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The combined effect of compost and biochar application on carbon sequestration and some soil properties

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Abstract

Compost and biochar are widely used to improve soil quality by carbon sequestration. A laboratory experiment focused on evaluating the effectiveness of compost or biochar (from the same source) additions individually or in combinations on the soil organic mineralization (SOM), carbon stocks and some soil chemical properties after 45- and 90-days incubation was done. Six treatments were performed based on even mixture of biochar and compost as control without any addition (C), 100% compost (T_1), 100% biochar (T_2), 75% biochar + 25% compost (T_3), 50% biochar + 50% compost (T_4), 25% biochar + 75% compost (T_5). The results clearly indicated that adding mixture of biochar and compost significantly reduced gaseous emissions and build up soil carbon content. Soil organic carbon decomposition percentage (SOC) was at a minimum amount when the soil treated by 100% biochar (T_2) since it was 1.03 and 2.27% after 45 and 90 days, respectively. While it was at a maximum amount when the soil treated by100% compost (T_1) since it was 3.29 and 4.74% after 45 and 90 days, respectively. These results suggested that charring would considerably sequester soil C, especially at high application rates and in fine-textured soils. Biochar application is considered a new economic and environmental protection process as well as reducing carbon dioxide emissions.

Keywords: biochar, compost, carbon dioxide emissions, soil carbon sequestration.

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1. Introduction

Composting and pyrolysis process can recycle nutrients from organic wastes, residue and grown crops (Duan *et al*., 2021; Mudiyanselage and Herat, 2021). Pyrolysis produces biochar, which is carbon (C) rich and contains many nutrients (Liao *et al*., 2022). Composting produces materials that contain organic matter, C and available nutrients (Greff *et al*., 2022). Biochar and compost offer significant potential for soil C sequestration. Biochar is a black carbon-rich solid produced by thermal decomposition of biomass under oxygen-limited conditions at temperatures between 300 and 700 °C (Jiao *et al*., 2021; Peng *et al*., 2018). Feedstock for biochar production may comprise purpose-grown biomass or diverse waste materials from industry including agriculture, on-farm vegetation such as ruches and clippings from hedgerows, hard- and soft-woods, biosolids and urban wastes (Peng *et al*., 2018; Rey-Salgueiro *et al*., 2016). Adding biochar on agricultural land is an important practice for improving degraded soils as it restores soil properties and in turn enhances plant growth (Al-Wabel *et al*., 2018). Compost properties vary widely depending on feedstocks and composting procedure (Stehouwer *et al*., 2022). Efficient use of composts relies on a better understanding of compost properties and their interaction with soils, how these changes over time and it is modulated by soil type. Compost has two main effects on soils, particularly nutrient-poor soils: replenish soil organic matter and supply plant nutrients (Elia and Boulos, 2019). Organic matter plays a crucial role in improving physical, chemical and biological properties of soils. Soil structure can be improved by the binding between soil organic matter and clay particles via cation bridges and through stimulation of microbial activity and root growth (Audette *et al*., 2021; Dalal and Bridge, 2020). A large proportion of carbon is lost due to the release of CO2 during organic matter decomposition (Awasthi *et al*., 2016). Up to 13% of N content in slurry can be lost as N_2O emissions due to nitrification and denitrification during anaerobic composting processes (Yang *et al*., 2019). The major effect of adding biochar could be most likely related to increase the total amount of soil organic matter (SOM) due to its intrinsic recalcitrance (Bi *et al*., 2021; Zhang *et al*., 2021a) and to the reduction of mineralization rate of the native SOM (Palansooriya *et al*., 2019). The way on which biochar can reduce SOM mineralization might be related to its sorbent properties, which could restrict the microbial access to essential nutrients, therefore limiting its activity. Also, to an increase in the amount of SOM physically occluded and chemically adsorbed, and then protected (Zhang *et al*., 2021b). Moreover, it suggested that the high C/N ratio of the biochar can cause a significant N immobilization so to reduce native SOM mineralization. On the other hand, it was mentioned a priming effect of black carbon that could enhance the mineralization forest humus (Dodor *et al*., 2018), thus the biochar effect on native SOM mineralization remains unclear (Li *et al*., 2019). Biochar addition to arable soil secures the nutrient loop and increases C sequestration, potentially forging a carbon-negative cycle. Due to the high C content (60–80%) and the C sequestration potential of biochar, it is considered a viable tool for climate change abatement. Therefore, calculation of C stocks and the stability of this store have become important (Simo *et al*., 2019). Preventing the decline of C stocks and indeed building C stocks through incorporation of organic amendments is supposed to be a new research area. This might be attributed to its highly recalcitrant OM. Also, biochar may contain significant quantities of labile material that could be mineralized in the short term. This paper aims to assess the effects of biochar and compost application on the SOM mineralization, carbon stocks and some soil chemical properties during different incubation periods.

