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Addition of Biochar to a Sandy Desert Soil: Effect on Crop Growth, Water Retention and Selected Properties

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Abstract: Agricultural and environmental applications of biochar (BC) to soils have received increasing attention as a possible means of improving productivity and sustainability. Most previous studies have focused on tropical soils and more recently temperate soils. However, benefits of BC addition to desert soils where many productivity constraints exist, especially water limitations, have not been widely explored. Thus, three experiments were designed using a desert soil from Saudi Arabia to address three objectives: (1) to evaluate the effect of BCs produced from date palm residues added at 8 t ha^{-1} on wheat growth, (2) to determine the effect of BC addition and BC aging in soil on water retention, and (3) to reveal the effect of BC on selected soil physical (bulk density, BD; total porosity; TP) and chemical (pH; electrical conductivity, EC; organic matter, OM; cation exchange capacity, CEC) properties. The feedstock (FS) of date palm residues were pyrolyzed at 300, 400, 500, and 600 °C, referred to here as BC300, BC400, BC500, and BC600, respectively. The BC products produced at low temperatures were the most effective in promoting wheat growth when applied with the NPK fertilizer and in enhancing soil water retention, particularly with aging in soil, whereas high -temperature BCs better improved the selected soil physical properties. The low-temperature BCs increased the yield approximately by 19% and improved water retention by 46% when averaged across the incubation period. Higher water retention observed with low-temperature BCs can be related to an increased amount of oxygen-containing functional groups in the low-temperature BCs, rendering BC surfaces less hydrophobic. Only the BC300 treatment showed a consistent positive impact on pH, OM, and CEC. Pyrolysis temperature of date palm residue along with aging are key factors in determining the potential benefit of BC derived from date palm residues added to sandy desert soil.

Keywords: biochar; desert soil; crop growth; water retention; nutrient; soil chemical properties; soil physical properties

1. Introduction

Biochar (BC) is a carbonaceous residue produced through the thermal breakdown of organic materials under limited conditions of oxygen. The use of BC as a soil amendment is not a new concept, but it has received growing attention in the last few years, generally due to its role in mitigating greenhouse gas emissions by sequestering carbon in the soils, reducing nitrous oxide emissions, improving soil properties and quality, and increasing nutrient use efficiency and crop production [1–4]. BC can influence crop growth and yield directly via its effects on pH and nutrient retention and supply or indirectly through improvement of soil physical and chemical properties of importance for crop production [3,5–7]. Impact of BC addition on crop yield is more pronounced in infertile and degraded soils compared to that in the soils of high fertility [7]. However, the extent to which BC can influence crop yield is largely dependent on BC production temperature and the feedstock (FS) [5–7]. In a recent review, it was reported that the fertilizing value of BC and its nutrient availability, especially N and P, decrease with increasing pyrolysis temperature [5]. Therefore, the effect of BC on crop yield and plant nutrition was found to be variable, and its use as a sole amendment was not always effective, having its supplementation with mineral fertilizers sometimes necessary to promote crop growth [8–16]. Some studies found BC to be the most effective when it is applied with mineral fertilizers [8,14,17–19]. Therefore, positive impact of BC on soil fertility and crop yield is not always certain, and it highly depends on FS, BC production temperature, and most importantly soil type [3,5–7,20].

BC benefits to soil also include improvement of soil physical properties. For instance, soil bulk density (BD) and porosity was found to be improved after BC application [20–26]. BC was also reported to increase the soil ability to retain water, and this is mostly attributed to the high total porosity (TP) of BC, retaining water in small pores and thereby increasing water holding capacity and infiltration [5,20,21]. However, enhancement of soil physical properties following BC application is more evident in infertile and course-textured soils [7,23].

Key soil chemical properties, such as pH, OM content, and CEC are also influenced by BC addition, affecting soil fertility and productivity [3,7,27–29]. In most cases, BC is alkaline, and therefore its effect on increasing acidic soil pH was demonstrated in several studies whereas its impact on alkaline soil pH is expected to be minimal [5–7]. Reviewed studies reported increases in CEC and organic matter in soil treated with BC; however, the magnitude of this effect varies according to the BC production condition, application rate, and soil type [3–7].

BC use is most frequently reported to be effective in tropical zones where soils are acidic and nutrient leaching potential is high [30]. Under these soils conditions, BC can have liming and nutrient availability effects, as BC was found to increase pH values of acidic soils and thereby improve nutrient bioavailability and use efficiency [7,31]. A meta-analysis using data from 103 studies found a better performance of BC addition in acidic soils than in neutral soils, and in sandy than in loam and silt soils, suggesting liming and physical property improvement effects of BC [32].

Less attention has been given to effects of BC in semi-arid [33–36] and especially arid environments [26,37–40] with few studies in true desert soils.

