`Vol. 5, No. 3, pp. 322-350, (September 2024)
DOI: 10.21608/aujes.2024.295308.1251
Aswan University Journal of Environmental Studies (AUJES)
Online ISSN: 2735-4237, Print ISSN: 2735-4229
Journal homepage: https://aujes.journals.ekb.eg/ E-mail: AUJES@aswu.edu.eg
Original research

The Potential Effect of Different Types of Biochar on Chemical and Hydrological Properties of Sandy Soil

Ahmed A. M. Awad[1*], Esraa S. M. El-Habashy[1], Mohamed A. El-Desoky[2], Atef A. A. Sweed[1]

[1]*Soil and Natural Resources Department, Faculty of Agriculture and Natural Resources, Aswan University, Aswan 81528, Egypt.*
[2]*Soil and Water Department, Faculty of Agriculture, Assiut University, Assiut 71515, Egypt*

Received: 11/6/2024 Accepted: 21/7/2024

Abstract:

Due to its distinctive properties, biochar (BC) achieves the most significant improvements among agricultural soil amendments. A pot experiment was performed at the Faculty of Agriculture and Natural Resources at Aswan University, Aswan province, Egypt (latitudes 24° 05′ 18″ N and longitudes 32° 54′ 00″ E) during 2022 to evaluate the effectiveness of two BCs derived from sugarcane manufacturing waste—namely, bagasse (BCBG) and filter-cake (BCFC), which were obtained at two different of pyrolysis temperatures (300 and 600 °C) at 0, 1 and 2% ~ 0.0, 50.0 and 100.0 $g.pot^{-1}$ on the hydro-chemical properties of sandy soil. This study employed a split–split plot structure in a Randomized Complete Block Design (RCBD) with three replicates. The results indicate that applying $BCFC_{300}$ had the greatest effect on organic matter content (OM) and available water content (AWC), while applying $BCFC_{600}$ gave the best results in terms of $CaCO_3$ (decreasing), as well as water holding capacity (WHC) and permanent wilting point (PWP). Likewise, $BCBG_{300}$ had superior effects on soil pH (decreasing it) and cation exchange capacity (CEC) and field capacity (FC). Furthermore, all the improvements seen in all the studied hydro-chemical properties, except PWP, were associated with BC-R_0 and BC-R_2. In conclusion, BCBG, PYT300 and BC-R_2 and their interactions were the most influential on soil chemical properties. Furthermore, the best hydrological properties (FC and AWC) in the sandy soil were obtained in the treatment without amendment. Additionally, BCFC x PYT_{600} x BC-R_2 and BCFC x PYT_{600} x BC-R_2 treatments were the most impactful on WHC and PWP, respectively.

Keywords: Sugarcane bagasse and filter-cake; pyrolysis temperature; chemical and hydrological properties of sandy soil; soil fertility status.

1. Introduction

The sugar manufacturing industry is one of the most successful industries in Egypt, given its contribution to the nation's economy. Sugar production factories are concentrated in Upper Egypt, an area that extends for 800 km, where sugar is the main crop. According to a statement issued by the Egyptian Economic Affairs Sector in 2021, the total cultivated area of sugarcane is estimated to be about 137,572 hectares, producing more than 16.8 million tons of residues.

Corresponding author*: E-mail address: ahmed.abdelaziz@agr.aswu.edu.eg

These wastes should be recycled instead of being disposed of via burning, as this causes environmental pollution **(Brewer et al. 2014)**. In the past two decades, converting these wastes into biochar (BC) has been one of the most promising solutions, given its low cost and unique properties, and it is one of the more environmentally friendly amendment processes **(Hossain et al. 2020)**. Generally speaking, BC is a solid and stable carbon-rich by-product obtained from the pyrolysis (300-1000) of a wide spectral range of feedstock biomasses at high temperatures under conditions devoid of oxygen or in an oxygen-limited atmosphere **(Diatta et al. 2020)**. Numerous previous studies have shown that BC is the best mode of agricultural soil amendment given its unique properties **(Meier et al. 2019)**. However, it is not an easily decomposed compound, due to its highly aromatic structure, with a large surface area and large cation exchange capacity **(Seleiman et al. 2020)**. Moreover, it contains a relatively high content of macro- and micronutrients **(El-Naggar et al. 2019a)**. Despite this, several scientists have systematically investigated the significant influence that BC can have when used in agriculture **(Wu et al. 2019 and Garcia-Perez et al. 2022)**, but very few works have focused on its potential when used on Egyptian soils. Several studies have indicated that the physical–chemical characteristics and structural properties of BC are closely associated with the pyrolytic conditions (temperature, heating rate and residence time) and the biomasses of the feedstock **(Kalina et al. 2022)**. As such, BCs could be generated from a wide range of biomasses—either from animal-based wastes such as manure, sewage sludge and urban yard residues, or plant-based residues such as pine wood **(Peng et al. 2019)**, switchgrass **(Diatta et al. 2020)**, sugarcane and rice waste **(Weber and Quicker, 2018)**, corn stalk, and rice and wheat straw **(Xu et al. 2016)**. Other scientists have shown that the pyrolysis temperature can greatly affect the BCs' features **(Seleiman et al. 2020)**. BCs obtained under high-pyrolysis-temperature conditions (>550 °C) are characterized by a large surface area and large aromatic content compared with BCs produced under low-temperature pyrolytic conditions (200-400 °C), which are characterized by the presence of more oxygen-containing functional groups such as hydroxyl (-OH), carboxyl (-COOH), ketone (C=O) and aldehyde (-CHO) **(Mandal et al. 2020)**. Furthermore, numerous studies have reported that under slow pyrolytic conditions, the available water capacity is markedly improved in both fine and coarse-textured BCs **(Ayaz et al. 2021 and Kalu et al. 2021)**. On the other hand, most of the work undertaken so far has indicated that the pyrolysis temperature directly affects other chemical properties of BC. According to **(Bista et al. 2019)**, acidified BC is produced at low temperatures (<400 °C), while alkaline BC is obtained at high temperatures (>400 °C). In addition, a high C content is related with a high pyrolysis temperature (300-800 °C) **(Campos et al. 2020)**.

The results in the literature reveal that the application of BC has a profound impact on soil's chemical properties. Cation exchange capacity (CEC) and organic carbon (OC) are positively affected in fine- or coarse-textured soils by BC application **(Meier et al. 2019; Singh et al. 2022)**. In addition, incorporating BC in soil clearly decreases its salinity levels by reducing anion concentrations, such as $CO_3^{=}$, HCO_3^{-}, $SO_4^{=}$ and Cl^{-} **(Tavakkoli et al. 2011)**. The documented information has shown the positive effects of BC addition in terms of reducing nutrient loss and enhancing nutrient use efficiency (NUE) and nutrient availability **(Liu et al. 2018 and Borchard et al. 2019)**. It is worth pointing out that BC addition effectively contributes by improving the soil's physical parameters and soil–water interactions. Previous studies have seen significant enhancements in water holding capacity (WHC) and soil aggregates stability **(Brantley et al. 2016)**. In addition, BC improves soil structure **(Molnár et al. 2016)** and soil bulk density **(Yusif et al. 2020; Li et al. 2020 and Karim et al. 2020)**.

Therefore, the objectives of our study are twofold: a) to recycle sugarcane manufacturing waste to produce BCs instead of disposing of them, and b) to evaluate the potential effectiveness of FSB, PYT and BC-RBC alone and in combination on some of the hydro-chemical properties and the macronutrient status of sandy soil.

2. Materials and Methods.

2.1. Study location.

This study focuses on the potential influence of two types of BCs derived from sugarcane manufacturing waste, including bagasse (BCBG) and filter-cake (BCFC) applied at 300 and 600 °C, on the chemical and hydrological properties of sandy soil. This research was conducted at the agricultural experimental unit at the Faculty of Agriculture and Natural Resources, Aswan University, Aswan, Egypt, between latitude 24° 05′ 18″ N and longitude 32° 54′ 00″ E.

2.2. Waste resources and BC production.

In January 2022, two types of standard BCs derived from sugarcane manufacturing waste, namely, BCBG and BCFC, were produced at two different pyrolysis temperatures (300 and 600 °C). The wastes of both were obtained from the sugar factory in the Kom-Ombo district, Aswan. Prior to pyrolysis, both waste samples were dried at 105 °C for 24 h. The BCs were produced by pyrolysis at 300 and 600 °C for 90 min under isothermal conditions using a custom-made electric oven (internal dimensions 250 x 250 x 250). The temperature of pyrolysis was selected according to previous studies assessing BC for use in soil amendment **(Mor et al. 2019)**.

2.3. BC characterization, experimental procedure, treatments and Experimental design.

After the pyrolysis process, the BCs were ground to small particle sizes that could pass through a 2 mm sieve before analysis. Some chemical and physical properties of BCs were measured, and the results are shown in **Table 3**. The reactivity (BC-pH) and electrical conductivity (BC-EC) of the BCs were assessed by calibrating them in a suspension of 1:10 (BC:Water), using a pH-meter (Jenway, UK) according to **Rajkovich et al. (2012).** An EC-meter (LF-191) from Conduktometer, Germany, was used as described in the International Biochar Initiative Guideline **(IBI, 2015)**. Scanning electron microscopy (Hitachi-TM3030, Japan) was used to elucidate the impact of PYT on the microstructures of the BCs. The elemental composition was determined using an Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES).

In March 2022, plastic pots with a diameter of 23 cm and height of 20 cm were filled with 5 kg of soil. In this study, the soil texture was determined to be sandy. The experiment was undertaken using a split–split plot structure with a Randomized Complete Block Design (RCBD). Two types of FSBs such as BCBG and BCFC were tested. While, the PYTs such as PYT_{300} and PYT_{600} used to obtain the BCs. Three rates of BCs (0.0, 50.0% and 100.0 $g.plot^{-1}$) as a soil application. Accordingly, the study involved 36 pots, (2 FSB) × (2 PYT) × (3 BC-R) × (3 replicates).

2. 4. Soil Sampling Collection and Chemical Determination of Soil Properties

The sandy soil samples were collected at a depth of 0-25 cm from the border areas of Sahari city. The soil samples were transported to the Soil, Water and Plant analysis Laboratory at Aswan University; they were then air-dried and crushed until they could pass through a 2 mm sieve to determine some of their chemical and physical properties, as presented in **Tables 1**. The particle size distribution was determined using the hydrometer method, as described by **Gee and Bauder, 1986**. The soil pH was directly measured in a saturated soil paste using a pH-meter

(Jenway, UK) according to the method of **McLean, 1981**. In the soil paste extract, the electrical conductivity (EC) was measured using an EC-meter (LF-191) from Conduktometer, Germany, as described in **Page et al. 1982**.

Table 1. Some physical and chemical properties of the soil in the current study

Soil property	Value
Particle size distribution (%)	
Sand	91.45
Silt	3.75
Clay	4.80
Soil texture	Sandy Soil
pH (in soil paste)	8.61
ECe ($dS.m^{-1}$)	0.163
SOM (%)	0.63
$CaCO_3$ (%)	3.66
CEC ($cmol_+kg^{-1}$)	1.02
Soluble ions ($mmol\ L^{-1}$)	
$CO_3^{=}$	---
HCO_3^-	2.12
Cl^-	0.25
$SO_4^{=}$	1.44
Ca^{++}	1.00
Mg^{++}	0.30
Na^+	1.39
K^+	1.12
Macronutrients ($mg.kg^{-1}$)	
Total N	7.01
Available P (extractable with $NaHCO_3$ pH=8.5)	3.57
Available K (extractable with NH_4OAC pH=7.0)	67.1
SBD ($g.cm^{-3}$)	1.23
FC (%)	7.30
AvW (%)	6.50
WHC (%)	20.30

pH – soil acidity; ECe – electrical conductivity; SOM – soil organic matter; $CaCO_3$ – calcium carbonate; CEC – cation exchange capacity. SBD-Soil bulk density, FC- field capacity, AvW- Available water and WHC- Water holding capacity.

The calcium carbonate ($CaCO_3$) content was determined using Collin's calcimeter according to **Piper, 1947**. Using the wet digestion method, the soil organic matter (SOM) content was determined as described by **Walkey and Sommers, 1978**. Soluble cations, i.e., calcium (Ca^{++}), magnesium (Mg^{++}), sodium (Na^+) and potassium (K^+), were extracted with 1 N NH_4AC, kept for 24 h, topped up to to 100 mL with distilled water, and filtered with Whatman filter paper NO. 42. Both Ca^{++} and Mg^{++} were determined via the titration method set out by **Jackson, 1973** using EDTA. Na^+ and K^+ were measured using flame photometry as described by **Jackson, 1973**. According to **McLean, 1982**, the soluble anions, i.e., carbonate (CO_3^{2-}), bicarbonate (HCO_3^-) and chloride (Cl^-), were determined using the titration method. The sulfates ($SO_4^{=}$) were calculated by the difference between total soluble cations and total soluble anions. The CEC was determined using the ammonium acetate technique according to **Munera-Echeverri et al. 2018**.

About 500 g of soil was taken from each pot and air-dried to determine some of its chemical and physical properties. In a saturated soil paste, the soil's pH was measured using a pH-meter (Jenway, UK) according to the method of **McLean, 1981**. The EC was measured in the soil paste extract using an EC-meter (LF-191) from Conduktometer, Germany, as described in

Page *et* al. 1982. The $CaCO_3$ content was determined using Collin's method according to **Piper, 1947**. The SOM content was determined using the wet digestion method according to **Walkey and Sommers, 1978**. According to the method of **Lindsay and Norvell 1978**, the available macro- and micronutrients were extracted using DTPA. TNC was determined using the modified micro Kjeldahl method, as described in **by Keeney and Nelson, 1983**. The APC was extracted and determined as described in by **Olsen, 1982**. Using 1 N of neutral normal ammonium acetate at pH = 7.0, the AKC was extracted and determined using a flame photometer (Jenway Model PFP-7) according to the method of **Helmke and Sparks, 1996**.

