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The Impact of Biochar and Compost as Soil Amendments, Combined with Poultry Manure, on the Growth, Yield, and Chemical Composition of Lettuce (*Lactuca sativa*)

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ABSTRACT

Farmers must prioritize soil enhancement methods to preserve soil health and sustainability as the world population grows, whereas arable lands deplete and degrade owing to poor land management and agricultural policy. Biochar and compost are essential for replacing nutrients and organic matter, improving soil quality. In 2019, an experiment was carried out at Jordan University of Science and Technology. Various soil amendments, including biochar and compost, both with and without the combination of poultry manure, were employed. The experimental design followed a completely randomized layout, with seven distinct treatments: T1 – soil (control), T2 – biochar (3%) (BC), T3 – compost (3%) (Comp), T4 – poultry manure (3%) (PM 3% (38.2 ton/ha)), T5 – Biochar (3%) + poultry manure (60 ton/ha) (BC + PM 60 ton/ha), T6 – compost (3%) + poultry manure (60 ton/ha) (Comp + PM 60 ton/ha), and T7 – poultry manure (60 ton/ha) (PM 60 ton/ha). The assessment encompassed the examination of various physicochemical characteristics of the soil, including bulk density, porosity, water holding capacity, pH, and EC. Morphological and physiological measurements comprised height and length of plant shoots and roots, number of leaves, fresh and dry weight of shoots and roots, leaf relative water content, and chlorophyll content. Additionally, the chemical composition, encompassing crude fibers, crude fats, antioxidant activities, total phenols, flavonoid content, and minerals were evaluated. Physicochemical results revealed that (BC + PM 60 ton/ha) excelled in water holding capacity and porosity, whereas PM 60 ton/ha exhibited the optimal soil pH. In terms of morphological results, (Comp + PM 60 ton/ha) and (PM 3% (38.2 ton/ha)) demonstrated superiority in plant height, shoot fresh and dry weight. The application of (BC) outperformed in root fresh and dry weight and leaf relative water content, while (Comp) exhibited the highest root length. Poultry manure applications scored higher values in chlorophyll content, with (BC+PM 60 ton/ha) recording the highest among them. Chemical analysis revealed that crude fibers were highest with the application of (PM 3% (38.2 ton/ha)), while (control) recorded the highest antioxidant activities, total phenols, and total flavonoids. In terms of mineral content in shoots, (Comp + PM 60 ton/ha) demonstrated the highest nitrogen content. Phosphorus, potassium, magnesium, and calcium were most abundant in (BC + PM 60 ton/ha). Moreover, PM (60 ton/ha) exhibited the highest sodium content. Notably, the (BC + PM 60 ton/ha) application excelled in physiochemical soil properties, excluding soil pH and EC, while also demonstrating superior mineral content in lettuce plants, except for sodium.

Keywords: biochar, compost, soil amendments, poultry manure, lettuce.

INTRODUCTION

The rapid global population growth has prompted the agricultural sector to intensify crop and animal production to fulfill the growing needs. Consequently, substantial waste residues are generated post-harvest, along with significant waste from animal farming. Improper disposal methods, such as burning in incinerators to prepare fields for the next crop, can result in increased atmospheric CO_2

levels, potentially contributing to climate change and environmental issues. In addition, inadequate management of animal wastes not only poses environmental threats but also raises concerns about health issues. To alleviate the environmental impact of certain materials, it is crucial to treat and convert them into economically valuable substances. This process enables the return of their primary components, organic matter, and nutrients, to the soil. Developing cost-effective, eco-friendly practices is essential for preserving environmental sustainability and ensuring a continuous nutrient supply. Treated wastes show promise as soil amendments in this regard. Unsustainable farming practices and overcropping contribute to soil degradation, leading to decreased soil fertility (El-Radaideh et al., 2014). In response, farmers often resort to using inorganic fertilizers for increased productivity (Turk and Tawaha, 2002; Al Tawaha et al., 2013; Al-Tawaha et al., 2017; Al-Tawaha et al., 2018; Al-Ghzawi et al., 2019; Amanullah et al., 2020; Ali et al., 2022; et al., 2022; Mitra et al., 2022; Reddy et al., 2022). However, excessive use of chemical fertilizers adversely affects soil quality and poses environmental challenges (Han et al., 2014). To address this issue, an alternative approach was proposed by encouraging farmers to utilize treated plant residues and poultry manure as fertilizers or soil amendments. This not only prevents waste accumulation but also mitigates potential environmental problems. Consumers increasingly prefer the vegetables grown without synthetic fertilizers due to the health concerns associated with chemical fertilizers (Asaduzzaman et al., 2010). Introducing soil amendments derived from organic materials, such as treated plant residues and poultry manure, offers a solution. These amendments help reduce the presence of toxic compounds like nitrates produced by conventional fertilizers in vegetables. This, in turn, improves both the quality and quantity of vegetable production, positively impacting human health (Masarirambi et al., 2010). Incorporating organic fertilizers, such as compost and manure, enriches the soil with organic matter and essential nutrients, enhancing plant nutrition (Jamsheed et al., 2023; Khan et al., 2023; Bayanati et al., 2023; Karnwal et al., 2023; Ranjan et al., 2023; Singh et al., 2023a, b, c; Tawaha et al., 2023; Wanikar et al., 2024). Soil amendments refer to materials incorporated to enhance the chemical and physical characteristics of the soil. Organic soil amendments consist of compounds derived from biomasses and living organisms, including compost, wood chips, biochar, animal feces, hay, husk, and geotextile (Al-Taey et al., 2019; Hani et al., 2019; Maiti and Ahirwal, 2019; Imran et al., 2021; Amanullah et al., 2021; Saranraj et al., 2021; Al Tawaha et al., 2022; Ali et al., 2022; Imran et al., 2022; Amanullah et al., 2022; Amanullah et al., 2023; Imran et al., 2023; Qaisi et al., 2023; Singh et al., 2023a, b, c; Al Tawaha et al., 2024; Singh et al., 2024). The incorporation of fresh organic matter into the soil has demonstrated benefits such as increased soil organic matter and nitrogen content, enhanced biological activity of soil, and improved crop yields (Gattinger et al., 2012; Lehtinen et al., 2014). Recent focus has been directed toward enhancing soil humus quality and quantity through amendments involving highly modified organic matter, particularly those derived from fermented biomasses (Piccolo, 2012). The addition of soil amendments, such as compost, has been shown to effectively sequester soil organic carbon for an extended period (Mondini et al., 2012). Utilizing organic waste-derived soil amendments is favored over mineral fertilizers and other inorganic amendments, because it addresses animal waste concerns and mitigates environmental pollution problems (Leogrande et al., 2013). Conversely, inorganic amendments using chemical fertilizers have demonstrated limited coverage, not exceeding 50%, and have shown minimal improvement in soil physical properties (Young et al., 2015). Continuous cropping without the addition of fertilizers diminishes soil nutrients in Jordan, especially in the soils lacking sufficient organic matter (Khresat et al., 1998). Jordanian soils are facing degradation due to improper farming practices, climate change, and soil erosion, creating an urgent concern (El-Radaideh et al., 2014). Soil amendments present a promising solution to these issues, offering the potential to enhance the quality of impoverished Jordanian soils without environmental hazards.

