range (Beck-Broichsitter *et al*. 2020) and coarse to medium pore are unable to transport water (Alaoui, *et al*., 2011; Beck-Broichsitter *et al*. 2020) and therefore narrower pores are expected to conduct moisture faster than soil with larger pores (Chen *et al*., 2016, Yu *et al*., 2024). Soils with larger pores are known to conduct water faster and have substantial contribution to soil water flow under saturated condition.

The results on soil $K_{2cm}$ due to the interaction of compaction and fertilizer treatments can be seen in Table 4. It was only significant on the second day of the experiment indicating that the interaction effects were less pronounced on $K_{2cm}$. The highest soil water

Table 1: Soil unsaturated hydraulic conductivity under varied moisture content at daily time scale

| MOISTURE | K-D1 | K-D2 | K-D3 | K-D4 | K-D5 | K-D6 | K-D7 | K-D8 | K-D9 | K-D10 | K-D11 | K-D12 | K-D13 | K-D14 | K-D15 | K-D16 | K-D17 | K-D18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ← | | | | | | | x10$^{-4}$ (m/s) | | | | | | | | | | → |
| 1 | 1.35 | 2.06 | 1.96 | 1.74 | 1.76 | 1.82 | 2.71 | 1.65 | 1.73 | 1.68 | 1.69 | 2.00 | 2.00 | 1.26 | 2.07 | 0.97 | 1.55 | 1.81 |
| 2 | 1.44 | 1.73 | 1.78 | 1.85 | 2.10 | 1.83 | 2.23 | 1.60 | 1.83 | 1.61 | 2.06 | 1.65 | 1.65 | 1.42 | 1.86 | 1.14 | 1.39 | 1.94 |
| LSD | NS | 0.29 | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |

1 – 50% field capacity; 2 - 70% field capacity; K-$D_x$ = K is soil hydraulic conductivity at 2 cm suction while D represents days of sample where x is from day 1 to 18.

Table 2: Unsaturated hydraulic conductivity of soil under different compaction at daily time scale

| COMPACTION (kg) | K-D1 | K-D2 | K-D3 | K-D4 | K-D5 | K-D6 | K-D7 | K-D8 | K-D9 | K-D10 | K-D11 | K-D12 | K-D13 | K-D14 | K-D15 | K-D16 | K-D17 | K-D18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ← | | | | | | | x10$^{-4}$ (m/s) | | | | | | | | | | → |
| 0 | 1.52 | 1.90 | 1.69 | 1.63 | 1.76 | 1.70 | 2.34 | 1.57 | 1.93 | 1.76 | 1.94 | 1.53 | 1.53 | 1.46 | 2.02 | 1.03 | 1.36 | 1.91 |
| 2 | 1.31 | 2.04 | 1.90 | 1.73 | 2.53 | 1.72 | 2.57 | 1.67 | 1.79 | 1.52 | 1.88 | 1.92 | 1.92 | 1.31 | 1.82 | 0.95 | 1.53 | 1.80 |
| 4 | 1.35 | 1.75 | 2.02 | 2.38 | 1.48 | 2.06 | 2.49 | 1.64 | 1.63 | 1.66 | 1.81 | 2.03 | 2.03 | 1.25 | 2.05 | 1.18 | 1.52 | 1.93 |
| LSD | NS | NS | NS | NS | 1.00 | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |

K-$D_x$ = K is soil hydraulic conductivity at 2 cm suction while D represents days of sample where x is from day 1 to 18.

