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ORIGINAL PAPER

Effects of Three Different Acidic Biochars on Carbon Emission and Quality Indicators of Poorly Fertile Soil During 8 Months of Incubation

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Abstract
The goals of the current study were to examine the effect of different kinds of acidic biochar [orange peel biochar (OPB), sorghum panicle biochar (SPB), and wood chips biochar (WCB)] and doses as well as incubation periods on (1) carbon emission, (2) carbon mineralization kinetic, and (3) soil properties in calcareous sandy soil. One hundred grams of air-dried soil was placed in plastic jar for this experiment, which is composed of 10 treatments: control (unamended treatment), 1% OPB, 3% OPB, 6% OPB, 1% SB, 3% SB, 6% SB, 1% WCB, 3% WCB, and 6% WCB. The biochar was added at three levels: 1, 3, and 6% (w/w). All the treatments were arranged in a completely randomized design with three replications. The double-exponential equation described the kinetics of carbon mineralization better than first-order and second-order equations. The half-lives of the carbon remaining in the soil were 2.13, 3.13, 4.79, 6.76, 3.33, 5.66, 7.77, 3.50, 5.39, and 7.75 years for control, 1% WCB, 3% WCB, 6% WCB, 1% SPB, 3% SPB, 6% SPB, 1% OPB, 3% OPB, and 6% OPB treatments, respectively. The results revealed that the biochar application at different levels significantly decreased soil pH compared with the control treatment. Applying WCB at all levels and 1% SPB caused a significant decrease in electrical conductivity compared to the control. Available phosphorus and potassium in the soil are significantly enhanced via adding different types and doses of biochar compared to unamended soil. Our study is useful when using acidic biochar producing at low temperature in soils with high pH. That can be improving chemical properties, supplying available nutrients, and carbon sequestration of infertile soils in arid regions. Additionally, biochar applications into the soil are relatively cheap.

Keywords Available phosphorus · Carbon emission · Carbon sequestration · Double-exponential equation · Soil pH

1 Introduction

In the soils of arid regions, the rapid decomposition of organic matter resulting from applying organic fertilizer leads to an increase in carbon dioxide (CO_2) emission from these soils. Therefore, the arid region mainly contributes to global climate changes (Tfaily et al. 2018). The increasing human population and anthropogenic activities have led to increased CO_2 emissions in the earth's atmosphere that were about 410.6 ppm in 2019, but CO_2 emissions in 1760s were 280 ppm (Zhang et al. 2019). Moreover, the agricultural sector plays an important role in the emission of greenhouse gasses; it is considered one of the causes of climate change occurring on our planet (Lu and Cheng 2009).

Converting agricultural residues into biochars is one of the most promising strategies in the sustainable agriculture (Yadav et al. 2019). Biochar properties such as porosity, surface area, elemental composition, dissolved organic carbon, and recalcitrant carbon content, all these properties are greatly affected by the physical and chemical properties of the feedstocks used in biochar production (Campos et al. 2020; Zhang et al. 2017). Stability of biochar in the soils is controlled by many factors such as biomass type, pyrolysis temperature, and particle size, as well as soil type, soil moisture, and dissolved organic matter (Nguyen and Lehmann 2009; Sigua et al. 2014). Using biochar as a soil amendment acquired an interest in recent years because it plays an important role in the mitigation of climate changes (Amin 2020a, 2020b) because the biochar application has a high efficiency in storing carbon in the soils (carbon sequestration), which highly dependent on its resistance to

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degradation by microorganisms (Tag et al. 2016; Yang et al. 2018; Wei et al. 2019).

For the pyrolysis of feedstocks under low temperatures, several studies found that biochars produced were alkaline pH (Liao et al. 2018; Mandal et al. 2018; Tang et al. 2019). Contrastingly, some studies have shown that the biochars produced were acidic (Campos et al. 2020; Xu et al. 2019). These researchers attributed the differences in biochar pH to feedstock kind and pyrolysis temperature. Biochar produced at low temperatures has a higher cation exchange capacity than biochar produced at high temperatures. This is due to the presence of acidic functional groups on biochar surfaces (Eduah et al. 2019). Biochar produced at low temperatures has many functional groups and beneficial for using as soil amendment; meanwhile, biochar produced at high temperatures depletes much energy and loses a lot of nutrients (Sarfaraz et al. 2020).

The calcareous sandy soil is characterized by poor physical, chemical, and biological properties which will hinder plant growth. Hence, it reduces the productivity of this soil (Brady and Weil 1999). Wherefore, biochar applications are advantageous to ameliorate the physical, chemical, and biological properties of numerous soils worldwide (El-Naggar et al. 2019; Yu et al. 2019). Some studies reported that biochar amendments help to improve soil fertility by providing the soil with organic matter, available potassium, available phosphorus (Amin 2020a, 2016), and some micronutrients (Yu et al. 2019). Many studies found that the applications of biochar produced at low temperature (acidic biochar) to the calcareous soil caused enhanced soil fertility and environmental quality due to the decrease of leaching nutrient because of increasing capacity of nutrient retention (Ippolito et al. 2012, 2016).

The current study illustrate important vision on the application of acidic biochar types on using kinetic models of the carbon mineralization in the soils of arid region. Based on many previous studies, we hypothesized that the application of different types of acidic biochar into a calcareous sandy soil can be caused changes in carbon mineralization, decrease of the soil pH, increase of cation exchange capacity, and enhancing nutrient availability. Therefore, the objectives of this study were to investigate the influence of different kinds and levels of acidic biochar on carbon emission, kinetic of the carbon mineralization, and quality parameters of calcareous sandy soil throughout 8 months of incubation.