Lettuce (Lactuca sativa), a crucial and widely cultivated vegetable globally, belongs to the Asteraceae family. It is adaptable to both open field and greenhouse conditions, typically grown in winter with a short growing cycle. Primarily used for salads, lettuce faces high demand worldwide. This demand has prompted lettuce farmers to explore greenhouse cultivation for increased yield and improved quality. Despite the importance of lettuce production, the knowledge about the most effective soil amendments, with or without poultry manure, remains limited. Hence, this research aimed to evaluate the response of lettuce plants, specifically the "Romaine" cultivar, to various soil amendments with and without fertilizers under greenhouse conditions. The hypothesis posits that incorporating poultry manure into the soil amendment will positively impact lettuce production, leading to improved quality when grown under greenhouse conditions, as tested in pot experiments. The overarching objective of this experiment was to explore the potential impact of soil amendments, both with and without the inclusion of poultry manure, on the growth, quality, and yield of lettuce.

MATERIALS AND METHODS

The study took place in the Greenhouses of the Agriculture Research Center at Jordan University of Sciences and Technology (JUST) campus during the winter growing season of 2019. The objective was to explore the potential impact of soil amendments (biochar and compost), both with and without the inclusion of poultry manure, on the growth, quality, and yield of lettuce, specifically the Romaine cultivar, under greenhouse conditions. This research comprised two phases. In phase I, lettuce seedlings were planted inside the greenhouse during the winter growing season, and measurements were taken on plant shoot and root development. In phase II, lettuce heads were subjected to oven drying at 35 °C for 7 days, followed by a comprehensive analysis in the laboratory to assess morphological, physiological, biochemical, and selected physicochemical properties.

Experimental design, layout and preparations

Lettuce cultivar Romaine served as the subject for this research. The experimental design adopted a completely randomized layout (CRD) featuring seven treatments, with four samples allocated to each treatment. The treatments included T1: soil, T2: Biochar (3%, 38.2 ton/ha, equivalent to 120 g/pot), T3: compost (3%), T4: poultry manure (3%), T5: Biochar (3%) + poultry manure (60 ton/ha, equivalent to 188.4 g/pot), T6: compost (3%) + poultry manure (60 ton/ha), and T7: poultry manure (60 ton/ha). The biochar used in this study was obtained from slow pyrolysis of tomato crop residue at 300–350 °C of tomato crop residue for an hour. After pyrolysis, the biochar was ground to a uniform particle size (2 mm) prior to experimental use. Compost was obtained from a local market in Irbid. Poultry manure was obtained from JUST animal farm. The biochemical properties of the soil, biochar, compost and poultry manure are shown in (Table 1).

Set up of the pot experiment

On November 3rd, 2019, lettuce cultivar Romaine seedlings were transplanted into plastic pots measuring 20 cm in diameter and 20 cm in height. The transplantation rate was one seedling per pot. Each pot was filled with approximately 4 kg of silt loam soil, with a composition of 24% sand, 74% silt, and 2% clay. Treatments were applied based on dry weight measurements. After the application of biochar, compost, and fertilizer, the soil in each pot was thoroughly mixed. Irrigation was conducted every 3 to 4 days, ensuring that all pots received an equal amount of water. Soil texture was determined through hydrometer analysis (Klute, 1986). The experiment concluded on December 30th, 2019.

Physicochemical measurements of treatments

In the initial week of November, the physicochemical properties of the treatments,

Table 1. Soil, biochar, compost and poultry manure biochemical analysis

Biochemistry analysis	Soil	Biochar	Compost	Poultry manure
N mg/kg	0.072	1.393	0.821	5.685
P mg/kg	1.42	620.82	568	1644.65
K mg/kg	54.95	132.9	167.65	744.45
Mg mg/kg	228.95	137.1	127	685.95
Ca mg/kg	1512.76	725.9	82.82	3968.72
Na mg/kg	419.65	108.32	125.95	820.62
OM	3.422	–	41.507	11.853
C:N	27.63	39.1	29.39	1.21

Note: N – nitrogen, P – phosphorus, K – potassium, Mg – magnesium, Ca – calcium, Na – sodium. All data represent the mean of 4 replicates.

encompassing bulk density, porosity, maximum water-holding capacity (WHC) at zero tension, pH, and electrical conductivity (EC), were assessed. The measurements followed the methodologies outlined by De Boodt and Verdonck (1971), Brown and Pokorny (1975), Landis (1990), and Sabahy et al., (2014). Laboratory assessments were conducted using a ratio of 1:4 (25 grams of treatment to 100 ml deionized distilled water). Bulk density was determined through the core method as per ISO standards (2017), and porosity was subsequently calculated from the bulk density measurements

Measurements and data collection

Morphological characteristic

Lettuce head height, the number of leaves, the shoot and root fresh and dry weights were measured.