Field capacity (FC) and permanent wilting point (PWP) were measured using a pressure membrane apparatus according to **Black, (1965)**. The available water content (AWC) was calculated by the difference between FC and PWP.

2. 5. Statistical analysis.

The impacts of FSB, PYT and BC-R alone and their interactions on the soil's hydro-chemical properties and nutrient status were analyzed using analysis of variance (ANOVA) and Duncan's test, the results of which were calculated using the InfoStat statistical package, version 2011 Infostat Microsoft **(Di Rienzo et al. 2011)**. Here, FSB, PYT and BC-R were considered the main, sub- and sub-sub-main factors, respectively. The standard error (±SE) was calculated for each treatment using Microsoft Excel 2016. The heat maps were calculated using IBM SPSS statistics 21 wizard.

3. Results

3.1. Characteristics of BC.

The results in **Table 3** show the elemental compositions and molecular ratios of the BCs derived from the two types of FSB—namely BCBG and BCFC—at two different PYTs (300 and 600 °C) via energy-dispersive X-ray (EDX). The results indicated that carbon (C) is the element most markedly increased by increasing the PYT. Higher C content values (81.45% and 44.91%) were obtained in sugarcane bagasse ($BCBG_{600}$) and filter-cake ($BCFC_{600}$) produced at 600 °C compared with the sugarcane bagasse ($BCBG_{300}$) and filter-cake ($BCFC_{300}$) heated at 300 °C, with 69.27 and 33.58%, respectively.

Table 3. Elemental composition and molecular ratios of BCs obtained from BCBG and BCFC at two different pyrolysis temperatures (300 and 600 °C).

Properties	$BCBG_{300}$	$BCBG_{600}$	$BCFC_{300}$	$BCFC_{600}$
BC-pH	5.46	9.10	7.43	9.95
BC-EC	0.098	0.122	1.680	1.380
CONH analysis ($mg.kg^{-1}$, dry basis)				
C	69.27	81.45	33.58	44.91
O	24.33	10.20	27.20	22.14
N	2.60	2.22	3.25	3.16
H	1.45	1.02	4.87	2.03
Mineral composition ($mg.kg^{-1}$, dry basis)				
P	0.04	0.17	1.05	2.99
K	0.09	0.03	0.57	0.38
Ca	0.18	0.52	4.76	12.17
Mg	0.04	0.19	0.27	0.38

Properties	$BCBG_{300}$	$BCBG_{600}$	$BCFC_{300}$	$BCFC_{600}$
Si	0.62	2.42	0.63	1.25
Cl	0.18	0.94	0.14	0.18
Others	0.58	0.84	23.77	10.32
Molecular ratios				
O/C	0.263	0.094	0.608	0.370
H/C	0.251	0.150	1.740	0.542
(O+N)/C	0.296	0.117	0.688	0.432
(O+N+H)/C	0.547	0.268	2.428	0.974

BC = biochar. $BGBG_{300}$ and $BCBG_{600}$ represent BCs derived from sugarcane bagasse at 300 and 600 °C, respectively. $BGFC_{300}$ and $BCFC_{600}$ represent BCs derived from sugarcane filter-cake at 300 and 600 °C, respectively.

In contrast, the oxygen (O), nitrogen (N) and hydrogen (H) contents decreased with the increase in the PYT. However, $BCBG_{300}$ and $BCFC_{300}$ gave values of 24.33 and 27.20 for O, 2.60 and 3.16 for N, and 1.45 and 4.87 for H, respectively.

As can be observed from **Table 3**, the mineral compositions of BCs, including phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), silicon (Si) and chloride (Cl) contents, were affected by the PYT either increasing or decreasing. However, the contents of all aforementioned elements increased with the increase in PYT, except for K, which decreased. The results regarding the molecular ratios were presented in **Table 3**. It could be observed that both the O/C and H/C ratios decreased with the increase in PYT. The highest values were produced in BCs at 300 °C compared with those at 600 °C. The FSB values, in descending order, rank BCFC > BCBG. While a H/C molecular ratio indicates aromatic BCs, a high H/C ratio indicates that the BCs have a large aromatic structure, and greater stability. Similarly, the values of (O+N)/C and (O+N+H)/C molecular ratios were reduced with the increase in PYT. The treatments employed can be ranked as $BCFC_{300}$ > $BCFC_{600}$ > $BCBG_{300}$ > $BCBG_{600}$ for both molecular ratios.

The scanning electron microscopy (SEM) results of BCs produced with different FSB values at PT_{300} and PT_{600} are presented in **Figure 1**. The SEM results elucidate the effects of different biomasses of FSB at two different PTs on the morphological characteristics of the BCs created. A visual inspection of the images shows differences in terms of irregular and distinct pore surfaces. However, the BCs obtained at a high PT (600 °C), such as $BCBG_{600}$, $BCFC_{600}$ and $BCPF_{600}$, have large pores compared with those produced at a low PT (300 °C).

3.2. Soil Chemical Properties

The results regarding the impact of FSB on some of the soil chemical properties are graphically illustrated in **Figure 2 A-D**. The best (reduced) values for soil pH (8.35) and $CaCO_3$ content (4.34%) were obtained as a result of the application of BCs produced from BCBG and BCFC, respectively. The highest values of soil pH (8.42) and $CaCO_3$ (4.54%) were recorded following the application of BCFC and BCBG, respectively. Meanwhile, the highest values of OMC and CEC (0.65% and 1.92 $cmol.kg^{-1}$) were yielded following the application of BCBG. Considering the highest and lowest values, the rates of decrease were very slight, and did not exceeded 0.83 and 4.41% for soil pH and $CaCO_3$, respectively. Moreover, the percentages of increase in OMC and CEC amounted to 18.18 and 36.12%, respectively. Statistically, there are no significant differences between treatments in terms of any of the chemical properties studied, except for $CaCO_3$, which showed significant differences (at $p \leq 0.05$).

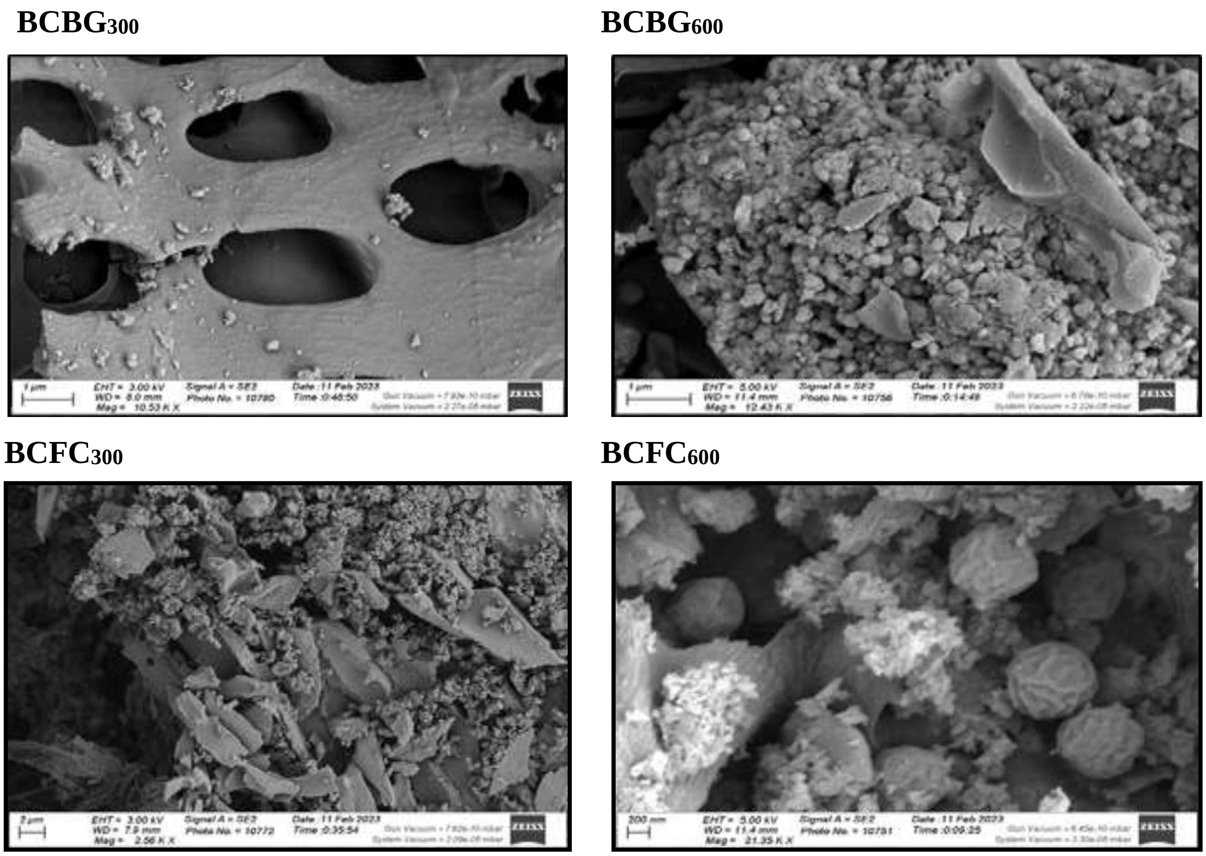


Figure 1. Scanning Electron Microscopy (SEM) of BCs derived from sugarcane bagasse at 300 and 600 °C ($BCBG_{300}$ vs. $BCBG_{600}$) and sugarcane filter- cake at 300 and 600 °C ($BCFC_{300}$ vs. $BCFC_{600}$) at 300 and 600 °C, respectively.

The individual effects of the different PYTs applied to produce BC are graphically demonstrated in **Figure 3 A-D**. The overall trend in our results indicates that a pyrolysis temperature of 300 °C (PYT_{300}) had the greatest impact on soil pH (decreasing it), with an average value 8.30; moreover, OMC and CEC increased, recording 0.65% and 2.02 $cmol.kg^{-1}$, respectively. On the contrary, PYT_{600} had the least impact on soil pH, OMC and CEC, with averages of 8.47, 0.56% and 1.31 $cmol.kg^{-1}$, respectively. PYT_{600} was the superior treatment, yielding a lower value (4.40%) than that (4.48%) obtained using PYT_{300}. Depending on whether the highest or lowest values were employed, the rates of improvement reached 2.00 and 1.79% (decreased) for soil pH and $CaCO_3$, and 16.07 and 54.20% (increased) for OMC and CEC, respectively. The results obtained from the statistical analysis indicate highly significant differences in soil pH and CEC, but no significant impacts on $CaCO_3$ or OM contents.

The results of the ANOVA reveal that the BC addition rates had significant effects (at $p \leq 0.01$) on soil pH, $CaCO_3$ and CEC, and significant effects (at $p \leq 0.05$) on OMC. There were differences in the results derived: the application of BC at 2% (BC-R_2) had the greatest effect on the soil pH (decreasing it), as well as on OMC and CEC (increasing them). As presented in **Figure 4 A-D**, the BC addition rates were as follows (ranked in ascending order): R_2 (8.22) > R_1 (8.32) > R_0 (8.61) for soil pH and R_0 (3.68) > R_2 (4.63) > R_1 (5.00) for $CaCO_3$. Further, these rates were ranked R_2 (0.74) > R_0 (0.57) > R_1 (0.50) for OMC and R_2 (2.54) > R_1 (1.43) > R_0

(1.02) for CEC. The rates of improvement were 4.53, 26.40, 29.83 and 149.02% for soil pH, $CaCO_3$, OMC and CEC, respectively.

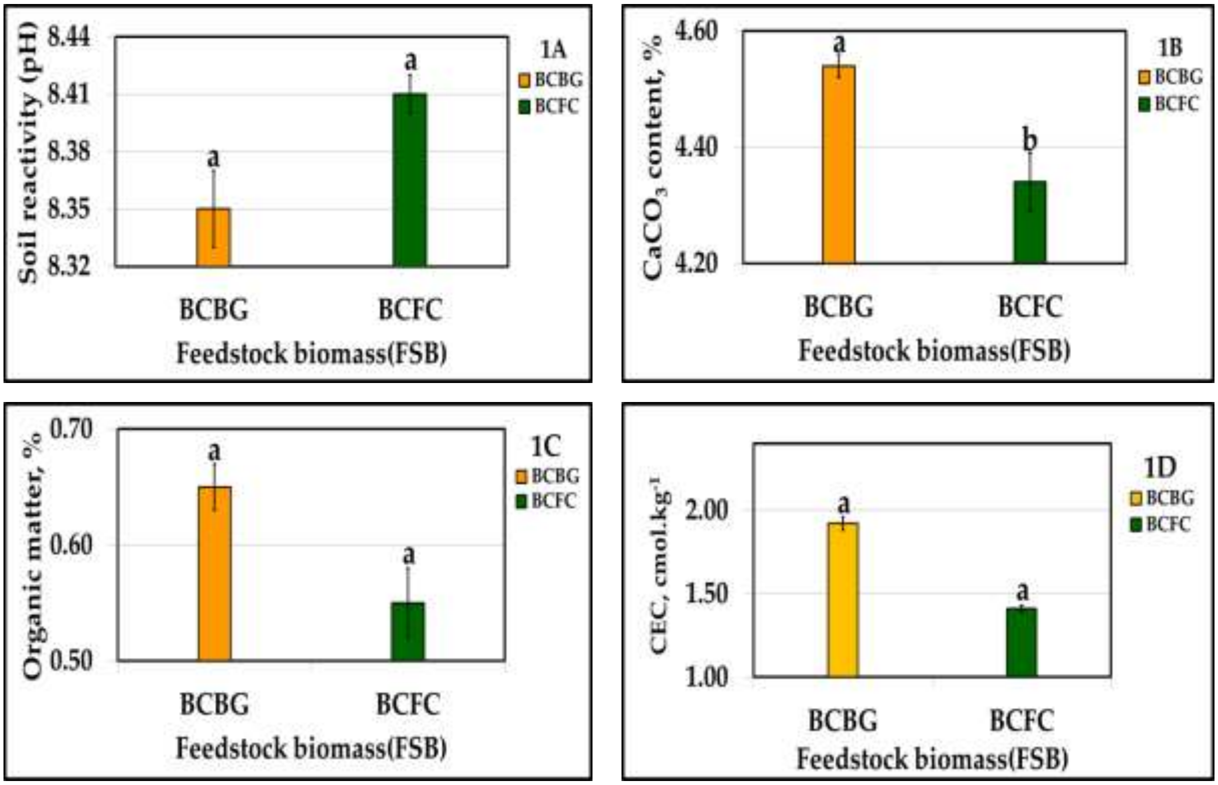


Figure 2. Impact of different biochars (BCs) on soil pH (2A), $CaCO_3$ content (2B), organic matter content (2C) and cation exchange capacity (2D) of sandy soil. BCBG and BCFC represent BCs derived from sugarcane bagasse and filter-cake, respectively. The small letters on the bars indicate significant differences between treatments at 5% probably levels, significant was tested using the Duncan's test.