Arid soils of Saudi Arabia are characterized in general by very low content of organic matter (<1%) and nutrients and sandy texture with poor water retention capacity and nutrient use efficiency [41]. The soils are alkaline, with a pH value in many cases found to be greater than 8.0 and have great abundance of calcium carbonate higher than 30% in some soils [41]. The use of BC from locally abundant feedstock, such as date palm residues as amendment can be a possible means to alleviate the productivity constraints of these desert soils. Therefore, the aim of the current study was to evaluate the effect of BC produced from date palm residues at different temperatures on wheat growth, soil water retention, and selected physical and chemical properties of a typical desert soil from Saudi Arabia.

2. Materials and Methods

2.1. Soil and Biochar

Soils were collected from a private farm near the City of Thadiq, approximately 120 km northwest of the City of Riyadh in Saudi Arabia. The particular site from where the soils were collected was abandoned and left uncultivated for ten years. Before abandonment, the site was under continuous cultivation of wheat and alfalfa for more than twenty years. Several soil samples were collected from 0–20 cm depth and thoroughly mixed to provide a composite sample. Soil was brought back to the laboratory, air-dried, and sieved (<2 mm). Prior to the experiments, the processed soil was analyzed for its basic characteristics. The soil was found to have an organic matter content of 0.48% OM. determined according to Nelson and Sommers (1996) [42], and a pH value of 8.4, EC of 0.47 dS m^{-1}, and 19.0% by weight of $CaCO_3$, determined according to the method of Loeppert and Suarez (1996) [43]. Soil pH and EC were measured in a 1:2.5 soil/distilled water suspension. The soil texture was determined as described by Gee and Bauder (1986) [44] and the textural class was loamy sand, having 79%, 14%, and 7% of sand, silt, and clay, respectively.

Date palm tree residues used as the FS for BC production included frond midrib and frond base residues. These residues were collected randomly from a local farm, chopped at the site, brought to the laboratory, and air-dried at 40 °C. A subsample was ground and prepared for direct application to soil. Another subsample was pyrolyzed for BC production. The pyrolysis process was carried out as described by Usman et al. (2015) [45]. Briefly, the fine-ground date palm residue was placed in a stainless steel container and closed tightly to exclude oxygen. The closed container was transferred to an electrical muffle furnace where it remained for 4 h at the desired temperature. The date palm residues were pyrolyzed at 300, 400, 500, and 600 °C, generating four BCs referred to as BC300, BC400, BC500, and BC600, respectively. The BCs were left to cool down to room temperature, followed by basic characterization analyses. This included analysis of pH, EC, total C, and total N. The pH was measured in 1:10 BC:water suspension, and the EC was measured in an extract of the same suspension. The total C and N were analyzed using a CHNS analyzer (Series II, PerkinElmer, Waltham, MA, USA). The basic characteristics of date palm residues and its BC are presented in Table 1.

Table 1. Basic characteristics of date palm residue BC used in the current study.

FS/BC	Parameters			
	C (%)	N (%)	pH	EC (dS m^{-1})
FS	42.8	1.5	7.20	3.00
BC300	61.4	0.75	7.67	5.61
BC400	65	0.93	8.22	6.67
BC500	71.7	1.0	8.40	7.53
BC600	73.0	1.1	8.75	8.07

2.2. Experimental Design

2.2.1. Experiment1: Wheat Growth

This experiment was designed to include treatments of FS and four BCs (BC300, BC400, BC500, and BC600) without and with a fertilizer, a fertilized control (FC), and an unfertilized control (UFC). The FS and BCs were applied at one rate of 8 t ha^{-1}. This rate of BC application is considered practical if BC is to be applied at a large scale under field conditions. The FS and BCs were weighed and mixed with 100 g soil followed by addition of NPK fertilizer as urea, triple superphosphate, and potassium sulphate applied at 200 kg N ha^{-1}, 100 kg P ha^{-1}, and 50 kg K ha^{-1}, respectively. In case of FS and BCs applied alone, no fertilizer was applied. The mixture was spread onto the surface of 900 g of air-dried sieved soil in a 1L plastic pot with a 12 cm height and a 12 cm diameter, bringing the total soil weight to 1 kg per pot. The FC treatment received 200 kg N ha^{-1}, 100 kg P ha^{-1}, and 50 kg K ha^{-1}, as urea, triple superphosphate, and potassium sulphate, respectively, whereas the UFC received no fertilizers or BCs. Each treatment was replicated four times. Pots were left to equilibrate for 24 h, and then seven seeds of wheat (*Triticum aestivum* L. cultivar YecoraRojo) were sown in each pot. Soil moisture was brought to 80% of field capacity and maintained at this moisture level by daily watering for the entire period of the study. The pots were placed in a controlled environment growth chamber set at 22–25 °C. After plant emergence, seedlings were thinned to three plants per pot. The plants were left to grow for six weeks after which the total aboveground biomass was cut at the soil surface, harvested, and dried at 60 °C, and dry matter weight was recorded. A finely ground subsample of the plant material was first digested as described by Thomas et al. (1976) [46] followed by colorimetric determination to determine N and P contents of the digested plant material.