Physiological measurements

Leaf relative water content (LRWC) and leaf chlorophyll content were measured.

Shoot biochemical analysis

Determination of total nitrogen content in shoot

The determination of the total nitrogen was carried out using the Kjeldahl method as described by the Association of Official Agricultural Chemists (AOAC, 1995).

Determination of phosphorus content in shoot

Total phosphorus in plant shoot was determined by dry ashing procedure using the spectrophotometer method, as described by (Chapman and Pratt, 1961).

Determination of sodium and potassium content in shoot

Concentrations of both sodium and potassium were directly obtained from a constructed standard curve (AOAC, 1995).

Determination of magnesium and calcium content in shoot

The magnesium and calcium contents were calculated by titration according to (Heald, 1965) in laboratory.

Quality analysis

Determination of total fibers in shoot

Total crude fibers were calculated according to Van (1966) methods in a laboratory.

Determination of total fat in shoot

Crude fat percentage was calculated by Ether Extract according to Thiex et al. (2003) methods in a laboratory.

Extract preparation for total phenolic content

Total flavonoids and free radical-scavenging activity for shoot.

Total phenolic content for shoot

The total phenolic content of the solvent extracts was determined using Folin-Ciocalteu reagent and Gallic acid as standard to produce the calibration curve (Slinkard and Singleton, 1977).

Determination of total flavonoid for shoot

The total flavonoid contents of lettuce plants were determined by the colorimetric method (Zhishen, Mengcheng and Jianming, 1999).

Free radical-scavenging activity: DPPH assay: (antioxidant activity)

Scavenging activity of DPPH radicals of lettuce plants was measured according to the method described by (Brand-Williams, 1995).

Statistical analysis

The data collected from this research were statistically analyzed using general linear model (GLM) analysis using the statistical software package SAS version 9.2 (2002). Means separation was performed according to the least significant difference (LSD) test at 0.05 probability level ($P \leq 0.05$).

RESULTS AND DISCUSSION

The various soil amendments, both with and without the addition of poultry manure, exhibited notable statistical variances in the physicochemical properties, morphological characteristics, physiological traits, and biochemical attributes of lettuce. These differences were observed despite the limited existing literature on the combined use of soil amendments with poultry manure, specifically in the (BC + PM 60 ton/ha) and (Comp + PM 60 ton/ha) treatments.

Physiochemical properties of treatments

The outcomes revealed significant variations in physicochemical properties among the treatments (refer to Table 2). The soil treated with biochar (BC) exhibited a notable increase in pH by 0.17 units. This pH elevation aligns with the findings from previous studies (Ghorbani et al., 2019; Mensah and Frimpong, 2018; Manolikaki and Diamadopoulos, 2017) where biochar amendments led to an increased soil pH. This rise can be attributed to the inherently high pH of biochar, primarily attributed to alkaline carbonates, alkaline earth metals, and organic anions (Li et al., 2016). However, all applications incorporating poultry manure resulted in a reduction in soil pH. The treatment with compost and poultry manure (Comp + PM 60 ton/ha) exhibited the lowest pH value, with a decrease of 0.55 units. This reduction may be attributed to the generation of organic acids during the decomposition of organic matter (Antil and Singh, 2007). Furthermore, the application of compost alone also contributed to a decrease in soil pH, possibly due to the acids released by microorganisms during the degradation of lipids and carbohydrates (Azim et al., 2018).

The electrical conductivity (EC) of the soil increased with the treatments containing biochar and poultry manure, reaching its highest value with the (BC + PM 60 ton/ha) application. This rise can be attributed to the inherently high EC in both biochar and poultry manure. Previous studies by Tasneem and Zahir (2017), Mohawesh et al. (2018), have suggested that biochar increases soil pH, potentially due to the presence of salts in biochar. Additionally, poultry manure contributes to increased soil EC, likely due to elevated levels of calcium ions (Ca^{+2}) (refer to Table 1), as observed in gypsum-amended soils where EC tends to increase. The treatments showed significant differences in soil water holding capacity percentage (WHC%). The highest WHC% was observed with the (BC + PM 60 ton/ha) application, potentially owing to the presence of biochar. Previous research has indicated that biochar has the capacity to enhance water holding capacity (Novak et al., 2009; Karhu et al., 2011). The improvement in water holding capacity with biochar amendments may stem from a combination of soil and biochar type, biochar amendment rate, and biochar properties (Barnes et al., 2014; Andrenelli et al., 2016). There was no significant difference between (BC + PM 60 ton/ha) and (Comp + PM 60 ton/ha), which may be attributed to the presence of compost. Compost is known for its water retention ability, providing a continuous water supply to plants over time. This characteristic is associated with the increase in large pores facilitated by compost, particularly those retaining water at a tension of around 5 kPa (Aggelides and Londra, 2000). Bulk density was consistently reduced across all treatments compared to the control. Previous studies have consistently shown that the application of organic matter to soils leads to a reduction in bulk density (Khaleel et al., 1981; Pengcheng et al., 2007; Pricea and Voroney, 2007; Evanylo et al., 2008; Ozenc and Ozenc, 2008; Curtis and Claassen, 2009). Among biochar applications, (BC + PM 60 ton/ha) resulted in the greatest reduction in bulk density. Changes in bulk density indicate alterations in soil macrostructure, influenced by particle aggregation from both biotic and abiotic processes (Bronick and Lal, 2005). Compost applications also contributed to reduced bulk density, attributable to increased porosity, as indicated by the expansion of pore spaces (refer to Table 2). This aligns with the findings of Rivenshield and Bassuk (2007). Moreover, applications of poultry manure, particularly (BC + PM 60 ton/ha), led to decreased bulk density, potentially due to increased soil biopores, improved soil aeration, higher soil organic carbon content, and enhanced soil aggregation. These factors collectively enhance soil porosity and water-holding capability (Gangwar et al., 2006). Porosity exhibited an increase across all treatments, with the highest score observed in the (BC + PM 60 ton/ha) application. This trend aligns with recent studies (Obia et al., 2016; Sekar, 2014), which suggest that biochar application can lead to an expected rise in total porosity, especially under the conditions conducive to a simultaneous reduction in bulk density. The inclusion of poultry manure in the (BC + PM 60 ton/ha) application may have played a role in enhancing porosity, as noted by Papini et al. (2011). Their research indicated that the applicaton of organic manure from various sources increased soil porosity, soil moisture content, and water-holding capacity, while also mitigating soil compaction and bulk density. Furthermore, applications of compost significantly increased porosity compared to the control. Khater (2015) emphasized that porosity is influenced by bulk