2 Materials and Methods

2.1 Acidic Biochar Preparation and Chemical Characterizations

In the current study, the feedstocks used to prepare biochars are wood chips, sorghum panicles, and orange peel. Wood chips of beech (*Fagus sylvatica*) were collected from a local carpentry workshop, sorghum (*Sorghum bicolor*) panicles residues were gathered after the threshing process of sorghum heads from a field, and orange (*Citrus sinensis*) peels were obtained from municipal solid waste because oranges are a fruit crop that is widely grown in Egypt. These feedstocks are placed individually in 18-l metal container. Then, these feedstocks were pyrolyzed individually at a temperature of about 270 °C under oxygen-limited conditions in electric furnace, and the total duration of the pyrolysis process varied between 3.5 to 4.5 h. The biochar samples were crushed by a stainless steel mill and passed through a 1-mm sieve. The pH of biochars was measured in suspension (1:5) by using a pH meter, while the electrical conductivity was measured in biochar extract (1:8) by EC meter (Baruah and Barthakur 1997). The total organic carbon (TOC) in biochars determined by the Walkley–Black procedure (Nelson and Sommers 1996). Dissolved organic carbon (DOC) in all biochar types was extracted by 0.5 M K_2SO_4 and shaken for 2 h. Then filtered (Jiang et al. 2019). The determination of DOC in all extract is via oxidation process with $K_2Cr_2O_7$ at 100 °C and a subsequent back titration of the unreduced dichromate (Vance et al. 1987). Available phosphorus was determined according to Olsen et al. (1954). The available potassium (K) was extracted with 1 M ammonium acetate, pH 7.0, and then measured by a flame photometer (Baruah and Barthakur 1997). Biochar chemical characterizations are displayed in Table 1.

2.2 Design of the Incubation Experiment

The incubation experiment was carried out on a surface soil sample (0–30 cm) collected from the Soils of Young Graduates, Arab El-Awamer, Assiut, Egypt. The studied soil is classified as Entisols; Typic Torripsamments (US Soil Taxonomy). The soil sample was air-dried at room temperature by leaving it in the air till making sure it is dry, homogenized, and sieved to pass a 2-mm mesh sieve before incubation. The properties of the soil are listed in Table 2. Air-dried soil samples (100 g) were placed in an airtight plastic jar (330 ml). In this experiment, three types of biochar, orange peels biochar (OPB), sorghum panicles biochar (SPB), and wood chips biochar (WCB), were added to the soil samples at levels of 1%, 3%, and 6% (w/w). This study composed of 10 treatments: control (without any amendment), 1% OPB, 3% OPB, 6% OPB, 1% SB, 3% SB, 6% SB, 1% WCB, 3% WCB, and 6% WCB with three replications used in a completely randomized design. All treatments were fertilized with a solution of $(NH_4)_2SO_4$ (127 mg N kg^{-1} soil) as a source of nitrogen. Then, adding distilled water to all treatments until the moisture content reached the field capacity and was maintained throughout the experiment using repetitive weight for jars. The CO_2 emitted from the

Table 1 Some chemical characterizations of different biochar types (data were mean ± standard deviation)

	Unit	Wood chips biochar	Sorghum panicles biochar	Orange peel biochar
pH (1:5)	–	5.32 ± 0.01	6.68 ± 0.02	5.97 ± 0.00
EC (1:8)	dS m^{-1}	0.47 ± 0.00	3.02 ± 0.04	3.11 ± 0.01
DOC	g kg^{-1} biochar	0.89 ± 0.04	5.92 ± 0.09	5.91 ± 0.07
TOC	g kg^{-1} biochar	254.29 ± 16.12	320.99 ± 3.18	373.29 ± 19.05
Available phosphorus	mg kg^{-1} biochar	18.80 ± 3.70	248.35 ± 1.98	74.28 ± 3.54
Available potassium	mmol kg^{-1} biochar	20.02 ± 0.05	232.32 ± 1.18	384.71 ± 3.22

EC, electrical conductivity; *DOC*, dissolved organic carbon; *TOC*, total organic carbon

soil was trapped by 10 ml of 2 M KOH solution placed in small vials inside of the incubation jars for four incubation periods, while the rest of the incubation periods used 15 ml of 2 M KOH. Periodically, the KOH solution in the vials was changed after 3, 7, 14, 33, 73, and 108 days. Two jars without soil, containing the same amount of KOH, were also run simultaneously as a blank at each incubation period. The incubation was done under normal conditions in the laboratory. All incubation jars performed in a dark with varying temperatures from 14 to 35.5 °C during the four seasons (autumn, winter, spring, and summer) for 8 months. The experiment started on 24 November 2019 and ended on 19 July 2020 and conducted at the Soil Chemistry Laboratory, Soils and Water Department, Faculty of Agriculture, Assiut University. At the end of the incubation experiment, soil samples were air-dried, crushed, and prepared for chemical analysis.