movement at 2 cm suction (3.10 x $10^{-4}$ m/s) occurred when organic fertilizer plus urea were added without any compaction and was followed by soil water flowing ($K_{2cm}$) at 2.92 x $10^{-4}$ m/s using the same fertilizer treatment when soil was compacted at relatively lower load (2 kg). The least $K_{2cm}$ (1.47 x $10^{-4}$ m/s) was observed when an uncompacted soil was amended with urea intercalated biochar, although the value (2.00 x $10^{-4}$ m/s) increased by 36% when the fertilizer was interacted with 2 kg load. The only occurrence of significant $K_{2cm}$ on the second day in an uncompacted soil amended with organic fertilizer plus urea, may be down to early microbial interaction on the non-recalcitrant organic materials used and the physical nature of the organic component that may both narrow the pore and yet allow water passage through 'ceramic effect' described by Kuncoro *et al*. (2014). The study further corroborated the work of Kuncoro *et al*. (2014) who reported that there was variation in hydraulic conductivity under different amendments with some not showing any difference from the control. Reduction in unsaturated hydraulic conductivity in soil amended with Redwood sawdust and wheat straw biochar, near soil saturation state, has also been observed by O'Keeffe *et al*. (2023). Concentration and increase in water flow in narrow pore, in moist unsaturated soil condition was evident in pots showing increment in flow under compacting load. This is further supported in pots in which no amendment was applied where $K_{2cm}$ increased from 1.53 x $10^{-4}$ m/s under no load to 2.07 x $10^{-4}$ m/s, a 35% increase, when 4 kg load was applied.

*3.0.* The significant interactive effects of compaction with fertilizer and moisture on soil $K_{2cm}$ occurred on 2nd and 4th days of the experiment and these were presented in Tables 5 and 6, respectively. On the second day of the experiment, soil compacted under 2 kg, at 50% FC and amended with urea plus organic fertilizer resulted in the highest $K_{2cm}$ (3.87 x $10^{-4}$ m/s) which was closely followed by uncompacted soil under the same moisture and organic amendment as the previous (3.73 x $10^{-4}$ m/s). The highest $K_{2cm}$ (2.57 x $10^{-4}$ m/s) in soil amended with urea intercalated biochar was observed for soil compacted under 2 kg load and 70% FC. The least values of $K_{2cm}$ occurred when soil at 70% FC was compacted under 4 kg and urea intercalated biochar fertilizer was added (1.17 x $10^{-4}$ m/s) and when soil with same moisture (70% FC) under 2 kg load was treated with biochar alone (1.27 x $10^{-4}$ m/s). It is apparent that soil moisture content and amendment type moderates soil water movement in soil pores under unsaturated condition particularly, early into application of soil amendment. The effect of compaction on soil moisture movement is attenuated by these two factors, particularly the type of amendment used, as biochar-based fertilizers comparatively reduced soil water flow few days after application in unsaturated soil. It was when no amendment was added at 50% FC and under 4 kg load, that the highest $K_{2cm}$ (2.70 x $10^{-4}$ m/s) was recorded compared to its value when the soil was uncompacted (1.36 x $10^{-4}$ m/s) underscoring the influence of narrow pore in water transport in unsaturated soil or at higher suction (Chen *et al*., 2016). The $K_{2cm}$ on the fourth day of the experiment was in many ways similar to what obtained on day 2 with the highest moisture movement also seen in soil amended with urea plus organic fertilizer but compacted under 4 kg load and 70% FC. One of the least $K_{2cm}$ (1.17 x $10^{-4}$ m/s) was also observed in soil treated with urea intercalated biochar fertilizer in combination with compaction under 2 kg load and 50% FC. However, uncompacted soil treated with urea plus organic fertilizer and at 70% FC was the least (1.02 x $10^{-4}$ m/s). Soils without amendment but subjected to compaction and varied moisture status follow same trend observed on the second day of the experiment. This implies that as soil gets dryer and such soil is not mediated by soil organic or organo-mineral amendments, higher moisture flow at relatively narrower pores. It is in narrow pore that fluid connectivity or fluid-filled pore connectivity and degree of saturation are guaranteed; factors that control unsaturated hydraulic conductivity (Gallage, *et al*. 2013) *Carbon dioxide emissions under varying soil moisture, compaction and their interactions with fertilizers*

The main effects of moisture and compaction on carbon dioxide loss from soil were minimal as presented in Tables 7 and 8. The only significant ($P<0.05$) loss of the gas occurred on the 19th day when soil kept at 50% FC emitted more of the gas than when the soil was at 75% FC. Similarly, it was only on the 3rd day of the experiment that soil compacted under 2 kg load released significantly higher ($P<0.05$) carbon dioxide than soil compacted under 4 kg load but there was no difference across all the rates for the other experimental days.