Table 2. The physiochemical properties of treatments

Treatments	Soil pH	Soil EC (µS/cm)	WHC (%)	Bulk density (g/cm^3)	Porosity (%)
Control	8.10^b	308.5^f	21.25^c	1.185^a	55.40^d
BC	8.27^a	1260.0^b	25.75^{ab}	1.068^c	59.73^b
Comp	7.97^c	329.3^f	24.00^{abc}	1.100^b	58.57^c
PM 3% (38.2 ton/ha)	7.74^d	571.3^e	21.25^c	1.095^b	58.68^c
BC+PM 60 ton/ha	8.15^b	1589.3^a	26.50^a	1.013^d	61.86^a
Comp+PM 60 ton/ha	7.55^e	799.5^d	25.75^{ab}	1.070^c	59.63^b
PM 60 ton/ha	7.71^d	877.5^c	23.25^{bc}	1.110^b	58.16^c
LSD	0.09	56.9	2.86	0.023	0.79

Note: BC – biochar, comp – compost, PM 3% – poultry manure 3%, PM 60 ton/ha – poultry manure 60 ton/hectare, pH – soil alkalinity, soil EC – soil electrical conductivity, WHC – water holding capacity. Readings with similar letters are not significantly different at $P \leq 0.05$. All data represent the mean of 4 replicates.

density and moisture content, both of which experience positive effects from compost applications.

Morphological measurements

The results exhibited significant variations among treatments in morphological measurements (refer to Table 3). Plant height increased with the application of (PM 3% (38.2 ton/ha)), (BC + PM 60 ton/ha), and (Comp + PM 60 ton/ha), potentially attributed to the addition of poultry manure to the soil. This increase could be linked to the substantial amounts of available nitrogen, available phosphorus per kilogram, and organic matter present in the manure (refer to Table 1). Interestingly, the lettuce grown at a lower dose than (PM 60 ton/ha) showed no significant difference in plant height, contradicting the findings of Masarirambi et al. (2012). Additionally, no significant difference was observed between (BC) and (control) in plant height, possibly due to nutrient deficiency resulting from the elevated pH and EC (refer to Table 2). Furthermore, the high pH of compost led to an insignificant difference in plant height compared to the (control). The number of leaves did not exhibit significant differences between treatments (refer to Table 3). Root characteristics, including root fresh weight, root dry weight, and root length, displayed significant differences among treatments. The application of (BC) yielded the highest values in root fresh and dry weight, aligning with the findings from Trupiano et al. (2017), Carter et al. (2013), and Upadhyay et al. (2014). This outcome could be attributed to the low bulk density, high porosity, high water holding capacity, and the nutrients provided by the addition of biochar (refer to Tables 1 and 2). Moreover, the application of (Comp) resulted in the highest root length and was significantly higher than the control in root dry weight. The obtained results indicated that compost can supply nutrients, organic matter, high water holding capacity, low bulk density, and high porosity, all contributing to better root growth (refer to Tables 1 and 2). Brito et al. (2015) reported that the application of compost at 30 ton/ha increased root fresh and dry weights compared to the control. However, all applications containing poultry manure led to a reduction in root fresh weight and length compared to the control. Despite the obtained results showing a significant decrease in root growth with poultry manure, previous studies indicated an increase in root growth in cassava plants, amaranthus plants, and lettuce plants (Biratu et al., 2018; Okoli and Nweke, 2015; Olasupo et al., 2018), respectively. Direct toxicity effects may also provide a justification, although these were not explicitly examined. Shoot fresh weight displayed significant differences between treatments. The application of (Comp + PM 60 ton/ha) yielded the highest value in shoot fresh weight. This increase may be attributed to the addition of nutrients and organic matter supplied by poultry manure and compost (refer to Table 1). Khalid et al. (2014) reported that poultry manure enhances plant vital processes, subsequently increasing crop yields. Surprisingly, the application of (PM 3% (38.2 ton/ha)) surpassed the application of (PM 60 ton/ha) in shoot fresh weight, contradicting the findings of Masarirambi et al. (2012). Shoot dry weight also demonstrated significant differences between treatments. The application of (Comp + PM 60 ton/ha) resulted in the highest shoot dry weight, indicating that poultry manure and compost contribute to enhanced soil macro and micro-nutrients, among other soil properties, benefiting lettuce growth.

