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Compost Combined with Peanut Shells Biochar: Enhanced Formation and Structural Characteristics of Soil Humic Acids and Yield of Wheat Crop in a Clay Loam Soil

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APPLICATION of compost alone could not enhance stability of soil humic acids (HA) particularly in short-term application in arid and semi-arid condtions due to the rapid loss of soil organic matter via oxidation. Therefore, mixing of compost with recalcitrant carbon (e.g. biochar) may enhance the stability of soil HA and improve soil characteristics. In this research, influence of peanut shells biochar combined with compost on the formation and structural characteristics of soil HA (as the most important fraction of soil organic matter), and the yield of wheat plant was investigated under a clay loam soil conditions. Five treatments were used: 1) no biochar or compost was added (Ck); 2) peanut shells biochar with 2.5 t ha^{-1} (BC); 3) 12.5 t ha^{-1} compost (compost); 4) 2.5 t ha^{-1} of biochar +12.5 t ha^{-1} of compost (BCL1+compost); 5) 5 t ha^{-1} of the biochar+12.5 t ha^{-1} compost (BCL2+compost). The results showed that the BCL2+compost amended soil had the highest grain yield, straw yield, biological yield, and harvest index. Although there was no significant difference between Ck and both BC and compost treatments, the mixing of compost with biochar together significantly reduced the soil pH. In addition, the BCL2+compost amended soil had the highest HS, HAc, FAc and Hum carbon content as well as the highest humification index (HAc/FAc). Concerning the elemental composition, the HA of the BC-treated soil had the highest O content, but the combination of BC and compost treatments raised the concentrations of C and N in the soil HA structure, and they increased with the increase of biochar mixing level. This result supports the ligno-protein theory of HS formation. The single application of peanut shells biochar and the combined treatments decreased the H/C molar ratio in the extracted soil HA, which indicated the high degree of aromaticity in the formed HA compared to the CK and the single application of compost. Unlike the compost, the FT-IR spectrum of the HA for the BC-treated soil showed a lowest band intensity of aliphatic functional groups. While the BCL1+compost-treated soil had a HA with the highest intensity of bands at 1544 and 1656cm^{-1} which confirmed the contribution of the biochar in the formed HA and increasing the aromaticity. This study concluded that the combined application of biochar (low level) and compost can be an effective practice for soil HA formation and enhancement of clay loam soil quality.

Keywords: Biochar, Compost, Combining application, Stability, Humic substances, Soil quality.

1. Introduction

Healthy soil is strongly associated with the quantity and quality of the soil organic matter (SOM). Stability of soil organic carbon are influenced by various parameters, such as type of soil, the incorporated organic material, biological diversity and climatic conditions (El-Ramady et al., 2024). Humic substances (HS) are the main component of the SOM. Such materials play a dynamic role in regulating soil fertility, nutrient preservation, and preventing soil degradation. According to the solubility in acid/base solutions, the HS can be fractionated into three main parts involves humic acids (HAs) which is insoluble under acidic conditions (pH<2); fulvic acids (FAs) which is represent the soluble fraction at all pH values; and humin (Hum) that is not soluble at any pH value (Sutradhar and Fatehi, 2023; Sarlaki et al., 2024). Humic acids is the most important fraction of the SOM due to its high molecular weight, aromatic rings, and functional groups. The most dominant functional groups on the humic acids surfaces includes carboxyl, carbonyl and phenol which play a crucial role in ion-exchange reactions and the stability of soil aggregates (Li et al., 2021, 2024). By altering the chemical, physical, and biological characteristics of soil, humic acid contributes significantly to soil improvement (Awad and El-Sayed, 2021). The stability of soil carbon is mainly regulated by the structural characteristics of humic acids (Stevenson, 1982; Wang et al., 2023), which are also influenced by the type of organic matter (Cui et al., 2017; Zhang et al., 2021).

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Compost is a sanitized organic amendment which produced through the biochemical conversion of biomass wastes (Sayara et al., 2020; Shaban et al., 2025). Application of compost have been demonstrated to be an efficient and recommended way to increase the SOM content, improve structure properties, nutrients availability, water retention, immobilize of soil contaminants, and as a sustainable source of soil humus (Fischer and Glaser, 2009; Atoloyea et al., 2022; Lucchetta et al., 2023; Elsonbaty and El-Sherpiny, 2024; Abdel-motaleb et al., 2025). The life cycle assessment of applying compost as a soil improver confirmed its role in nutrients supply and carbon sequestration (Martínez-blanco and Lazcano, 2013). A literature survey reported that long-term application of mature compost significantly increased the SOM content in comparison with the fresh and immature materials because of its higher stable carbon concentration (Adugna, 2018; Khadim et al., 2024). On the other side, several studies have found no changes in SOM content after applying of compost (Ren et al., 2014; Ryals et al., 2014; McClelland et al., 2022). Applying of compost to degraded soil with low level (6.7 Mg ha^{-1}) without irrigation did not improve SOC (McClelland et al., 2022). In addition, mature compost can contribute more than immature compost to the stabilization of soil organic matter (Wong et al., 2023). Although the stability of soil organic matter depends on the level of the stable carbon form (humus). However, using of compost to restore humus level in soil could require an immense and impractical application rate.

Biochar is a highly stable carbon byproduct obtained through the thermochemical conversions of the biomass, through a process called pyrolysis, at temperatures rainging between 250-900 °C in limited oxygen conditions (Rajput et al., 2024; Elhakem et al., 2025). It is considered the century's choice for carbon sequestration, promoting humus formation as well as restoring of soils against degradation (Liu et al., 2022; Mowrer et al., 2022). Despite the distinctive properties of biochar such as its higher content of recalcitrant organic carbon, surface functional groups, nutrients, and supporting the soil biological system (Nepal et al., 2024), however very small portion of biochar (4.2-5.4%) could be transformed to humic substances (Zhang et al., 2022).