Concerning the impact of the FSB × PYT interaction on the soil's chemical properties, the results in **Table 4** indicate that the BCs produced from sugarcane bagasse at 300 °C ($BCBG_{300}$) and sugarcane filter-cake at 600 °C ($BCFC_{600}$) had the greatest influences on soil pH and $CaCO_3$, yielding the lowest values (8.24 and 4.23%). In addition, the highest values (0.68% and 2.49 $cmol.kg^{-1}$) were obtained following the application of BC derived from sugarcane filter-cake heated at 600 °C ($BCBG_{300}$) and $BCBG_{300}$, respectively. Between the highest and lowest values, we can see reductions of 2.95% and 6.00% for soil pH and $CaCO_3$, respectively, while these percentages were 41.67% and 96.06% for OMC and CEC, respectively. The results of the ANOVA show that the FSB × PYT treatment had significant effects on soil pH and CEC, and no significant effects on $CaCO_3$ and OM. The results in **Table 4** elucidate the interactive effect of the PYT × BC-R treatment on the soil's chemical characteristics. However, the best results for soil pH were achieved when using BC generated from sugarcane bagasse with a 2% (PYT_{300}-R_2) application rate, recording 8.06, and OM and CEC reached 1.02 and 3.34%, respectively. It is notable that the non-amended soil, in general, achieved the best values, reaching 3.61% and 3.75%. The results obtained from the statistical analysis showed that all treatments had a significant influence (at $p \leq 0.01$) on soil pH, OMC and CEC, and a significant impact (at $p \leq 0.01$) on $CaCO_3$ content. As depicted in **Table 4**, the application of sugarcane filter-cake at a rate of 2% (BCFC × R_2) gave the best results in terms of OM and CEC, which reached their highest values (0.79% and 2.04 cmol.kg^{-1}, respectively). Furthermore, the application of sugarcane bagasse at a high rate (BCBG × R_2) was superior for its effects on soil pH, which reached an average of 8.14. As regards this metric, the untreated soil gave the lowest value (3.61%) compared with the BCBG × R_2-treated soil, which recorded the highest value (4.72%). The results of the statistical analysis indicate that there were only significant effects ($p \leq 0.01$) and impacts (at $p \leq 0.05$) on CEC, while no significant influences were shown for OM.

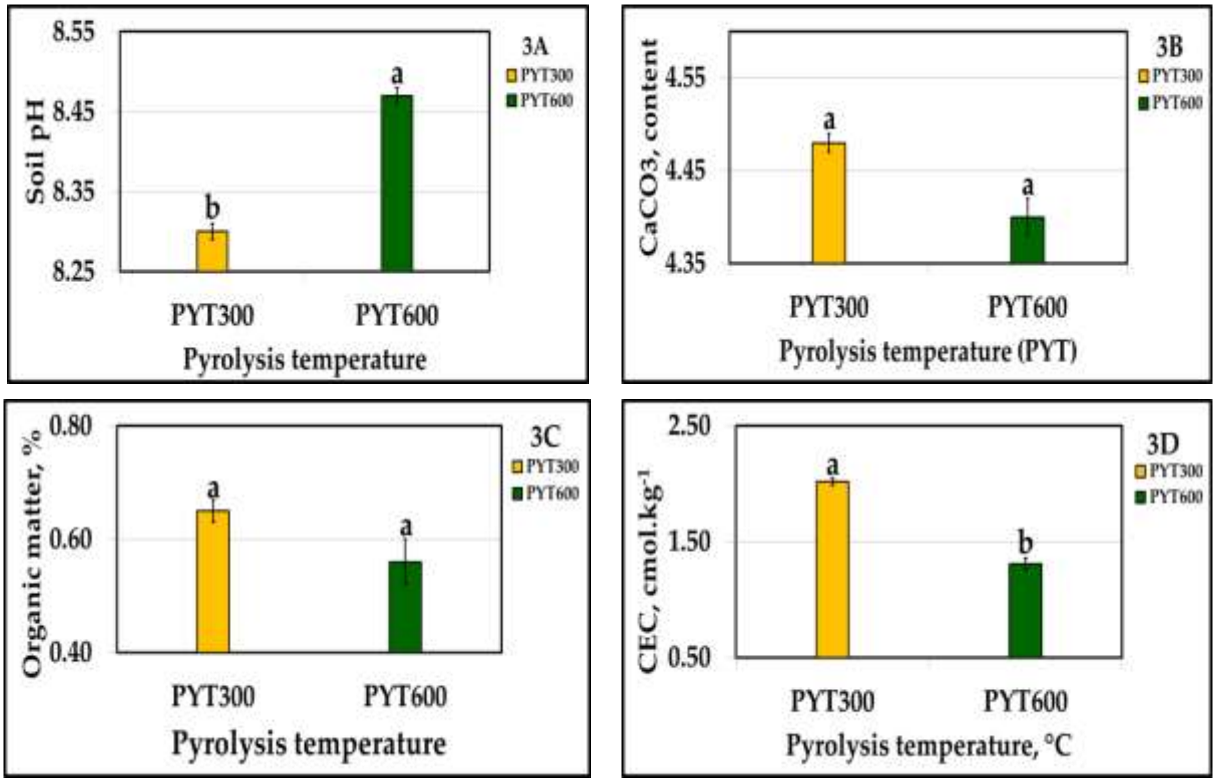
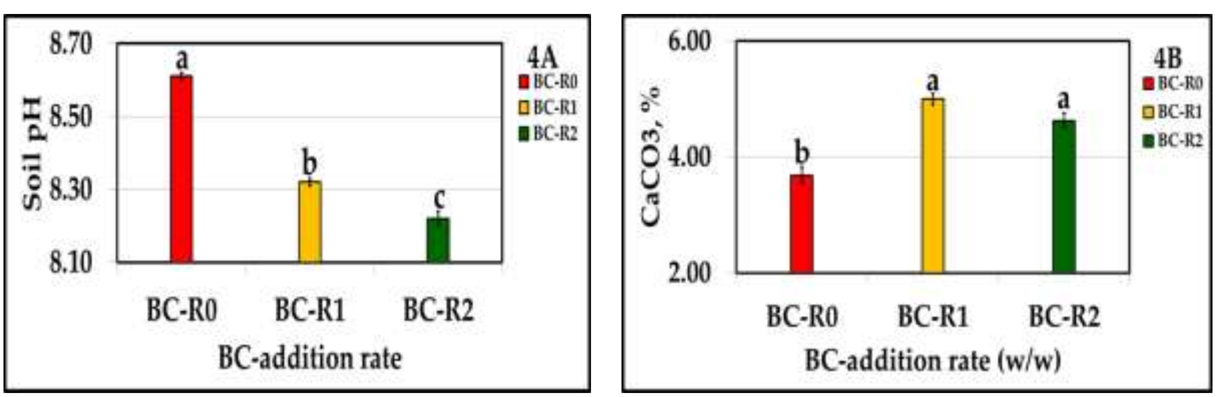
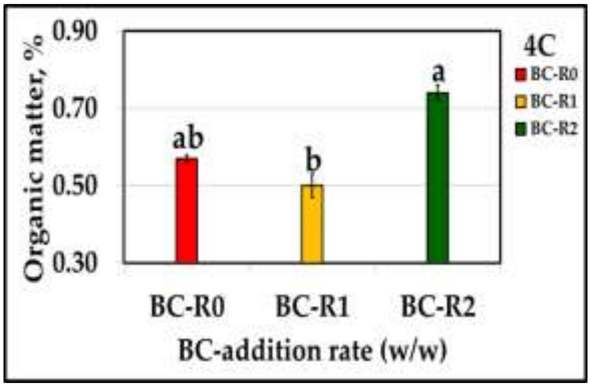


Figure 3. Impact of different pyrolysis temperatures (PYTs) on soil pH (3A), $CaCO_3$ content (3B), organic matter content (3C) and cation exchange capacity (3D) of sandy soil. PYT_{300} and PYT_{600} indicate PYT applied to produce BCs at 300 and 600 °C, respectively. Values represent the mean of three replicates. The small letters on the bars indicate significant differences between treatments at 5% probably levels, significant was tested using the Duncan's test.





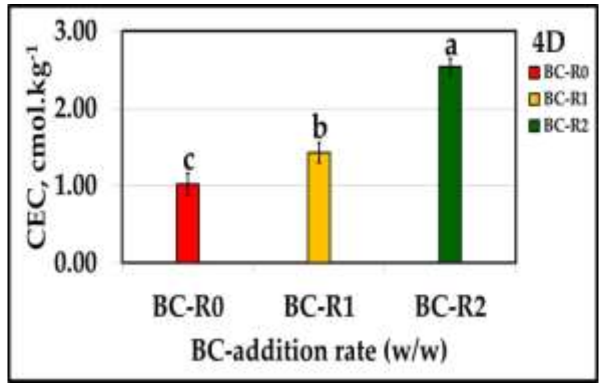


Figure 4. Impact of different BC-addition rates on soil pH (4A), $CaCO_3$ content (4B), organic matter content (4C) and cation exchange capacity (4D) of sandy soil. BC-R_0, BC-R_1 and BC-R_2 represent the BC-addition rate at 0.0, 50.0 and 100.0 $g.pot^{-1}$, respectively. The small letters on the bars indicate significant differences between treatments at $p \leq 0.05$.

Table 4. Impact of interactions of FSB × PYT, FSB × BC-R and PYT × BC-R on pH, $CaCO_3$ content, organic matter content and cation exchange capacity of sandy soil.

Interaction	Soil pH	$CaCO_3$	OM	CEC
		(%)		($cmol.kg^{-1}$)
FSB x PYT	*	ns	ns	*
BCBG x PYT_{300}	8.24c±0.02	4.50a±0.01	0.61a±0.02	2.49a±0.02
BCBG x PYT_{600}	8.45a±0.02	4.57a±0.02	0.48a±0.03	1.35b±0.02
BCFC x PYT_{300}	8.35b±0.04	4.45a±0.01	0.68a±0.01	1.55b±0.01
BCFC x PYT_{600}	8.49a±0.03	4.23a±0.02	0.64a±0.02	1.27b±0.02
PYT x BC-R	**	*	**	**
PYT_{300} x BC-R_0	8.60a±0.01	3.61c±0.01	0.33c±0.02	1.07c±0.01
PYT_{300} x BC-R_1	8.23c±0.01	4.72b±0.01	0.60bc±0.05	1.66b±0.02
PYT_{300} x BC-R_2	8.06d±0.01	5.09a±0.02	1.02a±0.01	3.34a±0.03
PYT_{600} x BC-R_0	8.62a±0.02	3.75c±0.01	0.81ab±0.02	0.97c±0.03
PYT_{600} x BC-R_1	8.40b±0.02	5.28a±0.03	0.41c±0.03	1.20c±0.02
PYT_{600} x BC-R_2	8.39b±0.01	4.17ab±0.03	0.47c±0.05	1.75b±0.02
FSB x BC-R	*	ns	ns	**
BCBG x BC-R_0	8.60a±0.02	3.61c±0.02	0.50a±0.02	1.02d±0.01
BCBG x BC-R_1	8.30b±0.03	5.28a±0.02	0.45a±0.03	1.69c±0.01
BCBG x BC-R_2	8.14c±0.02	4.72a±0.01	0.70a±0.03	3.05a±0.03
BCFC x BC-R_0	8.62a±0.04	3.75bc±0.01	0.63a±0.03	1.02d±0.03
BCFC x BC-R_1	8.33b±0.01	4.72a±0.02	0.56a±0.04	1.17d±0.02
BCFC x BC-R_2	8.31b±0.01	4.54ab±0.02	0.79a±0.02	2.04b±0.02

BC – biochar, FSB – feedstock biomass, and – BCs derived from sugarcane bagasse (BCBG) and filter-cake (BCFC), pyrolysis temperatures of 300°C (PYT_{300}) and 600°C (PYT_{600}), BC-R – BC addition rate. BC-R_0, BC-R_1 and BC-R_2 – the rates of 0.0, 50.0 and 100.0 $g.pot^{-1}$, respectively. $CaCO_3$ – calcium carbonate content. OMC – organic matter content. CEC – cation exchange capacity.

The data listed in **Table 5** showed that the soil amended with BC produced from sugarcane bagasse at 300 °C (BCBG x PYT_{300} x BC-R_2) recorded the best results in terms of soil pH (which dropped), OM and CEC (which increased), recoding 7.93, 1.04% and 4.22 cmol.kg^{-1}, respectively. In addition, the lowest $CaCO_3$ values (3.53, 3.89, 3.89 and 3.61) were obtained in non-amended sandy soil. On the other hand, the non-amended soil gave soil pH, OM and CEC values of 8.63, 0.16% and 0.91 cmol.kg^{-1}. Meanwhile, the soil treated with BC derived from sugarcane filter-cake processed at 300 °C with a rate of 1% (BCFC x PYT_{300} x BC-R_1) showed an increased $CaCO_3$ value. The analysis of variance indicates that there were no significant differences in terms of soil pH, $CaCO_3$ and OM, but significant influences can be seen on CEC.