Table 3. Growth parameters (plant height, leaves number, root fresh weight, root dry weight, root length)

Treatments	Plant height (cm)	Leaves number average	Root fresh weight (g)	Root dry weight (g)	Root length (cm)
Control	16.75^{d}	24.25	46.25^{bc}	4.77^{cd}	34.75^{ab}
BC	20.25^{cd}	30.25	70.00^{a}	15.54^{a}	27.00^{b}
Comp	19.75^{cd}	27.00	56.25^{ab}	8.06^{b}	36.25^{a}
PM 3% (38.2 ton/ha)	25.75^{ab}	31.50	40.00^{bcd}	6.91^{bc}	16.75^{c}
BC+PM 60 ton/ha	24.00^{bc}	32.00	28.75^{d}	2.73^{d}	12.75^{c}
Comp+PM 60 ton/ha	29.50^{a}	31.75	33.75^{cd}	4.64^{cd}	16.25^{c}
PM 60 ton/ha	21.50^{bcd}	27.75	23.75^{d}	2.92^{d}	9.00^{c}
LSD	5.12	NS	17.10	3.18	8.10

Note: BC: Biochar, Comp: Compost, PM 3%: Poultry manure 3%, PM 60 ton/ha: Poultry manure 60 ton/hectare NS: Not significant. Readings with similar letters are not significantly different at P ≤0.05. All data represent the mean of 4 replicates.

Physiological characteristics

Significant statistical differences in physiological measurements were observed among treatments (refer to Table 4). Leaf relative water content (LRWC) in lettuce plants reflects the metabolic activity of tissues or cells and is determined by LRWC, correlating with the transpiration rate. An increased transpiration rate may lead to a decreased LRWC (Hopkins and Hüner, 2004). The application of (BC + PM 60 ton/ha) resulted in the lowest LRWC compared to the control. This decrease could be attributed to the elevated electrical conductivity (EC) observed with (BC + PM 60 ton/ha) (refer to Table 2), hindering water uptake and consequently slowing LRWC growth. It is worth noting that there is a lack of literature on LRWC, and similar observations were made for the application of (Comp), which was also significantly lower than the control. Chlorophyll, one of the most crucial pigments in plants, plays a key role in photosynthesis. Reduction in chlorophyll content can lead to chlorosis and slowed growth due to a deceleration in photosynthetic reactions (Hopkins and Hüner, 2004). However, all applications containing poultry manure, such as (PM 3% (38.2 ton/ha)), (Comp + PM 60 ton/ha), (BC + PM 60 ton/ha), and (PM 60 ton/ha), exhibited significantly higher chlorophyll content than the control. This increase can be associated with nutrient absorption, especially nitrogen, as poultry manure is rich in available nitrogen (refer to Table 1), resulting in higher plastid pigment levels. This finding aligns with the results of Ullah et al. (2019), who reported an increase in the chlorophyll content in lettuce and rice plants with the application of poultry manure.

Shoot biochemical quality analysis

Shoot biochemistry analysis

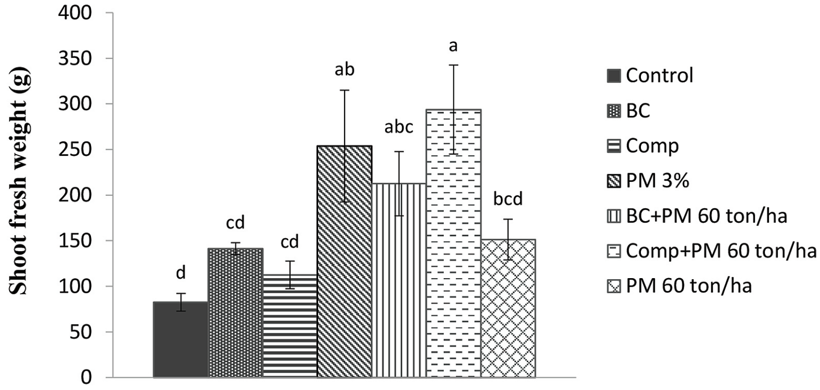
Total crude fiber values exhibited significant differences among treatments (refer to Figure 2A), with (PM 3% (38.2 ton/ha)) recording the highest value, likely attributed to the available nitrogen in poultry manure (refer to Table 1). However, (PM 60 ton/ha) showed no significant differences compared to the control. These findings aligned with Gasim, S.A (2001) and Adam (2004), who reported that increased nitrogen levels tend to reduce fiber content. In contrast, they contradicted the studies by Safdar (1997) and Tariq (1998), suggesting an increase in fiber content with higher nitrogen levels. Both (BC) and (Comp) applications exhibited significantly higher values than the control, possibly due to the nitrogen content introduced by (BC)

Table 4. Physiological characteristics: (the LRWC and chlorophyll content)

Treatments	LRWC (%)	Chlorophyll content (mg/m^{2})
Control	57.218^{a}	276.50^{b}
BC	58.11^{a}	316.25^{b}
Comp	26.138^{bc}	278.25^{b}
PM 3% (38.2 ton/ha)	43.26^{ab}	385.25^{a}
BC+PM 60 ton/ha	21.125^{c}	443.00^{a}
Comp+PM 60 ton/ha	42.045^{ab}	427.25^{a}
PM 60 ton/ha	56.790^{a}	416.25^{a}
LSD	20.52	67.64

Note: BC: Biochar, Comp: Compost, PM 3%: Poultry manure 3% (38.2 ton/ha), PM 60 ton/ha: Poultry manure 60 ton/hectare. Readings with similar letters are not significantly different at P ≤0.05. All data represent the mean of 4 replicates.

