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# Effect of biochar addition on legacy phosphorus availability in long-term cultivated arid soil

Khaled D. Alotaibi<sup>1\*</sup> , Melissa Arcand<sup>2</sup> and Noura Ziadi<sup>3</sup>

## Abstract

**Background:** Continuous application of phosphorus (P) nutrient in association with its low recovery results in large amounts of P being accumulated in soil in different forms. Use of biochar can be a possible means to mobilize soil legacy P and increase its bioavailability. Therefore, the aim of this study was to identify the potential impact of a range of biochar types on P fractions in a long-term cultivated arid soil with high legacy P content.

**Methodology:** The soil was treated with biochar produced from four feedstock sources (BFS): sewage sludge (SSB), olive mill pomace (OPB), chicken manure (CMB), and date palm residues (DRB) pyrolyzed at 300, 500, or 700 °C in addition to an untreated control. The soil biochar mixture was incubated for 1 month followed by soil P fractionations using sequential chemical extraction to separate soil P into: labile (Resin-Pi, NaHCO<sub>3</sub>-Pi, NaHCO<sub>3</sub>-Po), moderately labile (NaOH-Pi, NaOH-Po), and non-labile (HCl-Pi and Residual-P) pools.

**Results:** Biochar addition clearly influenced most of the soil P fractions; however, the extent of this effect greatly varied depending on BFS and pyrolysis temperature (PT). The most evident biochar impact was observed with labile P pool, with the greatest increase being observed in NaHCO<sub>3</sub>-Pi fraction in most biochar treatments. Irrespective of PT, SSB and CMB were the most effective biochar type in increasing labile inorganic P; the SSB and CMB increased Resin-Pi by 77 and 206% and NaHCO<sub>3</sub>-Pi by 200 and 188%, respectively. In contrast, DRB made no changes in any P fraction. Differences in effects of biochar types on labile P is presumably related to the higher content of P in biowaste-based biochar compared to plant-based biochar which have much lower P content. The SSB, CMB, and OPB produced at low temperature reduced HCl-Pi content, indicating that these biochars may have stimulated organic matter decomposition and thereby dissolution of non-labile Ca-associated P to labile P forms.

**Conclusion:** Overall, biochar addition appeared to be an effective approach in enhancing legacy P availability in arid soil. However, further studies are necessary to verify these findings in the presence of plant and for a longer period.

**Keywords:** Feedstock, Pyrolysis temperature, Alkaline soil, Phosphorus transformations, Phosphorus fractions

## Background

Phosphorus (P) is an essential plant macronutrient that plays a critical role in plant growth and development [1]. However, P deficiency is a global crop production constraint, and is estimated to impact crop yield in >40% of

agricultural soils [2]. These soils, however, usually contain a considerable amount of total P, but the issue is that plants can only take up orthophosphate ions (HPO<sub>4</sub><sup>2-</sup> and H<sub>2</sub>PO<sub>4</sub><sup>-</sup>) which are in low concentrations in soil solution [3]. Although inorganic and organic P fertilizers are applied to replenish this pool, orthophosphate in soil solutions rapidly reacts with soil components and transforms into other P forms that are not plant available [4]. Shortly after P fertilizer addition to soil, P associates with

\*Correspondence: khalotaibi@ksu.edu.sa

<sup>1</sup> Department of Soil Science, King Saud University, P.O. Box 2460, Riyadh 11451, Saudi Arabia

Full list of author information is available at the end of the article

calcium, iron, and aluminum and forms insoluble P compounds, resulting in a small percentage (10–30%) of the added P being taken up by the plant in the year of application [5, 6]. The rest of the applied P can be fixed to soil particles as adsorbed P or precipitates with soil constituents to form insoluble P compounds, or is immobilized into organic P, all of which are not readily available for plant uptake [5, 7]. Thus, most of the applied P remains in the soil, and long-term application of mineral and organic P fertilizer leads to accumulation of P in soil.

