Biochar as an Amendment to Sandy Soil Properties and Its Effect on Biochemical Composition and Growth of *Moringa oleifera*

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ABSTRACT

This study examined the long-term impacts of wheat straw biochar (WSB) and sugarcane bagasse biochar (SCBB) on sandy soil characteristics and growth of *Moringa oleifera*. A two-year field experiment was conducted using biochar rates of 0.00%, 0.25%, and 0.50% (w/w). Soil and plant samples were collected at the end of each year to examine soil pH, electric conductivity (EC), soil organic matter (SOM), cation exchange capacity (CEC), available macronutrients (N-P-K), and exchangeable cations (Ca^{2+}, Mg^{2+}, K^{+}). Biochemical composition and qualitative analysis of moringa plant were conducted. Results demonstrated that biochar addition slightly increased soil pH, but the overall increase during two seasons was not significant, while EC showed a slightly significant increase. The 0.50% SCBB addition significantly increased available N, P, and K by 42.86%, 43.54%, and 133.70%, respectively. SCBB was better than WSB for the increasing exchangeable cations due to its higher CEC value and SSA, significantly improving soil CEC. SOM increased with higher biochar doses, due to its high organic carbon content. Both biochar types significantly ($P < 0.05$) influenced moringa growth parameters, including leaves weight, plant height, trunk diameter, and seeds weight. Biochar's effects on soil properties were more obvious in the first year, while its effect on vegetative growth was more significant in the second year. Biochar treatments significantly ($P < 0.05$) influenced the biochemical compositions of plant and higher values of biochemical compositions were observed in the first season. The PCA analysis of all variables shows a favorable correlation between the biochemical compositions and the 0.50% SCBB in both seasons. Conclusion: 0.50% SCBB treatment was the most effective treatment. Annual biochar should be added to sustain its positive effect on soil characteristics and plant growth.

Keywords: Biochar; Sandy Soil; Soil chemical properties; Moringa; Biochemical Compositions

INTRODUCTION

Low agricultural output in the sandy soil is mostly due to declining soil fertility (Dania *et al.*, 2014). Sandy soils are found worldwide, that extend over 4,990.2 million hectares around (31%) of the entire global land area (Huang and Hartemink, 2020). These soils occupy more than 6% of the global surface area that located in various climates (Yost and Hartemink, 2018). In many agricultural systems, sandy soils are considered problematic and unproductive due to their low available water capacity (AWC) and nutrient retention. Another significant challenge for agriculture in sandy soils is their high hydraulic conductivity and low retention ability for water and nutrients, making it difficult for many plants to thrive in these conditions (Sohi *et al.*, 2010).

Recycling biowaste materials could improve the environment and provide a solution to the problem of waste disposal. However, reuse of these materials in an eco-friendly manner could be positively contributed to the environment. Since fresh organic residues decompose quickly in tropical climates with high temperatures, it is challenging to maintain the aggregate stability of soil over the long term by applying them. These are the circumstances in which soil might benefit from more stable biochar administration program (Hseu *et al.*, 2014). Biochar is a carbon-rich substance created

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by heating biomass in an anoxic condition. Its main component is carbon compounds, with minor amounts of oxygen, nitrogen, hydrogen, and sulfur (Yi *et al.,* 2020). Interestingly, biochar contributes to the reduction of greenhouse gas (GHG) emissions, which is a key Sustainable Development Goal (SDG) of the United Nations, by aiding in carbon storage and removing atmospheric carbon dioxide (Kamarudin *et al.,* 2022). Therefore, using biochar becomes ubiquitous because it is environmentally friendly. Notably, composition of biochar and its physicochemical properties are greatly influenced by the type of feedstock used and the manufacturing environment (Yi *et al.,* 2020 and Salma *et al.,* 2024). Due to biochar characteristics as a low bulk density, a complex pore structure, a high specific surface area and distinct functional groups, several researches introduced it as a soil amendment (Haider *et al.,* 2020 and Salma *et al.,* 2024). Abiotic surface interactions affect the chemistry of biochar's surface groups as its ages by oxidizing its surfaces, decreasing its pH, and elevating its cation exchange capacity (Cheng & Lehmann, 2009; Tayyab *et al.,* 2018 and Mahmoud *et al.,* 2020). This alteration, in turn, influences the soil nutrient retention, biology, mineralogy, and hydrology in media amended with biochar. For sandy soils, biochar not only raises soil carbon levels but also enhances soil function and structure. Additionally, it has many essential elements and provides plant nutrition (Spokas *et al.,* 2014). During heating of feedstock minerals precipitate inside the remnant plant structure when water in the cells of the plant evaporates (Sorrenti and Toselli, 2016). Furthermore, it was reported that biochar has a beneficial impact when it was applied to sandy soils (Haider *et al.,* 2020). However, some studies demonstrated that biochar has a neutral or negative effect on sandy soils (Lehmann *et al.,* 2003). The productivity of sandy soils may be increased when water is managed sensibly by utilizing technology for subsurface water retention, which is seen to be a potential solution to managing sandy soils. This is one of the economically feasible choices in addressing water scarcity (Alghamdi, 2018). Sandy soils often have a single-grained structure and inherent poor physical characteristics, which results in a limited water-holding capacity (Ismail & Ozawa 2007 and Huang & Hartemink, 2020). In tropical climates with high temperatures, it might be challenging to maintain the aggregate stability of soil over the long term by adding fresh organic wastes owing to their quick breakdown. Under these circumstances, more stable biochar can offer a solution for managing soil. For all these reasons, biochar has been considered as a suitable soil amendment for improving soil physicochemical properties, of degraded and sandy soils in subtropical and tropical regions (Hseu *et al.,* 2014).

Moringa oleifera - known as the horseradish tree - is highly nutritious, multipurpose shrub native to India sub-continent. Among the varieties of Moringa, *Moringa Oleifera* is commonly grown species with fast growth, drought tolerant, easy multiplication, excellent source of vitamins and minerals, used for medicinal, cooking and cosmetics (Fahey, 2005 and Andry *et al.,* 2009). This medium-sized tree belongs to the Moringaceae family and is adaptable to a wide range of soil types. However, it grows best in well-drained loam to clay loam, neutral to slightly acidic soils, but it cannot withstand prolonged waterlogging. Moringa trees thrive in temperatures ranging from 26 to 40 °C and require at least 500 mm of annual rainfall (Saini *et al.,* 2016). Interestingly, under the climatic conditions of Upper Egypt, it is demonstrated that organic fertilizers and drip irrigation had a significantly greater positive effect on *Moringa Oleifera* growth mineral fertilizers relative to and flood irrigation (Adebayo *et al.,* 2017). Studies have shown that different parts of this plant are considered source of protein, vitamins, and carotene, containing all essential amino acids, and phenolic components (EL-Sayed and Mahmoud, 2018). Furthermore, this tree is rich in antioxidants, anti-inflammatory properties, phytochemical elements, and lipids such as omega-3 and omega-6 (Randriamboavonjy *et al.,* 2016). *M. oleifera* ethanolic leaf extract has been presented to effectively promote the treatment for pneumonia-related inflammatory disorder, where vitamins B, A, and C, vital minerals, and the sulfur-containing amino acids cysteine and methionine are all abundant in it (Amaglo *et al.,* 2010 and Hamdy, 2023). Interestingly, Moringa is biased in favor of its therapeutic properties, as a result scientists concentrate on its medicinal potential. Thus, there has been an increase in demand for products based on these plants, influencing chlorophyll content, assimilating remobilization, nutrient uptake, and changing the quantity of photosynthetic pigments (Bosch *et al.,* 2004 and Imoro *et al.,* 2012). The development of moringa yield and soil moisture and fertility may be improved by using biochar (Ghaedi *et al.,* 2024).

In Egypt, wheat straw generates around 8.6 million tons every year, with the majority being used as animal feed. However, a significant quantity is burned in open air and used directly as a biofuel for cooking and heating in rural areas, contributing to air pollution and several environmental problems (Mahmoud *et al.,* 2009 and Hafiz *et al.,* 2021). Similarly, sugarcane bagasse, produced at around 4.7 million tons annually, is utilized in various sectors such as steam and electricity generation in sugar factories, animal feed, composting, paper production, and MDF manufacturing. Despite its usage, considerable quantities of bagasse from private juice shops are discarded as waste, causing environmental challenges (Abdelhady *et al.*, 2021). Notably, these mismanaged amounts of agricultural residues represent valuable resources for promoting a sustainable environment. Both mentioned wastes are considered lignocellulosic materials, making them ideal feedstocks for biochar production. Biochar applications to sandy soil planted with *Moringa oleifera* and its potential as a sustainable resource for enhancing soil chemistry in arid regions and productivity under field conditions are limited. The objective of this study was to examine the role of sugarcane bagasse biochar (SCBB) and wheat straw biochar (WSB) in improving the chemical properties of sandy soil and to understand the effect of long-term usage of biochar on sandy soil characteristics, in addition to evaluate the influence of SCBB and WSB on moringa growth.

MATERIAL AND METHODS

Biochar preparation

In this study, two types of biochar were utilized generated from sugarcane bagasse biochar (SCBB) and wheat straw biochar (WSB). The air-dried sugarcane bagasse (SCB) and wheat straw (WS) were purchased from the local countryside in Egypt. The raw materials were washed with tap water several times followed by distilled water to remove any impurities, including soil particles and dust that accumulate during the harvest and storage. The washing process was brief and did not involve soaking to avoid dissolving or leaching out non-structural nutrients then dried in the oven for 24 hours at 80 °C. The dried raw materials were pyrolyzed for 2 hr. at around 400 °C in absence of oxygen by using a traditional pyrolytic reactor (El-Gamal *et al.,* 2017 and Salem, 2023). Biochar was crushed and sieved by using a 2-mm polypropylene sieve.