Combined application method of biochar and compost to soil has attracted the attention of many scholars (particularly in sandy soils) due to its potential impact in carbon sequestration, improving soil characteristics, nutrients availability, crop productivity and restoring of soil fertility (Osman et al., 2022; Situmeang et al., 2024). In arid and semi-arid regions, the soil organic matter content is very low even with continues application of organic amendments due to the fast degradation rate of the soil organic matter because the harsh climatic conditions. Thus, sole application of compost in such regions could not be an economically approach for soil quality improvement. To the best of our knowledge, this is the first study to investigate the effect of the combined application of biochar and compost on the quantity and quality of soil humic acids. The aims of this work are include 1) study the effect of combined application of peanut shells biochar and compost on the soil characteristics, 2) the chemical composition and structural characteristics of the formed soil humic acids under both the combined and sole application of biochar and compost.

2. Materials and Methods

2.1 Experiment site

Field experiment (micro-plot) was conducted at the Research Farm of Faculty of Agriculture (27° 12′ 23″E and 31° 09 51″N), Al-Azhar University (Assiut branch), Assiut, Egypt, in November 20, 2022. The soil calssified as a clay loam in texture, which consisted of 25.5% sand, 36% silt and 38.5% clay, with bulk density of 1.52 g cm^3, pH (1:2.5 susp.) 7.72, EC_e (soil paste extr.) 1.03 dS m^{-1}, SOM 1.43 %, available N 28 mg kg^{-1}, available P 8.6 mg kg^{-1}, and available K 250 mg kg^{-1}.

2.2 Soil amendments preparation

Peanut shells (untoasted) from a local variety of Peanut (*Arachis hypogaea*) were collected, washed, air-dried, and then filled in a closed stainless tube and kept for the subsequent process. The tube was fed with 200 g of dried peanut shells and then inserted in a combustion Muffle at 400-450^{O}C in limited oxygen conditions for two hours (after reaching the required temperature). After downward the muffle temperature to the ambient temperature (≈25^{O}C), the prepared biochar was got out of the muffle, crushed, and then passed through a 0.5 mm sieve, and kept in a plastic jar until the subsequent test. Commercial compost (from plant wastes) was obtained from a local company (El-Nile company), Egypt. A part of general chemical characteristics of the produced biochar and the compost are presented in Table 1.

Table 1. Some physicochemical characteristics of the raw materials of the applied organic additives.

Materials	Bulk denesity (g cm^{-3})	pH (1:10 sus.)	EC (1:5 ex.) dS m^{-1}	Total nutrients content (g kg^{-1})			OM (g kg^{-1})	Total C (g kg^{-1})	C/N ratio
				N	P	K			
Compost	0.37 ±0.03	5.97 ±0.09	5.85 ±0.13	14.04 ±0.11	1.50 ±0.01	13.15 ±0.51	48.85 ±4.04	-	20.16
Biochar	0.33 ±0.01	8.41 ±0.05	1.17 ±0.05	8.10 ±0.48	1.23 ±0.24	9.36 ±0.25	-	82.76 ±3.41	-

2.3 Experiment setup

Field experiment (Micro-plot field experiment was placed in the center of the main plot (10.5m^2) using circular polyethylene pipes with some holes in the bottom for drainage the excess water; total area of each micro-plot was 0.0615m^2. Five treatments involved peanut shells biochar (BC) at a level of 2.5 ton/hectar (15.5g/micro-plot), compost with recommended level of 12.5 ton/hectar (77g/micro-plot), 2.5 t ha^{-1} biochar + 12.5 t h^{-1} compost (BCL1+compost), 5 t ha^{-1} biochar + 12.5 t h^{-1} compost (BCL2+compost), and the control treatment (CK) was prepared without addition any organic additives. Each organic treatment vigorously mixed within the surface (0-15cm) soil layer. All of the micro-plots fertilized with the recommended fertilizers doses for wheat plant (*Triticum aestivum*). The nitrogen (N) and phosphorus (P) fertilizers were applied in the form of urea (46 % N) and mono calcium phosphate (15% P_2O_5), at level of 2.81 and 1.5g/micro-plot, respectively. Wheat grains (local variety "Sakha 1") were sown (20 grain in each micro-plot) in November 20, 2022. The surrounding area of each main plot was sown with adequate amount of the same variety. Each treatment was repeated three times randomly. Harvesting was done for each micro-plot in May 2023. Grains yield, straw weight, and harvest index were calculated using the following equations:

Grains yield [GY (kg ha^{-1})] = $\frac{\text{Micro−plot grain yield (kg)}}{\text{Net micro−plot area (m2)}} * 16.25 * 10000$ ………………… (1)

Straw yield [SY (kg ha^{-1})]= $\frac{\text{Micro−plot straw yield (kg)}}{\text{Net micro−plot area (m2)}} * 16.25 * 10000$.......................(2)

Total Biomass yield [TBY (kg ha^{-1})] = [Grain yield (kg) + Straw weight (kg)……….(3)

Harvest index [HI (%)] = $\frac{\text{Grain yield (kg ha−1)}}{\text{Total Biomass yield (kg ha−1)}} * 100$ ……………………..……(4)

Where "16.25" refers to the number of micro plots in one square meter.

2.4 Soil sampling

After harvest, surface (0-15cm) soil layer (500g) was sampled from each micro-plot to represent the studied treatments. Each soil sample was homoginized, dried in closed room, crushed using wooden mortal, passed through 2mm sieve and then kept for subsequent analysis.