Phosphorus accumulation is particularly evident under arid soil conditions, due to poor P use efficiency in these soils [8, 9]. The soils of arid regions are typically characterized by an abundance of  $\text{Ca}^{2+}$ , alkaline pH, poor organic matter content, and presence of calcite ( $\text{CaCO}_3$ ). Soil pH is a critical soil characteristic that can influence many chemical and biological properties that will in turn determine the rate of solubility and availability of P [7, 10], and in alkaline soils, Ca-associated P precipitates are formed [7, 11, 12]. As such, low P use efficiency in arid soils is induced by these soil characteristics, and severe P deficiency will occur if sufficient fertilizer is not applied. Indeed, P fertilizers are often applied in excessive amounts exceeding crop needs to overcome soil P precipitation and adsorption processes and maintain optimal concentration of P in soil solution to ensure optimal crop production [13, 14]. Under long-term P fertilizer application, however, P exceeding the rates of crop removal accumulates in large amounts in agricultural soils creating what is widely known as “legacy soil P” [14, 15]. This legacy soil P can have the potential to be a P resource for crops; it is estimated to adequately maintain optimal crop yield globally for many years if it can be made accessible [16, 17]. Several approaches have been suggested to increase the bioavailability of legacy P, including use of biochar [15].

Biochar is a carbonaceous material produced through thermal conversion of organic materials under limited oxygen conditions [18]. The effects of biochar addition on soil physical and chemical properties and crop growth have been extensively studied in tropical and temperate soils [19–21]. Studies specifically addressing biochar impact on soil P fractions reported variable findings [22–33]. These studies showed that the effects of biochar on P fractions largely varied according to biochar feedstock type, pyrolysis temperature, and soil properties. However, studies particularly evaluating the biochar's ability to solubilize legacy P in cultivated arid soils are still limited. Biochar may not be a good direct source of P in arid soils which have alkaline pH [29], but may increase P availability indirectly in these soils via different mechanisms. This can include either the possible role of biochar in changing the soil chemical and physical

properties, such as soil particle surface properties, pH, cation exchange capacity (CEC), and extractable cations [15, 34] or changing soil conditions that alter microbial structure and diversity that can affect P solubilization and mineralization processes [35, 36]. Biochar may release organic acid compounds that can compete with P ions for exchange sites in soil, affecting the adsorption–desorption processes of P in soil solution as well as the precipitation–dissolution of P minerals [37, 38]. Besides biochar-induced changes in soil characteristics and processes, key biochar properties such as surface area, pH, P content, and CEC, properties largely driven by feedstock type, and pyrolysis temperature, play a significant role in determining the magnitude of biochar effects on soil P availability [35, 39–42]. Studies evaluating the impact of biochar on P forms and availability in arid soil with long-term fertilization have not been widely explored. Therefore, it is essential to determine to what extent biochar will affect P fractions in long-term cultivated arid soil, taking into consideration biochar type. This will allow a better understanding of P transformations and the possible contribution of legacy P to plant P nutrition in arid soils. It is hypothesized that P forms and availability will be largely dependent on type biochar type. The objective of current study was to investigate soil P fractions in long-term cultivated arid soil treated with a range of biochar type.

## Materials and methods

### Study soil collection and analysis

Soil was collected from a peach orchard field belonging to a private farm located in Aljouf governorate, North of Saudi Arabia. The field from which the soil was collected has been under long-term organic management, and organic P fertilizers have been added to the soil regularly since the establishment of the farm in 1990. The field received annually 200, 100, and 210 kg/ha of N, P and K, respectively. Selection of this site was determined after initial soil analysis indicated that this soil had a very high level of legacy P and is representative of many soils having high legacy P content reported in the previous studies [43, 44]. Soil samples were collected from four different points at a depth of 0–20 cm across the field and thoroughly mixed to provide a representative sample. This composite soil sample was brought to the lab, air-dried, sieved through 2 mm mesh.

The air-dried and sieved composite sample was subsampled for analysis for basic characteristics, including pH, EC, total nitrogen (N), total P, organic carbon (C), available P,  $\text{NH}_4\text{-N}$ ,  $\text{NO}_3\text{-N}$ , calcium carbonate ( $\text{CaCO}_3$ ), and particle-size distribution. A soil:distilled water ratio of 1:2 was used for soil pH and EC measurements. Soil content of organic C and total N were determined by

dry combustion method whereas total P was determined by acid digestion according to Thomas et al. [45]. Available P was measured following the method described by Olsen and Sommers [46]. Inorganic N forms ( $\text{NH}_4\text{-N}$  and  $\text{NO}_3\text{-N}$ ) were extracted and measured according to Keeney and Nelson [47]. The  $\text{CaCO}_3$  content and particle-size distribution were analyzed using the method of Loeppert and Suarez [48] and Gee and Bauder [49], respectively. The soil had a sandy loam texture, and its basic characteristics are given in Table 1. The remaining composite air-dried soil sample was sealed and stored at room temperature until its use in the incubation experiment.