Table 5. Impact of FSB, PYT and BC-R interactions on soil chemical properties.

FSB	PYT	BC-R	Soil pH	$CaCO_3$ (%)	OM (%)	CEC
BCBG	PYT_{300}	BC-R_0	8.57a±0.02	3.53c±0.14	0.16d±0.02	1.12f±0.13
		BC-R_1	8.22d±0.01	5.18ab±0.11	0.64a-d±0.01	2.13bc±0.10
		BC-R_2	7.93e±0.01	5.00ab±0.10	1.04a±0.02	4.22a±0.12
	PYT_{600}	BC-R_0	8.63a±0.3	3.89bc±0.13	0.49cd±0.02	1.02f±0.10
		BC-R_1	8.24cd±0.01	4.26a-c±0.10	0.56a-d±0.03	1.18ef±0.14
		BC-R_2	8.18d±0.02	5.19ab±0.12	0.99ab±0.01	2.45b±0.012
BCFC	PYT_{300}	BC-R_0	8.63a±0.01	3.89bc±0.11	0.84a-c±0.02	0.91f±0.11
		BC-R_1	8.38b±0.02	5.37a±0.13	0.27d±0.01	1.25ef±0.13
		BC-R_2	8.35bc±0.02	4.44a-c±0.15	0.35cd±0.01	1.88cd±0.13
	PYT_{600}	BC-R_0	8.60a±0.04	3.61c±0.13	0.77a-c±0.13	1.03f±0.10
		BC-R_1	8.42b±0.02	5.19ab±0.10	0.56a-d±0.01	1.15f±0.11
		BC-R_2	8.43b±0.2	3.89bc±0.09	0.58a-d±0.02	1.63de±0.12
FSB x PYT x BC-R			ns	ns	ns	*

BC – biochar. FSB – feedstock biomass. BCBG – BC derived from sugarcane bagasse and BCFC – from filter-cake, PYT_{300} and PYT_{600} – pyrolysis temperatures of 300 and 600 °C, respectively. BC-R – BC application rate. BC-R_0, BC-R_1 and BC-R_2 – biochar rates of 0.0, 50.0 and 100.0 g.pot^{-1}, respectively, ns – non-significant, and *significant (at 5%).

3.3. Soil nutrients status

The individual effects of FSB, PYT and BC-R on total nitrogen (TNC), available phosphorus (APC) and potassium (AKC) contents are presented in **Table 6**. Our results indicate that applying BCBG led to the maximum values of TNC (0.199%) and AKC (398.33 mg.kg^{-1}), respectively. The percentages of increase in the highest and lowest values were 17.53, 8.00 and 13.90 for TNC, APC and AKC, respectively. With regard to the influence of PYT, PYT_{600} was the most impactful on APC (9.81 mg.kg^{-1}) and AKC (386.11 mg.kg^{-1}). Meanwhile, the highest TNC value (0.195%) was obtained in the PYT_{300} treatment. The rates of increase reached 12.23, 3.92 and 6.68% for TNC, APC and AKC, respectively. The results of the statistical analysis indicate that the influences of both FSB and PYT were identical. However, no significant impacts were seen on TNC, nor any significant impacts (at $p \leq 0.05$) on APC or significant influences (at $p \leq 0.01$) on AKC.

Table 6. The individual impacts of feedstock biomass (FSB), pyrolysis temperature (PYT) and BC-addition rate (BC-R) on some macronutrients content of sandy soil under pot conditions.

Treatment	TNC	APC	AKC
	(%)	(mg.kg^{-1})	
FSB	ns	*	**
BCBG	0.199a±0.06	9.26b±0.03	398.33a±0.02
BCFC	0.169a±0.03	10.00a±0.02	349.72b±0.04
PYT	ns	*	**
PYT_{300}	0.195a±0.01	9.44b±0.02	361.94b±0.02
PYT_{600}	0.174a±0.01	9.81a±0.01	386.11a±0.03
BC-R	**	ns	**
$BC\text{-}R_0$	0.225a±0.01	9.30a±0.02	335.42c±0.01
$BC\text{-}R_1$	0.210a±0.01	9.88a±0.02	370.83b±0.02
$BC\text{-}R_2$	0.119b±0.02	9.70a±0.02	415.83a±0.02

BC – biochar. FSB – feedstock biomass. BCBG – BC derived from sugarcane bagasse and BCFC – from filter-cake, PYT_{300} and PYT_{600} – pyrolysis temperatures of 300 and 600 °C, respectively. BC-R – BC application rate. $BC\text{-}R_0$, $BC\text{-}R_1$ and $BC\text{-}R_2$ – biochar rates of 0.0, 50.0 and 100.0 g.pot^{-1},, respectively. TNC, TPC and TKC represent the total nitrogen content, available phosphorus and potassium contents, respectively. ns – Non-significant, and *significant (at 5%).

As observed in **Table 6**, dissimilar findings arose related to the BC addition rate. However, the $BC\text{-}R_0$, $BC\text{-}R_1$ and $BC\text{-}R_2$ treatments gave the highest values for TNC (224.71%), APC (9.88 mg.kg^{-1}) and AKC (415.83 mg.kg^{-1}).

Regarding the maximum and minimum values, the percentages of increment were 90.03, 6.24 and 23.98% for TNC, APC and AKC, respectively. Statistically, we found highly significant impacts on TNC and AKC, but no significant differences were seen APC. The results related to the FSB x PYT interaction are listed in **Table 7**. We found that the $BCBG_{300}$, $BCFC_{600}$ and $BCBG_{600}$ treatments had the greatest impact on TNC, APC and AKC, recording the highest values of 0.218%, 10.62 mg.kg^{-1} and 424.44 mg.kg^{-1}, respectively. On the contrary, the lowest values (0.167%, 9.00 mg.kg^{-1} and 347.78 mg.kg^{-1}) were produced following the application of the $BCFC_{600}$ treatment. The results depicted in **Table 7** show increases in the contents of TNC, APC and AKC by 34.57, 18.00 and 22.04%, respectively. The results of the ANOVA show that none of the treatments had any significant impact on TNC, but there were highly significant impacts on APC and AKC.

Unique results were obtained from the PYT x BC-R interaction. However, the results in **Table 7** show that the highest values (0.272%, 10.06 mg.kg^{-1} and 433.33 mg.kg^{-1}) were recorded in the untreated soil ($BC\text{-}R_0$), and in the soil subjected to BCFC x $BC\text{-}R_1$ and BCBG x $BC\text{-}R_2$ treatments, respectively. On the other hand, BC-R0 had the least impact on APC and AKC, with results of 9.09 and 287.50 mg.kg^{-1}, respectively, while the BCBG x $BC\text{-}R_3$ treatment yielded the lowest TNC value. The analysis of variance shows that there were significant impacts ($p \leq 0.05$) on TNC, and significant increments (at $p \leq 0.01$) were seen in AKC, while there were no significant effects on APC. The impact of the FSB x BC-R interaction on soil nutrients status is presented in **Table 7**. BCBG x BC-R_3 and BCFC x BC-R_3 were the superior treatments in terms of APK and AKC, recording values of 10.49 and 450.00 mg.kg^{-1}, respectively. Meanwhile, the highest TNC value (0.257%) was obtained in the non-amended soil. The statistical analysis shows that the FSB x BC-R treatment had a highly significant impact on APC and AKC, and significant effects on TNC.

Table 7. Impact of interactions between (FSB x PYT), (PYT x BC-R) and (FSB x BC-R) on soil chemical properties.

Treatment	TNC (%)	APC (mg.kg^{-1})	AKC
FSB x PYT	ns	**	**
BCBG x PYT_{300}	0.218a±0.01	9.51b±0.03	372.22b±0.02
BCBG x PYT_{600}	0.180a±0.01	9.00c±0.04	424.44a±0.02
BCFC x PYT_{300}	0.172a±0.02	9.38bc±0.02	351.67c±0.03
BCFC x PYT_{600}	0.167a±0.02	10.62a±0.02	347.78c±0.02
PYT x BC-R	*	ns	**
PYT_{300} x BC-R_0	0.272a±0.02	9.09b±0.03	287.50d±0.01
PYT_{300} x BC-R_1	0.209ab±0.03	9.71ab±0.01	365.00c±0.10
PYT_{300} x BC-R_2	0.105d±0.6	9.53ab±0.03	433.33a±0.06
PYT_{600} x BC-R_0	0.178bc±0.03	9.50ab±0.02	383.33bc±0.03
PYT_{600} x BC-R_1	0.211ab±0.03	10.06a±0.02	376.67bc±0.03
PYT_{600} x BC-R_2	0.132cd±0.02	9.88ab±0.01	398.33b±0.02
FSB x BC-R	*	**	**
BCBG x BC-R_0	0.257a±0.02	9.41b±0.01	323.33d±0.03
BCBG x BC-R_1	0.189ab±0.02	9.44b±0.02	421.67b±0.01
BCBG x BC-R_2	0.152bc±0.01	8.92b±0.01	450.00a±0.03
BCFC x BC-R_0	0.193ab±0.02	9.18b±0.02	347.50d±0.02
BCFC x BC-R_1	0.231a±0.01	10.33a±0.02	320.00d±0.02
BCFC x BC-R_2	0.084c±0.01	10.49a±0.03	381.67c±0.01

BC – biochar. FSB – feedstock biomass. BCBG – BC derived from sugarcane bagasse and BCFC – from filter-cake, PYT_{300} and PYT_{600} – pyrolysis temperatures of 300 and 600 °C, respectively. BC-R – BC application rate. BC-R_0, BC-R_1 and BC-R_2 – biochar rates of 0.0, 50.0 and 100.0 g.pot^{-1},, respectively. TNC, TPC and TKC represent the total nitrogen content, available phosphorus and potassium contents, respectively. ns – Non-significant, and *significant (at 5%).

The data presented in **Table 8** showed the effects of the interaction of FSB with PYT and BC-R on TNC, APC and AKC. The highest APC and AKC values (11.42 and 480.00 mg.kg^{-1}) were obtained in the sandy soil amended with BC derived from BCFC at 600 °C with a rate of 2% (BCFC x PYT_{600} x R_2) and the BC created from BCBG at 1% (BCBG x PYT_{300} x R_2), respectively. On the contrary, the highest TNC value (0.287%) was found in the non-amended soil. **Table 8** showed that the percentages of increase in the maximum and minimum values were

184.16, 37.09 and 100.00% for TNC, APC and AKC, respectively. The data obtained from the statistical analysis indicate significant differences (at $p \leq 0.01$) in AKC and no significant differences for TNC and APC.

Table 8. Impact of FSB, PYT and BC-R interactions on some nutrients status of sandy soil.

FSB	PYT	BC-R	TNC (%)	APC (mg.kg^{-1})	AKC (mg.kg^{-1})
BCBG	PYT_{300}	$BC\text{-}R_0$	0.287a±0.01	9.59b-e±0.01	240.00h±0.01
		$BC\text{-}R_1$	0.225a-c±0.01	9.43b-e±0.02	396.67c-e±0.01
		$BC\text{-}R_2$	0.141c-e±0.01	9.51b-e±0.02	480.00a±0.01
	PYT_{600}	$BC\text{-}R_0$	0.225a-c±0.05	9.23c-e±0.01	406.67cd±0.02
		$BC\text{-}R_1$	0.152b-e±0.03	9.44b-e±0.01	446.67ab±0.01
		$BC\text{-}R_2$	0.163b-e±0.02	8.33e±0.02	420.00bc±0.02
BCFC	PYT_{300}	$BC\text{-}R_0$	0.256ab±0.02	8.59de±0.01	355.00fg±0.02
		$BC\text{-}R_1$	0.191a-d±0.02	9.98bc±0.04	333.33fg±0.03
		$BC\text{-}R_2$	0.101e±0.01	9.55b-e±0.01	386.67c-e±0.03
	PYT_{600}	$BC\text{-}R_0$	0.129c-e±0.01	9.77b-d±0.02	360.00ef±0.02
		$BC\text{-}R_1$	0.271a±0.02	10.68ab±0.01	306.67g±0.01
		$BC\text{-}R_2$	0.107de±0.01	11.42a±0.02	376.67de±0.03
FSB x PYT x BC-R			ns	Ns	**

4. BC – biochar. FSB – feedstock biomass. BCBG – BC derived from sugarcane bagasse and BCFC – from filter-cake, PYT_{300} and PYT_{600} – pyrolysis temperatures of 300 and 600 °C, respectively. BC-R – BC application rate. $BC\text{-}R_0$, $BC\text{-}R_1$ and $BC\text{-}R_2$ – biochar rates of 0.0, 50.0 and 100.0 g.pot^{-1},, respectively. TNC, TPC and TKC represent the total nitrogen content, available phosphorus and potassium contents, respectively. ns – Non-significant, and *significant (at 5%).

4.3. Soil hydrological properties

As shown in **Table 9**, the application of BCBG manifested the highest water holding capacity (WHC), field capacity (FC) and available water content (AWC) values, at 24.21, 4.73 and 2.70%, respectively. On the other hand, the addition of BCFC had greater effects than BCBG on the permanent wilting point (PWP), producing 1.66%. In spite of this, the changes were relatively minimal. The percentages of increase were 2.11% for WHC, 8.49% for FC, 13.70% for AWC and 6.41% for PWP. Statistically, no significant differences could be seen in the studied hydrological properties of sandy soil between FSB treatments.

The overall trends in our results indicate that PYT_{300}, irrespective of the type of FSB, had the greatest effects on FC and AWC, manifesting 5.30 and 3.74%. On the other hand, the highest values of WHC and PWP (24.32 and 1.76%) were obtained from the PYT_{600} treatment. As shown in Table 4, the percentages of increase in the highest and lowest values were 3.05, 39.84, 84.24 and 12.82% for WHC, FC, AWC and PWP, respectively. The results of the ANOVA show that the PYT treatments had significant impacts (at $p \leq 0.01$) on FC and AWC, but no significant impacts on WHC and PWP. Statistically, changes in the BC addition rate manifested highly significant differences in the hydrological properties of the tested sandy soil, while the non-amended soil recorded the maximum values (5.62 and 4.41%) of FC and AWC, respectively. In addition, the $BC\text{-}R_2$ and $BC\text{-}R_1$ treatments were the most impactful on WHHC and PWP, with values of 25.62 and 2.19%, respectively. Table 4 shows that the rates of increment in the maximum and minimum values reached 19.61, 64.33, 142.31 and 82.50% for WHC, FC, AWC and PWP, respectively.