2.2.2. Experiment2: Water Retention

Five hundred grams of air-dried and sieved soil was placed into a plastic container. Then, BC was added and mixed manually with the soil. The soil mixed with BC was repacked into PVC columns with a 5.5 cm internal diameter and a 20 cm height, giving a soil depth of 15 cm. The columns were sealed at the bottom with glass wool to hold the soil during leaching. A headspace of approximately 3 cm was left above the soil surface to allow for water addition. The treatments included the four BCs used in this study applied at one rate of 50 t ha^{-1} without a fertilizer, in addition to untreated control. Each treatment was replicated three times. The rate of 50 t BC ha^{-1} used in this experiment was selected according to initial trials where low rates of BC did not show a clear effect on water retention. This is within the range of BC rates used in the literature where a rate of >20 t ha^{-1} is required in several studies to detect significant responses to BC addition [7,23,30]. The cylinders with soil were placed in a rack and allowed to stand. Then, the soil was brought to 50% of the field capacity and left to equilibrate for 24 h, after which the leaching events were conducted. Leaching was carried out by adding distilled water using a perforated container and allowing water to percolate through the soil overnight, and leachate was collected and its volume was recorded. The percentage of the retained water was calculated by subtraction of the volume of recovered leachate from the volume of the added water [47]. The leaching occurred five times at the beginning of the experiment and after 14, 30, 45, and 60 days, in order to investigate the effect of BC aging in soil on water retention.

2.2.3. Experiment3: Changes in Selected Physical and Chemical Properties

In this experimental setup, treatments included BC300, BC400, BC500, and BC600 applied without a fertilizer at the same rate (8 t ha^{-1}) as in experiment 1 in addition to the untreated control, but left for a longer time to allow for effects on physical and chemical properties to be fully revealed. The treatments were thoroughly mixed with the entire soil placed in a 1L plastic pot with a 12 cm height and a 12 cm diameter and incubated for eight months at 80% of field capacity and under controlled conditions. At the end of the eight-month incubation, soil BD and TP were determined using the core method [48]. For chemical analysis, soils were removed from the pots, air-dried, and analyzed for pH, EC, OM, and CEC. The OM concentration was analyzed according to the method of Nelson and Sommers (1996) [42]. The CEC was determined according to Rhoades (1982) [49].

2.3. Statistical Analysis

Data generated from experiments 1 and 3 were analyzed using a one-way analysis of variance (ANOVA) where treatment effects on plant and soil variables were tested. Data obtained from experiment 2 were analyzed using a two-way ANOVA where the effects of treatment, time of incubation, and their interaction on water retention were analyzed. Treatments effects were considered significant at $p < 0.05$ at which the mean comparisons was also performed using the Student–Newman–Keuls (SNK) test. Statistical analysis was performed using CoStat software package (CoHort Software, 2008). Each variable data were reported as the mean ± standard error of the treatment replicates. Statistical analysis outputs are either included in the tables or the figures.

3. Results

3.1. Wheat Yield and N and P Uptake Response to Biochar Addition

The impact of date palm residue BC amendment on wheat yield clearly varied according to the BC production temperature (Figure 1). This variation was also observed in either the presence or the absence of fertilizer addition (Figure 1). In general, the yield was higher in the presence of NPK compared to that using the same treatments without NPK. BC produced at 300 or 400 °C and added with NPK provided the highest yield compared to that with the NPK alone treatment and also compared to the BC produced at 500 or 600 °C treatments (Figure 1). The BC300 and BC400 treatments also had higher yield than the FS when NPK was added. The yield in the FS with a fertilizer did not exceed that in NPK alone treatment. Without a fertilizer, compared to the UFC, the FS and BC 300 treatments did not significantly increase yield, while yield was decreased in treatments with BC produced at higher temperature (BC400, BC500, and BC600). Compared to the FC, the fertilized BC300 and BC400 treatments led to higher yield while other treatments were not significantly different. A similar pattern was evident among treatments in fertilized versus unfertilized. In general, the most effective treatments were the BC300 and BC400 when applied with a fertilizer; both treatments resulted in the greatest yield that was significantly higher than any other treatment.