However, the application of fertilizers coupled with compaction had significant ($P<0.05$) implication on carbon emission in the soil (Table 9). On the 2nd day of the experiment, application of biochar intercalated urea fertilizer on soil compacted under 2 kg load lost the highest carbon dioxide (13.31 g/$m^2$/day) followed by soil treated with biochar and also under 2 kg load (12.32 g/$m^2$/day). Another significant loss of carbon dioxide occurred on 18th day of the study. The significantly highest ($P<0.05$) loss of the gas (21.68 g/$m^2$/day) was from an uncompacted soil treated with biochar intercalated urea fertilizer followed by soil treated with biochar and compacted under 2 kg load (20.70 g/$m^2$/day). The final significant emission of carbon dioxide was on day 19. The highest ($P<0.05$) loss was from soil treated with urea plus organic fertilizer and under 4 kg load (16.26 g/$m^2$/day) followed by uncompacted soil treated with biochar intercalated urea fertilizer (16.02 g/$m^2$/day).

From the foregoing, biochar-based amendments dominated the loss particularly when the soil was uncompacted after application of fertilizers or amendments. Apart from increasing the soil air-filled porosity and gas diffusivity, Yi *et al*. (2024) observed that

Table 3: Interaction effects of moisture and compaction on unsaturated soil hydraulic conductivity

| Compaction (kg) | Moisture 1 | Moisture 2 | Moisture 1 | Moisture 2 | Moisture 1 | Moisture 2 | Moisture 1 | Moisture 2 |
|---|---|---|---|---|---|---|---|---|
| | KD3 X $10^{-4}$ (m/s) | | KD6 X $10^{-4}$ (m/s) | | KD9 X $10^{-4}$ (m/s) | | KD18 X $10^{-4}$ (m/s) | |
| 0 | 1.83 | 1.54 | 1.81 | 1.59 | 1.99 | 1.88 | 1.54 | 2.28 |
| 2 | 2.39 | 1.41 | 2.04 | 1.40 | 1.39 | 2.19 | 2.19 | 1.41 |
| 4 | 1.64 | 2.40 | 1.62 | 2.49 | 1.83 | 1.44 | 1.71 | 2.16 |

Moisture: 1 – 50% field capacity; 2 – 70% field capacity; KD3 – $K_{2cm}$ at day 3; KD6 – $K_{2cm}$ at day 6; KD9 – $K_{2cm}$ at day 9; $K_{2cm}$ at day 18 where $K_{2cm}$ represents unsaturated hydraulic conductivity at 2 cm suction.

Table 4: Effects of interaction of fertilizer and compaction on soil unsaturated hydraulic conductivity

| Compaction (kg) | Fertilizer A | Fertilizer B | Fertilizer C | Fertilizer D |
|---|---|---|---|---|
| | KD2 X $10^{-4}$ (m/s) | | | |
| 0 | 1.53 | 1.52 | 3.10 | 1.47 |
| 2 | 1.73 | 1.52 | 2.92 | 2.00 |
| 4 | 2.07 | 1.57 | 1.65 | 1.70 |

A-control; B-biochar only; C-organic fertilizer with urea; D-urea intercalated biochar plus organic fertilizer; KD2 – $K_{2cm}$ at day 2

Table 5: Interaction effects of fertilizer, moisture and compaction on soil unsaturated hydraulic conductivity at experimental day 2

| Compaction (kg) | A 50% FC | A 75% FC | B 50% FC | B 75% FC | C 50% FC | C 75% FC | D 50% FC | D 75% FC |
|---|---|---|---|---|---|---|---|---|
| | KD2 X $10^{-4}$ (m/s) | | | | | | | |
| 0 | 1.36 | 1.70 | 1.60 | 1.43 | 3.73 | 2.47 | 1.50 | 1.44 |
| 2 | 1.37 | 2.10 | 1.77 | 1.27 | 3.87 | 1.97 | 1.43 | 2.57 |
| 4 | 2.70 | 1.44 | 1.77 | 1.36 | 1.43 | 1.87 | 2.23 | 1.17 |