Table 9. The individual impacts of feedstock biomass (FSB), pyrolysis temperature (PYT) and BC addition rate (BC-R) on some hydrological parameters of sandy soil under pot conditions.

Treatment	WHC	FC	AWC	PWP
	(%)			
FSB	**ns**	**ns**	**ns**	**ns**
BCBG	24.21a±0.05	4.73a±0.03	3.07a±0.01	1.56a±0.02
BCFC	23.71a±0.03	4.36a±0.04	2.70a±0.02	1.66a±0.02
PYT	**ns**	**	**	**Ns**
PYT_{300}	23.60a±0.02	5.30a±0.03	3.74a±0.03	1.56a±0.03
PYT_{600}	24.32a±0.03	3.79b±0.02	2.03b±0.02	1.76a±0.02
BC-R	**	**	**	**
$BC\text{-}R_0$	21.42b±0.03	5.62a±0.02	4.41a±0.01	1.20b±0.02
$BC\text{-}R_1$	24.85a±0.02	4.60a±0.02	2.41b±0.03	2.19a±0.02
$BC\text{-}R_2$	25.62a±0.02	3.42b±0.05	1.82b±0.02	1.59b±0.01

BC – biochar. BCBG – BC derived from sugarcane bagasse and BCFC – from filter-cake, PYT_{300} and PYT_{600} – pyrolysis temperatures of 300 and 600 °C, respectively. BC-R – BC application rate. $BC\text{-}R_0$, $BC\text{-}R_1$ and $BC\text{-}R_2$ – biochar rates of 0.0, 50.0 and 100.0 $g.pot^{-1}$,, respectively. WHC, FC, AWC and PWP represent the water holding capacity, field capacity, available water content and permanent wilting point, respectively. ns – Non-significant, and *significant (at 5%).

The results listed in **Table 10** showed the impacts of the FSB x PYT interactions. The $BCFC_{600}$ treatment had the greatest impact on WHC (24.42%) and PWP (1.94%). Meanwhile, the highest FC and AWC values (5.46 and 3.76%) were obtained following the $BCBG_{300}$ and $BCFC_{300}$ treatments, respectively. As shown in **Table 10**, the application of $BCFC_{300}$ had the lowest influence on WHC and PWP, at 23.00 and 1.39%, respectively. Moreover, the soil treated with $BCFC_{600}$ gave the lowest values of FC and AWC (3.58 and 1.64%, respectively). Between maximum and minimum values, the percentages of increment amounted to 6.17, 52.51, 129.27 and 39.57% for WHC, FC, AWC and PWP, respectively. The results of the ANOVA indicate non-significant differences between treatments in all studied hydrological properties, except PWP, which showed significant effects.

Table 11 clearly showed that the PYT_{600} x $BC\text{-}R_2$ and PYT_{600} x $BC\text{-}R_1$ treatments had superior effects on WHC and PWP, producing 25.63 and 2.82%, respectively. Meanwhile, the non-amended soil gave the highest values (7.78 and 6.54%) of FC and AWC. In contrast, the PYT_{600} x $BC\text{-}R_2$ treatment had the least influence on FC and AWC, recording values of 3.11 and 1.80%, respectively. Likewise, the lowest WHC and PWP values were obtained in non-amended soil, reaching 20.20 and 1.16, respectively. The data obtained from the statistical analysis show that the PYT x BC-R interaction had a highly significant influence on FC, AWC and PWP, but no significant impact on WHC.

Table 10. Impact of feedstock biomass (FSB) and pyrolysis temperature (PYT) interactions on some hydrological properties of sandy soil under pot conditions.

Treatment	WHC (%)		FC (%)		AWC (%)		PWP (%)	
	PYT_{300}	PYT_{600}	PYT_{300}	PYT_{600}	PYT_{300}	PYT_{600}	PYT_{300}	PYT_{600}
BCBG	24.20a±0.01	24.22a±0.07	5.46a±0.04	4.00b±0.02	3.72a±0.02	2.41b±0.02	1.73ab±0.02	1.59ab±0.01
BCFC	23.00a±0.02	24.42a±0.011	5.14a±0.01	3.58b±0.01	3.76a±0.01	1.64a±0.02	1.39b±0.01	1.94a±0.01
FSB x PYT	**ns**		**ns**		**ns**		*	

BC – biochar. BCBG – BC derived from sugarcane bagasse and BCFC – from filter-cake, PYT_{300} and PYT_{600} – pyrolysis temperatures of 300 and 600 °C, respectively. BC-R – BC application rate. $BC\text{-}R_0$, $BC\text{-}R_1$ and $BC\text{-}R_2$ – biochar rates of 0.0, 50.0 and 100.0 $g.pot^{-1}$,, respectively. WHC, FC, AWC and PWP represent the water holding capacity, field capacity, available water content and permanent wilting point, respectively. ns – Non-significant, and *significant (at 5%).

Table 11. Impact of pyrolysis temperature (PYT) and BC-addition rate (BC-R) interactions on some hydrological properties of sandy soil under pot conditions.

Treatment	WHC (%)		FC (%)		AWC (%)		PWP (%)	
	PYT_{300}	PYT_{600}	PYT_{300}	PYT_{600}	PYT_{300}	PYT_{600}	PYT_{300}	PYT_{600}
$BC\text{-}R_0$	20.20c±0.01	22.63b±0.01	7.78a±0.01	3.45b±0.01	6.54a±0.01	2.29b±0.02	1.23bc±0.01	1.16c±0.01
$BC\text{-}R_1$	25.00a±0.01	24.70ab±0.01	4.39b±0.03	4.81b±0.01	2.83b±0.02	1.99b±0.02	1.56bc±0.02	2.82a±0.02
$BC\text{-}R_2$	25.60a±0.01	25.63a±0.02	3.73b±0.01	3.11b±0.04	1.85b±0.02	1.80b±0.03	1.88b±0.02	1.30bc±0.02
PYT x BC-R	**ns**		**		**		**	

BC – biochar. BCBG – BC derived from sugarcane bagasse and BCFC – from filter-cake, PYT_{300} and PYT_{600} – pyrolysis temperatures of 300 and 600 °C, respectively. BC-R – BC application rate. $BC\text{-}R_0$, $BC\text{-}R_1$ and $BC\text{-}R_2$ – biochar rates of 0.0, 50.0 and 100.0 $g.pot^{-1}$,, respectively. WHC, FC, AWC and PWP represent the water holding capacity, field capacity, available water content and permanent wilting point, respectively. ns – Non-significant, and *significant (at 5%).

Table 12. Impact of feedstock biomass (FSB) and BC-addition rate (BC-R) interactions on some hydrological properties of sandy soil under pot conditions.

Treatment	WHC (%)		FC (%)		AWC (%)		PWP (%)	
	BCBG	BCFC	BCBG	BCFC	BCBG	BCFC	BCBG	BCFC
$BC\text{-}R_0$	20.50d±0.02	22.33cd±0.02	5.43ab±0.02	5.81a±0.02	4.37a±0.01	4.46a±0.01	1.04c±0.03	1.35bc±0.02
$BC\text{-}R_1$	25.87ab±0.03	23.83bc±0.01	4.82ab±0.02	4.38a-c±0.01	2.64b±0.02	2.18b±0.03	2.19a±0.02	2.19a±0.01
$BC\text{-}R_2$	26.27a±0.02	24.97av±0.01	3.94bc±0.03	2.90c±0.01	2.19b±0.01	1.46b±0.01	1.74ab±0.02	1.44bc±0.02
FSB x BC-R	*		**ns**		**ns**		**ns**	

BC – biochar. BCBG – BC derived from sugarcane bagasse and BCFC – from filter-cake, PYT_{300} and PYT_{600} – pyrolysis temperatures of 300 and 600 °C, respectively. BC-R – BC application rate. $BC\text{-}R_0$, $BC\text{-}R_1$ and $BC\text{-}R_2$ – biochar rates of 0.0, 50.0 and 100.0 $g.pot^{-1}$,, respectively. WHC, FC, AWC and PWP represent the water holding capacity, field capacity, available water content and permanent wilting point, respectively. ns – Non-significant, and * significant (at 5%).

As shown in **Table 12**, applying the BCBG-derived BC at 2% (BCBG x BC-R_2) led to the highest WHC values, with an average of 26.27%. The maximum FC and AWC values were achieving in the untreated soil. Furthermore, the application of BC derived from either BCBG or BCFC at a rate of 1% (BCBG x BC-R_1 or BCFC x BC-R_1) led to the highest PWP value. Despite the noticeable improvement, the results obtained from the statistical analysis indicate that there were significant differences (at $p \leq 0.05$) in WHC, and no significant differences in FC, AWC and PWP.

The overall trend of the results listed in **Table 13** indicated that the highest values (7.72 and 6.53%) of FC and AWC were obtained in untreated soil. Meanwhile, the BCBG x PYT_{600} x BC-R_2 and BCBG x PYT_{600} x BC-R_2 treatments were superior in terms of WHC and PWP, which recorded values of 26.67 and 3.07%, respectively. On the other hand, the lowest values (2.80 and 1.05%) were recorded following the application of BCBG x PYT_{600} BC-R_2 and BCBG x PYT_{600} BC-R_1, respectively. Accordingly, the non-amended soil gave the minimum values (20.00 and 0.87%) for WHC and PWP. In spite of the BC-based soil showing more positive effects than the non-amended soil, no significant differences were seen between treatments in the aforementioned hydrological parameters.

Table13. Impact of FSB, PYT and BC-R interactions on soil hydrological properties.

FSB	PYT	BC-R	WHC	FC	AWC	PWP
			(%)			
BCBG	PYT_{300}	BC-R_0	20.40d±0.02	7.77a±0.01	6.53a±0.02	1.22cd±0.01
		BC-R_1	26.33a±0.02	4.14bc±0.01	2.35bc±0.02	1.80b-d±0.02
		BC-R_2	25.87a±0.01	4.46bc±0.01	2.29bc±0.01	2.17a-c±0.01
	PYT_{600}	BC-R_0	20.60b±0.03	3.09bc±0.01	2.21bc±0.01	0.87d±0.01
		BC-R_1	25.40b±0.01	5.50ab±0.04	2.93bc±0.o03	2.58ab±0.03
		BC-R_2	26.67a±0.01	3.42bc±0.05	2.10bc±0.02	1.32cd±0.02
BCFC	PYT_{300}	BC-R_0	20.00b±0.02	7.79a±0.01	6.55a±0.02	1.24cd±0.02
		BC-R_1	23.67a±0.01	4.63bc±0.01	3.32b±0.03	1.32cd±0.02
		BC-R_2	25.33a±0.02	3.00bc±0.02	1.40bc±0.02	1.60cd±0.04
	PYT_{600}	BC-R_0	24.67a±0.02	3.82bc±0.01	2.36bc±0.01	1.46cd±0.03
		BC-R_1	24.00a±0.03	4.12bc±0.01	1.05c±0.01	3.07a±0.03
		BC-R_2	24.60a±0.04	2.80c±0.02	1.51bc±0.01	1.29cd±0.01
FSB x PYT x BC-R			ns	ns	ns	ns

BC=Biochar. FSB=feedstock biomass, BCBG and BCFC represent BC derived from sugarcane bagasse and filter-cake, respectively. PYT_{300} and PYT_{600} indicate the pyrolysis temperature at 300 and 600 °C, respectively. BC-R= BC addition rate, BC-R_0, BC-R_1 and BC-R_2 represent the rate at 0.0, 50.0 and 100.0 $g.pot^{-1}$,, respectively.

4.4.The heat map of correlation coefficient

The results presented in **Figure 5** showed the correlation coefficient between the chemical and hydrological properties and the nutrient status of sandy soil. The results indicated that the soil pH had strong negative correlations (r = - 0.522**, - 0.837**, -0.599** and – 0.538**) with the $CaCO_3$ content, CEC, WHC and AKC, respectively. On the other hand, soil pH correlated positively (r = 0.378*) with AWC. For $CaCO_3$, highly positive correlations (r = 0.516** and 0.501**) were observed with CEC, PWP, WHC and AKC, respectively, while strong positive correlations (r = 0.337* and 0.414*) were found with CEC and AKC, respectively.