### Biochar production and analysis

Four organic materials were used as feedstocks (FS) for biochar production: (1) sewage sludge (SS), (2) olive pomace (OP), (3) chicken manure (CM), and (4) date palm residues (DR). The selection of these materials were based on their local abundance; their conversion to biochar can be a good strategy of their management through recycling and utilization. All four organic materials were pyrolyzed at three temperatures: 300, 500, and 700 °C, with the exception of CM where only two pyrolysis temperatures (300 and 500 °C) were used. A homogenized sample of the feedstock was placed in a chamber that was then tightly sealed to maintain oxygen-limited environment. The sealed chamber containing the feedstock was placed into a muffle furnace that was then set at the target temperature at which the pyrolyzed material remained for 3 h. The resulting biochar was left to cool at the room temperature, ground manually to pass a 1.0 mm sieve, subsampled for basic characterization analysis, and

stored in the lab until its use. This resulted in 11 biochars to be used in the current study. Biochar produced from any given feedstock (FS) at 300, 500, or 700 °C is hereafter referred to as FSB3, FSB5, and FSB7, respectively. For example, sewage sludge charred at 300, 500, and 700 °C is hereinafter designated as SSB3, SSB5, SSB7, and so on.

Finely ground biochar sample was analyzed for basic characteristics included pH, EC, total C, total N, total P, and Brunauer–Emmett–Teller (BET) surface area. The biochar pH was measured in the suspension of 1:10 (B:water), and the extract of this suspension was used to measure the EC. The total C was analyzed using a CHNS analyzer (Series II, PerkinElmer, Waltham, MA, USA). Total N and P were measured by digesting the biochar sample in  $\text{H}_2\text{SO}_4\text{-H}_2\text{O}_2$  [45], followed by a colorimetric procedure [50]. Micromeritics Tristar II 3020 surface area analyzer was employed to measure biochar surface area using  $\text{N}_2$  gas BET [51]. Basic characteristics of the studied biochar types are given in Table 2.

### Incubation experimental design

Prior to the start of the experiment, 10 g air-dry soil was weighed into a plastic vial and preincubated for 3 days at 65% of its water holding capacity (WHC) followed by treatments' application. The experimental treatments included 11 biochars: SSB3, SSB5, SSB7, OPB3, OPB5, OPB7, CMB3, CMB5, DRB3, DRB5, and DRB7. Biochar was added at a rate of 3%, mixed with the soil, and incubated for 1 month at 65% of WHC in a dark chamber at 24–25 °C. The vials containing soil were covered with parafilm with small holes being poked into it to allow for air exchange and to ensure aerobic conditions. A soil received no biochar was added as a control (CONT) treatment. Each treatment was replicated three times. Soil moisture content was checked regularly during the entire period of incubation by weight loss, and water was added when needed. From agronomic perspective, an incubation period of 1 month for such study is assumed to be adequate, since the P demand is at the highest in the first month during the early stage of crop growth [52]. At the end of incubation, the treated soil samples were air-dried and prepared for P fractionation analysis.

### Soil P fractionation

Soil P was fractionated via sequential chemical extraction following the fractionation scheme based on Hedley et al. [53] and described in detail by Tiessen and Moir [54]. This method uses various extractants to separate the soil P into different pools varying in their solubility and bioavailability. In the sequential extraction procedure, 0.5 g air-dried soil was first shaken with deionized water and two strips of anion exchange resin membrane followed by a sequential extraction with 0.5 M  $\text{NaHCO}_3$

**Table 1** Basic characteristics of the arid soil collected from a long-term organically managed peach orchard and used for the current study

Properties	Value
SOC (%)	1.03
Total N ( $\text{mg kg}^{-1}$ )	910
Total P ( $\text{mg kg}^{-1}$ )	5577.3
Available P ( $\text{mg kg}^{-1}$ )	74.1
$\text{NH}_4\text{-N}$ ( $\text{mg kg}^{-1}$ )	8.41
$\text{NO}_3\text{-N}$ ( $\text{mg kg}^{-1}$ )	19.61
pH	7.58
EC ( $\text{ds m}^{-1}$ )	4.61
$\text{CaCO}_3$ (%)	4.0
Sand (%)	79.2
Silt (%)	8.8
Clay (%)	12.0