2. Materials and methods

2.1 Soil, biochar and compost preparation

Surface soil samples (0-30 cm) were collected from scatter points at The Experimental Farm, Agricultural research Station, Arab Al Awamer, Assiut, Egypt (27° 12- 16.67= N latitude and 31° 09- 36.86= E longitude). Before handling, the soil samples were homogenized, crushed, and passed through a 2-mm sieve for some chemical and physical analysis according to Page *et al*. (1982) and Klute (1986) and they are shown in Table (1).

Table (1): Some physical and chemical properties of the studied soil.

Property	Value
Sand (g/kg)	900
Silt (g/kg)	71
Clay (g/kg)	29
Texture	Sandy
$CaCO_3$ (g/kg)	261
pH (1: 2.5)	8.7
EC (dS/m) (1:2.5)	0.30
Organic matter (g/kg)	5.0
Available-N (mg/kg)	0.6
Available-P (mg/kg)	4.5
Available-K (mg/kg)	46

Both biochar and compost were produced from the same feedstocks, which are by-product of oil production from the oregano straw (*Origanum majorana*). The tested biochar was produced by the pyrolysis of marjoram straw at the temperature of 350 ^{o}C with residence time of three hours. The chemical analyzes of the tested biochar and compost is presented in Table (2).

Table (2): Chemical composition of the tested biochar and compost.

Property	Unit	Biochar	Compost
pH (1: 2.5)	---	10.8	7.8
EC	(dS/m)	12.0	7.6
Organic matter	(g/kg)	630	540.3
Total carbon	(g/kg)	313.4	365.4
C/N ratio	----	17.29	29.43
Available-N	(mg/kg)	3.9	4.2
Available-P	(mg/kg)	5.1	1.6
Available-K	(mg/kg)	37.2	3.2

2.2 Incubation experiment and design

Two hundred grams of soil sample were inserted into plastic cups and mixed well with different amounts of biochar or compost to form the following treatments:

- 100% compost T_1
- 100% biochar T_2
- 75 % biochar + 25 % compost T_3
- 50% biochar + 50 % compost T_4
- 25% biochar + 75 % compost T_5
- In addition to control treatment received neither biochar nor compost (C)

The experiment was laid out in a randomized block design with six treatments and three replications. The plastic cups were moistened to the field capacity and their moisture level was monitored and adjusted weekly. All treatments were subjected to two incubation periods of 45 and 90 days under laboratory condition (25–30 ^{o}C). Weekly measurements of C mineralized to CO_2 were carried out with 1N NaOH traps (Anderson, 1982) along the incubation period to allow the mineralization of both active and slow organic matter pools. Evolved carbon dioxide was estimated according to Stotzky (1965).