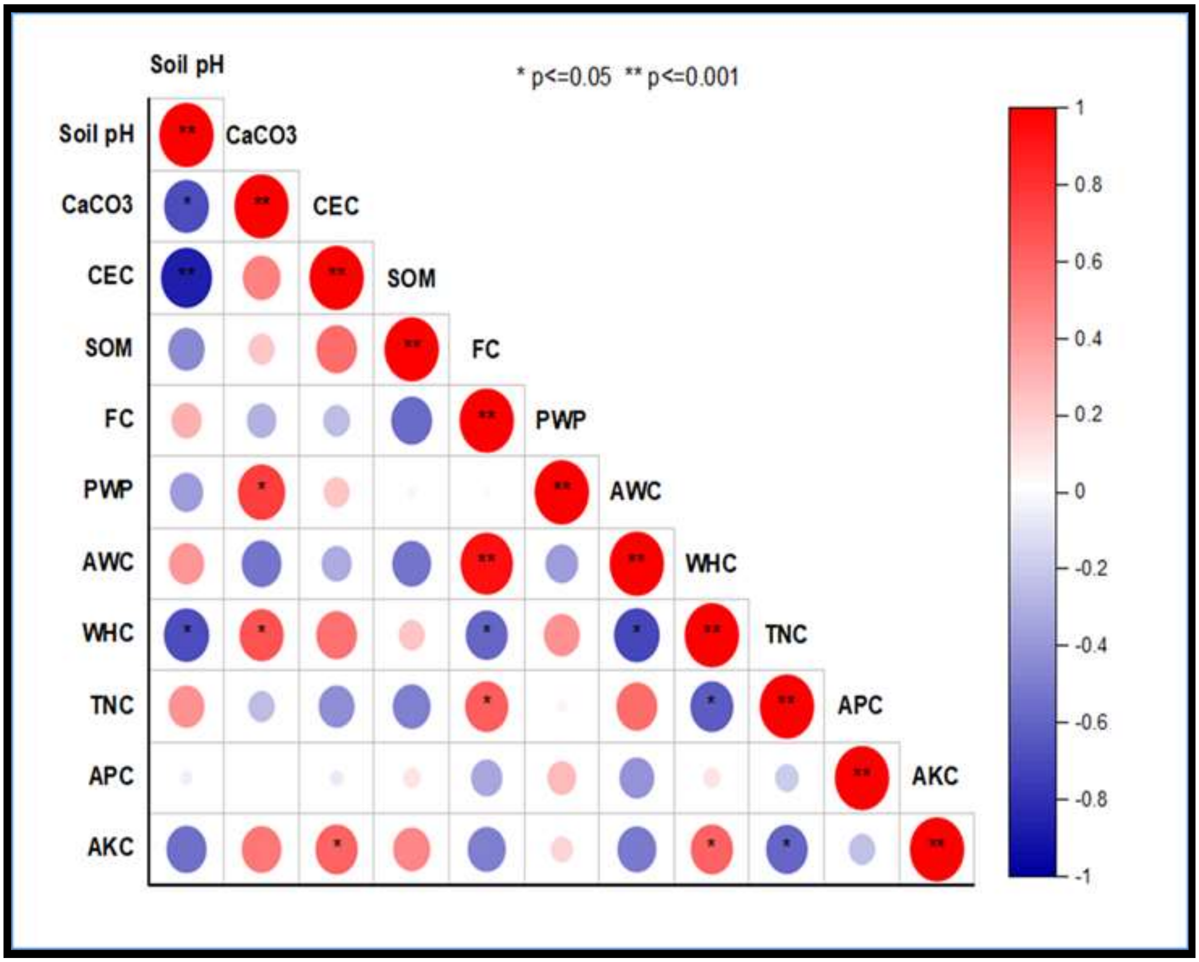


Figure5. The heat map Pearson's correlation coefficient between soil hydro-chemical properties and nutrients content.

Likewise, CEC showed strong, significantly positive correlations (0.467** and 0.559**) with WHC and AKC, respectively. With regard to the correlation coefficient between hydrological properties and other properties, our results indicated that the OM had significant negative correlations (r = - 0.343*, - 0.357* and - 0.349*) with AWC, FC and TNC, respectively, and a significant positive correlation (r = 0.334*) with AKC. Meanwhile, WHC positively and negatively correlated (r = - 0.473* and - 0.407*) with AKC and TNC, respectively. Also, we found that AWC had highly significantly negative correlations (r = -0.531** and -0.452**) with WHC and AKC, respectively, in spite of AWC showing a profoundly significant positive correlation (r = 0.428**) with TNC. Dissimilar results were obtained for the relation between FC and other properties; however, FC showed strong, significantly positive correlations (r = 0.924** and 0.424**) with AWC and TNC, and highly significant negative correlation (r = - 0.443**) with WHC, and a significant negative correlation (r = - 0.418*) with AKC.

5. Discussion

Sandy soils are distributed widely around the world, occupying approximately 4,990,200,000 hectares (ha), and accounting for 31% of the land **(Huang and Hartemink, 2020)**. About 96% of Egypt's land is considered desert, comprising soil with a sandy texture **(Al-Soghir et al. 2022)**. These sandy soils are structured with single grains and have undesirable chemical, hydrological and physical characteristics, which restrict plant growth and development. In addition, Egypt, as a developing country that suffers from increasing population growth, faces significant challenges in achieving its agricultural development goals **(Awad et al. 2022)**. It is expected that the population in Egypt will exceed 150 million by the year 2050 **(Awad and Al-Soghir, 2023)**. As such, we must urgently develop these soils and raise their efficiency in order to achieve national food security.

In the two last decades, the thermochemical conversion of FSB, of either vegetal or animal origin, into a stable, porous, carbonaceous substance under partial or anaerobic conditions at a PYT range of 300–1,000 °C, known as biochar (BC), has gained significant attention, given its unique properties (**Regmi et al. 2022; Bhat et al. 2022 and Aziz et al. 2023).** It is therefore important to study the chemical and physical properties of the BCs used in our study. The results in **Table 3** clearly indicate that carbon is the element most notably increased with the increase in PYT, which could be due to the carbonization and thermochemical decomposition of the FSBs at high pyrolysis temperatures (HPYTs) **(Singh et al. 2017)**. Meanwhile, the noticeable reductions in O and H with increases in PYT could be due to the removal of moisture, hydrocarbons, and some other gases such as H_2, CO_2 and CO **(Chun et al. 2004)**. Our results are supported by some other recent studies **(Huang et al. 2021 and Ghorbani et al. 2022)**. In another study **[71], Sun et al. (2014)** indicated that HPYTs could cause the cracking of weak bonds in the prepared BCs. The positive relationship between PYTs and Ca content could be ascribed to the presence of insoluble $CaCO_3$, which is calcinated into soluble calcium oxide **(Usman et al. 2015)**. Also, Mg is present in magnesium oxide and insoluble periclase **(Lehmann and Joseph, 2015)**. P content is positively affected by HPYT. In this regard**, Xiao et al. (2018) and Li et al. (2020)** showed that the availability of Ca and Mg both increased with increases in PYT. However, crop residue-derived BCs contained Ca ranging 0.20-1.57% **(Arif et al. 2016)** and Mg ranging 0.001-3.78% **(Yu et al. 2017 and Zhao et al. 2018)**. On the other hand, the K content was shown to negatively influence feedstock. In addition, the presence of adequate amounts of silicon (Si) and chloride (Cl) is related to the metallic oxides in BC samples **(Singh et al. 2017)**. The large variations in K content were also associated with feedstock types, and are likely caused by the concentration effect **(Xiao et al. 2018)**. Our results could be summarized in the statement that both FSB and PYT play pivotal roles in determining the elemental composition of BC samples. These results are in agreement with those from the previous reports of **Yuan et al. (2017)**. As for the molecular ratios (**Table 3),** the overall trends show that the O/C, H/C, (O+N/C) and (O+N+H)/C values decreased with the increase in PYT. In an earlier study**, Rajapaksha et al. (2016)** stated that the calculated O/C and H/C ratios can be used to predict some of the characteristics of the produced BCs. However, the O/C molecular ratio elucidates the degree of aging of the BC **(Rodriguez et al. 2020)**. The reports we have reviewed indicate that the O/C ratio is associated with the half-life of the BC. A value lower than 0.2 indicates a half-life greater than 1000 years, 0.6 shows a half-life of 100-1000 years, and a value above 0.6 means that the half-life is below 100 years **(Wang et al. 2021)**. The H/C molecular ratio indicates the aromatic nature of the BC. A high H/C ratio indicates that the BC has a highly aromatic structure, and more stability. In **Figure 1**, the SEM results show a porous internal structure; porosity is an important characteristic for agronomic applications, due to its direct influence on the chemical and hydrological parameters of soil, as well as its effect on the soil's nutrient and ion exchange capacities **(Lu and Zong, 2018)**.

Several studies have reported that the different properties of BCs mainly arise in relation to the FSB and PYT conditions **(Yuan et al. 2017)**. In the present research, we found that low soil pH values are linked with the application of BCBG and the use of PYT_{300} to produce it.

However, the effects of applying FSBs and PYTs on soil pH are not significant. In general, the pH of Egyptian soils is extremely alkaline (7.73–9.45) due to the nature of the prevailing parent materials and the abundance of basic cations, such as Ca^{2+} and Mg^{2+}, as well as the lower participation rate **(ElWa et al. 2021 and Al-Soghir et al. 2022)**. The effect of PYT_{300} in improving soil pH could be attributed to the release of nutrients during pyrolysis **(Qiao et al. 2018)**. These findings are in accordance with those reported by **Tan et al. (2018)**, who reported that increases in soil pH are closely related to the use of FSBs and PYTs, and their application rates. Based on earlier observations, we can infer that the increases in soil pH are related to the rate of BC addition. In one of the studies**, Ding et al. (2014)** stated the assumption that the pH of BCs is associated with the content of inorganic alkalis and the formation of carbonates. In line with some previous studies**, Ronsse et al. (2012)** suggested that the total contents of base cations and carbonates are the main factors contributing to the alkalinity of BC. In addition, their formation is positively related to an HPYT. To expand on this**, Spokas et al. (2012)** reported that increases in the contents of ash and O-containing functional groups could explain the increases in the alkalinity of BC. Further **[99], Yuan et al. (2011)** suggested that the relative increase in soil reactivity could have been caused by the formation of carbonates. Although the application of BCs led to a wide range of responses in the soil's chemical properties, the effect on pH was very limited **(Molnar et al., 2018)** due to the buffering capacity of the soils **(Cornelissen et al. 2018**. The slight increase in soil pH after the application of a BC could be attributed to the degree of chemical oxidation and microbial activity that occurred, related to the decomposition of the BC **(Alotaibi and Schoenau, 2019).** These findings cohere with those of a study by **Gul *et al*. (2015)**, which mentioned that the pyrolysis temperature and FS type are highly determinative of the alkalinity of BCs. Similar results have been achieved elsewhere **(El-Naggar et al. (2019)** observed responses in soil pH after amendment with BC. Regarding the role of BC in improving CEC, **[111] Sparks (2003)** noted that increases in soil pH could be due to the increasing retention of alkaline elements such as calcium (Ca^{2+}) and magnesium (Mg^{2+}). Many previous field trials have also documented marked increases in soil pH associated with BC application **(Raboin et al. 2016)**. In another words, the ash content of BC could be the main factor contributing to the increase in soil pH **(Song et al. 2018)**. Furthermore, $BCFC_{300}$ was regarded as the most effective in boosting the OM content in soils due to the significant effects of BC in improving the carbon reserves of soil, leading to increases in its nutrient holding capacity **(Ouyang et al. 2014)**. These results are in agreement with those documented by **Zhan et al. (2015)**, who proposed that the carbon content of the soil increased at a rate of 75.5%. Moreover, BC-R_2 was the most effective treatment in increasing the OM and CEC, regardless of the FSB and PYT used. Our results match those obtained in numerous studies; **El-Naggar et al. 2018 and El-Naggar et al. 2019** proposed that BCs, regardless of type, have a profound effect, particularly in coarse-textured soils. Similar findings have been documented by **Oladele et al. (2019)**. However, a high addition rate of BC significantly increased the OM and CEC. In other words, an HPYT (350-650 °C) causes a breakdown of carbon and rearranges the chemical bonds, leading to the formation of new functional groups such as phenol, carboxyl, lactol, ether, pyrone, pyridine, anhydride and quinine **(Mia et al. 2017)**. These changes result in the removal of surface functional groups and thus the formation of aromatic carbon **[122] (Joseph et al. 2010)**. These results conform to those of **Banik et al. (2018)**, who reported that reductions in CEC are closely related with an HPYT. Moreover, CEC mainly depends on the nature of the biomass applied in the production of BC and the distribution of functional groups containing oxygen. Therefore, the negatively charged sites on the surface of the BC could arise due to the presence of carboxylate and phenolate functional groups **[121] (Mia et al., 2017)**. Similar results were documented by **Gomez-Eyles et al. (2013)**.

Regarding the impact of PYT on soil macronutrients such as N, P and K, our results displayed that total nitrogen content of BCFC was the greater in compared with BCBG, moreover their nitrogen contents increased with increasing PYT. These results may be due to the residence time of pyrolysis. Like the N, the P content increased with increasing the PYT may be due to "concentration effect" depending on the reduced BC yield. Conversely, the reduction in soil K content might be due to negative influence of BCH on some chemical properties of soil such as soil pH.

As previously mentioned, sandy soil is characterized by undesirable hydrological properties, such as a low water holding capacity (WHC) and available water content (AWC), as well as high permeability and poor water retention **(Duarte et al., 2020)**. Generally, the WHC indicates the maximum amount of water that can be retained within the soil. Very recent reports have documented that improvements in the ability to retain water of soil incorporated with BC are related to increases in soil porosity **(Mclennon et al., 2020 and Razzaghi et al., 2020)**. The moisture content and water infiltration rate are notably improved after the addition of BC to soil **(Adekiya et al., 2020)**. In this regard, several studies have highlighted the impact of texture and BC addition rate on the ability of soil to hold water. **Razzaghi et al. (2020)** mentioned that applying BC increases the WHC, especially in coarse-textured soils compared to fine-textured soils. These results are similar to those reported by **Peake et al. (2014)**, who indicated the significant effects of BC on the ability of sandy loam and loamy sand soil to hold water. In addition, the WHC was markedly improved by increasing the BC addition rate **Oladela et al. 2019)**. In their comprehensive study, **Nair et al. (2017)** reported that the application of BC generally enhanced the ability of soil to retain water and decreased its bulk density, consequently increasing the total porosity. In other words, this beneficial effect of BC could be attributed to the hydrophilic functional groups on the surfaces and in the pores of BC, which have a high affinity for water **(Mandal et al. 2020)**. The author observed that the increase in the ability of soil to retain water as a result of BC application was more obvious in sandy soils compared with loamy and clay soils. Our findings are in good agreement with those from previous reports; **Uzoma et al. (2011)** reported that the application of BC markedly improved the AWC of coarse-textured soils. This makes it abundantly clear that the performance of the BC closely depends on the soil's texture.