2.3 Soil Chemical Analysis

Soil texture was determined by pipette method (Kroetsch and Wang 2008). Total organic carbon in the soil before incubation was determined by the Walkley–Black procedure (Nelson and Sommers 1996). Calcium carbonate ($CaCO_3$) in the soil before incubation was determined using calcimeter method (Pansu and Gautheyrou 2006). The emitted carbon dioxide (CO_2) is trapped in 2 M KOH and then determined by back titration of the excess KOH with 1 M HCl after carbonate precipitation by 1 M $BaCl_2$ (Hopkins 2008). The soil pH in before and after the end of incubation was determined in soil suspension (1:1) by the glass electrode. The electrical conductivity was measured in soil extract (1:2) by EC meter at before and after the end of incubation. Cation exchange capacity (CEC) of soil samples was determined by the sodium acetate method (Baruah and Barthakur 1997). Soil available phosphorus (Olsen-P) was determined according to Olsen et al. (1954). The soil available potassium (K) was extracted with 1 M ammonium acetate, pH 7.0, and then measured by a flame photometer (Baruah and Barthakur 1997).

Table 2 Some physical and chemical properties of the soil used in this experiment (data were mean ± standard deviation)

Property	Unit	Value ± SD
Sand	g kg^{-1}	932.0 ± 0.00
Silt	g kg^{-1}	32.0 ± 0.00
Clay	g kg^{-1}	36.0 ± 0.00
Texture		Sand
TOC	g kg^{-1}	4.37 ± 0.14
$CaCO_3$	g kg^{-1}	314.70 ± 8.06
pH (1:1)		7.95 ± 0.01
EC (1:2)	dS m^{-1}	0.23 + 0.00
Olsen-P	mg kg^{-1}	1.38 + 0.27
Available K	mmol kg^{-1}	0.81 ± 0.05

TOC, total organic carbon; *EC*, electrical conductivity

2.4 Kinetic Models of Carbon Mineralization

In this study, three equations were used to explain the kinetics of carbon mineralization:

First-order equation:

$$\ln C_t = \ln C_0 - kt \tag{1}$$

where C_t is the concentration of the remaining carbon concentration after incubation period t (day); C_0 is the concentration of carbon at $t = 0$; and k is the decomposition rate constant of carbon (day^{-1}). First-order equation parameters were determined from the regression line of a plot $\ln C_t$ against time where the slope is $-k$; the intercept is $\ln C_0$ according to Sposito (2008).

Second-order equation:

$$1/C_t = 1/C_0 + kt \tag{2}$$

where C_t is the concentration of the remaining carbon concentration after incubation period t (day); C_0 is the

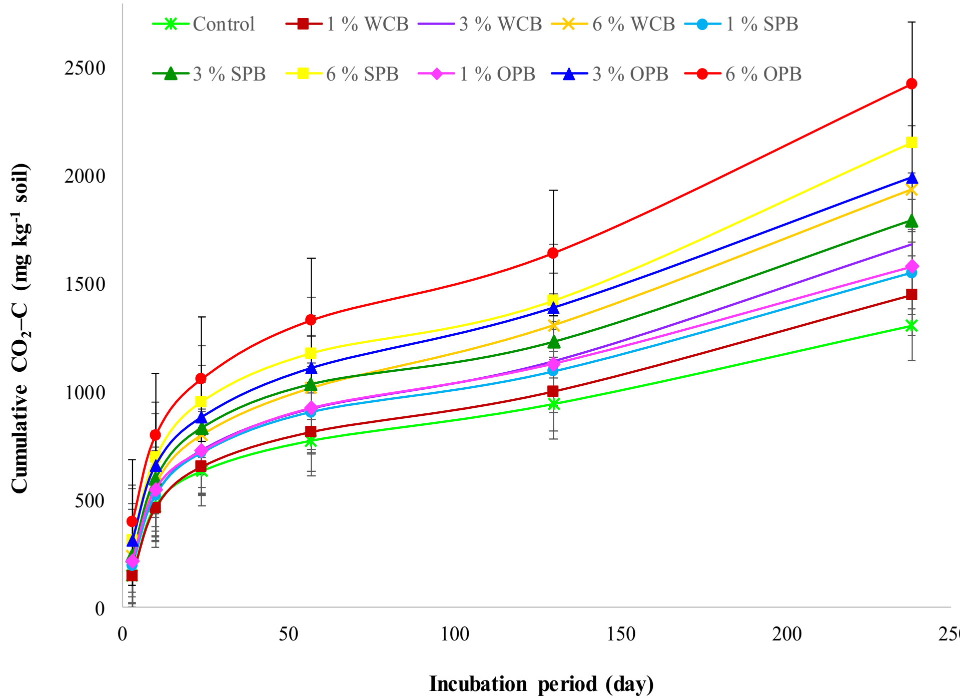

Fig. 1 Changes of cumulative CO_2-C in calcareous sandy soil as affected by different acidic biochars and their levels as well as incubation periods. Vertical bars indicate the standard error of the mean ($n = 3$ replicates). Control, unamended treatment; WCB, wood chips biochar; SPB, sorghum panicle biochar; OPB, orange peel biochar. Biochar additions were at three levels 1%, 3%, and 6% (w/w)

concentration of carbon at $t = 0$; and k is the decomposition rate constant of carbon (mg C kg^{-1} soil d^{-1}). In the second-order equation, a plot of the $[1/C_t]$ versus time $[t]$ is a straight line with a slope of k and intercept $[1/C_0]$ according to Sposito (2008).

Double-exponential equation:

$$C_t = C_1\left(e^{-k_1 t}\right) + C_2\left(e^{-k_2 t}\right) \tag{3}$$

where C_t is the concentration of the remaining carbon concentration after incubation period t (day); C_1 is the concentration smaller and easily mineralizable C; k_1 is higher turnover rate; C_2 is large stable C; and k_2 is a slow turnover rate. The double-exponential equation was carried by the non-linear regression using Sigma-Plot 12.5 software and plotting variables C_t vs. time, according to Liang et al. (2008) and Qayyum et al. (2012).