2.3 Laboratory analysis

Soil salinity expressed as electrical conductivity (EC) was determined in (1:2.5) soil-water extract using conductivity meter according to Jackson (1973). The soil reaction (pH) was determined in a soil to water ratio of 1:2.5 using a glass electrode pH meter (McLean, 1982). Total Nitrogen was determined using modified kjeldahl digestion procedure (Bremnen and Mulvaney, 1982). Organic Carbon was determined according to the method of Nelson and Sommers (1982). Decomposition percentage was estimated by calculating the percentage of soil organic C evolved as CO_2 after correction for the CO_2 evolved from untreated soil according to Ajwa and Tabatabai (1994) using the following equation:

$$C\ decomposition\ \% = [(X - Y)\ /\ Z)]\ x\ 100$$

Where: X = C evolved as CO_2 from soil-fertilizer treatments (mg), Y = C evolved as CO_2 from untreated soil (control) (mg), Z = C in the soil organic matter (mg). Available nitrogen, phosphorus and potassium were determined according to the method outlined by Burt (2004). carbon storage was calculated according to the formula of Rowell (1994) as follows:

$$\text{Carbon storage } \% = \text{organic carbon } \% / 100 \times \text{bulk density} \times \text{soil collection area} \times \text{soil collection depth}$$

2.4 Statistical analysis

Data were subjected to analysis of variance according to Snedecor and Chocran (1980), and treatment means were compared using Duncan's multiple range tests at 5% level according to Duncan (1955).

3. Results

3.1 Organic application and some soil properties

The effect of adding biochar and compost on soil salinity (EC) was significant ($P<0.05\%$) during all incubation periods (Table 3). The EC values ranged between 0.33 at C treatment and 0.60 at T_1 and T_3 after 45 incubation days. The EC values were 0.35 at C treatment and 0.68 at T_2 after 90 incubation days. The EC values increased by 57.4% at T_5 and by 82.0 at T_1 and T_3 after 45 incubation days compared to control treatment (C). Also, the EC values increased by 34.3% at T_5 and by 94.3% at T_2 after 90 incubation days compared to control treatment (C). Regarding soil reaction, the effect of adding compost or biochar significantly increased soil pH and these increases were more evident after 90 incubation days than those after 45 incubation days. Regardless the incubation period, the highest pH values were recorded at T2 and T3 treatments. The pH values increased by 0.82, 8.78, 6.67, 4.10 and 3.98% at T1, T2, T3, T4 and T5, respectively compared to C treatment after 45 incubation days. After 90 incubation days, the differences of pH values among all treatments were diminished.

Table (3): Effect of biochar and compost on soil pH (1:2.5) and electrical conductivity (EC, dS m^{-1}) during 45 and 90 days of incubation.

Treatments	pH		EC (1:2.5)	
	45 days	90 days	45 days	90 days
C	8.54 ± 0.08^{d}	9.03 ± 0.1^{b}	0.33 ± 0.01^{c}	0.35 ± 0.04^{d}
T1	8.61 ± 0.09^{d}	9.24 ± 0.33^{a}	0.60 ± 0.00^{a}	0.48 ± 0.01^{bc}
T2	9.29 ± 0.01^{a}	9.29 ± 0.15^{a}	0.58 ± 0.02^{a}	0.68 ± 0.03^{a}
T3	9.11 ± 0.06^{b}	9.24 ± 0.06^{a}	0.60 ± 0.03^{a}	0.52 ± 0.00^{b}
T4	8.89 ± 0.02^{c}	9.08 ± 0.05^{b}	0.58 ± 0.01^{a}	0.50 ± 0.02^{bc}
T5	8.88 ± 0.03^{c}	8.97 ± 0.05^{c}	0.52 ± 0.03^{b}	0.47 ± 0.00^{c}

C = without application, T_1 =100% compost, T_2 =100% biochar, T_3 = 75% biochar + 25% compost, T_4 = 50% biochar + 50% compost, T_5 = 25% biochar + 75% compost. Means (± SD, n = 10) denoted by the same letter indicate insignificant difference according to Duncan's test at $p < 0.05$.