(A)



(B)

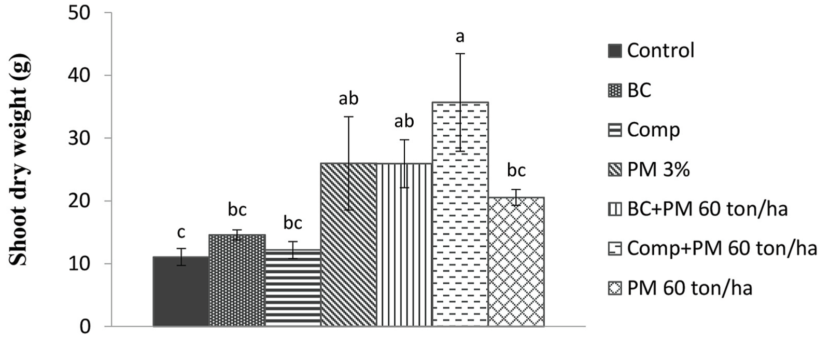


Figure 1. (A) Shoot fresh weight (g); (B) Shoot dry weight (g)

Note: BC – biochar, comp: compost, PM 3% – poultry manure 3% (38.2 ton/ha), PM 60 ton/ha: poultry manure 60 ton/hectare NS: not significant. Readings with similar letters are not significantly different at $P \leq 0.05$. (LSD – shoot fresh weight = 109.17, shoot dry weigh t = 13.97). All data represent the mean of 4 replicates

and (Comp). Ukom et al. (2009) and Nwite (2016) also reported that organic amendments generally enhance crude fiber content. Akachukwu et al., (2018) found that biochar increased the crude fiber content in Telfairia occidentalis leaves, supporting the results obtained in the presented study. No significant difference was observed between treatments regarding fat content (refer to Figure 2B). Antioxidants, essential for inhibiting oxidation in plant tissues, are often phenolic or polyphenolic compounds (Pratt, D. E., 1992). Nevertheless, all treatments showed significantly lower values than the control, except for (Comp), which was statistically the same as the control (refer to Figure 3A).

The application of (BC) was significantly lower than the control, while all poultry manure-containing applications had the lowest values, statistically the same as each other. This reduction may be attributed to the high and very high nitrogen levels in biochar and poultry manure, respectively (refer to Table 1). Coria-Cayupán et al., (2009) reported a decrease in antioxidant substances in lettuce with high nitrogen supply. Increased nitrogen application also reduced the ascorbic acid content in various horticultural crops (Lee and Kader, 2000), including crisp lettuce (Sørensen et al., 1994). No significant difference was observed between treatments regarding total phenols (refer to Figure 3B). Flavonoids, compounds extracted from plants with antioxidant properties, showed significantly lower values for all treatments compared to the control (refer to Figure 3C). Although the obtained results indicated an insignificant effect of biochar on flavonoids, previous studies reported an increase in flavonoid content with biochar application for tomato plants, chrysanthemum morifolium ramat plants, and lettuce plants (Petruccelli et al., 2015; Chen et al., 2018; Quartacci et al., 2017), respectively. Chen et al. (2018) suggested a strong correlation between total flavonoid content and soil pH, with (BC) significantly increasing soil pH compared to the control (refer to Table 2). However, the application of (Comp) was significantly lower

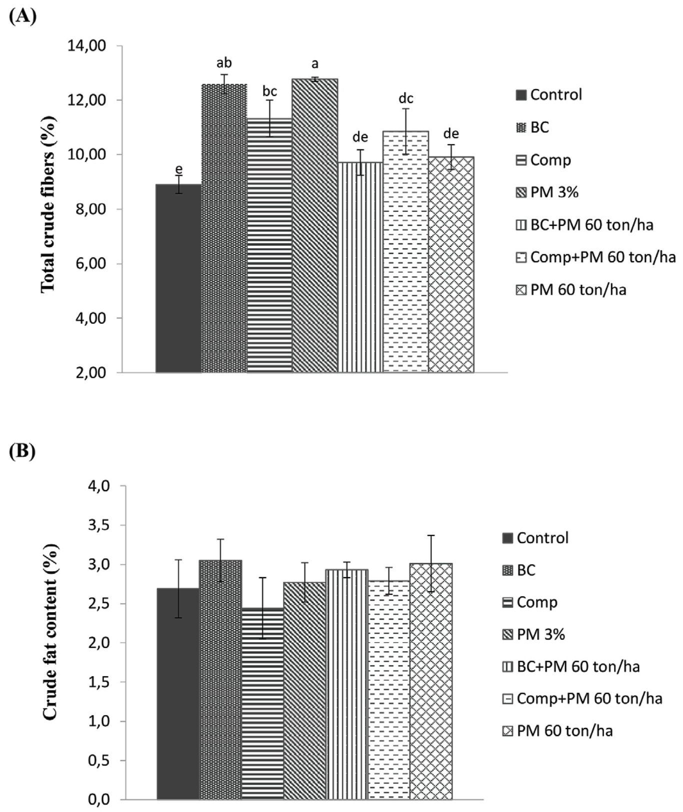


Figure 2. (A) Total crude fibers (%). (B) Crude fat content (%)

Note: BC – biochar, comp – compost, PM 3% – poultry manure 3% (38.2 ton/ha), PM 60 ton/ha – poultry manure 60 ton/hectare. Readings with similar letters are not significantly different at $P \leq 0.05$. (LSD – total crude fibers (%) = 1.41, crude fat content (%) = NS (not significant). All data represent the mean of 4 replicates

than the control, contradicting the findings by Ahmed et al. (2017) and Giménez et al. (2020). Unfortunately, literature on the reduction of flavonoids with (Comp) application was lacking. Moreover, all poultry manure-containing applications significantly reduced flavonoids, contrary to the findings by Aleman and Marques (2016); Baiyeri et al. (2016); Javanmardi and Ghorbani (2012). This reduction may be attributed to the inhibited root growth caused by poultry manure applications (refer to Table 3). Buer et al. (2010) suggested that flavonoids are selectively taken up by the roots and capable of long-distance movement within the plant.