SOC: soil organic carbon; EC: electrical conductivity;  $\text{CaCO}_3$ : calcium carbonate

**Table 2** Basic characteristics of the biochars used in the study

Biochar		pH	EC (ds m <sup>-1</sup> )	Total C (%)	Total N (%)	Total P (%)	BET surface area (m <sup>2</sup> g <sup>-1</sup> )
Feedstock	Pyrolysis temperature (°C)						
Sewage sludge	300	6.72	1.07	33.04	4.37	1.09	0.59
Sewage sludge	500	8.35	0.80	20.59	2.26	1.80	11.13
Sewage sludge	700	11.28	0.95	17.84	0.99	1.94	12.17
Olive mill pomace	300	8.71	3.25	65.8	1.66	0.28	2.60
Olive mill pomace	500	9.56	6.91	68.41	1.21	0.44	4.32
Olive mill pomace	700	9.63	7.63	65.9	1.24	0.50	9.28
Chicken manure	300	7.30	7.97	50.39	8.48	1.93	3.54
Chicken manure	500	10.37	12.60	48.44	3.90	3.36	5.77
Date palm residues	300	6.84	7.27	55.31	0.49	0.05	3.60
Date palm residues	500	8.62	6.76	66.54	0.39	0.06	142.94
Date palm residues	700	10.56	18.48	67.16	0.51	0.12	255.08

EC electrical conductivity, BET Brunauer–Emmett–Teller surface area

at a pH of 8.5, 0.1 M NaOH and 1 M HCl. The final step included a complete digestion in H<sub>2</sub>SO<sub>4</sub>–H<sub>2</sub>O<sub>2</sub> to obtain Residual-P. The suspension for each extraction step was shaken for 16 h followed by a centrifugation for 10 min at 10,000×g and then filtered through a 0.45-μm filter. The inorganic P (Pi) recovered by resin strip (Resin-Pi) and in each extract (NaHCO<sub>3</sub>-Pi, NaOH-Pi, HCl-Pi) and the Residual-P in H<sub>2</sub>SO<sub>4</sub>–H<sub>2</sub>O<sub>2</sub> digest were measured colorimetrically based on Murphy and Riley method [50] as described by Tiessen and Moir [54]. The organic P (Po) in NaHCO<sub>3</sub> and NaOH extracts was determined by analyzing these extracts for total P (Pt) using ICP-MS, and then, the organic P in NaHCO<sub>3</sub>-Po and NaOH-Po was calculated by subtracting Pi from Pt. The Resin-Pi is defined as readily bioavailable inorganic P. The NaHCO<sub>3</sub>-P mainly represents the easily mineralizable Po and exchangeable Pi that is adsorbed to soil minerals. The NaOH-P is moderately available P that is bound to Al- and Fe mineral (Pi) and humic acid (Po). The HCl-Pi is non-labile P form that is associated with Ca and Mg minerals and considered not plant available, whereas the Residual-P is a stable and recalcitrant P form that is strongly bound to P minerals [54].

To better explain the impact of biochar on the rate of change in plant available P, P availability response (PAR) based on the increase in readily plant available P (labile fraction) was calculated according to Teng et al. [55]

$$\text{PAR} = \frac{\text{AP in biochar treated soil} - \text{AP in the control}}{\text{AP in the control}} \times 100.$$

In the current study, Resin-Pi and NaHCO<sub>3</sub>-P fractions were summed and used as the total content of available P

as both fractions were defined as labile P and considered plant available [54].

### Statistical analysis

The effects of biochar feedstock sources (BFS), pyrolysis temperature (PT), and their interaction on soil P fractions were tested using two-way ANOVA method. Significance level of treatment effects was set at  $P \leq 0.05$  at which treatments means were separated as well using Student–Newman–Keuls (SNK) test.

## Results

### Effect on labile P pool

Resin-Pi, the freely exchangeable P, was significantly affected by biochar feedstock type (BFS), but not by the pyrolysis temperature (PT) or BFS and PT interaction (Table 3). The soil content of Resin-Pi ranged from 32.4 to 107.8 mg P kg<sup>-1</sup>, with the highest values being observed in CMB5 and CMB3 treatments followed by SSB5 and SSB7 treatments (Fig. 1A). These treatments significantly increased resin-P content relative to the control. Averaged across the pyrolysis temperatures, the greatest amount of Resin-Pi was found in CMB followed by SSB treatment, both of which were significantly higher than OPB and DRB treatments (Fig. 2A).