Nevertheless, the incubation period, there were a significant ($P<0.05$) increases in soil organic matter (SOM) content as a result of adding biochar and compost (Table 4). Among all treatments, SOM content varied from 0.46 and 0.65 and from 0.51 and 0.81% after 45 and 90 day of incubation periods, respectively. The highest SOM values were recorded at T1 and T2 treatments during both incubation periods. There were significant differences of soil C/N ratio as a result of adding biochar and compost. In general, the soil C/N ratio recorded higher value after 90 incubation days compared to that after 45 incubation days. The highest soil C/N ratio was found at T_5 (12.80), followed by T_1 (9.74) and T_3 (9.47) treatments after 90 incubation days (Table 4).

Table (4): Effect of biochar and compost on soil organic matter and C/N ratio during 45 and 90 incubation days.

Treatments	Organic matter (%)		C: N (ratio)	
	45 days	90 days	45 days	90 days
C	0.46 ± 0.02^{d}	0.51 ± 0.02^{c}	4.94 ± 0.57^{c}	6.65 ± 0.23^{e}
T_1	0.64 ± 0.02^{a}	0.74 ± 0.02^{ab}	6.02 ± 0.57^{b}	9.74 ± 0.68^{b}
T_2	0.65 ± 0.00^{a}	0.81 ± 0.02^{a}	7.72 ± 0.60^{a}	8.55 ± 0.32^{c}
T_3	0.62 ± 0.07^{a}	0.72 ± 0.07^{b}	5.12 ± 0.06^{c}	9.47 ± 0.29^{b}
T_4	0.53 ± 0.01^{b}	0.68 ± 0.02^{b}	5.07 ± 0.38^{c}	7.74 ± 0.27^{d}
T_5	0.52 ± 0.03^{b}	0.62 ± 0.03^{b}	6.38 ± 0.26^{b}	12.80 ± 0.48^{a}

C = without application, T_1 = 100% compost, T_2 = 100% biochar, T_3 = 75% biochar + 25% compost, T_4 = 50% biochar + 50% compost, T_5 = 25% biochar + 75% compost. Means (± SD, n = 10) denoted by the same letter indicate insignificant difference according to Duncan's test at $p<0.05$.

Meanwhile, T_4 treatment showed the lowest soil C/N ratio of 5.07 and 7.74 after 45 and 90 incubation days, respectively. Adding biochar and compost significantly increased nitrogen availability compared to the control treatment (Table 5). Nitrogen availability was declined as incubation time proceeded. The combined application of compost and biochar (T_3, T_4 and T_5)

increased available N compared to the compost (T_2) or biochar (T_1) only after 45 incubation days. T_4 and T_5 treatments gave the maximum available nitrogen. T_4 and T5 increased the availability of N by 144 and 375% over the control treatment after 45 and 90 days, respectively. Application of biochar and compost significantly increased available phosphorus as the incubation time increased (Table 5). Regardless the incubation time, the highest amounts of available P were realized at T_3 and T_4 while the lowest ones were recorded at T_2 and control treatment. In general, combined application of compost and biochar (T_3, T_4 and T_5) achieved the maximum available phosphorus.

Table (5): Effect of biochar and compost on available N, P and K (mgkg^{-1}) during 45 and 90 incubation days.

Treatments	N		P		K	
	45 days	90 days	45 days	90 days	45 days	90 days
C	28.1±0.6^d	41.1±3.6^d	9.6±0.8^a	12.9 ±0.3^d	97.5±8.3^d	145.2±3.8^d
T_1	77.0±4.5^c	46.3±4.0^c	14.9±1.2^a	21.8±0.2^c	207.6±12.0^b	366.4±298^c
T_2	92.0±7.8 ^{b}	77.73±9.9^b	11.1±0.9^b	15.7±1.1^d	167.6±19.3^c	571.2±35.3^a
T_3	119.1±7.6^a	70.72±8.9^b	16.3±0.5^a	24.8±1.0^b	216.5± 3.1 ^{a}	591.2±14.5^a
T_4	133.1±3.5a	132.0±7.2^b	16.3±0.8^a	28.7±2.5^a	193.1±6.7^b	461.5±54.2^b
T_5	115.7±17.6^a	100.7±9.8^a	15.8±1.2^a	17.0±1.7^d	155.6±10.8^c	337.2±18.6^c