A-control; B-Biochar only; C-organic fertilizer with urea; D- urea intercalated biochar plus organic fertilizer; KD2 – $K_{2cm}$ at day 2, FC – field capacity

Table 6: Interaction effects of fertilizer, moisture and compaction soil on unsaturated hydraulic conductivity at experimental day 4

| | Fertilizer | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | A | | B | | C | | D | |
| Compaction (kg) | 50% FC | 75% FC | 50% FC | 75% FC | 50% FC | 75% FC | 50% FC | 75% FC |
| | KD4 X $10^{-4}$ (m/s) | | | | | | | |
| 0 | 1.43 | 1.47 | 1.47 | 1.87 | 2.47 | 1.02 | 1.43 | 1.87 |
| 2 | 2.07 | 1.70 | 1.60 | 2.03 | 1.60 | 1.27 | 1.17 | 2.37 |
| 4 | 2.57 | 1.87 | 2.13 | 1.43 | 1.43 | 3.67 | 1.50 | 1.70 |

A-control; B-biochar only; C-organic fertilizer with urea; D- urea intercalated biochar plus organic fertilizer; KD4 – $K_{2cm}$ at day 4, FC – field capacity

biochar made from fir-wood enhanced even distribution of pore classes in coarse soil despite compaction, which favoured oxidation of methane to produce carbon dioxide among others. Furthermore, the larger pores in uncompacted soil may have enhanced gas permeability as observed in this case, as compaction leads to redistribution of pore system by primarily reducing large pores to form more medium pores while micropores are largely unaffected (van Verseveld and Gebert, 2020; Romero-Ruiz *et al*., 2023). Compaction has been identified to have more influence in the decline in advective soil permeability when used in combination with soil moisture content in an oxidation system established in loamy sand soils (van Verseveld and Gebert, 2020). Furthermore, addition of substrate such as biochar-based fertilizers/amendments etc. provide carbon and energy source for microbial respiration. Loss of carbon dioxide due to microbial activity on dissolved organic carbon from recent C source has been reported (Huang and Hall, 2017) and this may have been aided further by possible disruption of soil aggregates (Lundquist *et al*., 1999; Ruser *et al*., 2006; Jephita *et al*. 2023) due to slaking by repeated addition of water to soil to keep it at specified proportion of FMC leading to loss of carbon sorbed within the aggregates. The effects of interaction of compaction, fertilizer and moisture on carbon dioxide is shown in Table 10. The joint highest carbon dioxide release (16.26 $g/m^2/day$) was observed in soil that was not treated with fertilizer but compacted under 4 kg load and maintained at 50% FMC. The same amount of the gas was lost in soil treated with urea plus organic fertilizer, compacted under 2 kg load and was subjected to 75% FMC. It appears increase in compaction or moisture content as it is the case with the highest level of both factors in this study, led to highest emission of carbon dioxide from the soil. Similar relationship on the effect of moisture content and compaction on gas transport in soil was reported, as small decrease in air-filled porosity due to increase in either soil moisture content or compaction resulted in substantial increase diffusivity of ethylene in a sandy loam soil (Yu *et al*., 2024). Increase in soil moisture content had also be found to induce aggregation and promote secondary macropore formation that enhanced soil gas permeability (van Verseveld and Gebert, 2020).