Biochar characterization

Certain chemical and physical characteristics were determined for SCBB and WSB. pH and EC were determined at 1:20 w/v (biochar/water suspension). By using a CHNS Elemental Analyzer (Vario type, El, elemental analyzer), the mass percentage of nitrogen (N), hydrogen (H), carbon (C), and sulfur (S) were determined. The biochars were burned in a muffle furnace for 12 hours at 700 ℃ to determine the amount of ash content. Oxygen (O) fraction of biochar was calculated by subtracting the sum of H, C, N and ash contents from their total mass percentages. O/C, H/C, and (O+N)/C atomic ratios of biochar were calculated. Total concentrations of macro - and micronutrients were analyzed through ash dissolution in 10 ml of aqua regia reagent (1-part NHO_3: 3-part HCl, *v: v* concentrated acids). The amounts of potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), zinc (Zn), manganese (Mn), and copper (Cu) were measured using atomic absorption spectrophotometer (Varian, Spectra AA-220). Additionally, total phosphorus (P) was determined by forming a yellow-colored phosphomolybdate complex using the ammonium paramolybdate-vanadate reagent. The color intensity was measured at 420 nm using T80 UV/VIS Spectrophotometer, PG Instruments Ltd. Total surface area and the total volume of pores were determined by the N_2-BET method. Cation exchange capacity (CEC) was determined using a modified NH_4-OAc (I M, pH 7) compulsory displacement method (Gaskin *et al.,* 2008) (Table 1). By using Fourier-Transform Infrared Spectroscopy (FTIR—6100 JASCO spectrometer), the surface functional groups were identified by scanning WSB and SCBB with infrared rays in the range 4000 – 400 cm^{-1}. Samples of oven-dried (70 ℃) biochar were homogenized with KBr of spectroscopic-grade, then compacted using a 1.2 cm-diameter disc to a thickness of 1 mm. To provide a background reference, the KBr disc was scanned prior to the FTIR investigation. To identify the surface morphology of biochar samples, the scanning electron microscopy (SEM) instrument was handled at 15 kV/SED, and the images were captured at a magnification of X1000.

Organic Fertilize

Poultry manure (PM), derived from the Poultry Farm in Old Borg Al-Arab, west Alexandria, Egypt, was used as an organic fertilizer. The contents of ash element composition, pH, and EC of the oven-dried PM (48 h at 60 ℃) were analyzed as described in the previous section. PM contained 72.21% Ash, 18.34% C, 3.45% N, 0.78% P, and 2.01% K; the calculated C: N ratio was 5.32. The EC indicated moderate salinity (5.26 dS m^{-1}), while the pH was slightly acidic (6.73).

Study area

This study was carried out over two consecutive seasons during 2022-2023 and 2023-2024 in an open field located at Baloza Research Station (31°32'03" N and 32°362'03" E), the Elevation is 22 m, Desert Research Center (DRC), North Sinai Governorate, Egypt. During the experimental period, climatic data monthly was collected according to the Egyptian Climate Institute Table (2). The soil texture is sandy, and it was non-saline, with an electric conductivity (EC) value of 1.46 ds m^{-1} (Table 3). The drip irrigation system is common there (Shoman, 2017).

Treatments and Experimental Design

Moringa plant seedlings were prepared using seeds collected from mother plants cultivated at Baloza Research Station, from the seeds yield of the previous season’s harvest immediately. Two months later after germination, the seedlings were transferred to the seedling acclimatization unit at the station for five months until they were planted in the permanent study site. To prepare the permanent site, the soil was treated with poultry manure as an organic fertilizer, applied at a rate of 30 m^3 ha^{-1}. Additionally, mineral fertilizers including single superphosphate at a rate of 360 kg ha^{-1} and ammonium sulfate at a rate of 240 kg ha^{-1} were applied. Then, biochar was mixed into the soil to a depth of 0.50 m in the first only before transplanting moringa seedlings into the field. Once the seedlings were established, drip irrigation was applied every week at a rate of 8 liter hr^{-1} $plant^{-1}$. El-Salam Canal is the source of irrigation water. A randomized complete block design (RCBD) was utilized, featuring two biochar types (SCBB and WSB) over two levels in addition to control treatment (no biochar). The Biochar levels (w/w) 0.25% (≈ 19 ton ha^{-1}) and 0.50% (≈ 38 ton ha^{-1}). Each treatment was replicated three times, resulting in a total of 18 experimental units. Moringa seedlings were cultivated in November 2022. The first soil and plant samples were collected in December 2023, and the second collection took place in December 2024.

Soil analysis

Soil samples were collected periodically from the experimental field to a depth of 60 cm. The samples were air-dried for 48 hours and then sieved by using a 2-mm sieve. Following the methodology outlined by Page *et al.* (1982), some physical and chemical properties were determined (Table 3). In 1:2.5 (w/v) soil to water suspension, pH and Electrical conductivity (EC, dS m^{-1}) were measured by using Jenway pH-meter model 3305 and Jenway conductivity meter model 4310, respectively. By using the hydrometric method, the particle size of soil samples was determined. Soil organic matter was determined using the wet oxidative method (Page *et al.,* 1982). Cation exchange capacity (CEC) was determined by using ammonium acetate method; additionally, the amount of exchangeable Ca, Mg, and K were determined. The available phosphorus was extracted by 0.50 M $NaHCO_3$ (pH 8.5) and formed blue color using the ascorbic acid method was measured depending on its density at a wavelength of 882 nm using PG Instruments T80 UV/VIS Spectrophotometer (Olsen *et al.,* 1982). For available K, neutral NH_4OAc (1 N) was used as an extracting, then the extracted K was measured by a flame photometer (Knudsen *et al.,* 1982). By extracting with a KCl solution (2.0 M) and a Vapodest 30s Gerhardt Kjeldahel distillation unit, the quantity of available nitrogen (NH_4^+ and NO_3^-) was determined (Keeney and Nelson, 1982).

Physiological, Biochemical, and Nutrient analysis for Moringa plant

By the end of 2023 and 2024, fresh leaf samples were taken, the first part was dried, and the other part was preserved for physiological analysis.

Determination of certain nutrient elements, superoxide anion and carbohydrates

Determination of N, P, and K concentrations were carried out on the dry material. The wet digestion of 0.2 g plant material with sulfuric and perchloric acids was carried out on leaves and dry seeds (Piper, 1947). Total nitrogen was determined in the dry matter using Microkjeldahl method (Horneck and Miller, 1998). Then the crude protein was calculated according to the equation published by Association of official Analytical chemists (A.O.A.C. 2005). That equals total nitrogen multiplied by 6.25. Phosphorus was determined calorimetrically according to the method of Sandell (1950). Potassium was determined by the flame photometer model Carl-Zeiss (Horneck and Miller, 1998).

Carbohydrates were measured according to Dubois *et al.* (1956). Carbohydrates react with phenol and sulfuric acid to form a colored complex (orange-yellow), measurable at 490 nm. Nitro Blue Tetrazolium (NBT) used to determine superoxide anion according to Doke (1983).

Determination of Photosynthetic Pigments Content

Total chlorophyll content was measured with a portable chlorophyll meter (SPAD-502), and three samples with consistent growth representing the entire plot's growth were selected from each experimental area. The chlorophyll content in the upper leaves for every sample was estimated by averaging values across the three samples.

Relative Water Content (RWC)

One hundred mg of fresh leaf material was taken and kept in double distilled water in a Petri dish for two hours to make the leaf tissue turgid. The turgid weights of the fresh leaf materials were taken after carefully soaking the tissues between the two filter papers. Subsequently, this leaf material was placed in a butter paper bag and dried in an oven at 65 °C for 48 hours, then the dry weights were recorded (Anjum *et al.,* 2011). The RWC was calculated by using the formula.

$$RWC\ (\%) = \frac{\text{Fresh weight} - \text{Dry weight}}{\text{Turgid weight} - \text{Dry weight}} \times 100$$

Activity of peroxidase enzyme (APX) (μg g^{-1} fresh weight min^{-1}):

Peroxidase activity was measured by observing the change in absorbance at 470 nm, which is due to guaiacol oxidation according to Polle *et al.* (1994). The reaction mixture contained 100 mM potassium phosphate buffer (pH 7), 10 mM H_2O_2, 20 mM guaiacol, 0.05 ml enzyme extraction, and distilled water to make up the volume to 3 ml. The reaction started by adding H_2O_2 and the decrease in the absorbance was recorded at 470 nm (ε = 26.6 $mM^{-1}\cdot cm^{-1}$) for 1 min. Enzyme activity was computed by calculating the amount of H_2O_2 decomposed.

Qualitative analysis of moringa yield

In December 2023, various vegetative characteristics were measured in the first season including the number of branches $plants^{-1}$, fresh weight of leaves plant $^{-1}$ (g), and dry weight of leaves $plant^{-1}$. Notably, in the second season, the plants produced pods, resulting in an increase in the vegetative characteristics including plant height (cm), main trunk diameter (mm), fresh weight of leaves $plant^{-1}$ (g), and dry weight of leaves $plant^{-1}$ (g) were measured, as well as the yield characteristics were measured including seed weight $plant^{-1}$ (g).

Statistical Data Analysis

For soil and plant vegetative characteristics, according to Steel *et al.* (1997); the ANOVA test was used to perform the significance test. The significance of the results was expressed as a least significant difference test (LSD) at the 0.05 and 0.01 levels of probability.