C = without application, T_1 = 100% compost, T_2 = 100% biochar, T_3 =75% biochar + 25% compost, T_4 = 50% biochar + 50% compost, T_5 = 25% biochar + 75% compost. Means (± SD, n = 10) denoted by the same letter indicate insignificant difference according to Duncan's test at $p<0.05$.

Addition of biochar and compost significantly increased available potassium and these increases were magnified with incubation time (Table 5). After 45 incubation days, available K increased by 112.92, 71.90, 122.05, 98.05 and 59.59% at T_1, T_2, T_3, T_4 and T_5, respectively compared to control treatment (C). The corresponding values were 152.34, 293.39, 307.16, 217.84 and 132.23% after 90 incubation days.

3.2 Carbon dioxide emitted as affected by organic application

The soil CO_2 flux was high at the beginning of incubation time then reduced gradually as incubation time proceeded with almost steady flux after 8 weeks for all treatments (Figure 1). After the 1st week, soil CO_2 emission amounted of 15, 23, 16, 18, 19 and 22 mg carbon/ 200 g soil for C, T_1, T_2, T_3, T_4 and T_5 treatment, respectively. The corresponding values were 3, 12, 9, 12, 14 and 12 mg carbon/ 200 g soil after 6th weeks while soil CO_2 emissions were about 5 mg carbon/ 200 g soil after 12th weeks (Figure 1). In general, cumulative soil CO_2 emissions increased as with incubation time proceeded (Figure 2). The cumulative soil CO_2 flux varied from 57.2 to 98.6 and from 77.4 to 136.0 mg / 200 g soil after 45 and 90 incubation days, respectively. Regardless the incubation time, the amount of cumulative soil CO_2 flux from T_1 treatment realized the highest compared to other treatments.

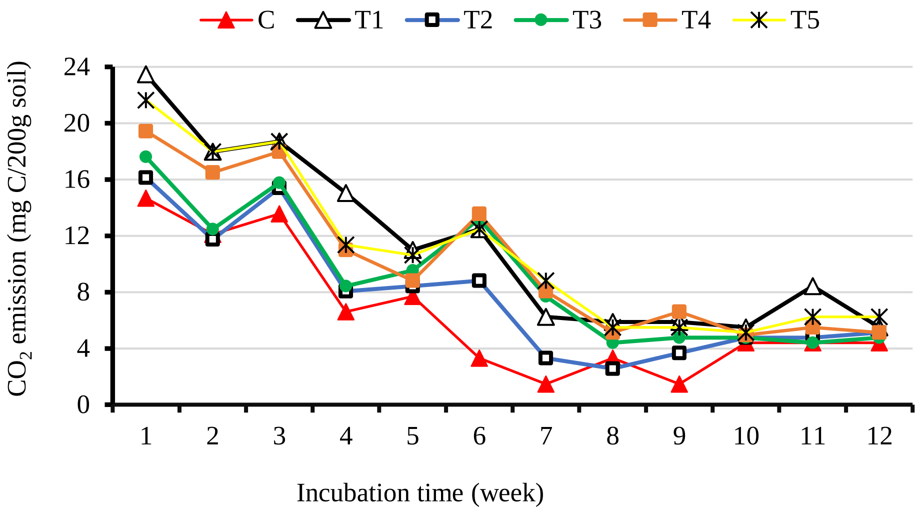

Figure (1): Soil CO_2 emission in relation to organic application during incubation time.