### *3.0. Changes in selected soil properties when compacted and interacted with fertilizer and moisture content*

Properties of soil parameters assessed at the end of the experiment following compaction and its interaction with fertilizers under varied moisture contents are presented in Tables 11-13. Surprisingly, simply compacting soil affected organic carbon content among the properties investigated (Table 11). Organic carbon content was significantly higher ($P<0.05$) under 2 kg load (1.33%) compared to 4 kg load (0.94%) but it was not significantly different from the uncompacted soil (1.07%). Increment in organic carbon content due to compaction relative to the uncompacted soil may be down to carbon accumulation due to inhibition of carbon loss either by inhibiting carbon transport or by inhibiting microbial activity in compacted soil. A little increase or changes in SOC easily reflect in sandy soils. This sensitivity of sandy soil to small changes in soil carbon stocks (Jephita *et al*. 2023) may have amplified the difference. It is possible that a range of compaction enhances carbon sequestration or there are pore sizes that comparatively serves as barriers to carbon loss which the 2 kg load may have created. Another reason may be down to level of arrangement of soil particles on SOC (Six and Paustian, 2014) which is favourable to SOC storage or inhibit SOC turnover in this case. Moisture alone did not affect organic carbon content and it is therefore not presented as earlier stated. Interaction of compaction with fertililzer and its significant ($P<0.05$) influence on saturated hydraulic conductivity ($K_{sat}$) and total porosity is presented in Table 12. Saturated hydraulic conductivity was significantly highest ($P<0.05$) in uncompacted soil treated with biochar

Table 7: Temporal evolution of carbon dioxide from soil under different moisture regime

| Moisture | D1 | D2 | D3 | D4 | D5 | D6 | D7 | D8 | D9 | D10 | D11 | D12 | D13 | D14 | D15 | D16 | D17 | D18 | D19 | D20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ← $CO_2$ (g/m$^2$/day) → | | | | | | | | | | | | | | | | | | | |
| 1 | 12.90 | 8.46 | 17.25 | 13.06 | 15.15 | 11.29 | 13.06 | 9.73 | 10.84 | 11.87 | 10.97 | 11.13 | 8.42 | 16.51 | 13.84 | 10.76 | 16.63 | 17.00 | 14.17 | 9.28 |
| 2 | 13.84 | 10.92 | 15.48 | 12.48 | 13.55 | 10.88 | 12.90 | 9.32 | 11.25 | 11.33 | 10.51 | 11.99 | 8.09 | 18.32 | 13.51 | 9.36 | 17.49 | 17.62 | 11.33 | 11.09 |
| LSD | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | 2.28 | NS |

1 – 50% FC; 2 - 70% FC; FC – field capacity; $D_x$ represents days of sample where x is from day 1 to 20

Table 8: Emission of carbon dioxide from soil under different compaction at a daily time scale

| COMPACTION (kg) | D1 | D2 | D3 | D4 | D5 | D6 | D7 | D8 | D9 | D10 | D11 | D12 | D13 | D14 | D15 | D16 | D17 | D18 | D19 | D20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ← $CO_2$ (g/m$^2$/day) → | | | | | | | | | | | | | | | | | | | |
| 0 | 13.37 | 9.12 | 15.28 | 12.94 | 13.00 | 11.21 | 12.26 | 7.76 | 9.92 | 10.72 | 11.27 | 9.79 | 8.07 | 16.69 | 13.61 | 10.35 | 15.77 | 17.56 | 13.12 | 10.53 |
| 2 | 13.24 | 9.92 | 20.45 | 12.75 | 15.71 | 10.23 | 11.52 | 11.03 | 11.52 | 12.20 | 9.92 | 12.57 | 6.78 | 16.32 | 11.83 | 9.49 | 17.68 | 16.39 | 12.26 | 10.90 |
| 4 | 13.49 | 10.04 | 13.37 | 12.63 | 14.35 | 11.83 | 15.15 | 9.79 | 11.70 | 11.89 | 11.03 | 12.32 | 9.92 | 19.22 | 15.59 | 10.39 | 17.74 | 17.99 | 12.87 | 9.12 |
| LSD | NS | NS | 5.52 | NS | NS | NS | NS | 2.84 | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |

FC – field capacity; $D_x$ represents days of sample where x is from day 1 to 20

Table 9: Interactions of compaction and different fertilizers on carbon dioxide release from soil

| Compaction (kg) | Fertilizer: A | B | C | D | A | B | C | D | A | B | C | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | D2 $CO_2$ (g/m$^2$/day) | | | | D18 $CO_2$ (g/m$^2$/day) | | | | D19 $CO_2$ (g/m$^2$/day) | | | |
| 0 | 11.09 | 11.58 | 6.90 | 6.90 | 14.54 | 16.76 | 17.25 | 21.68 | 15.03 | 9.36 | 12.07 | 16.02 |
| 2 | 6.16 | 12.32 | 7.88 | 13.31 | 17.49 | 21.19 | 15.77 | 11.09 | 13.80 | 9.61 | 15.28 | 10.35 |
| 4 | 9.86 | 9.86 | 9.12 | 11.33 | 17.49 | 19.71 | 14.04 | 20.70 | 9.36 | 14.78 | 16.26 | 11.09 |

A-control; B-biochar only; C-organic fertilizer with urea; D- urea intercalated biochar plus organic fertilizer; D – day while the number represents experimental day (e.g. D2 – day 2)

Table 10: Interactions of different fertilizers, compaction and moisture on carbon dioxide loss from soil

| | Fertilizer: A | | B | | C | | D | |
|---|---|---|---|---|---|---|---|---|
| Compaction (kg) | 50% FC | 75% FC | 50% FC | 75% FC | 50% FC | 75% FC | 50% FC | 75% FC |
| | D9 $CO_2$ (g/m$^2$/day) | | | | | | | |
| 0 | 7.39 | 13.31 | 8.38 | 13.30 | 10.35 | 8.87 | 6.90 | 10.84 |
| 2 | 12.81 | 13.31 | 11.33 | 6.41 | 10.84 | 16.26 | 12.32 | 8.87 |
| 4 | 16.26 | 8.87 | 12.81 | 9.86 | 10.84 | 12.81 | 9.86 | 12.32 |

A-control; B-biochar only; C-organic fertilizer with urea; D- urea intercalated biochar plus organic fertilizer; D9 – day 9

Table 11: Effects of varied compaction on selected soil properties

| COMPACTION (kg) | Organic C *(%)* | MWD *(mm)* | GMD *(mm)* | $K_{SAT}$ (m/s) | Porosity *(%)* | Db (g/cm$^3$) |
|---|---|---|---|---|---|---|
| 0 | 1.0709 | 4.2361 | 1.01622 | 0.0019738 | 44.09 | 1.41984 |
| 2 | 1.3279 | 3.9471 | 1.02589 | 0.0017848 | 44.71 | 1.44091 |
| 4 | 0.936 | 3.9431 | 1.01403 | 0.0012574 | 44.18 | 1.43355 |
| LSD | 0.286 | NS | NS | 0.0007 | NS | NS |

Organic – Organic carbon; MWD -mean weight diameter; GMD – Geometric mean diameter; $K_{SAT}$ – saturated hydraulic conductivity; $D_b$ – bulk density

Table 12: Interaction effects of fertilizers and compaction on saturated hydraulic conductivity and porosity

| Compaction (kg) | Fertilizer A | B | C | D | A | B | C | D |
|---|---|---|---|---|---|---|---|---|
| | $K_{SAT}$ X $10^{-3}$ (m/s) | | | | Porosity (%) | | | |
| 0 | 2.28 | 2.77 | 1.60 | 1.25 | 42.13 | 48.03 | 39.91 | 46.30 |
| 2 | 2.50 | 0.72 | 2.51 | 1.41 | 43.64 | 47.57 | 43.67 | 43.97 |
| 4 | 0.86 | 1.21 | 1.33 | 1.63 | 44.34 | 46.49 | 44.05 | 41.84 |

A-control; B-biochar only; C-organic fertilizer with urea; D – urea intercalated biochar plus organic fertilizer; $K_{sat}$-saturated hydraulic conductivity

Table 13: Interaction effects of fertilizer, moisture and compaction on soil bulk density

| Compaction (kg) | Fertilizer A | | B | | C | | D | |
|---|---|---|---|---|---|---|---|---|
| | 50% FC | 75% FC | 50% FC | 75% FC | 50% FC | 75% FC | 50% FC | 75% FC |
| | Db ($g/cm^3$) | | | | | | | |
| 0 | 1.49 | 1.50 | 1.32 | 1.39 | 1.46 | 1.42 | 1.37 | 1.40 |
| 2 | 1.47 | 1.45 | 1.47 | 1.36 | 1.42 | 1.51 | 1.44 | 1.41 |
| 4 | 1.49 | 1.50 | 1.40 | 1.47 | 1.43 | 1.42 | 1.44 | 1.33 |