The BFS and its interaction with PT had a significant effect on NaHCO<sub>3</sub>-Pi fraction (Table 3). All of the treatments showed significantly higher content of NaHCO<sub>3</sub>-Pi than the control, with the exception of date palm residue-derived biochar treatments (Fig. 1B). Compared to Resin-Pi fraction, the treatment effects were more pronounced and provided higher concentrations of NaHCO<sub>3</sub>-Pi, ranging from 67.7 to 289.2 mg kg<sup>-1</sup>, with the greatest amount being observed in SSB5 and CMB3 treatments (Fig. 1B).

**Table 3** Two-way ANOVA results ( $P > F$ ) of the effects of biochar feedstock sources, pyrolysis temperatures, and their interactions on soil P fractions

Source of variation	Resin-P <sub>i</sub>	NaHCO <sub>3</sub> -P <sub>i</sub>	NaHCO <sub>3</sub> -P <sub>o</sub>	NaOH-P <sub>i</sub>	NaOH-P <sub>o</sub>	HCl-P <sub>i</sub>	Residual-P
Biochar feedstock sources (BFS)	***	***	***	***	***	*	**
Pyrolysis temperature (PT)	NS	NS	***	***	***	*	**
BFS × PT	NS	***	***	***	***	*	**

NS not significant

\*\*\* $P < 0.001$ \*\* $P < 0.01$ \* $P < 0.05$ 

The organic P content in NaHCO<sub>3</sub> extraction was significantly affected by the BFS, PT, and their interaction (Table 3). However, the concentrations of this fraction in most treatments were much lower than the inorganic P in the same extraction, ranging from 54.6 to 270.7 mg kg<sup>-1</sup> (Fig. 1C). This fraction was only increased in CMB5 treatment compared to the control or any other treatment, but significantly decreased in SSB3, SSB5, SSB7, OPB3, OPB5, OPB7, and CMB3 treatments (Fig. 1C). The DR feedstock showed the greatest amount of NaHCO<sub>3</sub>-Po, regardless of PT, yet was no different than the control. In general, the labile P pool of Resin-Pi and NaHCO<sub>3</sub>-P (NaHCO<sub>3</sub>-Pi and NaHCO<sub>3</sub>-Po) represented a small percentage of total P, ranging from 4.0% in the control to 7.9% in the CMB5 treatment (Fig. 3).

#### Effect on moderately labile P pool

The BFS, PT, and their interaction had a significant effect on NaOH-Pi and NaOH-Po content in soil (Table 3). The NaOH-Pi content was higher than NaOH-Po in any given treatment, and the SSB3 and SSB5 treatments showed significantly higher content than the control treatment for both fractions, whereas the NaOH-Pi fraction content was only significantly higher in CMB3 and CMB5 treatments compared to the control (Fig. 4a, b). The NaOH-P pool (both inorganic and organic) represented a very small proportion of total P, ranging from 1.6 to 3.9% (Fig. 3).

#### Effect on non-labile P pool

Inorganic P extracted with HCl (HCl-Pi) was significantly affected by BFS, PT, and their interactions (Table 3). The content of HCl-Pi fraction was significantly reduced in SSB3, OPB3, OPB5, and CMB3 treatments compared to the control (Fig. 5a). The HCl-Pi was the dominant P fraction in all treatments, ranging from 65 to 82% of total P (Fig. 3). The BFS, PT, and their interaction had a significant impact on soil content of Residual-P (Table 3). However, treatments' comparison including the control showed that it was only the CMB5 treatment that was

significantly higher than any other treatment (Fig. 5b). None of the other treatments showed Residual-P content significantly different from that in the control (Fig. 5b). The Residual-P fraction represented a small percentage of soil total P in this study, ranging from 4.5 to 6.0% of total P (Fig. 3).