The rate of BC application plays a significant role in the resulting WHC and moisture content. One of the studies conducted by **Kätterer et al. (2019)** indicated that continuously adding BC for 10 years considerably increased WHC compared with untreated soil. In another study, **Ndor et al. (2015)** observed a 10.8% increase in moisture content in soil amended with BC derived from sawdust and rice husks at 5-10 $Mg.ha^{-1}$, compared with non-amended soil. These results are in agreement with the findings obtained by **Are et al. (2019)**, who documented that the moisture content of sandy loam soil increases by as much as 33% following the application of poultry litter BC. Several studies indicated the conflicting findings related to reduce in FC and AWAC with increasing biochar application rates. In their research, **Major et al. 2012** documented that the application of BC at rate 20 $Mg.ha^{-1}$ had no significant influences on water retention. Similarly, **Gaskin et al. 2007** noted that applying biochar at 11 and 22 $Mg.ha^{-1}$ had no significant impact on WHC.

6. Conclusion

Sugarcane is the most important crop in Egypt, especially given that Upper Egypt produces huge amounts of waste related to this crop, namely, bagasse and filter-cake. Both wastes can be used as a type of soil conditioner known as biochar (BC), which involves converting them into BC instead of disposing of them, usually by burning them or leaving them in landfills, which acts have negative environmental impacts. In recent decades, BCs have gained great attention due to their unique characteristics and multiple effects in modifying soil properties. Our pot study was conducted to determine the effects of individual BCs (BCBG and BCFC), pyrolysis temperatures (PYT_{300} and PYT_{600}) and BC addition rates ($BC\text{-}R_0$, $BC\text{-}R_1$ and $BC\text{-}R_2$), as well as their interactions, on some of the chemical and hydrological properties of sandy soil. The results reveal that both BCs were fairly equal in terms of their influence on the soil properties studied. The relative superiority of the PYT_{300} treatment was determined in relation to most of the studied hydro-chemical properties. $BC\text{-}R_2$ was the most impactful compared with both $BC\text{-}R_0$ and $BC\text{-}R_1$. BCBG x PYT_{300} x$BC\text{-}R_2$ and BCBG x PYT_{300} x $BC\text{-}R_1$ can be considered the best treatments for their effects on soil's chemical properties. Likewise, the best hydrological properties were obtained following the application of BCBG x PYT_{600} x $BC\text{-}R_2$ and BCFC x PYT_{600} x $BC\text{-}R_1$, in relation to WHC and PWP, respectively. Moreover, the non-amended soil yielded the best FC and AWC.

7. References

Adekiya, A.O.; Agbede, T.M.; Olayanju, A.; Ejue, W.S.; Adekanye, T.A.; Adenusi, T.T.; Ayeni, J.F. (2020). Effect of biochar on soil properties, soil loss, and cocoyam yield on a tropical sandy loam alfisol. Sci. World J., 2020.

Al-Soghir, M.M.A.; Mohamed, A.G.; El-Desoky, M.A.; Awad, A.A.M. (2022). Comprehensive assessment of soil chemical properties for land reclamation Purposes in the Toshka area, EGYPT. Sustainability, 14, 15611. https://doi.org/10.3390/su142315611.

Alotaibi, K.D. and Schoenau, J.J. (2019). Addition of biochar to a sandy desert soil: effect on crop growth, water retention and selected properties. Agronomy; 9:327.

Are, K.S. (2019). Biochar and soil physical health. In Biochar-An Imperative Amendment for Soil and the Environment; IntechOpen: London, UK, 21–33.

Arif, M.; Ali, K.; Jan, M.T.; Shah, Z.; Jones, D. L. and Quilliam, R. S. (2016). Integration of biochar with animal manure and nitrogen for improving maize yields and soil properties in calcareous semi-arid Agro-ecosystems. Field Crops Research, 195, 28-35. https://doi.org/10.1016/j.fcr.2016.05.011.

Awad, A. A. M. and Al-Soghir, M. A. GIS-Based (2023). Assessment of Soil Chemical and Physical Properties as a Basis for Land Reclamation in Toshka Area, Aswan, EGYPT. Open J. Geology, 13, 697-719. https://doi.org/10.4236/ojg.2023.137030.

Ayaz, M.; Feizienè, D.; Tilvikienè, V.; Akhtar, K.; Stulpinaitè, U. and Iqbal, R. (2021): Biochar role in the sustainability of agriculture and environment. Sustainability, 13, 1330.

Aziz, M.A.; Wattoo, F.M.; Khan, F.; Hassan, Z.; Mahmood, I.; Anwar, A.; Karim, M.F.; Akram, M.T.; Manzoor, R.; Khan, K.S.; et al. (2023). Biochar and polyhalite fertilizers improve soil's biochemical characteristics and sunflower (*Helianthus annuus* L.) yield. Agronomy, 13, 483. https://doi.org/10.3390/agronomy13020483.

Banik, C.; Lawrinenko, M.; Bakshi, S. and Laird DA (2018). Impact of pyrolysis temperature and feedstock on surface charge and functional group chemistry of biochars. J Environ Qual 47:452–461.

Bhat, A.S.; Kuriqi, A.; Dar, M.U.D.; Bhat, O.; Sammen, S.S.; Towfiqul Islam, A.R.M.; Elbeltagi, A.; Shah, O.; AI-Ansari, N.; Ali, R.; et al. (2022). Application of biochar for improving physical, chemical, and hydrological soil properties: A Systematic Review. Sustainability, 14, 11104. https://doi.org/10.3390/su141711104.

Bista, P.; Ghimire, R.; Machado, S. and Pritchett, L. (2019). Biochar effects on soil properties and wheat biomass vary with fertility management. Agronomy. 9(10), 623.

Black, C.A. (1956). Methods of soil analysis" Part 1. Amer. Soc. Agron. Inc. Pub. Madison, Wisconsin, USA.

Borchard, N. et al (2019). Biochar, soil and land-use interactions that reduce nitrate leaching and N_2O emissions: a meta-analysis. Sci. Total Environ, 651:2354–2364. https ://doi.org/10.1016/j.scito tenv.2018.10.060

Brantley, K.E.; Savin, M.C.; Brye, K.R.; Longer, D.E. (2016). Nutrient availability and corn growth in a poultry litter biochar-amended loam soil in a greenhouse experiment. Soil Use Manag, 32:279–288. https ://doi.org/10.1111/sum.12296.

Brewer, C.E.; Chuang, V.J.; Masiello, C.A.; Gonnermann, H.; Gao, X.; Dugan, B.; Driver, L.E.; Panzacchi, P.; Zygourakis, K. and Davies, C.A. (2014). New approaches to measuring biochar density and porosity. Biomass Bioenergy, 66, 176–185.

Campos, P.; Miller, A.Z.; Knicker, H.; Costa-Pereira, M.F.; Merino, A.; De la Rosa, J.M. (2020). Chemical, physical and morphological properties of biochars produced from agricultural residues: implications for their use as a soil amendment. Waste Manag. 105, 256–267.

Chun, Y.; Sheng, Gand Chiou, C. T. (2004). Evaluation of current techniques for isolation of chars as natural adsorbents. Environmental science & technology, 38(15), 4227-4232.

Cornelissen, G.; Rutherford, D.W.; Arp, H.P.H.; Dorsch, P.; Kelly, C. N. and Rostad, C. E. (2013). Sorption of pure N2O to biochars and other organic and inorganic materials under anhydrous conditions. Environmental Science & Technology, 47, 7704-7712. https://doi.org/10.1021/es400676q.

Di Rienzo, J.A.; Casanoves, F.; Balzarini, M.G.; Gonzalez, L.; Tablada, M.; Robledo, C.W. InfoStat versión. Group InfoStat, FCA, (2020). Universidad Nacional de Córdoba, Argentina. 2011. Available online: http://www.infostat.com.ar (accessed on 29 September 2020).

Diatta, A.A.; Fike, J.H.; Battaglia, M.L.; Galbraith, J.M.; Baig, M.B. (2022). Effects of biochar on soil fertility and crop productivity in arid regions: A review. Arab. J. Geosci. 13, 595.

Ding, W.; Dong, X.; Ime, I.M.; Gao, B. and Ma, L.Q. (2014). Pyrolytic temperatures impact lead sorption mechanisms by bagasse biochars. Chemosphere 105:68–74.

Duarte, S.D-J.; Glaser, B.; Pano, B.L.P. and Cerri, C.E.P. (2020). Biochar and sugar cane filter cake interaction on physical and hydrological soil properties under tropical field conditions. Biochar, 2:195–210.

El-Naggar A, et al. (2019). Biochar application to low fertility soils: a review of current status, and future prospects. Geoderma, 337:536–554. https ://doi.org/10.1016/j.geoderma.2018.09.034.

El-Naggar, A.; Lee, S.S.; Awad, Y.M.; Yang, X.; Ryu, C.; Rizwan, M.; Rinklebe, J.; Tsang, D.C.W. and Ok, Y.S. (2018). Influence of soil properties and feedstocks on biochar potential for carbon mineralization and improvement of infertile soils. Geoderma, 332, 100–108.

El-Naggar, A.; El-Naggar, A.H.; Shaheen, S.M.; Sarkar, B.; Chang, S.X.; Tsang, D.C.W.; Rinklebe, J.; Ok, Y.S. (2019). Biochar composition dependent impacts on soil nutrient release, carbon mineralization, and potential environmental risk: A review. J. Environ. Manag., 241, 458–467.

Elwa, A.M.; Abou-Shady, A.M.; Sayed, A.; Showman, H. (2021). Impact of physical and chemical properties of soil on the growing plant in El Mounira-El Qattara New Valley. Egypt. J. Appl. Sci., 36, 148–175.

Garcia-Perez, T.; Pelaez-Samaniego, M.R.; Delgado-Noboa, J.; and Chica, E.J. (2022). Combined effect of biochar and fertilizers on Andean highland soils before and after cropping. Sustainability, 14(14), 8912.

Gee, G. and Bauder, J. (1986). Hydrometer method. Methods Soil Anal., 1, 404–408.

Ghorbani, M.; Amirahmadi, E.; Neugschwandtner, R.W.; Konvalina, P.; Kopecký, M.; Moudrý, J.; Perná, K. and Murindangabo, Y.T. (2022). The impact of pyrolysis temperature on biochar properties and its effects on soil hydrological properties. Sustainability, 14, 14722. https://doi.org/10.3390/ su142214722.

Gomez-Eyles, J.; Beesley, L.; Moreno-Jiménez, E.; Ghosh, U. and Sizmur, T. (2013). The potential of biochar amendments to remediate contaminated soils. In: Ladygina N, Rineau F (eds) Biochar and soil biota. CRC Press, Boca Raton.

Gul, S.; Whalen, J. K.; Thomas, B. W.; Sachdeva, V. and Deng, H. Y. (2015). Physico-chemical properties and microbial responses in biocharamended soils: mechanisms and future directions. Agriculture, Ecosystems and Environment, 206: 46–59.

Helmke, P.A, and Sparks, D.L. (1996). Lithium, sodium, potassium, rubidium, and cesium. Methods Soil Anal., 5, 551–574.

Hossain, Md. Z.; Bahar, Md. M.; Sarkar, B.; Donne, S. W.; Ok, Y. S.; Palansooriya, K. N.; Kirkham, M. B.; Chowdhury, S. and Bolan, N. (2020). Biochar and its importance on nutrient dynamics in soil and plant. Biochar, https://doi.org/10.1007/s42773-020-00065-z.

Huang, H.; Reddy, N.G.; Huang, X.; Chen, P.; Wang, P.; Zhang, Y.; Huang, Y.; Lin, P. and Garg, A. (2021). Effects of pyrolysis temperature, feedstock type and compaction on water retention of biochar amended soil. Scientific Reports. 11:7419. https://doi.org/10.1038/s41598-021-86701-5.

Huang, J. and Hartemink, A. E. (2020). Soil and environmental issues in sandy soils. Earth-Science Reviews, 208, 1-22.

IBI International Biochar Initiative. (2015). Standardized product definition and product testing guidelines for biochar 6 that is used in soil.

Jackson, M.L. (1973). Soil Chemical Analysis, 1st ed.; Prentice Hall of India Pvt. Ltd.: New Delhi, India.

Joseph, S.D.; Camps-Arbestain, M.; Lin, Y.; Munroe, P.; Chia, C.H.; Hook, J.; Van Zwieten, L.; Kimber, S.; Cowie, A.; Singh, B.P.; Lehmann, J.; Foidl, N.; Smernik, R.J. and Amonette, J.E. (2010). An investigation into the reactions of biochar in soil. Aust J Soil Res 48:501–515.

Kalina, M.; Sovova, S.; Svec, J.; Trudicova, M.; Hajzler, J.; Kubikova, L. and Enev, V. (2022). The Effect of Pyrolysis Temperature and the source biomass on the properties of biochar produced for the agronomical applications as the soil conditioner. Materials, 15, 8855. https://doi.org/10.3390/ma15248855.

Kalu, S.; Simojoki, A.; Karhu, K. and Tammeorg, P. (2021). Long-Term Effects of Softwood Biochar on Soil Physical Properties, Greenhouse Gas Emissions and Crop Nutrient Uptake in Two Contrasting Boreal Soils. Agric. Ecosyst. Environ., 316, 107454

Karimi, A.; Moezzi, A.; Chorom, M. and Enayatizamir, N. (2020). Application of biochar changed the status of nutrients and biological activity in a calcareous soil. J. Soil Sci. Plant Nutr., 20, 450–459.

Kätterer, T.; Roobroeck, D.; Andrén, O.; Kimutai, G.; Karltun, E.; Kirchmann, H.; Nyberg, G.; Vanlauwe, B. and Röing de Nowina, K. (2019). Biochar addition persistently increased soil fertility and yields in maize-soybean rotations over 10 years in sub-humid regions of Kenya. Field Crop. Res. **2019**, 235, 18–26.

Keeney, D.R. and Nelson, D.W. (1983). Nitrogen—Inorganic forms. Methods Soil Anal., 9, 643–698.

Lehmann, J. and Joseph, S. (2015). Biochar for environmental management: Science, Technology and Implementation. Routledge, London. https://doi.org/10.4324/9780203762264.