RESULTS AND DISCUSSION

Biochar characterizations

The data in Table (1) showed the physical and chemical characteristics of the WSB and SCBB. pH values of both biochar types were alkaline (8.30 and 8.81, respectively) due to the loss of acidic functional groups and the formation of the basic functional groups, alkali earth, and carbonates during pyrolysis (Ippolito *et al.,* 2020). EC values for both biochars were not saline, although the sugarcane bagasse biochar exhibited a higher EC value (1.61 dS m^{-1}) compared with the wheat straw biochar (1.06 dS m^{-1}), indicating SCBB has more soluble salts than WSB. The ash percentage of WSB was higher than that of SCBB by about 5.70%, which may be due to the influence of the main component of each raw material. It was reported that the raw biomaterial had the greatest influence on the ash of produced biochars (Ippolito *et al.,* 2020). The cation exchange capacity (CEC) of WSB (46.78 $cmol_c$ kg^{-1}) was lower than that of SCBB (59.43 $cmol_c$ kg^{-1}), that could be attributed to its high content of ash. Moreover, surface functional groups, such as carboxylic and phenolic groups, provide a vital role in the CEC value of biochar. In general, the elemental contents of SCBB exhibited slightly higher than those of WSB. For example, the carbon and oxygen percentages in SCBB were around 51.36% and 26.43%, while in WSB the mentioned element concentrations were 49.61% and 21.72%, respectively. On the other hand, Mn, N and H in WSB were higher than that detected in SCBB. The molar ratios of H:C and O:C are lower than 1.00 and 0.4, respectively, which improved carbon stability and aromaticity. The H:C molar ratio > 0.6 is favorable for soil application. It is reported that a higher O:C molar ratio (> 0.2) generally correlates with higher the polarity and hydrophilicity, that means improving soil water retention (Ippolito *et al.,* 2020 and Emran *et al.,* 2024). In the same vein, the total surface area of SCBB (170.51 m^2 g^{-1}) was higher than that of WSB (97.38 m^2 g^{-1}).

The SEM images of the biochar structure morphology of SCBB and WSB were presented in Fig. (1). It was clear that the images of both biochar materials (magnified at X1000) showed noticeable differences in the surface structure with a multi-channel and micropores (<10 μm). The wheat straw-derived biochar represented a sieve plate morphological structure with poly-porous that formed due to the degradation of volatile components during the pyrolysis process (Chen *et al.,* 2005). On the other hand, sugarcane bagasse biochar image showed more tubed channel structures with different thicknesses and diameters, that also developed due to thermal degradation of the volatile compound during pyrolysis resulting in such porous structure (Abdelhady *et al.,* 2021; El-Hassanin *et al.,* 2023 and Salem, 2023). Interestingly, the presence of pores in biochar plays a vital role in supporting microbial activity and retaining soil nutrients due to increase their specific surface area. These pores create an ideal environment for microorganisms to thrive. The macro pores in biochar provide an ample space for microbial colonies to establish and grow, resulting in improved biochar performance as a soil amendment (Salem *et al.,* 2021). Thus, due to the variation of macro- and micro-pore distribution of both studied biochar, the huge numbers of microporosity of SCBB support durable nutrient retention and carbon sequestration in soil. On the other hand, WSB's microporosity enhances immediate microbial activity and plant stress tolerance.

Fourier-Transform Infrared Spectroscopy (FTIR) is a powerful technique used to identify the various functional groups of both biochars. As presented in Fig. (2), there was less variation in the FTIR spectra between SCBB and WSB in terms of intensity. The FTIR analysis of both biochar materials presented two distinct spectral regions, depending on the wavelength intensity. The first region characteristic extended from 4000 to

1750 cm^{-1} referred to no specific spectra due to the effect of the thermal degradation and removal of the main functional groups of volatile organic compounds present in the feedstock during the pyrolysis process. On the other hand, the second one is related to the fingerprint region ranging from 1750 to 450 cm^{-1}, which depicted a relative relationship between both biochar types regardless of the peak intensity. Interestingly, biochar samples displayed similar chemical groups, with a slight change in peak width and intensity between WSB and SCBB in the fingerprint region. The FTIR spectra demonstrated the presence of multiple functional groups where the band at 1690 - 1688 cm^{-1} revealed the presence of stretching C=O vibration carbonyl groups and aromatic ring that suggested the conjugated ketones, aldehydes, and carboxylic acids that formed during the degradation of cellulosic compounds and lignin (Khan *et al.,* 2024). The bending C=C aromatic ring was detected at 1581 - 1571 cm^{-1}, which denoted to high aromaticity degree (Shin *et al.,* 2021). The bands detected at 1428 and 1372 cm^{-1} declared the occurrence of C-H bonds that were assigned to aliphatic compounds and carboxyl-carbonate groups (Ding *et al.,* 2022). Stretching C-O carboxylic and phenolic compounds and bending C-H aromatic compounds were declared by band obtained at 1205 cm^{-1} indicating that some functional groups in the original raw materials were preserved or modified and formed new aromatic compounds during pyrolysis (Ippolito *et al.,* 2020). Stretching C-O aliphatic compounds and alcohol, in addition to stretching Si-O-Si at 1069 – 1041 cm^{-1} were associated with ethers, esters, phenols, primary alcohols, and the presence of siloxane. The peaks at 880 – 613 cm^{-1} bending C-H Stretching and =CH vibrations of the aromatic ring provided additional evidence of aromatic ring structure, reinforcing the presence of a highly stable carbon structure during pyrolysis (El-Gamal *et al.,* 2017). Si-O at 470 - 454 cm^{-1} referred to organ silicon compounds of silica and informed on the quartz part of the inorganic matrix (Mansee *et al.,* 2023).

Table 1. Some physical and chemical characteristics of wheat straw biochar (WSB) and sugarcane bagasse biochar (SCBB)

Properties	Unit	WSB	SCBB
Physicochemical Characteristic			
Biochar yield	%	42.07	37.81
Ash	%	24.61	18.91
pH (5%, *w:v*)	---	8.91	8.30
EC (5%, *w:v*)	dS m^{-1}	1.06	1.61
CEC	$cmol_c\ kg^{-1}$	46.78	59.43
Nutritional Characteristic			
Carbon (C)	%	49.61	51.36
Hydrogen (H)	%	2.93	2.54
Oxygen (O)	%	21.72	26.43
Nitrogen (N)	%	0.82	0.76
Sulfur (S)	%	0.32	0.34
Phosphorus (P)	g kg^{-1}	5.21	10.70
Potassium (K)	g kg^{-1}	32.40	37.77
Magnesium (Mg)	g kg^{-1}	5.30	6.00
Calcium (Ca)	g kg^{-1}	13.13	19.90
Iron (Fe)	mg kg^{-1}	434.40	1109.20
Zinc (Zn)	mg kg^{-1}	31.62	115.25
Manganese (Mn)	mg kg^{-1}	62.13	59.74
Cupper (Cu)	mg kg^{-1}	5.41	19.98
Molar ratios Characteristic			
H:C		0.71	0.59
O:C		0.33	0.39
(N+O):C		0.34	0.40

Table 2. Mean of climate conditions at the experimental site during the study period

Month	Precipitation, Mm month^{-1}	Temperature,			Relative Humidity, %	Wend Speed, m s^{-1}
		Max.	Min.	Mean		
Jan	26	16.8	9.3	13.1	50.8	5
Feb	13	18.6	10.5	14.6	46.9	4.6
Mar	13	18	10.6	14.3	43.7	5.2
Apr	0	24.9	15.8	20.4	45.5	4.8
May	0	26.7	18.6	22.7	45.5	5
Jun	1	30.2	23.2	26.7	47.3	4.5
Jul	0	31.9	24.5	28.2	49	4.2
Aug	0	31.8	25.8	28.8	51.3	4.3
Sep	0	30.7	24.8	27.8	50.8	4.4
Oct	18	27.6	21.9	24.8	52.1	4
Nov	10	24.2	17.5	20.9	49.8	4
Dec	37	21.6	14.5	18.1	55.1	3.8

Table 3. Some chemical and physical characterization of the experimental soil

pH, 1:2.5	EC, dS/m 1:2.5	Available macro nutrients, mg kg^{-1}			Sand, %	Silt, %	Clay, %	Texture
		Nitrogen	Phosphorus	potassium				
8.52	1.46	31.01	2.15	37.12	89.10	6.35	4.55	Sandy

EC: electric conductivity.

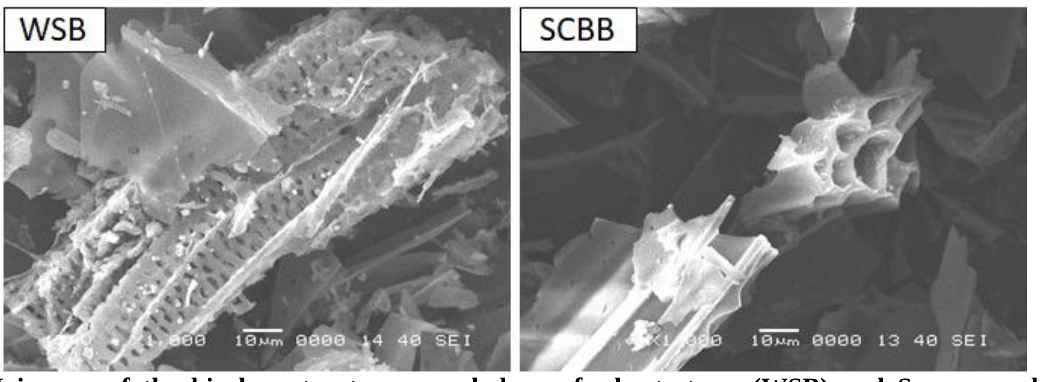


Fig. 1. SEM images of the biochar structure morphology of wheat straw (WSB) and Sugarcane bagasse (SCBB) biochars