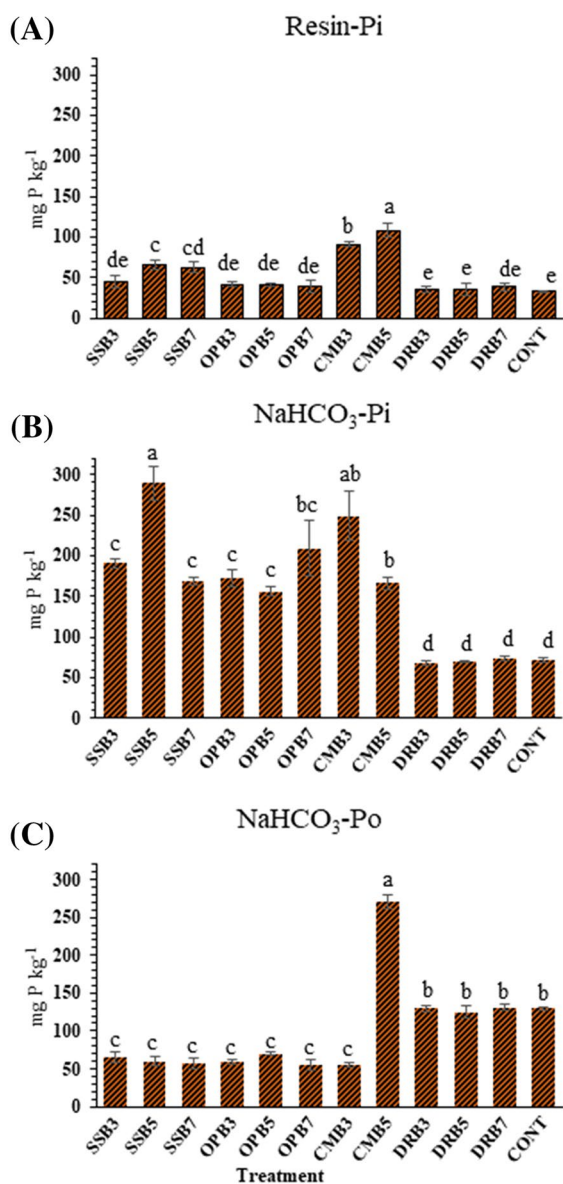
#### Effect of biochar on P availability response rate

The rate of P availability response (PAR) was significantly influenced by biochar addition, with the SSB5 and CMB3 being the most effective treatments in increasing the PAR (Fig. 6). At the end of incubation, the SSB5 and CMB3 treatments were found to increase PAR by 240 and 226%, respectively. With the exception of date palm residues biochar treatments where the PAR value was very low and near zero in DRB3 treatment, the PAR in all treatments ranged from 89 to 240% (Fig. 6). Averaged over the pyrolysis temperatures, the B treatments in order of descending PAR were CMB > SSB > OPB > DRB.

#### Discussion

It has widely been documented that the key characteristics of biochar are largely influenced by the feedstock type and production temperatures [19–21]. Accordingly, these characteristics largely determine the effectiveness of biochar use and functions in soil. In general, the basic characteristics of the biochar used in the current study were clearly influenced by the feedstock type and pyrolysis temperature, and this is in line with the previous findings [27, 56–58]. The pH, EC, TN, TP, and BET surface area increased with increasing the pyrolysis temperature and were generally within the range observed in the other findings [57, 59]. In contrast, the total C in chicken manure and sewage sludge-derived biochar decreased with increasing the pyrolysis temperature, and this is in agreement with previously reported findings on similar materials [56, 57, 60], attributing this decline to the higher content of soluble C being rapidly lost with increasing pyrolysis temperature. Consequently, it was shown in the current study that the effects of biochar on