Shoot minerals analysis

The analysis of nitrogen shoot content revealed significant variations among treatments (refer to Table 5). Notably, (Comp + PM 60 ton/ha) exhibited the highest nitrogen content in lettuce leaves, likely attributed to the elevated concentrations and availability of nitrogen in both compost and poultry manure (Table 1). Metwally (2015) reported a similar increase in nitrogen levels in the lettuce plants with compost addition, and Moyin-Jesu (2015) found that poultry manure positively influenced the nitrogen levels in cabbage. However, the application of (Comp) alone, despite having high nitrogen levels (Table 1), recorded significantly lower values than (Comp + PM 60 ton/ha), possibly due to the lower pH influenced by poultry manure in (Comp + PM 60 ton/ha). Surprisingly, (BC) showed no significant difference compared to the control, despite having substantial available nitrogen (Table 1). This could be attributed to the elevated pH, electrical conductivity (EC), and immobilization caused by the high carbon-to-nitrogen ratio (Tables 1 + 2). These results align with Mohawesh et al. (2018), who found no significant effect of biochar on the leaf nitrogen content in tomato and bell pepper. Phosphorus content exhibited significant differences among treatments (refer to Table 5), with (BC + PM 60 ton/ha) recording the highest values in lettuce leaves. This increase may be attributed to the abundant amounts of phosphorus and exchangeable potassium present in

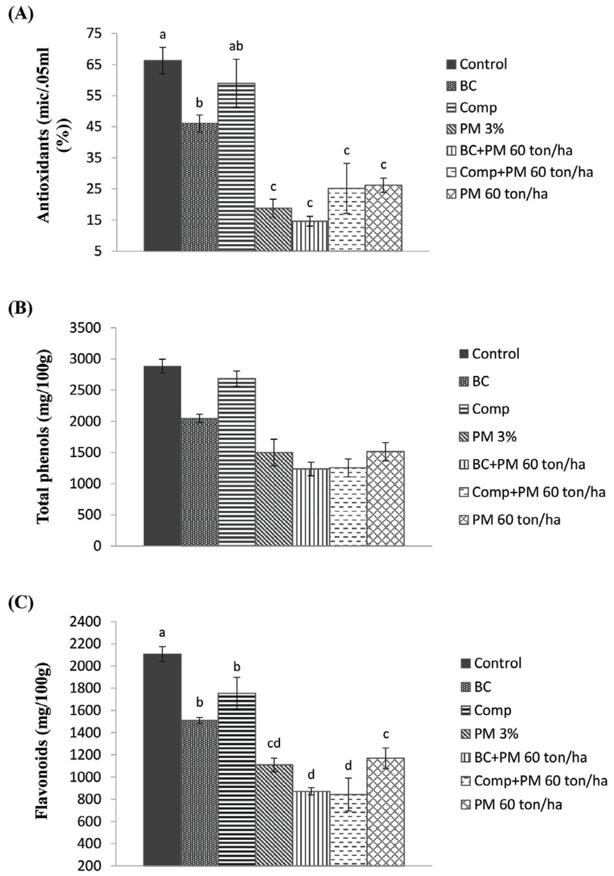


Figure 3: (A) Antioxidants (mic/.05ml (%)). (B) Total phenols (mg/100g). (C) Flavonoids (mg/100g)

Note: BC – biochar, comp – compost, PM 3% – poultry manure 3% (38.2 ton/ha), PM 60 ton/ha – poultry manure 60 ton/hectare. Readings with similar letters are not significantly different at P ≤ 0.05. (LSD: antioxidants = 14.09, total phenols = NS (not significant), flavonoids = 266.9). All data represent the mean of 4 replicates

Table 5. Shoot minerals analysis

Treatments	Plant N (%)	Plant P (mg/kg)	Plant K (mg/kg)	Plant Mg (mg/kg)	Plant Ca (mg/kg)	Plant Na (mg/kg)
Control	1.30^{c}	46.35^{c}	917.0^{e}	573.13^{e}	611.30^{e}	216.00^{c}
BC	1.58^{c}	76.30^{a}	1507.0^{ab}	941.88^{ab}	1004.50^{ab}	238.00^{c}
Comp	1.45^{c}	60.35^{b}	1207.0^{dc}	754.38^{dc}	804.50^{dc}	217.00^{c}
PM 3% (38.2 ton/ha)	2.93^{b}	72.05^{a}	1417.0^{bc}	885.63^{bc}	944.50^{bc}	347.00^{ab}
BC+PM 60 ton/ha	3.59^{ab}	83.60^{a}	1672.0^{a}	1045.00^{a}	1114.50^{a}	339.00^{ab}
Comp+PM 60 ton/ha	3.72^{a}	75.17^{a}	1533.0^{ab}	958.13^{ab}	1021.90^{ab}	282.00^{bc}
PM 60 ton/ha	3.25^{ab}	49.25^{bc}	1005.0^{de}	628.13^{de}	669.80^{de}	356.00^{a}
LSD	0.68	11.62	245.1	153.21	163.38	66.84

Note: BC– biochar, comp: compost, PM 3%: poultry manure 3%, PM 60 ton/ha: poultry manure 60 ton/hectare, plant N– plant nitrogen, plant P – plant phosphorus, plant K – plant potassium, plant Mg– plant magnesium, plant Ca – plant calcium, plant Na – plant sodium. Readings with similar letters are not significantly different at P ≤0.05. All data represent the mean of 4 replicates.