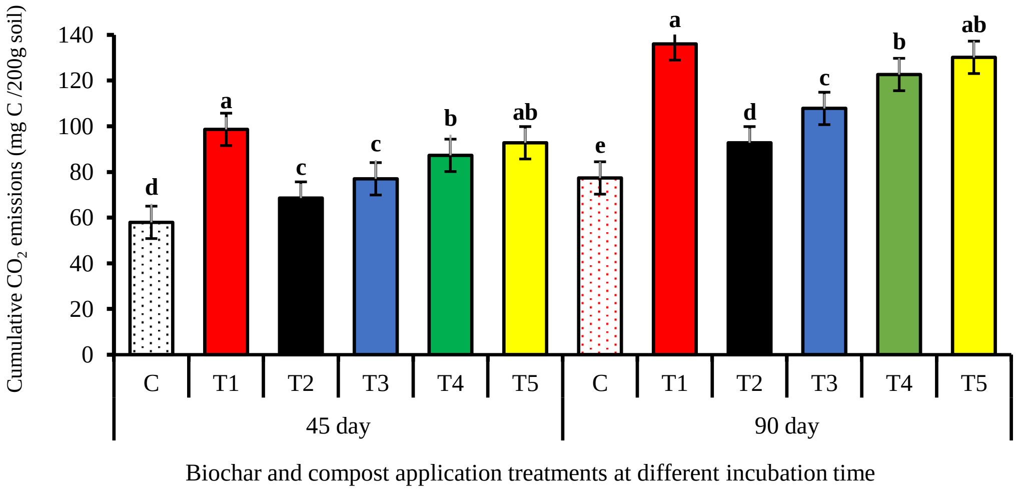

Figure (2): Cumulative CO_2 emissions in relation to organic application after 45 and 90 incubation days.

3.3 Organic application and soil organic carbon decomposition

The impact of biochar and compost on soil organic carbon decomposition after 45 and 95 incubation days is shown in Figure (3). Biochar and compost realized a significant effect ($p<0.05$) on SOCD (Figure 3). It was observed that SOCD was at a minimum amount when the soil treated by 100% biochar (T_2) and it was at a maximum amount when the soil treated by 100% compost (T_1 treatment). The SOCD % recorded at T_2 ranged from 1.03 and 2.27%, while it varied from 3.29 and 4.74% at T_1 treatment after 45 and 90 incubation days, respectively. In general, data indicated that SOCD increased when soil treated by both biochar and compost compared to the biochar only.

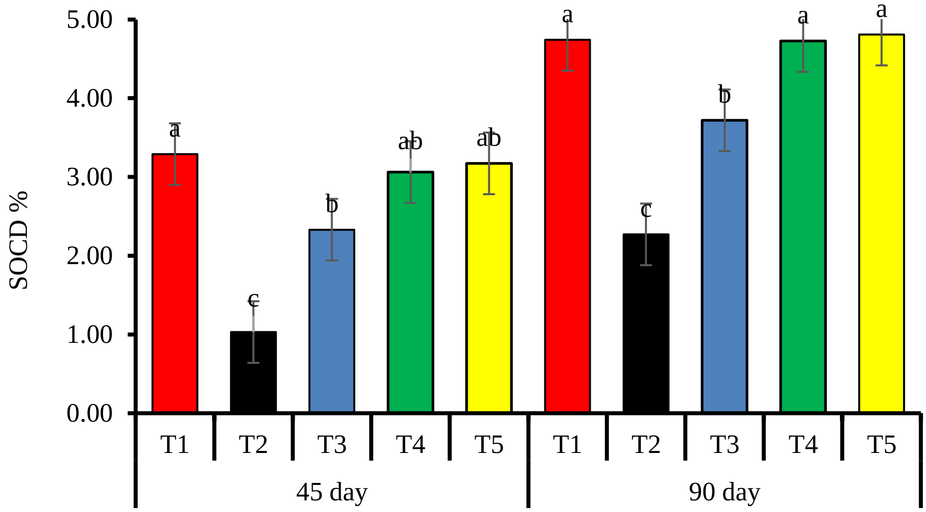

Figure (3): Soil organic carbon decomposition (SOCD %) in relation to incubation time when soil treated by biochar and compost.