The half-life of carbon is calculated by using the two equations according to Sposito (2008):

$$t_{1/2} = \frac{0.693}{k \text{ or } k_2} \tag{4}$$

for the first-order equation and double-exponential equation.

$$t_{1/2} = \frac{1}{k\,C_0} \tag{5}$$

for second-order equation.

2.5 Statistical Analyses

The data of this study were analyzed using the MSTAT-C program (version 2.10) and statistical analysis system (SAS) program as well as performing an analysis of variance (ANOVA) to evaluate the difference among the treatments. Tukey's honestly significant difference was conducted for significance to differentiate the means of treatments at a 1% significance level.

3 Results

3.1 *Effect of Acidic Biochar Type on Carbon Dioxide (CO_2) Emissions*

The presence of all acidic biochar types in calcareous sandy soil significantly increased ($p \le 0.01$) the cumulative CO_2-C emissions from the soil compared to the control treatment. The values of cumulative CO_2-C emission significantly increased with increased biochar doses (Fig. 1). At the beginning of incubation (i.e., after 3 days), the CO_2-C emission values were recorded 145.3, 145.3, 202.0, 237.4, 194.9, 237.4, 308.3, 216.1, 308.3, and 393.3 mg kg^{-1} soil for control, 1% WCB, 3% WCB, 6% WCB, 1% SPB, 3% SPB, 6% SPB, 1% OPB, 3% OPB, and 6% OPB treatments, respectively; these values increased to 1304.8, 1446.9, 1682.3, 1937.4, 1550.9, 1794.5, 2153.0, 1578.5, 1993.2, and 2425.1 mg kg^{-1} soil for control, 1% WCB, 3% WCB, 6% WCB, 1% SPB, 3% SPB, 6% SPB, 1% OPB, 3% OPB, and 6% OPB treatments, respectively, after 238 days from incubation. The lowest values of cumulative CO_2-C emission were noticed at the beginning of incubation, while the highest cumulative CO_2-C emission values were found at the end of the incubation period (i.e., after 238 days) for 3% OPB, 6% SPB, and 6% OPB treatments (Fig. 1). The minimum value of cumulative CO_2-C emission was found at 3 days in the control and 3% WCB treatments (145.27 mg kg^{-1} soil) and the maximum value in the 6% OPB treatment (2425.12 mg kg^{-1} soil) was observed at end incubation time (Fig. 1). The results revealed that the addition of acidic biochars to the calcareous sandy soil led to significant increases in the CO_2-C emission rate compared to the unamended control (Table 3). The CO_2-C emission rate increased significantly with increasing biochar levels. The values of CO_2-C emission rates after the 3-day incubation were 48.42, 48.42, 67.32, 79.13, 64.96, 79.13, 102.75, 72.04, 102.75, and 131.10 mg C kg^{-1} soil day^{-1} for control, 1% WCB, 3% WCB, 6% WCB, 1% SPB, 3% SPB, 6% SPB, 1% OPB, 3% OPB, and 6% OPB treatments, respectively (Table 3). After the end of incubation period, the treatments showed noticeable reduction in the values of CO_2-C emission rates which were 3.36, 4.14, 5.02, 5.83, 4.24, 5.22, 6.78, 4.16, 5.59, and 7.25 mg C kg^{-1} soil day^{-1} for control, 1% WCB, 3% WCB, 6% WCB, 1% SPB, 3% SPB, 6% SPB, 1% OPB, 3% OPB, and 6% OPB treatments, respectively. The highest CO_2-C emission rates were observed at the beginning of the incubation (day 3) and then tended to decrease with incubation time (Table 3).

3.2 Effect of Acidic Biochar Type on Carbon Mineralization Kinetics

Three equations were tested to study the kinetics of carbon mineralization of different types of acidic biochars in calcareous sandy soil. Based on the measures related to each equation, the judgment on the model that is appropriate to the given data depends on the value of the determination factor (R^2). From the data in Table 4, we find that one of the equations that best represent the data is the double-exponential equation, compared to the rest of the equations. The following results will be specific to the double-exponential model; the values of easily mineralizable carbon (C_1) parameter increased significantly by applying 3% SPB, 6% SPB, and 6% OPB to calcareous sandy soil compared to the control, 1% WCB, and 3% WCB treatments. The highest C_1 value was found in the 6% OPB treatment (868.22 mg C kg^{-1} soil) and the lowest C_1 value in the 3% WCB (697.37 mg C kg^{-1} soil). Easily mineralizable carbon increased with increased levels of acidic biochars (Table 4). All investigated treatments except 6% SPB resulted in significant decreases in the turnover rate of easily mineralizable carbon (k_1) values compared with the control. The values of slowly mineralizable

Table 3 Effect of acidic biochar types and their levels on rate of carbon dioxide (CO_2) emissions in calcareous sandy soil