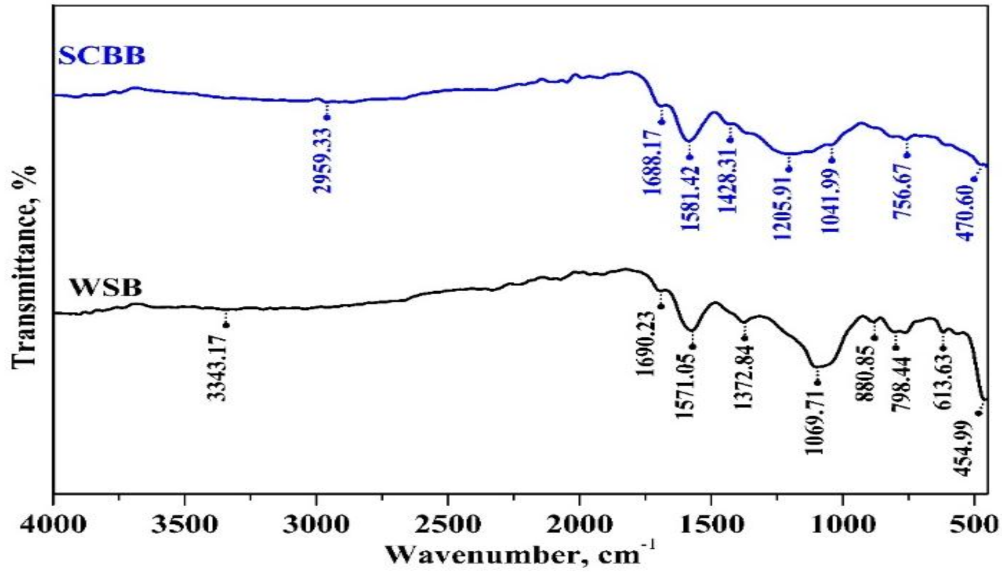


Fig. 2. FTIR spectra of wheat straw (WSB) and sugarcane bagasse (SCBB) biochars

Assessment of the chemical properties of biochar-amended soil

Soil pH

Fig. (3) illustrates a modest increase in soil pH compared with control over two growing seasons. This increase in soil pH may be attributed to the alkaline nature of the biochar, 8.81 for WSB and 8.30 for SCBB (Table 1) (Jamroz *et al.*, 2022). Consequently, alkaline biochar could supply the soil with base cations in soil solutions (Elshony *et al.*, 2019). Notably, higher application rates (0.50%) of both biochars resulted in a smaller percentage increase in pH relative to lower doses (0.25%). During the first season, the pH increase percentages were 4.39% (0.25% WSB), 1.60% (0.50% WSB), 4.63% (0.25% SCBB), and 3.23% (0.50% SCBB) relative to control. This might be related to increased chemical oxidation and microbial activity at elevated biochar rates. The porous structure of biochar may create a suitable environment for microorganisms, potentially stimulating the production of acidic compounds. Therefore, slight increase in the pH value at high biochar dose compared to lower dose. In contrast, the second season exhibited no significant pH changes. Statistically, the overall increase in soil pH during two seasons was insignificant ($P > 0.05$). The obtained result agreed with previous studies by Zhang *et al.* (2016) and Elshony *et al.* (2019), which reported a slight insignificant increase in soil pH after biochar addition to sandy and sandy loam soils, especially between different biochar treatments.

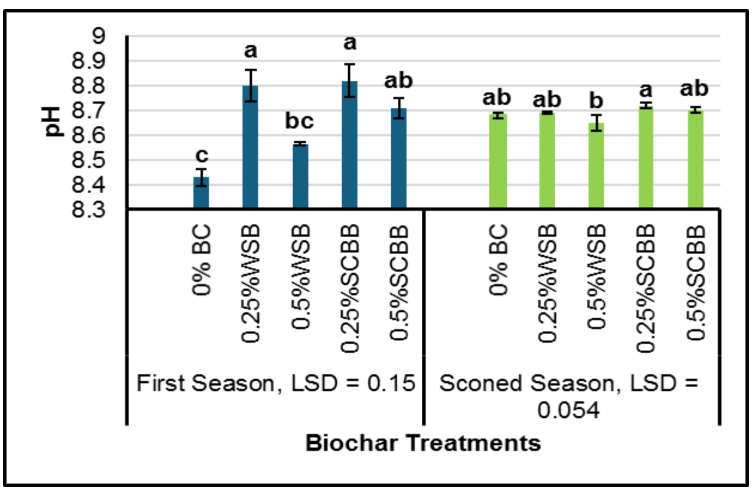


Fig. 3. Effect of biochar types applied at different rates over two years on pH of sandy soil

Letters above bars indicate significant differences (LSD, $P < 0.05$) compared to the control.

Electrical conductivity (EC)

The electric conductivity (EC) of the biochar-amended soil exhibited a slight but significantly increase relative to control treatment. The EC of the biochar treated soil was affected by the doses of biochar applied (Fig. 4). In the first season, the highest dose of wheat straw biochar (0.50%WSB) increased EC value to 0.88 dS m^{-1}, followed by 0.50% sugarcane bagasse biochar (0.50 % SCBB) elevated EC to 0.74 dS m^{-1}, compared to the control treatment (0.65 dS m^{-1}). This difference correlates with ash content in WSB relative to SCBB (Table 1). Conversely, the lower dose of both biochars (0.25%) resulted slightly decreased in EC values. These results were insured by Shareef *et al.* (2018) who explained these observations by releasing of weakly bonded ions from biochar surface. In addition, soil EC was affected by biochar type, where the percentage of increase in the case of SCBB was 13.85% and for WSB was 35.38% at the same rate (0.50%). El-Hassanin *et al.* (2023) observed that WSB increased the EC of sandy soil after incubation experiment and argued that to the content of salts in WSB. On the other hand, EC in the second year showed no systematic increase, and the reason is not clear. Despite the increasing in soil EC, the soil salinity remained within the safety limit with the addition of the mentioned biochar types.

Available content of macronutrients (NPK)

NPK in the treated soil significantly increased due to biochar addition compared to control soil (Fig. 5), where biochar doses and types affected on available content of nitrogen (N), phosphorus (P), and potassium (K) in the treated sandy soil. Available nitrogen increased by 7.14%, 14.29%, 21.80%, and 42.86% in the biochar amended soil with 0.25% WSB, 0.50% WSB, 0.25% SCBB, and 0.50%SCBB, respectively, demonstrating a dose-depending response. Available phosphorus content in soil varied depending on biochar type, where soil treated with SCBB contained more phosphorus than that treated with WSB, possibly due to the high content of phosphorus in SCBB relative to WSB (Table 1). In addition, the dose of biochar had a positive effect on available phosphorus content, where SCBB-amended soil showed higher P availability for 0.50% SCBB (43.54 %) followed by 0.25% SCBB (23.80%) then 0.50% WSB (21.14%) and 0.25% WSB (7.22 %). These results were compatible with Timilsina *et al.* (2017), who observed that the highest rate of biochar application in loamy sand soil increased phosphorus availability to 4.0 mg kg-^{1} relative to control (2.2 mg kg^{-1}). Likewise, available potassium followed a similar pattern, with the highest increase observation at 0.50% SCBB (133.70%), followed by 0.25% SCBB (88.89%), 0.50% WSB (86.16%), and 25% WSB (30.13 %). Accordingly, the ability of the studied soil environment to retain nutrients increased by addition SCBB than WSB at the same dose. This could be due to the higher specific surface area of SCBB than WSB (Table 1). Enhanced NPK availability in sandy soil treated with biochar might be direct nutrient release from biochar's mineral composition supplying essential nutrients for plant growth (Alling *et al.*, 2014 and Obia *et al.*, 2015).

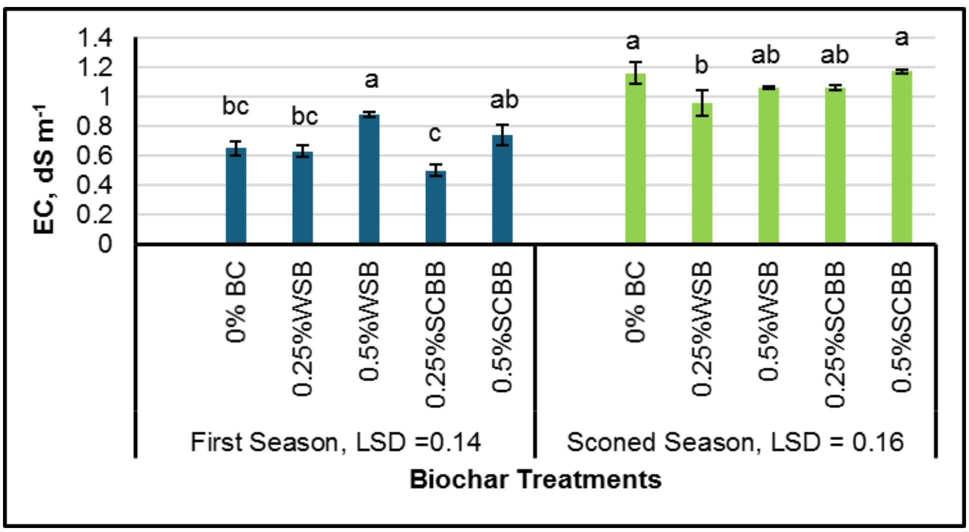


Fig. 4. Effect of biochar types applied at different rates over two years on sandy soil electric conductivity (EC)
Letters above bars indicate significant differences (LSD, $P < 0.05$) compared to the control.