2.5 Soil analysis

Soil reaction (pH) was measured by pH meter apparatus in a soil /water suspension (1:2.5 w/v) after shaking the suspension for one hour. Electrical conductivity (EC_e) was estimated in the soil paste extract according to the standard method. Soil organic mater (SOM) content was determined by potassium dichromate method. Briefly, 0.5g of soil sample placed in 250ml conical flask, 10ml of 1.0 N potassium dichromate was added and 20ml of concentrated sulfuric acid (98%) was dropped on the sample to accelerate the oxidation of soil organic matter. Ammonium ferrous sulfate (0.5 N) was dropped to neutralize the remaining dichromate in the presence of divinylamine indicator (Walkley and Black, 1934).

2.6 Extraction and determination of soil humic substances

Humic substances (HS) were extracted from the represented soil samples using the International Humic Substances Society (IHSS) recommended method for extracting HS from soil (Swift, 1996). Briefly, 5.0g of 0.250mm dried soil sample plus 30 ml of 0.1M NaOH solution was filled into a 100 ml centrifuge tube and shaken at 145 rpm for 1 h. Then the suspension was centrifuged at 3500 rpm, filtered through 0.45 µm filter paper and then transferred into a 50 ml volumetric flask. The residual solid sample was washed with 20ml of the same alkaline solution, then centrifuged and filtered. After that, the flask completed to the volume using 0.1 M NaOH. The extracted HS solution was acidified by 6.0 M HCl at pH 1 overnight to precipitate humic acid (HA) fraction. After filtration through 0.45 µm filter paper, the coagulated part is representing the HA, While the supernatant represented the fulvic acid (FA) fraction. The HA part was dissolved in warming solution of 0.05 M NaOH and transferred into a 50 ml volumetric flask. Similarly, FA was completed by 0.05 N H_2SO_4 into a 50 ml volumetric flask. The remaining solid sample represented the humin fraction (Hum). Finally, the potassium dichromate method was used to determine the carbon content in the soil HS, HA and FA for each soil sample.

2.7 Isolation and Purification of soil humic acids

Twenty grams of dried, fine, and homogenized soil sample (passed through a 0.250mm sieve) was filled in a 250ml bottle. Each soil sample was washed with 200 ml of 0.1M hydrochloric acid solution (calcination). The ratio of soil/solution is 1:10. After closing tightly, the bottle was shaken for 15 minutes and left overnight. The next day, the clear solution (supernatant) was removed out. The precipitate part immersed with 250ml of 0.2 M of NaOH, and shaken using end by end shaking device (145 rpm) for 30 minutes and then centrifuged at 4000 rpm for 15 minutes. The supernatant represents the humic substances (HS), while the precipitated part represents humin (Hum) fraction (Aiken et al., 1985). This step was repeated four times until colorless supernatants were obtained. The extracted and filtered solutions of HS were acidified with 5.0 M HCl to pH ≈2, kept for 24 h at room temperature, and then centrifuged at 4000 rpm for 15 minutes. The supernatant represented fulvic acids fraction (FA), while the coagulated part represented humic acids (HA) fraction. The solid humic acids fraction was washed with 10 volumes of a dilute HF– HCl solution [5 mL HCl (12 M) + 5 mL HF (48%, v/v)], and kept overnight, and then centrifuged at 16000 rpm for 15 minutes. This step was repeated three times to clearly purification. The HA was washed three times with deionized water, and then filled in dialysis unit against deionized water using a 12–14-kD cut-off membrane until-chloride free. The dialyzed HA was freeze-dried and saved in a sterilized glass bottle to investigate its structural characterization.

2.8 Elemental composition of soil HA

The elemental composition (C, H, N and S) of HA extracted from the soil under different treatments was determined using Vario ELIII elemental analyzer, Germany. Briefly, about 1.4mg of the solid HA sample was weighted in aluminum capsule and filled into the instrument. The oxygen content (O) was calculated by differential subtracting.

2.9 FTIR spectroscopic analysis

The functional groups of the solid HA samples for the treatment were examined by the FT-IR spectroscopy apparatus (Nicole IS 10, USA). Briefly, 2.0 mg of the purified HA sample mixed with 400mg of upgrade KBr to make the pellet. The spectra have been acquired with the scanning rate of 16 and the phase dimension of 1/cm in the limits of 400–4000cm^{-1} wavenumbers.

2.10 E6/E4 spectroscopic ratio

The extracted soil HA of each treatment was neutralized to pH 7 using solutions of 0.05M H_2SO_4 and 0.05M NaOH, and filled in the spectrophotometer cell (2ml), and the absorbance at 465 and 665 nm was separately measured to calculate the E4/E6 ratio in order to determine the optical density of the extracted soil humic acids (Piccolo, 2002).

2.11 Humification ratio (HA/FA)

The process of low molecular weight components transforming into high molecular weight structures (polymers) is called polymerization or humification (Perminova et al., 2012; Sannino et al., 2016). This ratio reflects the degree of humification, which is the process of converting organic matter into stable humic substances. The HA/FA ratio was calculated for each treatment. Figure 1 shows overall framework of the experiment.