3.4 Organic application and carbon storage

Changes in carbon storage due to adding biochar and compost after 45 and 95 incubation days are shown in Figure (4). The carbon storage was significantly ($P<0.05$) increased as a result of adding biochar and compost compared to control treatment. In general, carbon storage increased with incubation time proceeded. The carbon storage ranged between 1.35 and 2.34 kg/m^2 land after 45 and 90 incubation days, respectively whatever the treatments are. Regardless of the incubation time, the highest values of carbon storage were observed for T_2 (100% biochar) while the lower ones were noticed for T_5 treatment.

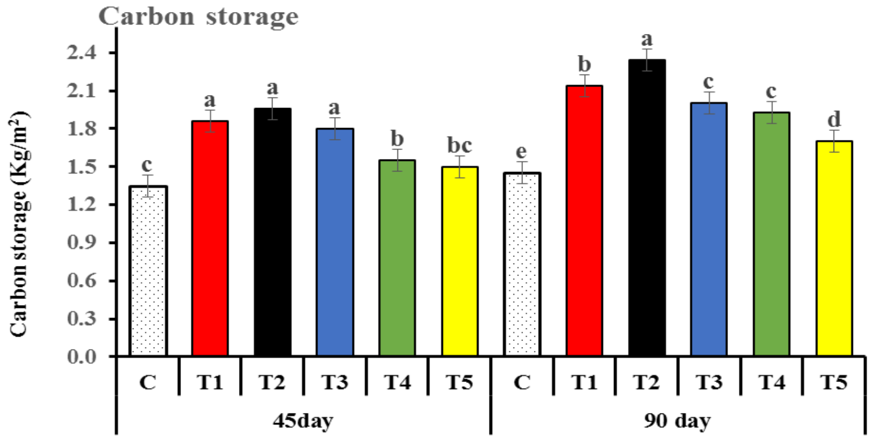

Figure (4): Effect of biochar and compost on carbon storage after 45 and 90 incubation days.

4. Discussion

4.1 Soil properties

During all incubation time, adding biochar and compost significantly increased soil salinity and soil reaction. The increase in soil salinity with adding biochar and compost could be due to their high salt content. Shah *et al*. (2017) revealed that adding biochar increased soil salinity (EC) and alkalinity (pH). Kloss *et al*. (2014) found slight increment of soil pH (0.3 units) in an acid soil after application of woodchip-derived biochar. Soil pH was increased from 4.0 to 4.5 due to addition of biochar, (Rodriguez *et al*., 2009). Bista *et al*. (2019) found that biochar produced from Douglas fir (*Pseudotsuga menziesii*) at 900 °C and applied to a silt loam at 22.4 Mg ha^{-1} increased soil pH and organic carbon. The application of biochar and compost with all treatments showed a significantly higher organic matter (OM) compared to control treatment after incubation time (Table 4). In general, OM was increased with individual addition of compost (T_1) or biochar (T_2) compared to their combination (T_3, T_4 and T_5). Nyambo *et al*. (2018) found that biochar increased soil organic carbon by almost 2.25% compared to control after 140 days. Scislowska *et al*. (2015) explained that biochar, regardless of its origin, improved soil carbon content and soil's water holding capacity by a certain degree based on the type of soil. Widowati *et al*. (2020) found that some soil properties, such as OM% and phosphorus content were significantly increased by adding biochar nevertheless of the recommended NPK dosage compared to control. Combined biochar and compost (T_3, T_4 and T_5) significantly increased NPK availability compared to control (C) and 100% compost (T_1) treatments. Thus, biochar appears to be a helpful material for recycling NPK in agricultural systems. This is due to the ability of biochar to retain soil nutrients and reduce leaching into drainage water or beyond the root zone (Cao *et al*., 2017; Gul *et al*., 2015). The higher the quantity of biochar applied, the higher the magnitude of total N, available P and K is observed. This might be attributed to the large carbon component of biochar and the elemental composition of biochar which consists of different minerals such as Nitrogen, Phosphorus, exchangeable bases etc. (Lehmann *et al*., 2009). The thermo chemical conversion of manure into biochar seems to be a helpful practice to minimize the production of mineral P fertilizer (Steinfeld *et al*., 2006). Recycling P from organic residues has environmental benefits compared to direct land application (e.g., protection of water bodies) and can provide a continuous P source for soils (Manolikaki *et al*., 2016).