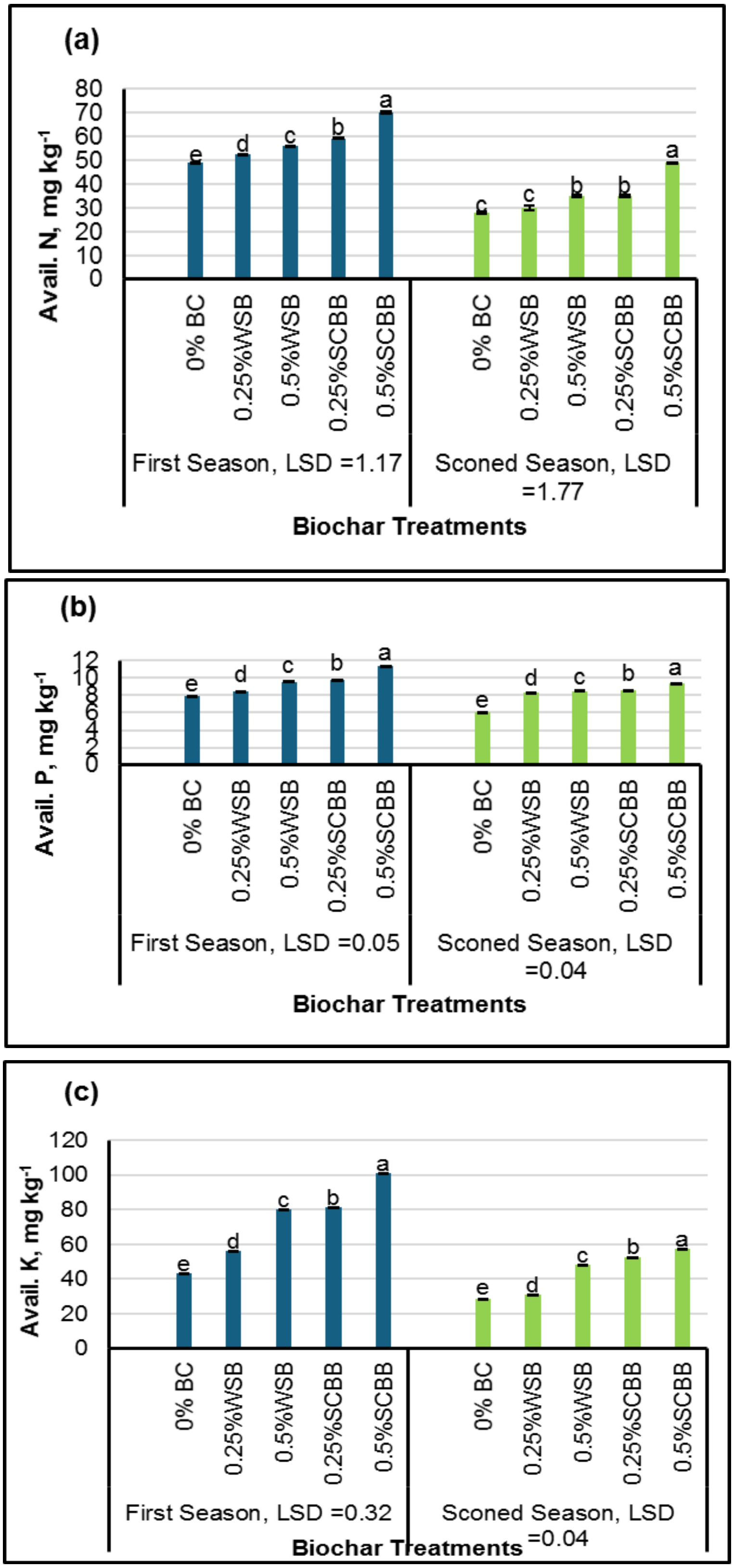


Fig. 5. Effect of biochar types applied at different rates over two years on the macronutrient availability in sandy soil: nitrogen (a); phosphorus (b); potassium (c)

Letters above bars indicate significant differences (LSD, $P < 0.05$) compared to the control.

Furthermore, it is reported that biochar enhanced soil organic carbon and nutrient availability, including P, and K, where incorporating biochar into soil could increase surface area and improve water retention, particularly in sandy soils (Obia *et al.,* 2015). Biochar addition to sandy soil reduced leachate of mineral N thus increases soil available N (Li *et al.,* 2019 and Bekchanova *et al.,* 2024).

All these factors besides organic fertilizer that had been added to soil in the beginning of the first cultivation season increase microbial activity and accelerate the biodegradation of biochar. However, in the second year, the amounts of NPK were less than in the first year that might be due to land use and plant growth (Elshony *et al.*, 2019).

Cation Exchange Capacity (CEC)

Cation exchange capacity, an important indicators of soil fertility, significantly ($P < 0.05$) increased biochar-amended soil compared to the control (Fig. 6). The highest CEC was noted in soil amended with a higher application rate (0.50%), followed by 0.25% for both biochars in the order 0.50% SCBB > 0.50% WSB > 0.25% SCBB > 0.25% WSB. The increase in the CEC values of the studied sandy soil might be attributed to the enhanced surface charge that provided by biochar's oxygen functional groups (Ibrahim *et al.,* 2022). Another study reported an improvement in CEC of sandy soil amended with rice husk biochar (Thi *et al.,* 2021). Notably, a diminishment in CEC values was recorded in the second year compared to the first one, potentially that might be due to biodegradation of biochar and organic matter added at the beginning of the experiment. Where, the degradation was found to be significant in warm climates (Elshony *et al.,* 2019), which may reduce its long-term physico-chemical benefits.

Exchangeable Cations

The impact of biochar amendments on soil exchangeable cations (Ca^{2+}, Mg^{2+} and K^{+}) was evaluated over two growing seasons (Fig. 7). Both SCBB and WSB significantly ($P < 0.05$) increased the exchangeable cation levels compared to control, correlating with enhanced cation exchange capacity of the biochar amended soils. Similarly, the results were consistent with Hossain *et al.* (2020) and El-Hassanin *et al.* (2023), who studied the effect of wheat straw and rice husk biochars on different types of soils. SCBB exhibited superior efficacy, elevating Ca^{2+}, Mg^{2+} and K^{+} more markedly than WSB at equivalent application doses. This difference might be due to the higher content of these elements in SCBB compared to WSB, in addition to its higher CEC value and SSA compared to WSB (Table 1). In the second year, there was a decline in the amounts of exchangeable cations (Ca^{2+}, Mg^{2+} and K^{+}) due to a reduction in CEC values over time (Mahmoud *et al.,* 2020).

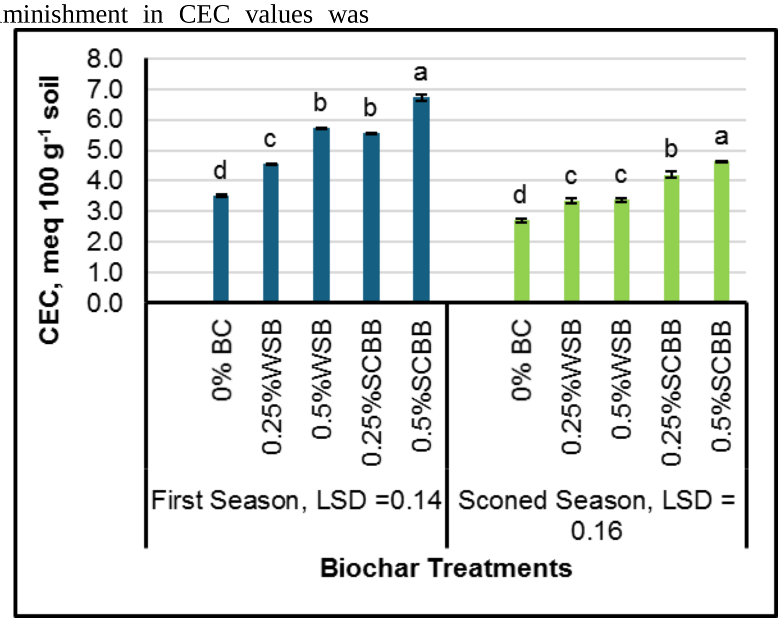


Fig. 6. Effect of biochar types applied at different rates over two years on sandy soil cation exchange capacity (CEC).

Letters above bars indicate significant differences (LSD, $P < 0.05$) compared to the control.

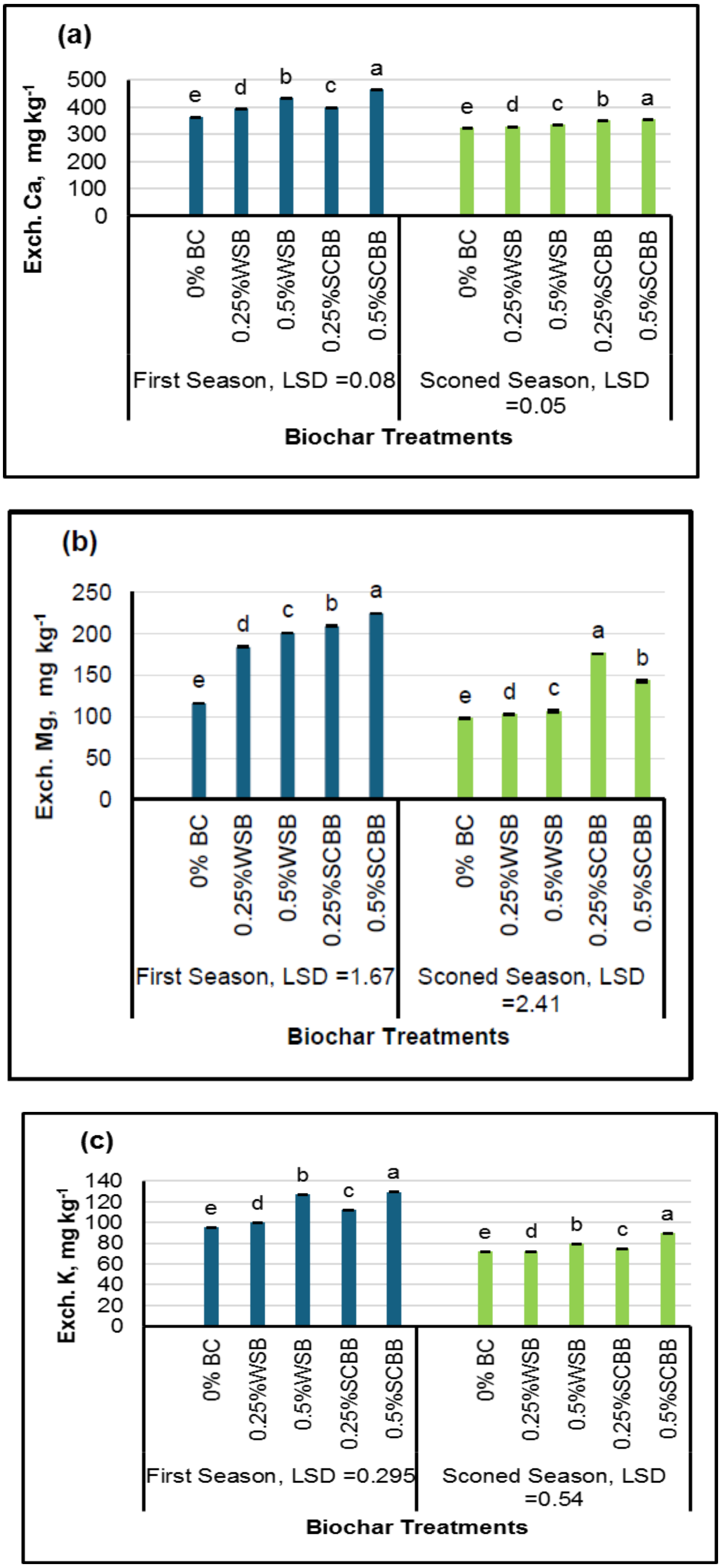


Fig. 7. Effect of biochar types applied at different rates over two years on sandy soil exchangeable cations: calcium (a); magnesium (b); potassium (c)