Treatment	Incubation period (day)	Rate of CO_2-C emissions (mg C kg^{-1} soil)
Control	3	48.42 ± 1.18hi
	10	46.28 ± 1.37ij
	24	11.57 ± 0.10p
	57	4.28 ± 0.08stuvwxy
	130	2.33 ± 0.00y
	238	3.36 ± 0.03vwxy
1% WCB	3	48.42 ± 1.18hi
	10	44.96 ± 0.91j
	24	13.71 ± 0.23nop
	57	4.87 ± 0.17rstuvwx
	130	2.57 ± 0.05xy
	238	4.14 ± 0.07tuvwxy
3% WCB	3	67.32 ± 1.18e
	10	45.23 ± 0.46j
	24	15.03 ± 0.40mno
	57	5.82 ± 0.10qrstuv
	130	3.01 ± 0.10wxy
	238	5.02 ± 0.00rstuvwx
6% WCB	3	79.13 ± 1.18c
	10	47.86 ± 0.79hi
	24	16.21 ± 0.40lmn
	57	6.60 ± 0.19qrst
	130	3.98 ± 0.17uvwxy
	238	5.83 ± 0.20qrstuv
1% SPB	3	64.96 ± 1.18e
	10	46.54 ± 0.46ij
	24	14.04 ± 0.20nop
	57	5.71 ± 0.17rstuv
	130	2.57 ± 0.05xy
	238	4.24 ± 0.03tuvwxy
3% SPB	3	79.13 ± 1.18c
	10	51.28 ± 0.46 g
	24	16.88 ± 0.23klm
	57	6.12 ± 0.08qrstu
	130	2.69 ± 0.15xy
	238	5.22 ± 0.07rstuvw
6% SPB	3	102.80 ± 1.18b
	10	54.98 ± 1.58f
	24	18.59 ± 0.40kl
	57	6.80 ± 0.42qr
	130	3.33 ± 0.22vwxy
	238	6.78 ± 0.12qrs
1% OPB	3	72.04 ± 1.18d
	10	47.33 ± 0.46ij
	24	12.65 ± 0.40op
	57	6.04 ± 0.17qrstu
	130	2.82 ± 0.10wxy
	238	4.16 ± 0.04tuvwxy

Table 3 (continued)

Treatment	Incubation period (day)	Rate of CO_2-C emissions (mg C kg^{-1} soil)
3% OPB	3	102.80 ± 1.18b
	10	49.84 ± 0.40gh
	24	16.08 ± 0.91 mn
	57	6.88 ± 0.29qr
	130	3.83 ± 0.05uvwxy
	238	5.59 ± 0.03rstuv
6% OPB	3	131.10 ± 1.18a
	10	57.35 ± 0.79f
	24	18.85 ± 0.60 k
	57	8.22 ± 0.29q
	130	4.27 ± 0.10tuvwxy
	238	7.25 ± 0.07qr

Different letters within the same column indicate the significant differences between treatments according to Tukey's honestly significant difference test at $p \leq 0.01$. *Control*, unamended treatment; *WCB*, wood chips biochar; *SPB*, sorghum panicle biochar; *OPB*, orange peel biochar. Biochar additions were at three levels 1%, 3%, and 6% (w/w). Data were mean ± standard deviation

carbon (C_2) were significantly increased by adding the different types of acidic biochars to this soil compared to the control treatment (Table 4). The C_2 values significantly increased with increasing the biochar doses. The turnover rate of the slowly mineralizable carbon (k_2) significantly decreased at applying acidic biochars (Table 4). The values of k_2 significantly decreased with increasing biochar levels. The maximum was observed at control treatment, while the minimum k_2 value in 6% OPB treatment. The results pointed out significant increases in the half-life values with acidic biochars addition. Increasing levels of biochar caused significantly increased half-lives (Table 4). The half-lives of the carbon remaining in the calcareous sandy soil after different types of acidic biochar were 2.13, 3.13, 4.79, 6.76, 3.33, 5.66, 7.77, 3.50, 5.39, and 7.75 years for control, 1% WCB, 3% WCB, 6% WCB, 1% SPB, 3% SPB, 6% SPB, 1% OPB, 3% OPB, and 6% OPB treatments, respectively (Table 4).

3.3 Effect of Acidic Biochar Type on Soil Chemical Properties

All the results of the chemical analysis were performed at the end of the incubation experiment. The application of all types and levels of acidic biochars produced at low temperatures to calcareous sandy soil caused a significant decrease ($p \leq 0.01$) of soil pH compared to the control treatment (Table 5). The soil pH declined with increasing biochar levels for all biochar types. Applying biochars to calcareous sandy soil decreased values of soil pH from 7.54 for control to 7.40, 7.34, 7.21,

Table 4 Kinetic parameters of some models for carbon mineralization in sandy calcareous soil as affected by type and doses of acidic biochar