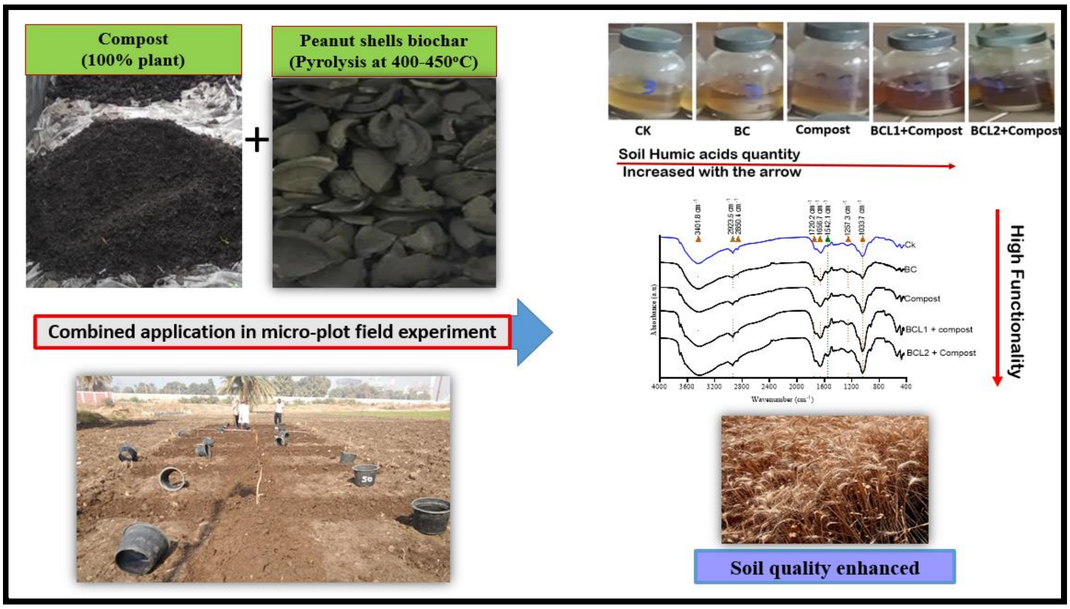

Fig. 1. Overall framework of the conducted experiment.

2.12 Statistical analysis

The obtained data were subjected to analysis of variance (ANOVA) using the general liner model procedure of Minitab statistical software version 17.1.0 (Minitab ® Inc., 2013). Means for the treatments (n=3) were compared using Duncan statistical model at probability level of 5% ± SD. GraphPad prism software version 8.1 (GraphPad Software Inc., USA) was used to draw the data of the FT-IR after fitting using Omnic 8.2 software (Thermo Fisher Scientific, Inc., 2010).

3. Results

3.1 Harvest indexes

The application of biochar and compost alone or in combination had positive influences on most of the measured harvest parameters (Table 2). The micro-plots amended with biochar + compost treatments (BCL1+compost, and BCL2+compost) had higher total straw yield (Sy), grain yield (Gy), and total biomass yield (TBy) as well as harvest index (HI) than the soil without organic amendments (CK). The increase in harvest indexes increased with the biochar level increasing (Table 2).

Table 2. Measured and calculated harvest indexes of wheat crop as affected by different organic additives.

Treatments	Gy	Sy	TBy	HI
		(Mg ha^{-1})		(%)
Ck	5.69±0.04 c	4.33±0.13 c	10.02±0.17 b	56.79±0.14 b
BC	5.85±0.31 c	4.51±0.22 c	10.36±0.52 b	56.47±0.41 b
Compost	7.86±0.09 b	4.75±0.26 b	12.61±0.35 a	62.34±0.15 a
BCL1+compost	8.36±0.29 ab	4.90±0.32 a	13.26±0.61 a	63.05±0.31 a
BCL2+compost	8.87±0.20 a	4.67±0.27 ab	13.54±0.47 a	65.52±0.26 a

Ck = no biochar or compost; BC = peanut shells biochar with 2.5 t ha^{-1}; compost with application level of 12.5 t ha^{-1} (compost); 2.5 t ha^{-1} of biochar +12.5 t ha^{-1} of compost (BCL1+compost); 5 t ha^{-1} of the biochar+12.5 t ha^{-1} of compost (BCL2+compost). Inside each column, means with different letters are significantly different at $p \leq 0.05$. Gy: grains yield; Sy: straw yield; TBy: total biomass yield; HI: harvest index.

The single application of biochar (BC) treatment raised the Gy, Sy, and TBy by 2.81, 4.16, and 2.78%, respectively, compared to CK treatment but they had similar HI value. In general, the BCL2+compost amended soil had the highest Gy, Sy, TBy, and HI with increase by 55.89, 7.85, 35.13, and 16.01%, respectively compared to the Ck.

3.2 Soil Characteristics

As can be seen in Table (3), the soil pH values varied under the effect of the different soil amendments. In general, the combined application of biochar with compost treatments reduced the soil pH than the individual application of either biochar (BC) or compost. The reduction in the soil pH decreased with the increasing of biochar level in the combined treatments. The BCL1+compost treatment reduced the soil pH by 3.7 and 2.6% compared to the pH value of the soil treated with the BC and compost, respectively. Generally, the lowest pH value (7.59) was detected under the application of BCL1+compost treatment, while the soil treated with the BC had the highest pH value (7.88). Although there was no significant difference between Ck treatment and both BC and compost treatments, however the mixing of compost with biochar together significantly reduced the soil alkalinity. Therefore, the reduction in the soil pH can be arranged in the order of BCL1+compost > BCL2+compost > BC > Compost = Ck.

Table 3. Some soil chemical characteristics as affected by various organic amendments.

Treatments	Soil pH (1:2.5)	EC_e (dS m^{-1})	SOM (g kg^{-1})
CK	7.79	1.19±0.08b	17.77±1.62e
BC	7.88	1.19±0.05b	21.35±0.12d
Compost	7.79	1.34±0.01ab	25.37±1.31c
BCL1+compost	7.59	1.36±0.03a	29.98±0.71b
BCL2+compost	7.75	1.38±0.08a	34.26±1.03a

#Ck = no biochar or compost; BC = peanut shells biochar with 2.5 t ha^{-1}; compost with application level of 12.5 t ha^{-1} (compost); 2.5 t ha^{-1} of biochar +12.5 t ha^{-1} of compost (BCL1+compost); 5 t ha^{-1} of the biochar+12.5 t ha^{-1} of compost (BCL2+compost). Inside each column, means with different letters are significantly different at $p \leq 0.05$. EC_e (Electrical conductivity of the soil paste extract); SOM= soil organic matter.