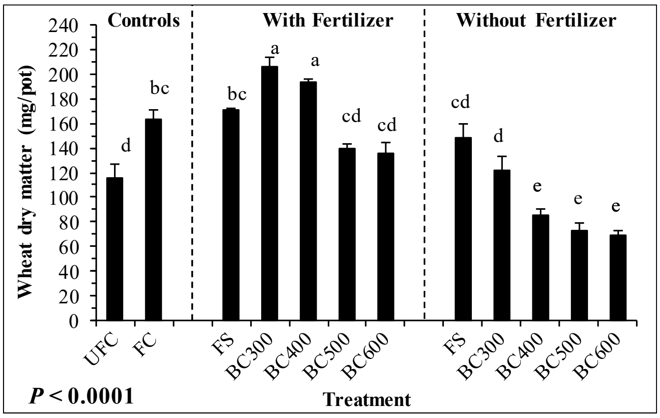

Figure 1. Response of total biomass yield of wheat grown for 5 weeks to application with and without a fertilizer of 8 t ha^{-1} of four date palm residue biochars (BCs) that were produced with different pyrolysis temperatures (BC300, BC400, BC500, and BC600) and the BC feedstock (FS). Treatments also included an unfertilized control (UFC) and a fertilized control (FC). Bars sharing the same letter among treatments are not significantly different according to the Student–Newman–Keuls (SNK) test ($p \leq 0.05$). Errors bars represent the standard error of the mean ($n = 4$).

Treatments had a significant impact on plant N and P uptake (Figures 2 and 3) that followed a similar pattern to that of the impact on yield. The BC300 treatment with a fertilizer showed the greatest N and P uptake (Figures 2 and 3). Higher-temperature BCs (BC500 and BC600) treatments reduced plant N and P uptake to the background level either when applied alone or in combination with the NPK fertilizer. Application of BCs produced at high temperatures may limit N and P through retention processes and/or result in reduced uptake due to a phytotoxic effect.

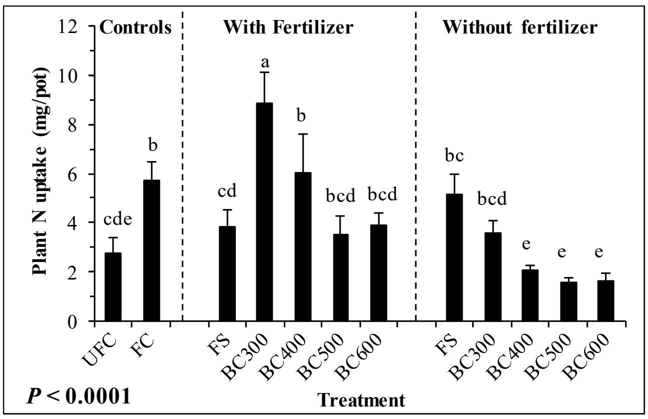

Figure 2. Plant N uptake in soil receiving 8 t ha^{-1} of four date palm residue BCs produced with different pyrolysis temperatures (BC300, BC400, BC500, and BC600) and the BC FS with and without a fertilizer added. Treatments also included a UFC and an FC. Bars sharing the same letter among treatments are not significantly different according to the SNK test ($p \leq 0.05$). Errors bars represent the standard error of the mean ($n = 4$).

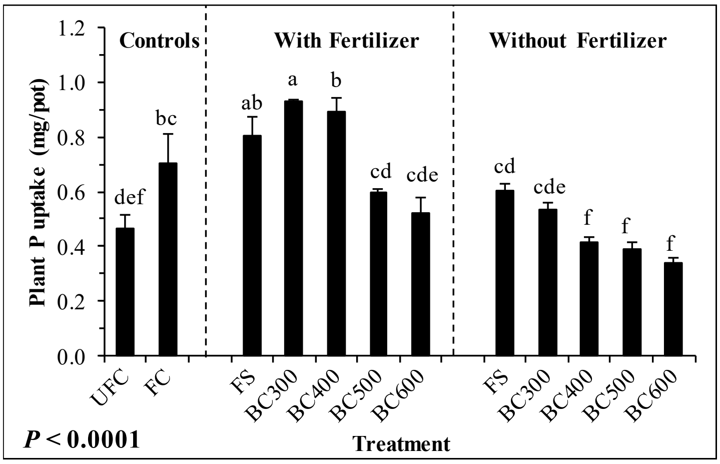

Figure 3. Plant P uptake in soil receiving 8 t ha^{-1} of four date palm residue BCs produced with different pyrolysis temperatures (BC300, BC400, BC500, and BC600) and the BC FS with and without a fertilizer added. Treatments also included a UFC and an FC. Bars sharing the same letter among treatments are not significantly different according to the SNK test ($p \leq 0.05$). Errors bars represent the standard error of the mean (n = 4).