Li, H.; Li, Y.; Xu, Y. and Lu, X. (2020). Biochar phosphorus fertilizer effects on soil phosphorus availability. Chemosphere 10:244. https ://doi. org/10.1016/j.chemo spher e.2019.12547 1

Liu, Q. et al (2018). How does biochar influence soil N cycle? A metaanalysis. Plant Soil, 426:211–225. https ://doi.org/10.1007/s1110 4-018-3619-4

Lu, S. and Zong, Y. (2018). Pore structure and environmental serves of biochars derived from different feedstocks and pyrolysis conditions. Environ. Sci. Pollut. R., 25, 30401–30409.

Mandal, S.; Pu, S.; Adhikari, S.; Ma, H.; Kim, D-H.; Bai, Y. and Hou, D. (2020). Progress and future prospects in biochar composites: application and reflection in the soil environment. Crit Rev Environ Sci Technol. https ://doi.org/10.1080/10643 389.2020.17130 30.

McLean, E.O. (1982): Soil pH and lime requirement. In Methods of Soil Analysis. Part2. Chemical and Microbiological Properties; Page, A.L., Ed.; Am. Soc. Agron.: Madison, WI, USA, pp. 199–224.

Mclennon, E.; Solomon, J.K.Q.; Neupane, D. and Davison, J. (2020). Biochar and nitrogen application rates effect on phosphorus removal from a mixed grass sward irrigated with reclaimed wastewater. Sci. Total Environ., 715, 137012.

Meier, S. et al. (2019). Effects of three biochars on copper immobilization and soil microbial communities in a metal-contaminated soil using a metallophyte and two agricultural plants. Environ Geochem Health**.** https ://doi.org/10.1007/s1065 3-019-00436 –x.

Mia, S.; Singh, B. and Dijkstra FA (2017). Aged biochar affects gross nitrogen mineralization and recovery; A 15 N study in two contrasting soils. Glob Change Biol Bioenergy 9:1196–1206.

Molnár, M.; Vaszita, E.; Farkas, É.; Ujaczki, É.; Fekete-Kertész, I.; Tolner, M.; Klebercz, O.; Kirchkeszner, C.; Gruiz, K.; Uzinger, N. and Feigl, V. (2016). Acidic sandy soil improvement with biochar – a microcosm study. Science of The Total Environment, 563–564: 855–865.

Mor, S.; Negi, P. and Ravindra, K. (2019). Potential of agro-waste sugarcane bagasse ash for the removal of ammoniacal nitrogen from landfill leachate. Environ. Sci. Pollut. Res., 26, 24516–24531.

Munera-Echeverri, J.L.; Martinsen, V.; Strand, L.T.; Zivanovic.; Cornelissen, G. and Mulder, J. (2018). Cation exchange capacity of biochar: An urgent method modification. Sci. Total Environ., 642, 190-197.

Nair, V.D.; Nair, P.K.R.; Dari, B.; Freitas, A.M.; Chatterjee, N. and Pinheiro, F.M. (2017). Biochar in the agroecosystem-climate-change-sustainability nexus. Front Plant Sci 8:2051

Ndor, E.; Jayeoba, O.J. and Asadu, C.L.A. (2015). Effect of biochar soil amendment on soil properties and yield of sesame varieties in Lafia, Nigeria. J. Exp. Agric. Int., 9, 1–8.

Nelson, D.W. and Sommeres, C.E. (1982). Total Carbon, Organic Carbon and Organic Matter. In Method of Soil Analysis. Part 2, 2nd ed.; Page, A.L., Ed.; Agronomy Monographs; Soil Science Society of America: Madison, WI, USA, 539–571.

Oladele, S.O.; Adeyemo, A.J. and Awodun, M.A. (2019). Influence of rice husk biochar and inorganic fertilizer on soil nutrients availability and rain-fed rice yield in two contrasting soils. Geoderma 336, 1–11.

Olsen, S. (1982). Phosphorus. Methods Soil Anal., 2, 403–430.

Ouyang, L.; Tang, Q.; Yu, L. and Zhang, R. (2014). Effects of amendment of different biochars on soil enzyme activities related to carbon mineralisation. Soil Res 52(7):706–716.

Page, A.L.; Miller, R.H. and Keeney, D.R. (1982). Method of Soil Analysis. Part 2. Chemical and Microbiological Methods; American Society of Agronomy, Madison, WI, USA, pp. 225–246.

Peake, L.R.; Reid, B.J. and Tang, X. (2014). Quantifying the influence of biochar on the physical and hydrological properties of dissimilar soils. Geoderma, 235–236, 182–190.

Peng, C.; Li, Q.; Zhang, Z.; Wu, Z.; Song, X.; Zhou, G. and Song, X. (2019). Biochar amendment changes the effects of nitrogen deposition on soil enzyme activities in a Moso bamboo plantation. J Forest Res, 24:275–284. https ://doi.org/10.1080/13416 979.2019.16469 70

Piper, C.S. (1974). Soil and Plant Analysis; International Science Publishers Inc.: New York, NY, USA.

Qiao, J.T.; Li, X.M.; Li, F.B. (2018): Roles of different active metal-reducing bacteria in arsenic release from arsenic-contaminated paddy soil amended with Biochar. J. Hazard. Mater., 344, 958–967.

Raboin, L.-M.; Razafimahafaly, A.H.D.; Rabenjarisoa, M.B.; Rabary, B.; Dusserre, J.; Becquer, T. (2016): Improving the fertility of tropical acid soils: Liming versus biochar application? A long-term comparison in the highlands of Madagascar. Field Crop. Res., 199, 99–108.

Rajapaksha, A.U.; Chen, S.S.; Tsang, D.C.W.; Zhang, M.; Vithanage, M.; Mandal, S.; Gao, B.; Bolan, N.S.; Ok, Y.S. (2016): Engineered/designer biochar for contaminant removal/ immobilization from soil and water: Potential and implication of biochar modification. Chemosphere, 148, 276–291.

Rajkovich, S.; Enders, A.; Hanley, K.; Hyland, C.; Zimmerman, A.R.; Lehmann, J. (2012): Corn growth and nitrogen nutrition after additions of biochars with varying properties to a temperate soil. Biol. Fertil. Soils, 48, 271–284.

Ralebitso-Senior, T.K. and Orr, C.H. (2016): Microbial ecology analysis of biochar-augmented soils: setting the scene. In: Ralebitso-Senior TK, Orr CH (eds) Biochar application: essential soil microbial ecology, 1st edn. Elsevier, Oxford, p 330.

Razzaghi, F., Obour, P. B. & Arthur, E. Does biochar improve soil water retention? A systematic review and meta-analysis. Geoderma **361**, 114055 (2020).

Regmi, A.; Singh, S.; Moustaid-Moussa, N.; Coldren, C.; Simpson, C. (2022): The Negative Effects of High Rates of Biochar on Violas Can Be Counteracted with Fertilizer. Plants, 11, 491. https://doi.org/10.3390/plants11040491.

Rodriguez JA, Lustosa Filho JF, Melo LCA, de Assis IR, de Oliveira TS (2020): Influence of pyrolysis temperature and feedstock on the properties of biochars produced from agricultural and industrial wastes. J Anal Appl Pyrolysis 149:104839.

Ronsse F, van Hecke S, Dickinson D, Prins W (2012): Production and characterization of slow pyrolysis biochar: influence of feedstock type and pyrolysis conditions. Glob Chang Biol Bioenergy 5:104–115.

Seleiman, M.F.; Alotaibi, M.A.; Alhammad, B.A.; Alharbi, B.M.; Refay, Y.; Badawy, S.A. (2020). Effects of ZnO nanoparticles and biochar of rice straw and cow manure on characteristics of contaminated soil and sunflower productivity, oil quality, and heavy metals uptake. Agronomy **2020**, 10, 790.

Singh, B.; Camps-Arbestain, M. and Lehmann, J. (2017). Biochar: A Guide to Analytical Methods; Csiro Publishing: Clayton Southy, Australia, ISBN 9781486305094.

Singh, H.; Northup, B.K.; Rice, C.W. and Vara Prasad, P.V. (2022). Biochar applications influence soil physical and chemical properties, microbial diversity, and crop productivity: a meta-analysis. Biochar, 4:8 https://doi.org/10.1007/s42773-022-00138-1

Song, D.; Tang, J.; Xi, X.; Zhang, S.; Liang, G.; Zhou, W. and Wang, X. (2018). Responses of soil nutrients and microbial activities to additions of maize straw biochar and chemical fertilization in a calcareous soil. European Journal of Soil Biology 84:1–10.

Sparks, D.L. (2003). Ion exchange processes. In Environmental Soil Chemistry; Sparks, D.L., Ed.; Academic Press: Burlington, VT, USA, 187–205. ISBN 9780126564464.

Spokas, K.A.; Cantrell, K.B.; Novak, J.M.; Archer, D.W.; Ippolito, J.A.; Collins, H.P.; Boateng, A.A.; Lima, I.M.; Lamb, M.C., McAloon, A.J., et al. (2012). Biochar: A synthesis of its agronomic impact beyond carbon sequestration. Journal of Environmental Quality, 41, 973-989. https://doi.org/10.2134/jeq2011.0069.

Sun, L.Y.; Li, L.; Chen, Z.Z.; Wang, J.Y. and Xiong, Z.Q. (2014). Combined effects of nitrogen deposition and biochar application on emissions of N_2O, CO_2 and NH_3 from agricultural and forest soils. Soil Science and Plant Nutrition, 60, 254-265. https://doi.org/10.1080/00380768.2014.885386.

Sweed, A. A. A. and Awad, A. A. M. (2020). Lead adsorption on to clay soil treated with sugarcane organic Waste Biochar. International Journal of Plant & Soil Science. 32(4):51-61.

Yuan, J-H.; Xu, R-K. and Zhang, H. (2011). The forms of alkalis in the biochar produced from crop residues at different temperatures. Bioresour Technol 102:3488–3497.

Tan, Z.; Ye, Z.; Zhang, L. and Huang, Q. (2018). Application of the 15N tracer method to study the effect of pyrolysis temperature and atmosphere on the distribution of biochar nitrogen in the biomass–biochar-plant system. Sci. Total Environ., 622, 79–87.

Tavakkoli, E.; Lyons, G.; English, P. and Guppy, C. N. (2011). Silicon nutrition of rice is affected by soil pH, weathering and silicon fertilisation. J. Plant. Nutr. Soil. Sc., 174, 437–446 (2011).

Usman, A.R.; Abduljabbar, A.; Vithanage, M.; Ok, Y.S.; Ahmad, M.; Ahmad, M.; Elfaki, J.; Abdulazeem, S.S. and Al-Wabel, M.I. (2015). Biochar production from date palm waste: Charring temperature induced changes in composition and surface chemistry. J. Anal. Appl. Pyrolysis 2015, 115, 392–400.

Uzoma, K.C.; Inoue, M.; Heninstoa, A.; Ahmad, Z. and Nishihara, E. (2011). Influence of biochar application on sandy soil hydraulic properties and nutrient retention. J Food Agric Environ 9(3):1137–1143.

Walkey, A. and Black, C.A. (1934). An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chronic acidification method. Soil Sci., 37, 29–38.

Wang, F.L.; Wang, X.X. and Song, N.N. (2021). Biochar and vermicompost improve the soil properties and the yield and quality of cucumber (Cucumis sativus L.) grown in plastic shed soil continuously cropped for different years. Agr. Ecosyst. Environ. **315**, 107425.

Weber, K. and Quicker, P. (2018). Properties of biochar. Fuel, 217:240–261. https ://doi.org/10.1016/j.fuel.2017.12.054.

Wu, P.; Ata-Ul-Karim, S.T.; Singh, B.P.; Wang, H.; Wu, T.; Liu, C.; Fang, G.; Zhou, D.; Wang, Y. and Chen, W. (2019). A sciento metric review of biochar research in the past 20 years (1998–2018). Biochar, 1, 23–43.

Xiao, R. et al. (2018). Biochar produced from mineral salt-impregnated chicken manure: fertility properties and potential for carbon sequestration. Waste Manag, 78:802–810. https ://doi. org/10.1016/j.wasma n.2018.06.047.

Xu, N.; Tan, G.; Wang, H. and Gai, X. (2016). Effect of biochar additions to soil on nitrogen leaching, microbial biomass and bacterial community structure. Eur. J. Soil Biol., 74, 1–8.

Yu, K. L.; Lau, B. F.; Show, P. L.; Ong, H. C.; Ling, T. C.; Chen, W.-H.; Ng, E. P. and Chang. J.-S. (2017). Recent developments on algal biochar production and characterization. Bioresource Technology 246:2–11. doi: 10.1016/j.biortech.2017.08.009.

Yuan, Y.; Bolan, N.; Prevoteau, A.; Vithanage, M.; Biswas, J.K.; Ok, Y.S. and Wang, H. (2017). Applications of biochar in redox-mediated reactions. Bioresour Technol. https ://doi.org/10.1016/j.biort ech.2017.06.154.

Yusif, S.A.; Mohammed, M.A.; Popoola, N.O.; Yekeen, H.; Nabayi, A. and Yakubu, H. (2020). Ameliorative Effect of Biochar Application on Selected Chemical Properties of Acidic Soil. Bulgarian Journal of Soil Science, 5(2), 142-151.

Zhan, X.; Peng, J.; Wang, Y.; Liu, Y.F.; Chen, K.; Han, X.R.; Wang, H.F.; Lin, W.C. and Li, X.Y. (2015). Influences of application of biochar and biochar-based fertilizer on brown soil physiochemical properties and peanut yields. Journal of Plant Nutrition and Fertilizers 21 (6):1633–1641. doi: 10.11674/zwyf.2015.0631.

Zhao, B.; O'Connor, D.; Zhang, J.; Peng, T.; Shen, Z.; Tsang, D.C.W.; Hou, D. (2018). Effect of pyrolysis temperature, heating rate, and residence time on rapeseed stem derived biochar. J. Clean. Prod., 174, 977– 987.