Salinity is a common factor that limits soil quality and productivity. Unlike the compost, the BC treatment did not increase the electrical conductivity (EC_e) of the soil paste extract compared to the Ck (Table 3). While the compost, BCL1+compost, and BCL2+compost treatments increased the soil EC_e by 12.61, 14.29, and 15.97%, respectively, compared to the Ck. Soil organic matter (SOM) content significantly differed among the individual and combined application of the BC and compost (Table 3). All treatments raised the SOM content compared to the Ck treatment. The highest SOM (34.26 g kg^{-1}) content was investigated when the soil was treated with the BCL2+compost, while the Ck had the lowest SOM (17.77 g kg^{-1}) content.

3.3 Quantity of soil humic substances as affected by different organic amendments

Humic substances (HS) are the sensitive soil organic matter fraction that regulate the geochemical processes in soils. Unlike the compost, the single application of biochar (BC) did not increase the of carbon content of the soil humic substances (HSc) and their fractions except the humin (Hum) carbon content. While the combination of biochar with compost increased the HSc and their fractions (Table 4). In the combined treatments, as the biochar level increase the soil humic acids carbon content (HAc) increased. The concentration of the soil HS carbon content increased by 52, 43, and 15% in the soils treated with the BCL2+compost, BCL1+compost, and compost, respectively. Concerning the fractions of the HSc, the humic acids carbon (HAc) content increased by 68.4, 57.4, and 14.7% in the soil amended with BCL2+compost, BCL1+compost , and compost, respectively compared to the HAc content of both BC and Ck treatments. The concentration of fulvic acids carbon (FAc) content increased by 36.7, 30.2, and 22.3% under the application of BCL2+compost, BCL1+compost , and compost, respectively, in compared to CK. In general, the highest HAc and FAc content was recorded when the soil was amended with the BCL2+compost treatment, while the CK and BC exhibited the lowest HAc and FAc carbon content (Table 4). Regarding to the humin carbon (Hum) content, it significantly increased with the increasing of the SOM content. The HAc/FAc ratio is a good parameter to determine the polymerization, which is considered as stability index. Although, the BC treatment did not encourage polymerization of low molecular weight components (fulvic acids) in the soil but the mixing of peanut shells biochar with the compost enhanced this process. The HAc/FAc ratio increased by 20.4 and 23.5% in the BCL1+compost and BCL2+compost treatments compared to the Ck treatment. On contrast, the compost treatment decreased the HAc/FAc ratio by 7.0% compared to the BC-treated soil. The highest HAc/FAc ratio gained in the soil treated with the BCL2+compost.

Table 4. Humic substances carbon content and its fractions under different organic amendments .

Treatments	*HSc	HAc	FAc	Hum	HAc/FAc
	($g\ kg^{-1}$)				
CK	2.75±0.22^{c}	1.36±0.14^{c}	1.39±0.08^{c}	7.79±1.16^{c}	0.98±0.04^{b}
BC	2.74±0.33^{c}	1.36±0.08^{c}	1.38±0.19^{c}	9.60±0.40^{bc}	0.99±0.03^{b}
Compost	3.16±0.18^{b}	1.56±0.20^{b}	1.70±0.09^{b}	10.44±0.54^{bc}	0.92±0.19^{b}
BCL1+compost	3.93±0.29^{a}	2.14±0.21^{a}	1.81±0.14^{b}	12.49±0.70^{b}	1.18±0.06^{a}
BCL2+compost	4.18±0.07^{a}	2.29±0.08^{a}	1.90±0.00^{a}	16.10±1.38^{a}	1.21±0.05^{a}

***** HSc means the humic substances carbon content; HAc is the humic acids carbon content; FAc is the fulvic acids carbon content; and Hum is humin carbon content; HAc/FAc = humification index; Ck = no biochar or compost; BC = peanut shells biochar with 2.5 t ha^{-1}; compost= compost with application level of 12.5 t ha^{-1}; BCL1+compost = 2.5 t ha^{-1} of biochar +12.5 t ha^{-1} of compost; BCL2+compost = 5 t ha^{-1} of the biochar+12.5 t ha^{-1} of compost. Inside each column, mean values with different letters are significantly different at $p \leq 0.05$.

3.4 Elemental composition of soil humic acids

The elemental composition (C, H, N, S and O) and the O/C and H/C molar ratios of the isolated and purified soil humic acids (HA) under various soil amendments are presented in Table 5. Concerning the BC treatment, the HA of the BC-treated soil had the lowest concentrations of C, H, N, and S but it had a highest O content in compared to the other treatments. This is due to the presence of oxygenated functional groups on the biochar surfaces. The combination of biochar and compost treatments raised the concentrations of C and N in the soil HA compared to the sole application of BC and compost treatments. The C and N content increased with the increase of biochar mixing level. Moreover, the concentration of H increased with the increase of biochar mixing level in the combined treatments in compared to the BC treatment. The soil HA of the BCL2+compost treatment had the highest C and N content in comparing with all treatments. With reference to the O/C and H/C molar ratios of the soil HA, the sole application of peanut shells biochar gave the highest O/C molar ratio, but it reduced the H/C molar ratio of the isolated HA compared to the CK and compost treatments. The soil HA of the BC, BCL1+compost and BCL2+compost had lower H/C than CK and compost treatments, which indicates the higher degree of aromatization in the formed HA. The H/C molar ratio versus O/C molar ratio diagram, which is called Van Krevelen diagram has been used to show the variations in humic substances as a function of source (Rice and MacCarthy, 1991). As illustrated in Figure 2, the decrease in the H/C molar ratio with the increase of biochar level in the combining treatments of biochar and compost confirmed the higher degree of aromatization of the formed HA under the mixing treatments. The optical density of the neutralized HA solution (pH≈7) under the various treatments was determined through measuring the absorbance at 465 and 665 nm to calculate the E4/E6 ratio. This ratio is often used to characterize humus. It is also inversely linked to the degree of condensation, aromatization of the humic substances, degree of humification, and correlated with the condensation of free radical (Stevenson, 1994). The E4/E6 ratio of the soil HA samples for the studied treatments shown that the degree of condensation increased significantly in the order: BC > CK > BCL2+compost > BCL1+compost > compost. The humic acids isolated from the BC-treated soil appears to be characterized by high condensation of the aromatic structure and low in aliphatic chain content. The results of optical density of the soil HA under the various treatments is in harmony with the results obtained using FTIR spectroscopy.