3.2. Impact of Date Palm Residues Biochars on Water Retention

The effects of treatment, time of incubation, and their interaction on water retention were statistically significant (Figure 4). The positive effect of BC treatments on water retention in the soil increased with increasing time of incubation and was greatest for the low pyrolysis temperature BC (BC300). This indicated that, as BC ages in soil, it can be more effective in promoting water retention, especially the low pyrolysis temperature BC. When averaged across the time of incubation periods, the BC300 treatment showed the greatest amount of retained water, significantly higher than that observed in BC400 treatment (Figure 5A) and higher than the BC500and BC600 treatments. The treatments in order of retained water amounts were BC300>BC400>BC500≥BC600>unamended control. Averaged across all the treatments, water retention was greatest at the end of the incubation (Figure 5B), with Day45≥Day60>Day30>Day14>Day0.

3.3. Impact of Date Palm Residues Biochars on Soil Bulk Density and Total Porosity

The statistical analysis showed a significant treatment effect on soil BD (Figure 6A) and TP (Figure 6B). All the treatments significantly reduced the BD in comparison to the control; however, the effect of the treatments varied in their magnitude (Figure 6A). The lowest decreases in BD were observed with FS, BC300, and BC400 treatments, all of which did not significantly differ from each other. The greatest decreases in BD were shown in soil treated with BC500 and BC500, both of which did not significantly differ from each other but were significantly different from any other treatment (Figure 6A). The lowest value of TP was observed with the control treatment; however, it was the only BC600 treatment that provided a significantly higher TP value than the control (Figure 6B).

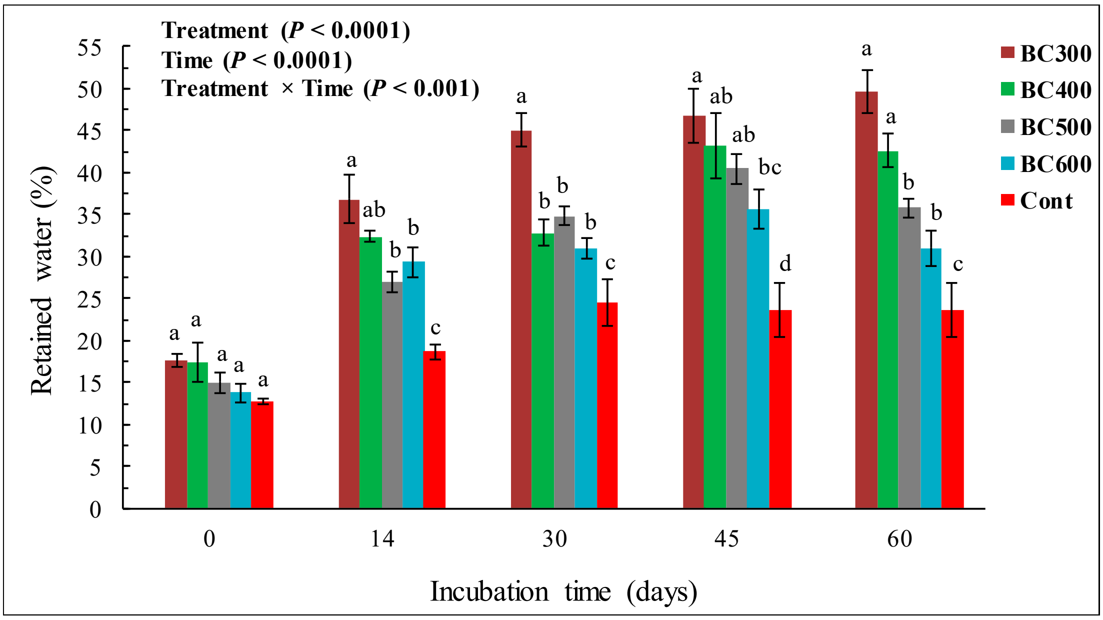

Figure 4. Percentage of retained water in sandy desert soil treated with 50 t ha^{-1} of four date palm residue BCs produced with different pyrolysis temperatures (BC300, BC400, BC500, and BC600) over time. Bars sharing the same letter among treatments are not significantly different according to the SNK test ($p \leq 0.05$). Errors bars represent the standard error of the mean ($n = 3$).