Letters above bars indicate significant differences (LSD, P < 0.05) compared to the control.

Organic matter

Soil organic matter (OM) percentage increased significantly in biochar amended soil compared to control (Fig. 8). Initial OM (1.07%) rose to 1.94%, 2.28%, 1.98%, and 2.89% for the treatments of 0.25%WSB, 0.50%WSB, 0.25% SCBB, and 0.50% SCBB, respectively. This indicates a clear dose-dependent response, with SCBB than WSB at equivalent rates. These results agreed with Stańczyk-Mazanek (2023), who observed a positive effect of biochar dose on soil organic matter in sandy soil. In addition, the upsurge was greater with SCBB than with WSB due to the higher organic carbon content in SCBB than in WSB (Table 1). It was reported that corncob biochar influences sandy soil organic carbon (SOC) linearly ($p < 0.05$) with increasing biochar rates due to their inherent organic carbon content. Additionally, the biodegradation rate of biochar in amended soil influences soil organic matter dynamics, which are affected by biochar particle size. The biodegradation rate of biochar increases as its particle size decreases (Gerges *et al.*, 2023). Furthermore, alterations in soil organic matter in freshly biochar-amended soils may result from the biodegradation of condensed volatile gases on the biochar surface during pyrolysis. However, the pyrogenic carbon in biochar is more resistant to rapid mineralization. Although biochar persistence duration depends on its physical and chemical properties and environmental conditions, these results indicate that biochar enhances soil organic matter by sequestering carbon directly and maintaining its stability over time. The increasing in soil organic matter was more significant in the first year than in the second year. This could be due to the biodegradation of organic matter under the climate conditions of the studied area. The combination of biochar and organic fertilizer enhanced soil microbial activity, that accelerate the biodegradation process. Notably, biochar and organic fertilizer were applied only once at the beginning of the experiment. It is demonstrated that applying biochar in sandy soil was more efficient in the short term compared to the long term (Ibrahimi and Alghamdi, 2022).

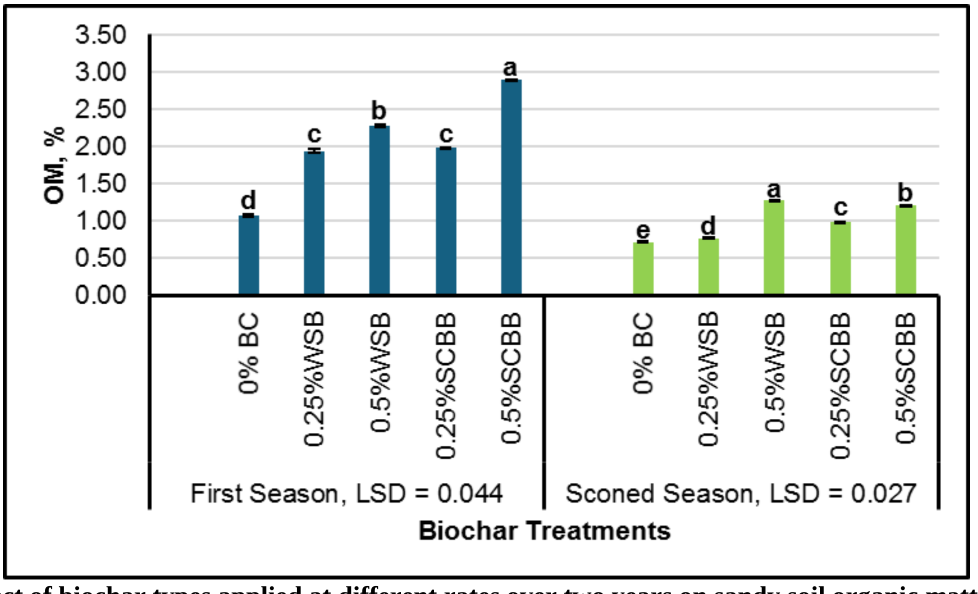


Fig. 8. Effect of biochar types applied at different rates over two years on sandy soil organic matter (OM)
Letters above bars indicate significant differences (LSD, $P < 0.05$) compared to the control.

Effect of biochar application on ameliorating morphological features of *Moringa oleifera*

Generally, vegetative growth characteristics were significant affected by biochar addition. Data in Table (4) showed no significant difference in the number of branches between biochar treatments compared to control, except for 0.50% WSB in the first season. However, in the second season, all biochar treatments differed significantly ($P < 0.05$) from the control (Table 5). Leave dry weight – measured at the end of each season - increased significantly by 1.79-, 2.21-, 2.52- and 2.61-fold for the treatments of 0.25% WSB, 0.50% WSB, 0.25% SCBB, and 0.50% SCBB, respectively, compared to control in the first season (Table 4). In the second season raised by 1.24-, 9.76-, 10.44- and 22.51-fold for the same treatments, respectively. These improvements correlated with enhanced soil parameters, particularly soil macronutrients and exchangeable cations. Similarly, plant height, main trunk diameter, and seed weight had the same trends due to the addition of biochar compared to control (Table 5). Statically, the treatment of 0.50% SCBB represented the highest significant increase, followed by 0.50%WSB. It is observed that the biochar dosage was positively effective on the plant height and main trunk diameter than its type. While weight of seeds was significantly affected by the type and dose of biochar (Table 5).

The increase in biomass of *Moringa oleifera* in this study was probably attributed to the increase in nutrient availability such as N, K, and P, as mentioned in the soil characterization section. In addition, it was confirmed that biochar applied to sandy soil improved the cation exchange capacity of the soil environment after biochar addition. As well, soil amended with biochar can retain more irrigation water and enhance microbial activity that positively improved essential nutrient availability to plants, subsequently increasing soil fertility (Xia *et al.*, 2024). Similar results demonstrated an increase in the stem size of water spinach due to soil amendment by rice husk biochar and wood biochar (Varela Milla *et al.*, 2013 and Mahmoud *et al.*, 2019). In addition, these results were assured by Abukari and Iddrisu Nasare (2020), when they studied the impact of rice husk biochar on the diameter and weight of leaves of the moringa plant. Other studies confirmed the significant positive effect of biochar on the vegetative growth of moringa cultivated in sandy soil (Dania *et al.*, 2014 and He *et al.*, 2020). They argued this improvement after biochar addition increases organic carbon in a stabilized form, which could improve soil nutrient contents. Likewise, high dry matter production resulted from increasing nitrogen availability due to biochar addition at a higher rate.

Table 4. Effect of Biochar treatments on some vegetative growth parameters of *Moringa oleifera* during the 2022-2023 growing season. Each value represents the average of three replicates. Different letters indicate statistically significant differences (LSD; $P < 0.05$) between biochar treatments and the control

Treatments	No. of branches	Leaves dry Weight, g Plant^{-1}
0%BC	1.67 b	35.73 c
0.25% WSB	3.00 b	63.81 b
0. 50% WSB	8.67 a	78.98 ab
0.25% SCBB	4.00 b	90.13 ab
0.50% SCBB	3.33 b	93.10 a
L.S.D. at 0.05	2.51	27.49

Table 5. Effect of Biochar treatments on some vegetative growth parameters of *Moringa oleifera* during 2023-2024 growing season. Each value is the average of 3 replicates. letters suggest significant difference (LSD; $P < 0.05$) between biochar treatments compared to control

Treatments	No. of branches	Leaves dry Weight, g Plant^{-1}	Plant height, cm	Main trunk dimeter, mm^{-1}	Weight of seeds, g plant^{-1}
0%BC	10.00 b	14.14 c	201.00 c	37.67 c	11.82 d
0.25% WSB	16.00 ab	17.51 c	295.00 ab	57.00 b	16.85d
0. 50% WSB	15.67 a	137.99 b	307.67 ab	80.67 a	43.30 b
0.25% SCBB	17.00 a	151.91 b	285.00 b	62.00 b	30.00 c
0.50% SCBB	16.67 a	318.33 a	335.00 a	89.00 a	56.93 a
L.S.D. at 0.05	6.63	66.15	44.28	12.35	9.90