A-control; B-biochar only; C-organic fertilizer with urea; D – urea intercalated biochar plus organic fertilizer; FC- field capacity

($2.77 \times 10^{-3}$ m/s) followed by soil compacted under 2 kg load but amended with urea plus organic fertilizer ($2.51 \times 10^{-3}$ m/s). It was least in soil compacted under 4 kg load with no amendment applied by an order of magnitude ($8.6 \times 10^{-4}$ m/s). It implies that $K_{sat}$ drops with level of compaction and invariably with the amount of macropores in soil as it is the macropore that often collapses when soil is compacted (Zhang *et al*., 2006; Romero-Ruiz, 2023). Kuncoro *et al*. (2014) also reported a decline in $K_{sat}$ due to loss of macropore. It is also obvious that effect of compaction on $K_{sat}$ was ameliorated by the amendments applied with biochar treated soil performing best confirming the impact of soil organic carbon content that come from the amendments in improving $K_{sat}$ through its influence on SOC (O'Keeffe *et al*., 2023; Falk *et al*., 2024). Similarly, porosity also responded positively when soil was not compacted but treated with biochar-based amendments. It was significantly highest ($P<0.05$) in uncompacted soil treated with biochar (48.03%) followed by uncompacted soil treated with biochar intercalated urea fertilizer (46.3%). Improvement in porosity and reduction in bulk density following biochar application is consistent with the findings of O' Keeffe *et al*. (2023). Interaction of compaction with moisture, and interaction of fertilizer with moisture had no impact on the soil properties investigated. However, interaction of compaction, fertilizer and moisture raised the bulk density to the comparatively highest level ($P<0.05$) when soil compacted with 2 kg load was amended with urea plus organic fertilizer and kept at 75% FMC (Table 13). Generally, in Table 13, high bulk densities were dominance where no amendment was used while the least were observed in soils treated with biochar-based amendments (1.33 g/cm under biochar intercalated urea fertilizer under 4 kg weight plus 75% FC and 1.32 g/cm under biochar amended plots that was not compacted plus 50% FC). This underscores the potentials of biochar-based amendments to remediate soil hydraulic properties of sandy loam when subjected to some levels of compaction. It also implies that moisture content may have enhanced microbial activity (Abad *et al*., 2023), particularly when optimum (Leuther *et al*., 2023) with attendant ecosystem service such as the production of SOC that reduced the bulk density. In cases involving high bulk densities at 75% FMC in the absence of any amendment, the moisture content may have controlled the susceptibility of soil to compaction or high bulk density (Romero_Ruiz *et al*., 2023).

## 4.0. Conclusions.

The daily monitoring of carbon dioxide footprint and $K_{2cm}$ in response to the interactive effects of the soil amendments, moisture and compaction is revealing in many ways. Few significant changes in carbon dioxide and $K_{2cm}$ occurred while the study lasted. Increase in carbon dioxide emission is driven by the combination of biochar-based amendment (e.g. biochar intercalated urea fertilizer) plus uncompacted soil; underscoring the importance of mild compaction in reducing carbon loss in amended sandy loam soils in a moisture range between 50% to 75% FC. Unsaturated hydraulic conductivity was more enhanced when soil was compacted and amended with urea plus organic fertilizer. Contrastingly, biochar-based amendments in an uncompacted soil, enhanced saturated soil water flow, porosity and bulk density more than any other treatment combinations. Organic carbon increased in soil under 2 kg load but declined when soil was compacted under 4 kg while soil aggregates were not affected. Thus, combination of compaction, fertilizer and soil moisture as management technique yielded varied response in soil properties and associated carbon emission to the atmosphere. The choice of the best management option can be explored based on the target of end-users.

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