Table 5. Elemental composition of soil humic acids under the different organic amendments.

Treatments	C	H	N	O	S	O/C	H/C	E4/E6
			(%)					
CK	22.23	2.55	3.69	69.63	1.90	2.35	1.123	2.73±0.25b
BC	21.24	1.47	2.62	73.68	0.99	2.60	0.830	2.33±0.22a
Compost	28.16	2.38	3.28	64.41	1.77	1.72	1.013	6.86±0.05e
BCL1+Compost	28.87	2.02	3.90	64.16	1.05	1.67	0.840	5.81±0.30c
BCL2+Compost	32.83	2.29	4.04	59.41	1.43	1.36	0.837	5.32±0.22d

***** Ck = no biochar or compost; BC = peanut shells biochar with 2.5 t ha^{-1}; compost = compost with application level of 12.5 t ha^{-1}; 2.5 t ha^{-1} of biochar +12.5 t ha^{-1} of compost (BCL1+compost); 5 t ha^{-1} of the biochar+12.5 t ha^{-1} of compost (BCL2+compost); The O/C and H/C mean the molar ratio of oxygen/carbon and hydrogen/carbon; E4/E6 is the optical density of the humic acids solution at 465 and 665nm.

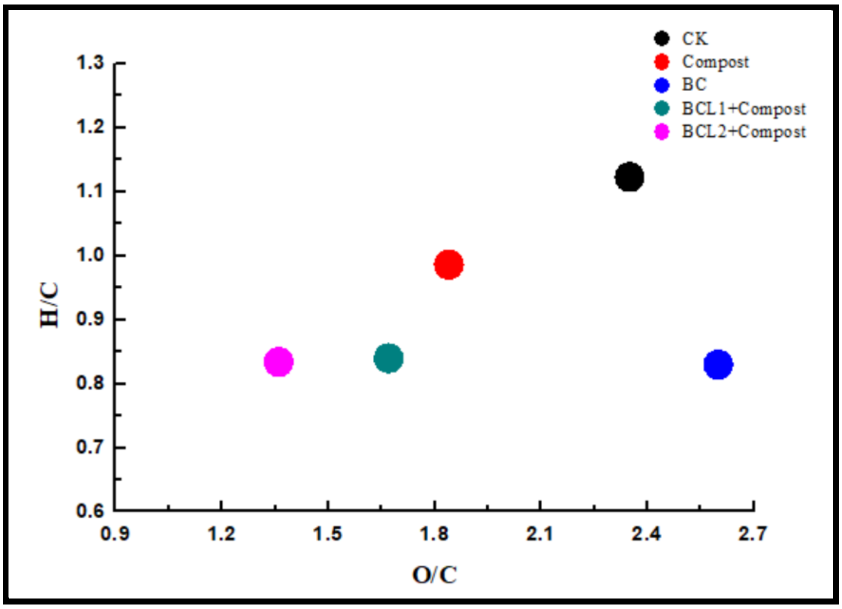

Fig. 2. Relationship between H/C and O/C molar ratios of the soil HA samples under the effect of different organic treatments.

3.5 FTIR spectra of the soil HA

The FTIR spectra of the isolated and purified soil HA under the various organic treatments are shown in Figure 3 as well as the corresponding assignments of the various functional groups are explained in Table 6. It can be inferred that all of the HA spectra shared similar bands assignments at 3400, 2920, 2850, 1720, 1630, 1541, 1224, and 1023 cm^{-1} with some differences in their relative intensities. These band correspond to the stretching vibration of H-OH, C–H, C–H, –COOH, C=O, C=C, C–O stretch, and C-H stretching of polysaccharide, respectively. Correspond to the aliphatic functional groups (3400, 2920, 2850, 1720, 1224, and 1023cm^{-1}), the HA spectrum of the BC-treated soil exhibited a lowest band intensity at the wavenumber of 2920, 2850, and 1024cm^{-1} in comparing with the Ck and the other treatments. While, the HA spectra of the soil treated with the compost, BCL1+compost and BCL2+compost had the same bands with higher intensities than BC due to the addition of compost.