Experimental factors effects on the biochemical composition

The influence of biochar type (WSB and SCBB) and application rates (0.25% and 0.50%) on the biochemical compositions of *Moringa oleifera* was evaluated across two growing seasons (Table 6). Generally, the results demonstrated that all measured parameters exhibited numerically higher values in the first season compared to second, this may be due to plant physiological responses and environmental stressors (e.g., temperature, water availability). Statistical, analyses revealed no significant differences ($P < 0.05$) between biochars levels for nitrogen, phosphorus, thioredoxins, protein, and carbohydrates in both seasons. However, other investigated parameters, including relative water content, hydrogen peroxide, superoxide anion, protein thiol, transferase, glutathione, total flavonoids, and nitric acid, showed significant differences ($P < 0.05$), except potassium, sulfur, total chlorophyll, and anthocyanins in the first season, and total phenolic in the second season. Overall, in the first season, the 0.50% SCBB treatment consistently improved all studied biochemical compositions of *Moringa oleifera* compared to other treatments. However, in the second season, phosphorus, total chlorophyll, relative water content, total phenolics, anthocyanins, and carbohydrates recorded the highest values under the same treatment, while the other biochemical compounds were higher under the treatment of 0.50% WSB, except for hydrogen peroxide, superoxide, and nitric acid, which were higher in the 0.25% WSB treatment. The biochar type and rate can influence the nutrient uptake, which is alter the content of biochemical compositions. The same results were confirmed in the study on safflower planted in fine-loamy soil under water stress in soil treated with biochar of wheat and cotton combined with different nitrogen and phosphorus fertilizers on the biochemical properties, yield and nutrient content. It was reported that biochar types and its properties positively affected nutrient uptake that directly can modify the of safflower chlorophyll content (Ghaedi *et al.,* 2024). Interestingly, biochar application can enhance the soil moisture and water availability to plant, which directly improves leaf relative water content and dry matter production through increasing the electron transport rate in photosystem II (Liu *et al.,* 2016). Other research has documented significant effects of biochar treatments on biochemical parameters in moringa (Hafiz *et al.,* 2021), maize and wheat (El-Sharkawy *et al.,* 2022), and lettuce (Cakmakci *et al.,* 2022).

Similar results were reported in the previous studies related to seasonal variations in the biochemical composition of *Moringa oleifera* (Ralepele *et al.,* 2021 and Farswan *et al.,* 2024). Notably, biochar enhanced nitrogen, phosphorus, and potassium in the plants over both seasons (El-Sharkawy *et al.,* 2022). Biochar treatments enhanced several biochemical components of *Moringa oleifera* in comparison to the control, including the amounts of acid phosphatase, chlorophyll-a, and chlorophyll-b (Zubair *et al.,* 2021). Cornelissen *et al.* (2018) found that while biochar generated from cocoa shells increased maize output for two seasons, the benefits subsided in the fifth. The biochar treatment application significantly increases chlorophyll content, photosynthesis rate, and relative water content under stress conditions, plant nutrient contents, and other physio-biochemical traits (Zhang *et al.,* 2016; Haider *et al.,* 2020; Cakmakci *et al.,* 2022; El-Sharkawy *et al.,* 2022 and Ghaedi *et al.,* 2024). Similarly, in drought-stressed plants, the use of biochar increased photosynthetic pigments, water relations, antioxidant activity, and total plant growth (Sattar *et al.,* 2019). It is well known that the chemical composition of plants, including food crops, is influenced by the seasons variations (Shih *et al.,* 2011). These effects are driven by shifts in physiological needs and metabolic activities rather than nutrient availability in plant tissues (Sgarbossa *et al.,* 2019). Seasonal fluctuations have a considerable impact on the content of secondary metabolites in *Moringa* oleifera (Farswan *et al.,* 2024). It was reported that the ability of plants to synthesize metabolites represents an adaptive strategy for crops to mitigate the adverse conditions of the growing environment that may require the synthesis of different types of complex chemicals as a protective mechanism (Farswan *et al.,* 2024). The biochar applied to low-quality sandy soils can enhance plant growth by improving photosynthesis and soil-plant water relations that influence chlorophyll content, assimilating remobilization, nutrient uptake, and changing the quantity of photosynthetic pigments (Haider *et al.,* 2015 and Ghaedi *et al.,* 2024). The beneficial properties of biochar can help mitigate the adverse effects of extreme weather events, aiding in the restoration of the soil-plant system (Kumar *et al.,* 2022). That means biochar demonstrates significant potential as an alternative growing medium for nursery-grown plant seedlings in low-fertility soils. However, biochar application significantly developed moringa growth in sandy soil and improved soil chemical characteristics and fertility. By augmenting soil structure, nutrient retention, and moisture-holding capacity that directly correlated with superior growth performance in Moring (Hafiz *et al.,* 2021).

Table 6. Interaction effect of the biochar treatments on the biochemical compositions of *Moringa oleifera* under the 2022-2023 and 2023-2024 seasons

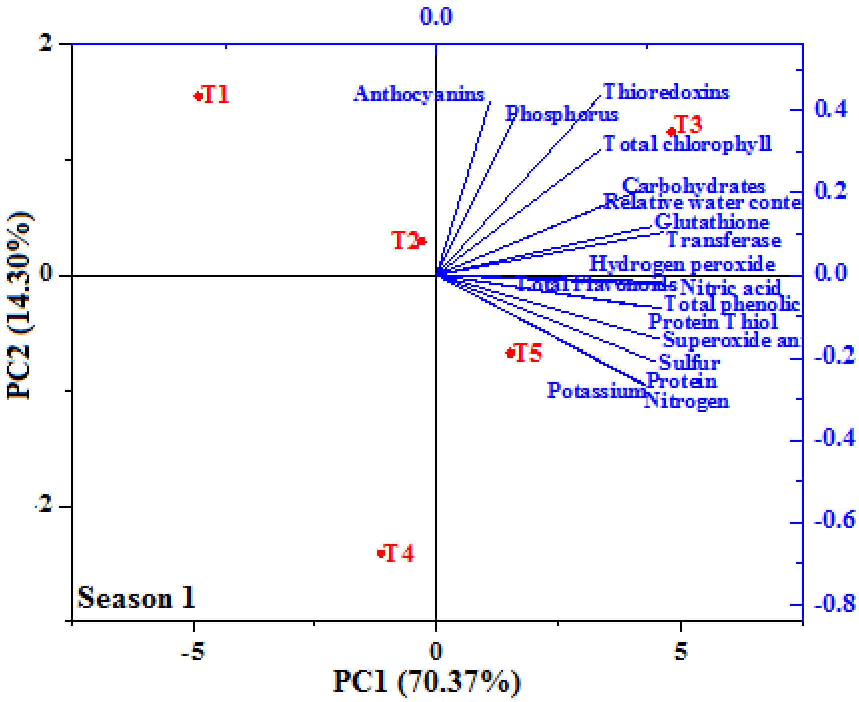
Seasons	Treatments	Nitrogen, mg g^{-1}	Phosphorus, mg g^{-1}	Potassium, mg g^{-1}	Sulfur, mg g^{-1}	Total chlorophyll, mg g^{-1}	Relative water content, %	Hydrogen peroxide, mg g^{-1}	Superoxide anion, mg g^{-1}	Protein Thiol, %
Season 1	T1	1.14	0.70	1.63	2.55	7.52	62.90	27.11	26.26	2.92
	T2	1.25	0.64	1.87	2.76	7.14	70.57	31.61	34.71	7.47
	T3	1.46	0.72	1.97	3.04	8.44	73.53	40.80	49.94	8.23
	T4	1.39	0.64	1.91	2.89	7.12	65.85	31.75	40.72	5.96
	T5	1.40	0.70	1.89	2.93	7.88	63.44	39.12	43.20	6.21
LSD	**0.05**	NS	NS	NS	NS	NS	7.26	5.20	7.11	1.41
	0.01	NS	NS	NS	NS	NS	NS	7.57	10.35	2.04
Season 2	T1	0.86	0.52	1.23	1.92	5.23	47.30	20.38	19.74	2.20
	T2	0.97	0.47	1.37	2.03	5.66	51.92	22.63	24.71	4.28
	T3	1.08	0.58	1.50	2.32	6.34	55.61	28.45	29.59	4.49
	T4	0.98	0.42	1.31	2.03	5.49	52.04	30.95	35.07	5.52
	T5	1.12	0.54	1.57	2.37	6.06	48.39	25.83	34.04	6.27
LSD	**0.05**	NS	NS	0.11	0.28	0.63	4.89	4.20	7.32	1.13
	0.01	NS	NS	0.16	NS	NS	NS	6.11	10.65	1.65

Seasons	Treatments	Thioredoxins, mg^{-1} min^{-1}	Transferase, mg^{-1} min^{-1}	Glutathione, mg^{-1} min^{-1}	Total phenolic, mg^{-1} min^{-1}	Total Flavonoids, mg^{-1} min^{-1}	Anthocyanins, mg^{-1} min^{-1}	Protein, mg^{-1} g^{-1}	Carbohydrates	Nitric acid
Season 1	T1	15.38	3.17	8.39	6.98	2.16	18.50	7.15	3.71	25.73
	T2	16.05	5.77	16.89	9.10	6.54	18.63	7.85	4.05	33.76
	T3	16.98	10.35	19.61	13.84	8.39	20.00	9.12	4.17	39.65
	T4	14.43	4.34	10.42	10.58	4.72	17.30	8.70	3.70	31.85
	T5	15.81	8.60	16.83	10.77	7.29	16.05	8.76	4.06	34.88
LSD	**0.05**	NS	1.14	3.24	1.35	1.36	NS	NS	NS	7.54
	0.01	NS	1.66	4.72	1.96	1.98	NS	NS	NS	10.79
Season 2	T1	11.56	2.38	6.31	5.25	1.62	13.91	5.38	3.05	19.35
	T2	11.57	3.07	8.14	6.42	2.84	15.43	6.09	2.73	27.02
	T3	11.50	4.15	10.21	9.20	4.64	15.66	6.73	3.35	21.39
	T4	11.56	5.80	13.12	8.72	4.92	11.61	6.14	2.47	30.07
	T5	12.84	7.19	14.10	8.00	6.06	13.07	6.99	3.14	27.32
LSD	**0.05**	NS	1.21	3.21	NS	0.96	1.22	NS	NS	3.93
	0.01	NS	1.77	4.67	NS	1.40	1.77	NS	NS	5.72

Season1: first year 2022-2023; Season 2: **second year**; 2023-2024; **WSB:** wheat straw biochar; **SCBB:** sugarcane bagasse biochar.
Each value is the average of 3 replicates. **LSD**: least significant differences at $P < 0.05$, $P < 0.01$.