Treatment	Parameters of the first-order equation				Parameters of the second-order equation				Parameters of Double-exponential equation					
	C_0 (mg C kg^{-1} soil)	k (d^{-1})	Half-life (year)	R^2	C_0 (mg C kg^{-1} soil)	k (mg C kg^{-1} soil d^{-1})	Half-life (year)	R^2	C_1 (mg C kg^{-1} soil)	k_1 (d^{-1})	C_2 (mg C kg^{-1} soil)	k_2 (d^{-1})	Half-life (year)	R^2
Control	3970.7 ± 3.5j	0.00114a	1.66 ± 0.01 g	0.89	3977.7 ± 4.2j	0.000000324a	2.12 ± 0.01 g	0.92	718.6 ± 23.9 cd	0.173 ± 0.007a	3803.3 ± 4.7j	0.000890a	2.13 ± 0.01 h	0.998
1% WCB	6516.9 ± 9.5i	0.00077b	2.47 ± 0.02f	0.90	6523.2 ± 11.3i	0.000000128b	3.28 ± 0.05f	0.92	698.2 ± 17.5d	0.155 ± 0.002cb	6337.4 ± 13.1i	0.000606b	3.13 ± 0.05 g	0.996
3% WCB	11,506.3 ± 5.7f	0.00049e	3.87 ± 0.00d	0.92	11,511.0 ± 5.4f	0.000000045e	5.29 ± 0.04d	0.93	697.4 ± 8.6d	0.147 ± 0.002cb	11,319.3 ± 8.3f	0.000396e	4.79 ± 0.04e	0.996
6% WCB	19,131.5 ± 8.1c	0.00034 g	5.59 ± 0.16b	0.93	19,135.1 ± 7.3c	0.000000018 g	7.81 ± 0.23b	0.94	727.3 ± 11.0 cd	0.148 ± 0.008cb	18,937.1 ± 13.6c	0.000281 g	6.76 ± 0.23b	0.997
1% SPB	7121.8 ± 4.6 h	0.00073c	2.60 ± 0.04ef	0.90	7127.3 ± 4.7 h	0.000000111c	3.47 ± 0.05ef	0.92	719.1 ± 7.1 cd	0.144 ± 0.004c	6925.9 ± 2.5 h	0.000570c	3.33 ± 0.04 fg	0.996
3% SPB	13,470.7 ± 3.1e	0.00043f	4.42 ± 0.00c	0.90	13,474.1 ± 3.1e	0.000000033f	6.10 ± 0.11c	0.91	804.4 ± 9.0b	0.145 ± 0.003c	13,252.3 ± 2.7e	0.000335f	5.66 ± 0.04c	0.994
6% SPB	23,023.3 ± 12.7b	0.00030 h	6.37 ± 0.02a	0.92	23,026.8 ± 12.8b	0.000000013 h	9.15 ± 0.01a	0.92	850.7 ± 28.1ab	0.160 ± 0.004ab	22,808.8 ± 17.2b	0.000244 h	7.77 ± 0.02a	0.992
1% OPB	7625.8 ± 7.6 g	0.00069d	2.75 ± 0.04e	0.91	7630.9 ± 7.8 g	0.000000098d	3.68 ± 0.09e	0.92	716.6 ± 10.1 cd	0.150 ± 0.003cb	7436.9 ± 12.7 g	0.000543d	3.50 ± 0.07f	0.997
3% OPB	14,988.3 ± 8.0d	0.00043f	4.38 ± 0.06c	0.93	14,993.0 ± 8.0d	0.000000030f	6.03 ± 0.11c	0.94	756.9 ± 13.3c	0.145 ± 0.005c	14,782.6 ± 16.5d	0.000352f	5.39 ± 0.03d	0.997
6% OPB	26,068.0 ± 3.5a	0.00029 h	6.47 ± 0.13a	0.93	26,072.0 ± 3.4a	0.000000012 h	8.96 ± 0.17a	0.94	868.2 ± 11.3a	0.152 ± 0.005cb	25,840.8 ± 11.4a	0.000245 h	7.75 ± 0.11a	0.995

Different letters within the same column indicates the significant differences between treatments according to Tukey's honestly significant difference test at $p \leq 0.01$. *Control*, unamended treatment; *WCB*, wood chips biochar; *SPB*, sorghum panicle biochar; *OPB*, orange peel biochar. Biochar additions were at three levels 1%, 3%, and 6% (w/w). Data were mean ± standard deviation

Table 5 Effect of type and levels of biochar on some soil chemical properties at the end of the incubation (data were mean ± standard deviation)

Treatments	Soil properties				
	pH	**EC dS m^{-1}**	**CEC cmol kg^{-1}**	**Olsen-P mg kg^{-1}**	**Available K mmol kg^{-1}**
Control	7.54 ± 0.01a	1.30 ± 0.02e	3.59 ± 0.04 h	4.96 ± 0.02ef	1.52 ± 0.02i
1% WCB	7.40 ± 0.02bc	1.24 ± 0.01f	4.34 ± 0.05 g	4.29 ± 0.19f	1.84 ± 0.03 h
3% WCB	7.34 ± 0.01c	1.18 ± 0.01 g	6.11 ± 0.08d	4.75 ± 0.52ef	2.67 ± 0.01 g
6% WCB	7.21 ± 0.02d	1.13 ± 0.02 h	7.37 ± 0.05b	6.54 ± 0.51e	3.79 ± 0.06f
1% SPB	7.39 ± 0.02bc	1.25 ± 0.00f	4.29 ± 0.01 g	9.18 ± 0.22d	4.05 ± 0.02f
3% SPB	7.24 ± 0.02d	1.38 ± 0.01d	5.40 ± 0.22e	15.26 ± 0.70b	9.31 ± 0.16d
6% SPB	7.12 ± 0.01e	1.57 ± 0.00b	6.56 ± 0.11c	27.30 ± 0.51a	16.84 ± 0.08b
1% OPB	7.42 ± 0.01b	1.30 ± 0.00e	4.86 ± 0.02f	5.50 ± 0.08ef	5.69 ± 0.13e
3% OPB	7.42 ± 0.04b	1.42 ± 0.00c	7.11 ± 0.12b	11.31 ± 0.52c	14.60 ± 0.09c
6% OPB	7.25 ± 0.01d	1.65 ± 0.00a	9.19 ± 0.06a	11.58 ± 1.17c	24.13 ± 0.05a

Different letters within the same column indicate the significant differences between treatments according to Tukey's honestly significant difference test at $p \leq 0.01$. *Control*, unamended treatment; *WCB*, wood chips biochar; *SPB*, sorghum panicle biochar; *OPB*, orange peel biochar. Biochar additions were at three levels 1%, 3%, and 6% (w/w)