4.2 Soil CO_2 emissions

In addition to increasing soil fertility and quality, adding biochar is basically aimed at increasing C sequestration for climate change mitigation (Du *et al*., 2017; Windeatt *et al*., 2014). High CO_2 emissions rate was found at the beginning of incubation time then it declined as the incubation time proceeded (Figure 1). The rate of soil CO_2 flux reached a peak in the 1st and 3rd week from biochar and compost addition, mainly might be due to the microbial activity or the dissociation of carbonates. The cumulative CO_2 emissions from 100% biochar treatment (T_2) were significantly lower than those of 100% compost (T_1), 75% biochar + 25% compost (T_3), 50% biochar + 50% compost (T_4) and 25% biochar +75% compost (T_5) treatments during incubation time. The CO_2 emissions were proportional to the amount of adding biochar. These results suggest that charring would considerably improve soil C sequestration, especially at high application rates and in fine-textured soils. These results are in line with the findings of several studies that observed decreased CO_2 evolution from soil treated with biochar (Egamberdieva and Wirth, 2015; Yao *et al*., 2015). The high C sequestration potential found for biochar-amended soils are in agreement with previous findings (Du *et al*., 2017; Ouyang *et al*., 2014). Similarly, increasing biochar addition caused a progressive reduction of CO_2 emissions (Prayogo *et al*., 2013), which may be ascribed to the sorption of labile C onto the surface or into the pores of biochar (Lehmann *et al*., 2011).

4.3 Soil organic carbon decomposition (SOCD %)

The decrease in SOCD rate with increasing the level of biochar addition followed the order of $T_2 > T_3 > T_4 > T_5$. This might be because the biochar is characterized by its high content of more stable organic carbon compounds compared to compost, therefore it slowly decomposes in the soil (Eissa, 2019; Mahmoud *et al*., 2018). Also, Benito et al., (2005) reported that, when immature compost is applied, its high content of water soluble carbon can lead to stimulation of microbial activity followed by an increased carbon dioxide (CO_2) fluxes and higher soil organic matter (SOM) decomposition through priming effect.

4.4 Soil C storage

The calculation of C stocks and the stability of this store have become important **(**Simo *et al*., 2019). Adding biochar and compost individually or in combination realized positive effects on the amount of carbon storage in the soil during the incubation periods. It was noticed that the stored carbon increased with the increase the level of adding biochar as follows $T_2 > T_3 > T_4 > T_5$. Carbon in biochar is highly stable (Raya-Moreno *et al*., 2017). Its stability and low H/C ratio (less than 0.7) make it difficult to decompose (International Biochar Initiative, 2015) resulting in significantly high levels of carbon storage in soils with added rice husk biochar (RHB). Even though rice husk biochar and vermicompost contain carbon, the amount of carbon in the vermicompost is less than in the RHB and is also in a form that is more easily decomposed compared to the carbon in rice husk biochar (Kim *et al*., 2012).

5. Conclusion

It might be concluded that additions of compost and biochar separately or in combination enhanced soil quality in terms of increased organic matter, nutrients NPK and carbon storage. Furthermore, the low of soil organic carbon decomposition in all biochar treatments regardless if it was added solely or in combination with compost, increasing the level of addition from biochar led to an increase in soil C stabilization exemplified by lower CO_2 emissions in biochar amended soils compared to compost amended treatment attributable to a relatively high labile C availability in the sole compost treatment.

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