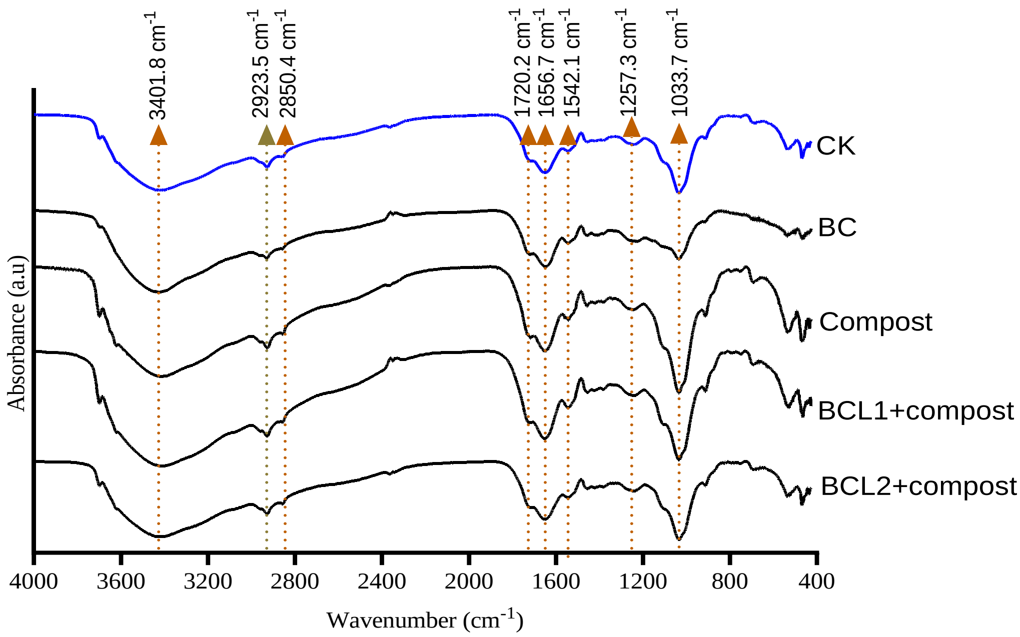

Fig. 3. FTIR spectra of the isolated soil humic acids (HA) samples for control (CK), biochar (BC), compost (Compost), biochar with level of 2.5 t ha^{-1} +12.5 t ha^{-1} of compost +compost (BCL1+compost), biochar with level of 5 t ha^{-1} + compost (BCL2+compost) treated soil.

Regarding to aromatic functional groups, all of the soil HA spectra had a wide band at 1656 cm^{-1} but the FTIR spectra of the soil HA isolated from the BCL1+compost and BCL2+compost had higher relative intensity at the same wavenumber (Figure 3). This means that the addition of biochar in combining with the compost increased the peak intensity of 1656cm^{-1}. Therefore, biochar increased the aromaticity of the soil HA. The spectrum of soil HA isolated from the BCL1+compost treatment had a greatest intensity at the band of 1542cm^{-1}

Table 6. Attributions functional groups of the FTIR peaks of the extracted soil humic acids under different organic treatments.

Wavenumber (cm^{-1})	Functional group
3400	O-H stretching of phenols, alcohols, organic acids, as well as H bonded N-H groups.
2930	Symmetric C-H stretching in $-CH_3$ and $-CH_2-$ of aliphatic chains.
2850	Asymmetric C-H stretching in $-CH_3$ and $-CH_2-$ of aliphatic chains.
1720	C=O stretching of COOH and other carbonyl groups
1656	C=C skeletal vibrations of aromatic and C= O stretching of quinine
1545	C=C stretching of aromatic.
1237	C-O stretching of aryl ethers and phenols
1024	C-O stretching of polysaccharide and polysaccharide-like substances,

3.6 Economic Viability

In this experiment, the single application of peanut shells biochar decreased the net profit by 45% compared to the Ck treatment (Table 7). On the other hand, the combined application of biochar with compost increased the net profit by 262 and 267% in the BCL1+compost and BCL2+compost, respectively. However, the application of compost alone also increased the net profit by 93% compared to the treatment without organic amendments. Therefore, the application of the BC + compost is economically the best practice.

Table 7. The economical viability from the applied soil amendments.

Treatments	**sTotal Inputs**		**Total Outputs**		Gross profit (US $/ha)	Total expenses (US $/ha)	Net profit (US $/ha)
	Farming Costs (US $/ha)	Mean price of the total applied amount of soil amendment (US $/ha)	Total price of grain yield (US $/ha)	Mean price of accumulated soil humic substances (US $/ha)			
CK	1,000	0	1,458	0	1,458	1,000	458
BC	1,030	200	1,483	0	1,483	1,230	253
Compost	1,050	250	1,899	286	2,185	1,300	885
BCL1+Compost	1,080	450	2,073	1,114	3,187	1,530	1,657
BCL2+Compost	1,090	650	2,094	1,329	3,423	1,740	1,683

#Farming costs (US$/ha) = the rent of one hectar of soil +labor costs/ha +inorganic fertilizers costs/ha +irrigation costs/ha+ harvest costs/ha; Mean price of the total applied amount of soil amendment (US$/ha)= the applied amount of soil amendment (t/ha) * the price of a ton of this amendment (US$); Total price of grain yield (US $/ha)= the grain yield (t/ha) * the price of one ton; Mean price of accumulated soil humic substances (US$/ha) = the accumulated amount from each treatment (t/ha) * the price of a ton (US$); Gross profit (US $/ha)= Σ of outputs; Total expenses (US $/ha)= Σ of inputs; Net profit (US $/ha)= Total outputs-Total inputs.

4. Discussion

4.1 Harvest indexes and soil characteristics

The positive and significant effect of application compost individually or mixed with the biochar strongly supports the importance of compost in grain filling due to its higher nutrients than BC. Agegnehu et al. (2017) demonstrated that grain yield and total biomass of maize crop were higher in the combined application of biochar and compost plus chemical fertilizers than them in the untreated soil. In contrast to the obtained result, Gebremedhin et al. (2015) found that the single application of biochar amended soil was superior the grain and straw yields of wheat plant than mixing of biochar and compost treatment in clay soil. Compost combined with biochar could further increased the chelation of nutrients by humic acid to become more available to plants (Situmeang et al., 2024).