7.39, 7.24, 7.12, 7.42, 7.42, 7.25 for treatments of 1% WCB, 3% WCB, 6% WCB, 1% SPB, 3% SPB, 6% SPB, 1% OPB, 3% OPB, and 6% OPB, respectively. The lowest values of soil pH were observed by applying SPB treatments. SPB and OPB applications at levels 3 and 6% increase significantly the electrical conductivity in soil comparison with the control treatment (Table 5). Values of electrical conductivity increased from 1.30 dS m^{-1} at control treatment to 1.38, 1.57, 1.42, and 1.65 dS m^{-1} for 3% SPB, 6% SPB, 3% OPB, and 6% OPB, respectively. Contrastingly, applying WCB at all levels and 1% SPB caused a significant decrease in electrical conductivity. The electrical conductivity values decreased from 1.30 dS m^{-1} (control) to 1.24, 1.18, 1.13, and 1.25 dS m^{-1} for 1% WCB, 3% WCB, 6% WCB, and 1% SPB, respectively. The lowest values of electrical conductivity were noticed at all levels of WCB treatments, while the highest value of electrical conductivity was observed at 6% OPB treatment (Table 5). Cation exchange capacity (CEC) of calcareous sandy soil significantly increased with amending by all biochar types at all levels (Table 5). The values of CEC increased from 3.59 cmol kg^{-1} soil for the control treatment to 4.34, 6.11, 7.37, 4.29, 5.40, 6.56, 4.86, 7.11, and 9.19 cmol kg^{-1} soil at 1% WCB, 3% WCB, 6% WCB, 1% SPB, 3% SPB, 6% SPB, 1% OPB, 3% OPB, and 6% OPB treatments, respectively. The highest CEC value was found at 6% OPB treatment. The effectiveness of the biochar in increasing the CEC of this soil was in the order of OPB > WCB > SPB (Table 5).

3.4 Effect of Acidic Biochar Type on Nutrient Availability

All the results of the nutrient availability were carried out at the end of the incubation experiment. Phosphorus availability (Olsen-P) in calcareous sandy soil significantly improved with different types of acidic biochar treatments compared to the control (Table 5). Olsen-P significantly increased with increasing biochar levels. The concentration of Olsen-P increased from 4.96 mg kg^{-1} soil for control treatment to 6.54, 9.18, 15.26, 27.30, 5.50, 11.31, and 11.58 mg kg^{-1} soil for 6% WCB, 1% SPB, 3% SPB, 6% SPB, 1% OPB, 3% OPB, and 6% OPB treatments, respectively. In contrast, the application of 1% WCB and 3% WCB caused insignificantly decreased the Olsen-P compared with the control. The highest concentrations of Olsen-P were observed at 3% SPB and 6% SPB treatments, while the lowest Olsen-P concentration in the 1% WCB treatment. Effectiveness of treatments in increasing Olsen-P concentrations was in the order of 6% SPB > 3% SPB > 6% OPB > 3% OPB > 1% SPB > 6% WCB > 1% OPB > control > 3% WCB > 1% WCB. The result indicated that incorporating different types of acidic biochar into the soil significantly improved the concentration of available potassium compared to the unamended soil treatment (Table 5). Soil available potassium significantly increased with increasing the doses of applying biochar in the soil. The concentrations of available potassium increased from 1.52 mmol kg^{-1} soil (control) to 1.84, 2.67, 3.79, 4.05, 9.31, 16.84, 5.69, 14.60, and 24.13 mmol kg^{-1} soil for treatments of 1% WCB, 3% WCB, 6% WCB, 1% SPB, 3% SPB, 6% SPB, 1% OPB, 3% OPB, and 6% OPB, respectively. The highest increase in the available potassium concentrations was in the soil treated with 6% OPB. These treatments can be ranked in the enhancing available potassium of this soil in the order of 6% OPB > 6% SPB > 3% OPB > 3% SPB > 1% OPB > 1% SPB > 6% WCB > 3% WCB > 1% WCB > control (Table 5).

4 Discussion

Actually, the decomposition of biochar in soil occurs through two important processes, chemical oxidation and microbiological degradation (Novak et al. 2009; Nguyen and Lehmann 2009). Numerous studies have found that the addition of biochar produced at low temperatures into the soils led to increasing CO_2 emissions more than unamended soil (Brassard et al. 2018; Sial et al. 2019); this increase in CO_2 emissions from the soil has resulted from mineralization of biochar prepared at low temperature (less than 300 °C), which in turn may be attributed to high amounts of dissolved organic carbon (Gui et al. 2020; Wei et al. 2019), volatile compounds, and aliphatic organic matter (Keiluweit et al. 2010; Zimmerman 2010) and abundance of functional groups such as carboxyl and hydroxyl (Nguyen and Lehmann 2009; Yaashikaa et al. 2020). The content of dissolved organic carbon, volatile compounds, and functional groups in biochars strongly correlated with feedstock type and pyrolysis temperatures (Wei et al. 2019; Yaashikaa et al. 2020). Furthermore, increased carbon dioxide emissions from infertile sandy soil amended with biochar, this is due to the fact that biochar is an important source of the nutrient, carbon, and energy supply for microorganisms which increasing the activity and community of microorganisms in the soil that lead to enhancing mineralization of biochar (Han et al. 2020). Consequently, these previous factors will inevitably lead to increased decomposition of biochar in the soils.