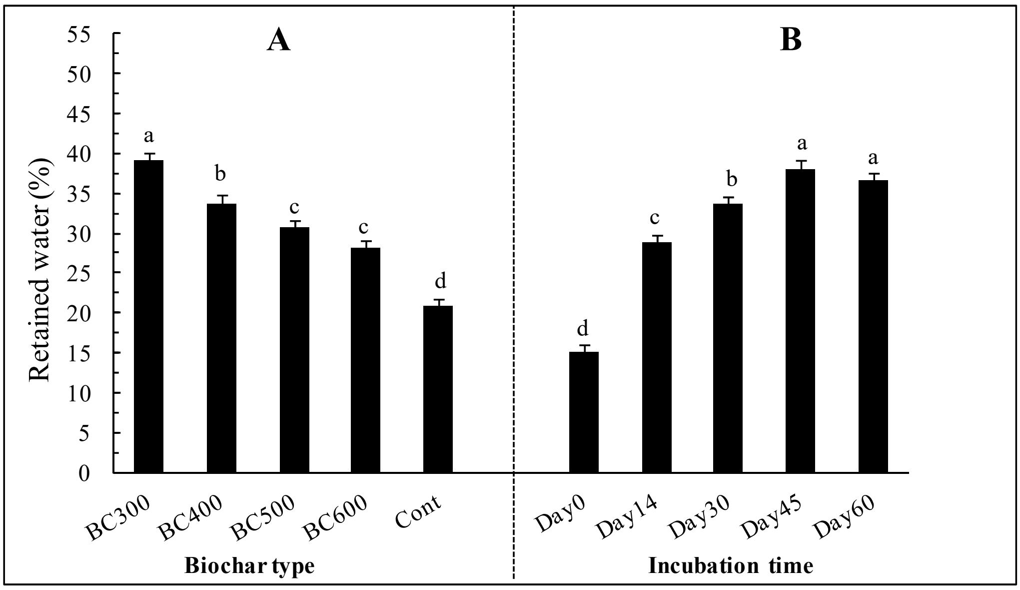

Figure 5. Percentage of retained water in sandy desert soil treated with 50 t ha^{-1} of four date palm residue BCs produced with different pyrolysis temperatures (BC300, BC400, BC500, and BC600) averaged across the time of incubation (**A**) and incubation time averaged across the BC products(**B**). Bars sharing the same letter among treatments are not significantly different according to the SNK test ($p \leq 0.05$). Errors bars represent the standard error of the mean.

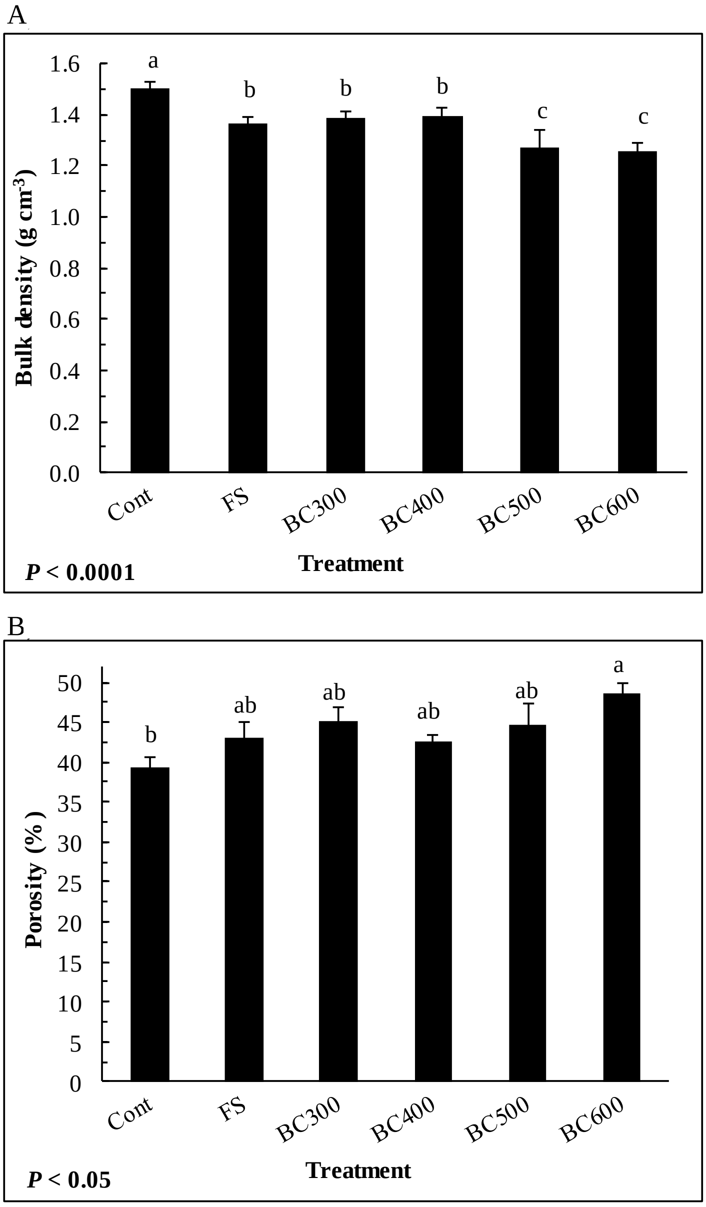

Figure 6. Effects of 8 t ha^{-1} of four date palm residues BCs (BC300, BC400, BC500, and BC600) and the FS on soil bulk density (**A**) and total porosity (**B**) after eight months of incubation. Bars sharing the same letter among treatments are not significantly different according to the SNK test ($p \leq 0.05$). Errors bars represent the standard error of the mean ($n = 4$).