Principal component analysis (PCA)

The PCA was performed to evaluate the relationships between the biochemical compositions of *Moringa oleifera* under biochar treatments in two growing season (Fig. 9). The analysis revealed that PC1 and PC2 mainly distributed and distinguished the biochar treatments and the biochemical compositions of *Moringa oleifera* in different groups, explaining 84.67% (first season) and 83.16% (second season) of total variation. PC1 alone accounted for 70.37% and 57.76% of the variability in the first and second seasons, respectively, demonstrating its dominant role. PC1 exhibited positive correlation with all measured biochemical traits in both seasons, except for anthocyanin content in the second season. Several studies used PCA to determine the relationships between the total variability among the traits under biochar treatments, which was accounted 78.66% (Ghaedi *et al.*, 2024), 63.2% (Abban-Baidoo *et al.*, 2024), and 92.00 % (Guo *et al.*, 2025). Notably, 0.50% SCBB (T3) and 0.50% WSB (T5) treatments showed the strongest associations with PC1, suggesting their pronounced influence on biochemical profile. Under the biochar treatments in both growing seasons, a sharp angle between most of the biochemical compositions of *Moringa oleifera* was found, indicating a positive correlation between these variables, but they differed in their degree and consistency in quantity (Abban-Baidoo *et al.*, 2024; Ghaedi *et al.*, 2024 and Guo *et al.*, 2025). A perfect positive correlation was observed between nitrogen and protein in both seasons and between phosphorus and carbohydrates in the second season. The number of positive correlations among the biochemical compositions in the first season was higher than in the second season. The strongest positive correlations were noticed in the first season among nitrogen, sulfur, superoxide anion, and protein, as well as glutathione and carbohydrates. In contrast, the second season showed strong association between potassium and sulfur, and among superoxide anion, transferase, and glutathione. These parameters emerged as the most effective differential between biochar treatments. Conversely, phosphorus demonstrated negative correlation with potassium in the first season and nitric acid in the second seasons, respectively. Generally, all analyzed variables by PCA indicate that the 0.50% SCBB and 0.50% WSB are positively correlated with the biochemical compositions of *Moringa oleifera* in both seasons. These results indicated that several biochemical traits of plants played a significant role under the 0.50% SCBB and 0.50% WSB treatments (Ghaedi *et al.*, 2024 and Guo *et al.*, 2025).



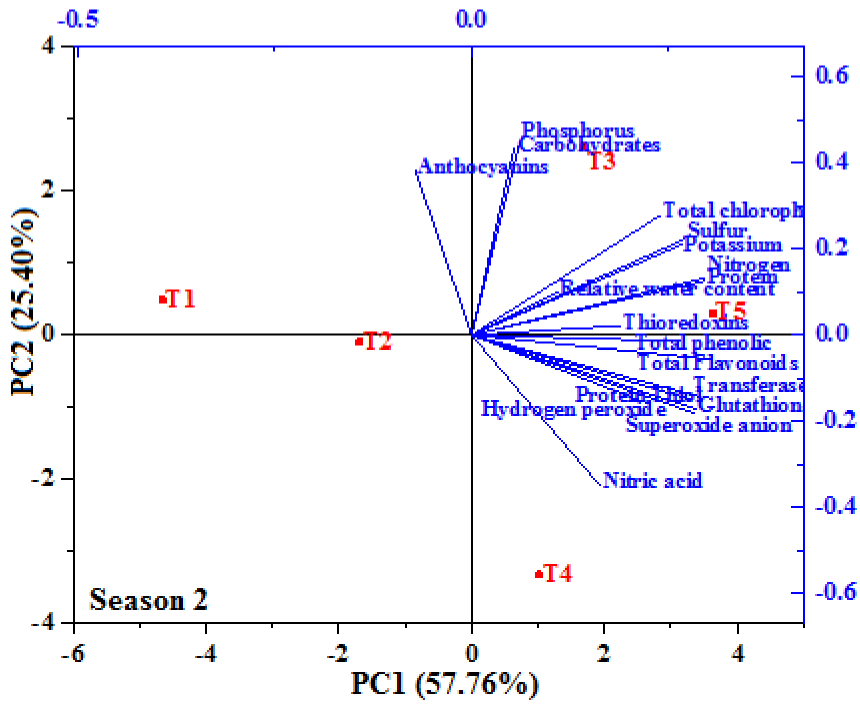


Fig. 9. Biplot diagram between PC1 and PC2 shows similarities and dissimilarities in relationships between the biochemical compositions of *Moringa oleifera* (blue color) under the biochar treatments (red color) in both growing seasons

CONCLUSION

This study demonstrated the role of two types of biochar, sugarcane bagasse (SCBB) and wheat straw (WSB), in improving sandy soil properties and their effects on *Moringa oleifera* growth parameters. Regarding soil characteristics, soil pH showed a slight increase with both biochar types. Electrical conductivity (EC) showed a slight significant increase due to biochar addition, but the treated soil remained non-saline. Essential macronutrients availability (N-P-K), exchangeable cations (Ca, Mg, and K), CEC of soil environment and soil organic matter were positively influenced by biochar addition. This improvement in soil characteristics could be attributed to the high specific surface area of biochar, the presence of more functional groups that improve cation exchange capacity, in addition to its the nature of the porous structure, and the addition of organic fertilizer. The highest percentage of increase in soil parameters was attributed to the addition of SCBB at a higher dose of 0.50% compared to other treatments. Vegetative growth parameters, such as dry weight of leaves, plant height, trunk diameter, and weight of seeds, were positively influenced by biochar addition, with slightly non-significant differences among treatments. The effect of biochar on soil properties was more pronounced in the first year than in the second. Similarly, the biochemical composition of *Moringa oleifera* exhibited greater values in the first year, with 0.50% SCBB and 0.50% WSB showing the most significant effects on the plant's biochemical composition, which confirmed by Principal Component analysis. Finally, biochar, particularly when applying SCBB at a high dose (0.50%), demonstrated a beneficial effect on sandy soil properties and promoted plant growth. This study recommended that biochar should be added annually to maintain the improvements in key sandy soil properties, which significantly enhance plant growth parameters

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الملخص العربي

الفحم الحيوي كمحسن لخواص التربة الرملية وتأثيرة على التركيب البيوكيميائي ونمو نبات المورينجا

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تناولت هذه الدراسة الآثار طويلة المدى للفحم الحيوي من قش القمح (WSB) والفحم الحيوي من بقايا قصب السكر (SCBB) على خصائص التربة الرملية (محطة بحوث بالوظه) ونمو نبات المورينجا أوليفيرا. أجريت تجربة حقلية لمدة عامين باستخدام معدلات الفحم الحيوي ٠,٠٠٪ و ٠,٢٥٪ و ٠,٥٠٪ (وزن/وزن). تم جمع عينات من التربة والنبات في نهاية كل عام لفحص درجة حموضة التربة والتوصيل الكهربائي (EC) والمادة العضوية في التربة (SOM) والسعة التبادلية الكاتيونية (CEC) والمغذيات الكبرى المتاحة (N-P-K) والكاتيونات القابلة للتبادل (Ca^{2+}, Mg^{2+}, K^{+}).تمت دراسة التركيب البيوكيميائي والتحليل النوعي لنبات المورينجا. أظهرت النتائج أن إضافة الفحم الحيوي زادت قليلاً من درجة حموضة التربة، ولكن الزيادة الإجمالية خلال الموسمين لم تكن ذات دلالة إحصائية، بينما أظهرت ECزيادة طفيفة ذات دلالة إحصائية. أدى إضافة ٠,٥٠٪ SCBB إلى زيادة كبيرة في N و P و K المتاحة بنسبة ٤٢,٨٦٪ و ٤٣,٥٤٪ و ١٣٣,٧٠٪ على التوالي. كان SCBBأفضل من WSB في زيادة الكاتيونات القابلة للتبادل بسبب ارتفاع قيمة SSA و CEC ، مما أدى إلى تحسين CECللتربة بشكل كبير. زادت المادة العضوية في التربة مع الجرعات أعلى من الفحم الحيوي، بسبب محتواها العالي من الكربون العضوي. أثرا كلا من نوعي الفحم الحيوي بشكل كبير (P <0.05) على معايير نمو المورينجا، بما في ذلك وزن الأوراق وارتفاع النبات وقطر الجذع ووزن البذور. كانت تأثيرات الفحم الحيوي على خصائص التربة أكثر وضوحًا في السنة الأولى، بينما كان تأثيره على النمو الخضري أكثر أهمية في السنة الثانية. أثرت اضافة الفحم الحيوي بشكل كبير (P < 0.05) على التركيب البيوكيميائي للنبات ولوحظت قيم أعلى للتركيب البيوكيميائي في الموسم الأول. يُظهر تحليل PCA لجميع المتغيرات وجود علاقة إيجابية بين التركيب البيوكيميائي للنبات و ٠,٥٠٪ SCBB في كلا الموسمين. الاستنتاج: كانت اضافة SCBB بنسبة ٠,٥٠% هي الأكثر فعالية. ينبغي إضافة الفحم الحيوي سنويا للحفاظ على تأثيره الإيجابي على خصائص التربة ونمو النبات.

الكلمات المفتاحية: الفحم الحيوي؛ التربة الرملية؛ الخصائص الكيميائية للتربة؛ المورينجا؛ التركيب البيوكيميائي.