The mineralization of biochar and CO_2-C emissions from the sandy soils increased with the increasing incubation period, while the rate of biochar mineralization and CO_2-C emissions decreased with an increasing incubation period (Amin 2020a, 2020b; El-Naggar et al. 2018). The rate of biochar mineralization and CO_2-C emissions was high during the initial incubation periods because of the high activity of soil microorganisms due to the presence of dissolved organic carbon and nutrients (El-Mahrouky et al. 2015). Previous studies have found that several factors control the mineralization of carbon in the soils such as feedstock type and pyrolysis temperature of biochar production, dissolved organic carbon, incubation period, moisture content, and soil texture (Sigua et al. 2014; Wang et al. 2016).

Many researchers reported that the double-exponential model is the best equation to explain the kinetics of carbon mineralization when adding biochar into the soils (Liang et al. 2008; Qayyum et al. 2012). Qayyum et al. (2012) found that the half-life of different types of biochar ranged between 6.33 and 36.52 years in three different soils, while some other studies showed that the half-life of biochar ranged between hundreds and thousands of years (Hammes et al. 2008; Ippolito et al. 2020; Liang et al. 2008). The molar ratio of O/C and H/C as well as the pyrolysis temperature are important factors that affect the half-life of the biochar (Ippolito et al. 2020; Spokas, 2010). The half-life of carbon mineralization in the soil is dependent on several factors: soil texture, organic matter content, and temperature (Yang et al. 2006). Whenever the lower k_2 values, the half-life values are high, and this indicates the stability of the biochar are similar results have been found by Liang et al. (2008) and Qayyum et al. (2012).

The soil chemical properties were greatly affected by the application of different types of acidic biochar and its levels. The pyrolysis temperature and feedstock types are important factors affecting the pH of produced biochar (Liao et al. 2018; Yu et al. 2019). Many studies reported that the application of different types of acidic biochar produced at low-temperature pyrolysis into calcareous soils caused decreased soil pH (Naeem et al. 2017; Karimi et al. 2019, who found that the decrease in soil pH was attributed to the increase in the acidic functional groups present on the surface of the biochar produced at low-temperature pyrolysis). Additionally, the oxidation and decomposition of biochars in soils are producing acidic compounds causing a decline of soil pH (Al-Wabel 2019). The biochars prepared at the pyrolysis of lower temperatures were acidic because of producing organic acids and phenolic substances from cellulose during the decomposition process (Zhang and Wang 2016). The pH values in calcareous soil decrease with increasing application doses of acidic biochar (Ippolito et al. 2016). The electrical conductivity of biochar is mainly dependent on types of feedstock and pyrolysis temperature (Senbayram et al. 2019; Zhang et al. 2017). The application of biochar into the soils led to a decrease in the EC values, which may be attributed to the adsorption of salts onto the surfaces of biochar and fixing salts in biochar pores (Saifullah et al. 2018) as well as the values of EC for biochars produced from wood were low (Zhang et al. 2017). On the other hand, applying biochar increased the EC values in the soils, especially calcareous sand (Alotaibi and Schoenau 2019; Amin 2020a); this increase of EC is because the biochars contain on the soluble salts of alkali and alkaline earth cations as well as the EC values increased with increasing biochar doses (Smider and Singh 2014). The effectiveness of adding biochar to the soil in influencing the cation exchange capacity depends on many factors such as feedstock types, pyrolysis temperature, ash content, application rate, original soil CEC, and soil organic matter content (Domingues et al. 2020; Liao et al. 2018; Yu et al. 2019). The addition of biochars produced at lower pyrolysis temperature to the sandy calcareous soil increased the cation exchange capacity compared to the unamended soil (Amin 2020b; Alotaibi and Schoenau 2019); that increase may be due to the oxidation of acidic functional groups present on biochar surfaces (Eduah et al. 2019), higher charge density, carboxyl groups, and porous structure (Liang et al. 2006). The CEC values were raised with increasing biochar levels in the soil (Karimi et al. 2019).

Many studies reported that applying biochar to calcareous sandy soil enhanced phosphorus and potassium availability (Amin 2016; El-Naggar et al. 2015). The phosphorus and potassium concentrations in biochar were greatly influenced by feedstock types and pyrolysis temperature (Cao et al. 2018; Liao et al. 2018). Generally, all types of biochar are rich in base cations especially potassium (Xu et al. 2013). The concentrations of Olsen-P and available potassium in soil increased with increasing doses of biochar application (Amin 2016; Song et al. 2019).

5 Conclusions

The type of feedstock plays an important role in influencing the chemical characteristics of biochar produced at low temperatures and its suitability for application in arid regions. Common major problems of the soil chemical properties in arid regions include low fertility, low cation exchange capacity, and high alkalinity. Biochars produced from different feedstocks such as wood chips, sorghum panicles, and orange peels at low temperatures (270 °C) are acidic. Biochar decomposition in the soil can be relied on type and dose of biochar addition. The application of acidic biochars into calcareous sandy soil had a great role in influencing many of soil chemical properties such as pH and cation exchange capacity. Therefore, biochar greatly affects nutrient retention and plays a major role in maintaining the ecosystem. The addition of wood chips biochar led to decreasing electrical conductivity of the soil; this, in turn, enables us to use biochar amendment as a modern strategy for reclamation of saline soils. The nutrient availability of phosphorus and potassium was amelioration by applying acidic biochars. Thenceforth, adding different types of acidic biochar was effective on carbon sequestration, improved soil quality indicators, and soil fertility of sandy soil. The biochar applications into the soil are relatively inexpensive compared to the chemical fertilizers and amendments.

Declarations

Conflict of Interest The authors declare no competing interests.

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