3.4. Impact of Date Palm Residues Biochars on Selected Soil Chemical Properties

The soil pH, EC, OM, and CEC (Table 2) were significantly impacted by amendment treatment. The greatest decrease in soil pH was observed with the FS treatment followed by that with BC300 treatment, both of which were significantly different from each other and significantly lower than any other treatment (Table 2). None of the other treatments differed from the control. A significant increase in soil EC comparison to the control was observed, with the greatest increase in EC found in BC600 and FS treatments followed by that with BC500 or BC300 treatment (Table 2). Only the BC300 treatment resulted in higher soil OM and CEC in comparison to all the other treatments (Table 2).

Table 2. Effects of experimental treatments on the selected soil chemical properties.

Treatment	pH	EC	OM	CEC
		dS m^{-1}	%	meq/100
Control	8.25 ± 0.01 [a]	0.48 ± 0.03 [c]	0.62 ± 0.00 [b]	6.86 ± 0.42 [b]
FS	8.07 ± 0.02 [c]	1.51 ± 0.06 [a]	0.69 ± 0.04 [b]	8.24 ± 0.48 [b]
BC300	8.14 ± 0.04 [b]	1.22 ± 0.18 [a,b]	1.18 ± 0.12 [a]	9.86 ± 0.40 [a]
BC400	8.23 ± 0.02 [a]	1.09 ± 0.04 [b]	0.70 ± 0.07 [b]	7.09 ± 0.11 [b]
BC500	8.27 ± 0.01 [a]	1.22 ± 0.03 [a,b]	0.60 ± 0.04 [b]	7.92 ± 0.15 [b]
BC600	8.19 ± 0.01 [a,b]	1.54 ± 0.05 [a]	0.57 ± 0.02 [b]	7.72 ± 0.21 [b]
LSD (0.05)	0.06	0.26	0.19	0.99

Means within a column sharing the same letter are not significantly different at $p = 0.05$.

4. Discussion

4.1. Wheat Growth Response to Date Palm Residue Biochar Addition

The BCs derived from date palm residues were more effective when combined with NPK fertilizer, and a better wheat response was evident with BCs produced at the lower temperatures of 300 and 400 °C compared to those at 500 and 600 °C. Similarly, greenwaste BC produced at 450 °C increased radish yield in presence of N fertilizer, but had no effect when applied alone [8]. Rice husk BC produced at 450 °C was also found to increase total biomass and grain yields of wheat and rice when applied with N, but no effect was found in absence of N [13]. Many other studies found BC to be the most effective in crop yield when applied with mineral fertilizers [8,14,15,17,18,50,51]. Alburquerque et al. (2013) [14] found decrease in or no effect on total plant biomass in response to wheat straw and olive tree pruning BCs produced at low temperature and applied alone under growth chamber conditions. Oat hulls BC produced at 450 °C showed also a limited effect on crop yield under field conditions [16]. In contrast to the results of the current study, other studies, however, reported increases in yield when BC was applied alone [9–12,15]. Decrease in N plant uptake following BC addition has been reported [14], related to the ability of BC to adsorb N and limit its availability. The BC surface area and microporosity increase with increasing pyrolysis temperature, resulting in BCs of higher physisorption capacity [52,53]. Thus, the BC produced here at higher temperatures (>400 °C) reduced yield and N and P uptake, and this could be attributed to their high adsorption/sorption capacity, restricting soil nutrient availability for plant uptake. Addition of fertilizer may also enhance microbial decomposition and reduce any phytotoxic effects of BC as appeared to be evident with the high-pyrolysis-temperature BC in the current study. This may also explain the decreased yield and N and P plant uptake in higher-pyrolysis-temperature BC treatments without a fertilizer added observed in the current study. It was previously reported that mineral N availability is essential in stimulating microbial decomposition of organic materials [54,55]. Under the conditions of the current study, it appears that date palm residues BC did not supply nutrient, and its effect on wheat yield and N and P uptake was related to other factors, mainly improvement of soil water holding capacity and physical properties.