Concerning soil properties, combined application of compost and biochar could neutralize soil reaction (pH) through consumption of protons by the released OH groups during dissociation of phenolic function groups. In addition, biochar is recalcitrant carbon which could stabilized the labile OM when the biochar is combined with compost and therefore provides a negative priming effect (Fischer and Glaser, 2012). On opposite, the application of biochar alone (BC) was increased soil pH because of the alkaline nature of the applied biochar. Iqbal et al. (2015) reported that application of biochar alone increased the soil pH through the OH groups those released from the dissociation of phenolic functional groups. Mikajlo et al. (2024) found that the single application of composted biochar and compost neutralized the soil pH in Fluvisol and Luvisol, while the application of biochar (alone or combined with compost) slightly increased the soil pH. In contrast, the mixing application of goat manure compost and chicken manure biochar results in an increase in the soil reaction (Situmeang et al., 2024).

In relation to the EC_e, the higher EC_e values of the compost, BCL1+compost and BCL2+compost treated soils is corresponded to the high EC value of the applied compost (5.85 dS m^{-1}) (Table 1). Combined application of biochar and compost reduced the concentration of dissolved salts, pH and bulk density in saline calcareous soils compared to untreated soil (Shaaban et al., 2024). The reduction of soil EC and pH under the combined application of biochar and compost enhanced the absorption of specific micronutrients and aids to regulate the ionic balance of the soil solution (Garau et al., 2024; Shaaban et al., 2024). The increase of SOM is due to the high OC content of the applied raw materials.

4.2 Quantity assessment of soil humic substances

The lowest HSc in the BC-treated soil could be due to the low humic substances carbon content of the applied biochar. On the other side, the high HSc, HAc and FAc in the soils treated with BCL1+compost and BCL2+compost treatments is strongly supporting the importance role of the free radicals of biochar in polymerization of released organic acids (from compost), which is considered as a good index for SOM stability assessment. The FTIR spectra are in the same line of these results. Combined application of caw biochar and caw compost increased the soil HA and FA carbon compared to single application of each of them (Situmeang et al., 2024). In composting, treating of composting wastes with biochar increased carbon content and stability of HA and FA with composting substrates well as enriched the HA with carboxylic and aromatic functional groups (Jindo et al., 2016).

4.3 Quality assessment of soil humic acids

The lower H/C molar ratio of the soil HA isolated form BC, BCL1+compost, and BCL2+compost amended soils, confirmed the presence of lignin in the applied biochar which indorses the contribution of biochar in the formation of HA with more stability. In addition, the high E4/E6 ratio refers to the presence of O-containing functional groups such as hydroxyl, carbonyl, carboxyl, and ester groups, while low E4/E6 ratio indicates the presence of humic acids with higher molecular weight constituents. The ratio lower than 5 is characteristic of humic acids while fulvic acids have higher ratios; this ratio is independent of the concentration of humic materials but it is differed from soil to another due to the differences in the soil additives. Piccolo, (2002) stated that the E4/E6 ratio of the humic substances is related to the degree of condensation of the aromatic carbon lattice, a weak ratio indicating a high degree of condensation of the aromatic humic components, while a strong ratio indicating the presence of a higher proportion of low molecular weight constituents (aliphatic structures).

Regarding to the results of FTIR, the bands belong to aliphatic structures decreased in the charred materials like biochar, while it increased in the compost treatment due to the decomposition of easily degradable organic matter. Thus, the application of compost into the soil could enhance the aliphatic functional groups in the formed humic acid. Zhang et al. (2014) stated that the band of 1024cm^{-1} is related to C–O stretching of polysaccharides or polysaccharide-like substances in the HA structure. The band at 1542cm^{-1} is also attributed to C=C stretching vibration of aromatic functional group (Wu et al., 2016) which indicates the interaction between the oxygenated functional groups on the surface of biochar and the native soil HA which lead to form more strong and stable HA.

5. Conclusions

Enhancing SOM stability is required to mitigate soil degradation. The sole application of compost under the arid conditions leads to rapid oxidation rate of easily oxidizable carbon materials (e.g., compost). This could lead to negatively impact on the stability of organic matter under these conditions. Biochar plays a vital role in the dry climate, as it is a carbonaceous material that is not easily to degrade and has the ability to interact with the compost constituents, leading to the production of more stable humic substances under these conditions. Therefore, mixing of biochar with the compost is not only beneficial for sandy soil improvement but it has a curial role in the formation and stability of soil humic materials particularly in heavy clay soils in the arid and semi-arid conditions. In this study, applying compost alone into a clay loam soil increased its content of humic substances but did not support the stability. To maximize the formation and stability of soil humic acids particularly in short-term application, charred materials like peanut shells biochar should be combined with the compost for soil HS stability enhancement. In addition, application of compost and biochar together into the soil increased grains yield, straw yield, total biological yield, and harvest index higher than individual application of both of them. Moreover, the soil characteristics such as pH decreased, while the soil EC_e and SOM were increased under the combined application of peanut shells biochar and compost. Although, single application of biochar did not increase the soil HS carbon and their fractions (HAc and FAc), but the combination treatments of biochar with compost increased the quantity and quality of soil HS. The BCL2+compost treatment increased the soil HS, HAc, FAc, Hum, HAc/FAc, and E4/E6. In addition, the stability of the HA structure was more under the application of combination biochar and compost. Thus, the combining application of biochar and compost is an important strategy for mitigation soil degradation through soil quality enhancement. Future researches are required to test many types of biochar combined with compost from different sources.

Declarations

Ethics approval and consent to participate

Consent for publication: The article contains no such material that may be unlawful, defamatory, or which would, if published, in any way whatsoever, violate the terms and conditions as laid down in the agreement.

Availability of data and material: Not applicable.

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