both biochar and poultry manure (Table 3). Studies have reported that biochar addition to soils enhances plant phosphorus concentration (Woldetsadik et al., 2018; Mohawesh et al., 2018). Similarly, Moyin-Jesu (2015) found that poultry manure positively influenced the phosphorus content in cabbage. Additionally, all compost-containing applications increased phosphorus content, consistent with the previous studies reporting elevated phosphorus levels in lettuce with compost application (Marchi et al., 2015; Metwally, 2015). Potassium content was significantly influenced by the treatments (refer to Table 5), with (BC + PM 60 ton/ha) exhibiting the highest values among all treatments. This increase can be attributed to the concentrations of available phosphorus and exchangeable potassium found in both biochar and poultry manure (Table 1). Previous studies have reported that biochar addition to soils increases plant potassium tissue concentration (Taiz and Zeiger, 2002; Chan and Xu, 2009; Mohawesh et al., 2018), and Moyin-Jesu (2015) found that poultry manure positively influenced the potassium content in plant tissues. However, (PM 60 ton/ha) recorded lower potassium content than (PM 3% (38.2 ton/ha)), potentially due to the elevated sodium levels introduced with the higher doses of poultry manure (Table 1). Compost applications scored higher values than the control, likely due to the concentrations of available phosphorus and exchangeable potassium found in compost (Table 1). Fricke and Vogtmann (1993) emphasized the significance of compost as a potential potassium source for crops, with over 85% of total potassium content being available to plants. Magnesium content, crucial for chlorophyll pigments, exhibited significant differences among treatments (refer to Table 5), with (BC + PM 60 ton/ha) recording the highest values. This suggests that the magnesium concentration in lettuce plants is strongly associated with the nutrient-supplying potential of biochar and poultry manure (Table 1). Woldetsadik et al. (2018) reported that biochar addition significantly enhanced the magnesium content of lettuce leaves, and Moyin-Jesu (2015) found that poultry manure significantly increased magnesium content in cabbage. Additionally, Moyin-Jesu (2015) noted that applying poultry manure at lower doses increased magnesium availability, supporting the obtained finding that (PM 3% (38.2 ton/ha)) scored a higher value than (PM 60 ton/ha). However, Levy and Veilleux (2007) highlighted that high sodium concentration induces calcium and magnesium nutritional deficiencies in plants (Table 1). All compost-containing applications scored higher values than the control, as reported by Hernández et al., (2010), who found that compost usage increased the magnesium content in lettuce plants due to the available magnesium in compost (Table 1). Calcium content exhibited significant differences among treatments (refer to Table 5), with (BC + PM 60 ton/ha) recording the highest values. This increase may be attributed to the abundant available calcium in biochar and poultry manure (Table 1). Woldetsadik et al., (2018) reported that applying 20 ton/ha biochar significantly increased the calcium content in cabbage. However, (PM 60 ton/ha) recorded lower values than (PM 3% (38.2 ton/ha)), potentially due to the high sodium levels introduced with higher doses of poultry manure (Table 1). Compost applications significantly increased the calcium content in lettuce plants, contrary to the findings by Reis et al., (2014), who reported insignificant calcium content in lettuce plants with various compost applications (6, 15, 30, 60 ton/ha) compared to control. However, compost components depend on the types of wastes they are made of, which can affect their performance at the field scale. Sodium content exhibited significant differences among treatments (refer to Table 5). Surprisingly, (PM 60 ton/ha) recorded the highest values among other treatments, potentially due to the abundant available sodium in poultry manure (Table 1). (PM 3% (38.2 ton/ha)) scored lower values, likely due to the lower dose applied. Despite biochar and compost containing substantial sodium amounts (Table 1), (BC + PM 60 ton/ha) and (Comp + PM 60 ton/ha) did not exceed (PM 60 ton/ha) values, possibly due to the high available amounts of potassium and calcium in biochar, compost, and poultry manure. This enhanced the absorption of these cations compared to decreased sodium uptake. Interestingly, (BC) did not significantly differ from the control. This aligns with the findings of Mohawesh et al., (2018), who reported that applying biochar at 2.5% did not significantly increase sodium content. However, Hernández et al. (2010) found that compost application increased the sodium content in lettuce, contradicting findings obtained in this study. As with other compost-containing amendments, the components of compost can influence its performance at the field scale.

CONCLUSIONS

Given the imperative of safeguarding soil health and sustainability, especially amid the challenges posed by a growing global population and the depletion of arable lands due to inadequate land management and agricultural policies, it is essential for farmers to prioritize soil improvement techniques. Among these techniques, biochar and compost play pivotal roles in enriching soil quality by substituting nutrients and organic matter. This approach not only enhances agricultural productivity to meet the rising global food demand but also contributes to mitigating soil degradation and enhancing soil fertility. Biochar and compost, derived from organic biomass, regulate water availability, pH levels, electrical conductivity, and carbon storage in the soil, while also promoting plant nutrition and disease control, without relying on chemical fertilizers. However, it is crucial to acknowledge certain limitations. For instance, elevated salt concentrations in poultry manure may hinder plant growth, requiring careful monitoring. Additionally, compost production typically takes longer than charcoal manufacturing. To ensure agricultural safety and mitigate hazardous compound presence, proper sterilization and sanitation protocols must be adhered to when using poultry manure. In a study comparing various soil improvement methods, it was found that BC demonstrated superior performance in terms of root fresh and dry weight, as well as leaf relative water content, while compost (Comp) resulted in the greatest root length. Application of poultry manure (PM) led to increased chlorophyll content, with the highest recorded value observed in the BC + PM treatment at a rate of 60 ton/ha. Chemical analysis revealed that PM application at 3% (38.2 ton/ha) resulted in the highest crude fiber levels, whereas the control group exhibited the highest antioxidant activities, total phenols, and total flavonoids. Regarding mineral composition in shoots, Comp + PM at a rate of 60 ton/ha showed the highest nitrogen concentration, while BC + PM at the same rate had the highest concentrations of phosphorus, potassium, magnesium, and calcium. Notably, PM at 60 ton/ha displayed the highest sodium concentration. Overall, the application of BC + PM at a rate of 60 ton/ha exhibited exceptional performance in terms of physiochemical soil parameters, except for soil pH and electrical conductivity. It also demonstrated superior mineral content in lettuce plants, except for sodium levels.

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