4.2. Effect of Date Palm Residue Biochar Addition on Water Retention

Several studies that previously investigated soil water retention in sandy soils after BC addition showed variable results [20–22,24,26,56–60]. The results of the current study clearly indicated that the residence time of BC in soil and the pyrolysis temperature are significant factors in determining effect of BC on water retention. All the BCs used in the current study significantly increased soil water retention in the sandy desert soil, and the effect increased with the time of incubation. The low pyrolysis temperature BCs (BC300 and BC400) enhanced water retention the most when compared to the high-pyrolysis-temperature BCs. Some other findings have indicated BC hydrophobicity (water repellency) to decrease with increasing pyrolysis temperature, indicating potentially greater soil water retention enhancement with higher-pyrolysis-temperature BC [61–63]. Jeffery et al. (2015) [59] reported that the hydrophobicity of BC reduced water infiltration into the BC particles and this can limit water retention. The hydrophobic surface of low-temperature BC is created by formation of aliphatic compounds that get volatilized at high pyrolysis temperature [61,62,64]. However, low pyrolysis temperature BCs were also reported to show higher oxidation rates that could render BC surfaces less hydrophobic via increasing the amount of oxygen-containing functional groups [62,63,65]. This can explain the increase in soil water retention with time in the current study, especially with low-temperature BCs which are considered to be more labile, and with greater potential for oxidation changes in their surface functionalities and porosity. In agreement with the current findings, BC produced at 500 °C increased sandy soil water retention and the increase was more evident with time of incubation, attributed to a change of BC surfaces from hydrophobic to hydrophilic [56]. Similarly, clay soil amended with BC produced at 400 °C retained less water immediately after application, but after a 180-day incubation, its effect on water retention was comparable to those produced at 600 or 800 °C [66]. BC addition was also found to increase available water content in sandy loam and loamy soils in the first growing season, and this impact continued to increase in the second growing season, highlighting the importance of BC aging in soil [67].

4.3. Impact of Date Palm Residues Biochars on Selected Soil Physical and Chemical Properties

All BC treatments in the current study reduced soil BD. The observed decrease in BD and increase in TP in soil amended with BC in the current study are in agreement with previous studies [22,23,25,68]. However, the impact of BC on BD and TP varies according to the FS type, rate of application, soil texture, and pyrolysis temperature [25]. In the current study, the high-temperature BCs (BC500 and BC600) showed the greatest decrease in BD, and this was also associated with the highest increase in TP, especially in BC600 treatment, which was significantly higher than in the control. Increase in pyrolysis temperature yields BC with high surface area and porosity, the most important physical properties that would enhance BC capabilities of improving soil physical properties, such as adsorption capacity, BD, and porosity [62,69]. However, the lower soil BD and higher porosity observed with the high-temperature BC used here were not associated with higher water retention when compared to low-temperature BC. This can be in part attributed to changes in surface chemistry of BC during the incubation as explained earlier or effects on pore size distribution.

Generally, pyrolysis of most organic FSs results in BCs with alkaline pH; however, the effect varies according to pyrolysis temperature and FS type [3]. As a result, BC addition is frequently found to increase soil pH in acid soils [3,7,27–29]. Conversely, in the current study with a soil of alkaline pH, the BCs had little effect on soil pH, with the exception of FS and BC300 treatments that showed a minor but significant decrease in soil pH. Other studies in neutral to alkaline soils also showed a limited effect of BC amendment on soil pH [70]. A decrease in soil pH was reported in alkaline soils following BC application [36,71,72]. This is probably related to some chemical oxidation and microbial decomposition of BC in soil, resulting in acidic compounds being produced and therefore lowering soil pH. This may be more evident with low-temperature BC which is expected to go through microbial decomposition to some extent. The pronounced effect of BC300 treatment in this study can support this explanation. All treatments increased soil EC, and this can be attributed to the salts contained within these materials, which is expected to elevate soil EC. Increases in soil EC were also reported in other studies [28,71]. This impact needs to be further monitored if these materials are to be applied frequently to arid soils, as without removal by leaching, they may cause soil salinity. It was only the BC produced at 300 °C which significantly increased soil organic matter content. Previous findings also report that greater increase in soil organic carbon with BC produced at low temperature than with high temperature BC [72,73]. A positive impact of BC on CEC is commonly reported, particularly in course-textured soils [7,36,73]. However, the impact of BC treatments on CEC in the current study was minimal and may be related to the low rate of application (8 t ha^{-1}) compared to those in other studies, and only the BC300 treatment showed significantly higher CEC than any other treatment. The CEC increase in soil amended with BC produced at 300 °C is consistent with the positive impact of this treatment on the other crop and soil parameters tested in this study.

5. Conclusions

The effect of date palm residues BC addition on sandy desert soil was evaluated under controlled environment conditions. The BCs produced at low pyrolysis temperatures (300 and 400 °C) were the most effective in promoting wheat growth when applied with a mineral fertilizer, enhancing soil water retention, particularly with aging in soil, whereas high temperature BCs better improved the selected soil physical properties (BD and TP). Soil pH was slightly reduced whereas all treatments increased soil EC. Soil OM content and CEC were only increased in the BC300 treatment. It appeared the pyrolysis temperature and aging are key factors in determining the potential benefit of BC addition to sandy desert soil.

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