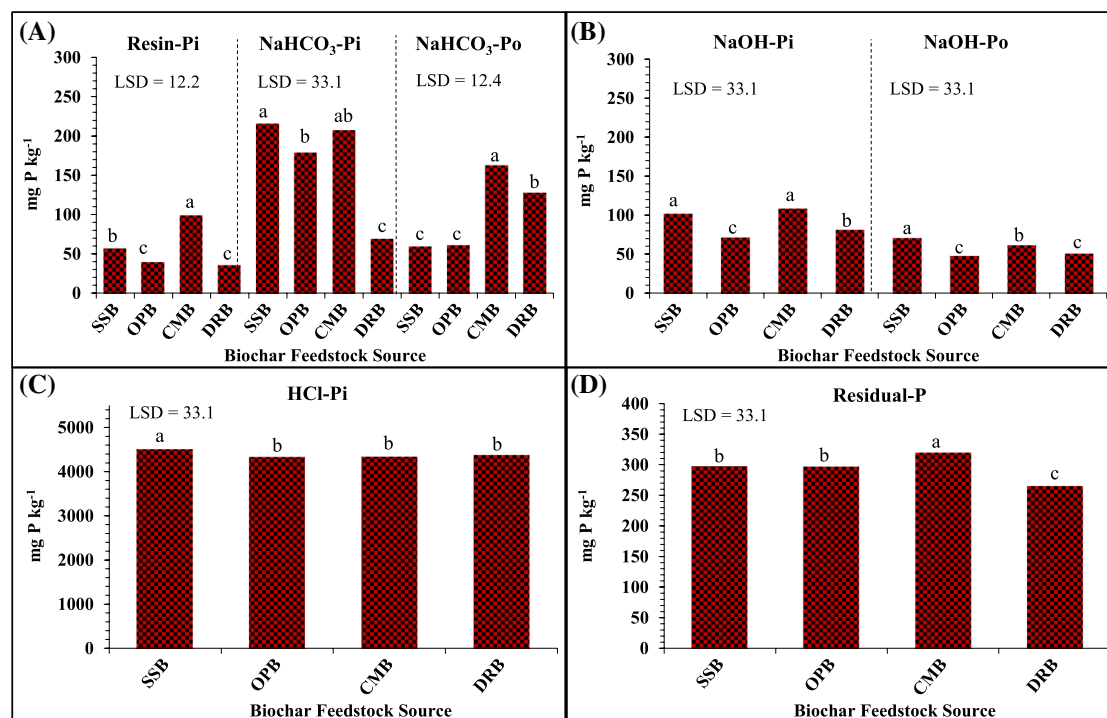


**Fig. 1** Effects of biochars derived from sewage sludge (SSB), olive pomace (OPB), chicken manure (CMB), and date palm residues (DRB) produced at 300 (3), 500 (5), or 700 (7) °C in comparison to a control treatment (CONT) on soil labile inorganic (Pi) and organic P (Po) fractions: **A** Resin-Pi, **B** NaHCO<sub>3</sub>-Pi, and **C** NaHCO<sub>3</sub>-Po. For a P fraction, treatments sharing the same letter are considered not significantly different based on Student–Newman–Keuls (SNK) test–LSD test at  $P < 0.05$ . Errors bars represent standard error of treatment mean ( $n = 3$ )

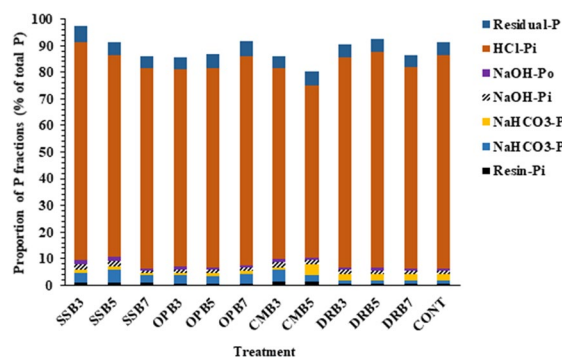
the soil P fractions and availability were variable and, to a large extent, influenced by the type of feedstock from which the biochar was produced and also the pyrolysis temperature.

Biochar treatments had the most pronounced effect in the labile P pool (Resin-Pi and NaHCO<sub>3</sub>-P). The sewage sludge and chicken manure biochars pyrolyzed at high temperatures significantly enriched the Resin-Pi pool, whereas all biochar treatments except the date residue-derived biochar enriched the NaHCO<sub>3</sub>-Pi fraction. The sewage sludge and chicken manure biochars contained much higher total P, resulting in much higher total P being added compared to olive pomace or date residue biochars, since all treatments were applied to soil based on equal mass. This may in part explain the significant increase in the labile P pool observed with the biochars derived from sewage sludge and chicken manure feedstock. This is in line with what have previously been demonstrated where animal- and sludge-based biochar were found to have much higher content of total and available P than lignocellulosic-based biochar [37, 56, 61–63]. Previous research also found that plant available P was significantly correlated to total P added to soil amended with various types of biochar [64]. In general, the soil content of NaHCO<sub>3</sub>-Pi fraction in the current study was higher in biochars produced at pyrolysis temperatures less than 700 °C. This is also demonstrated in other studies where the available P content in biochar decreased with increasing production temperature [23, 24, 27]. However, the available P fraction was found to only represent a small percentage of total P in biochar [37, 42, 56, 61]. Unlike Resin-Pi and NaHCO<sub>3</sub>-Pi fractions, the NaHCO<sub>3</sub>-Po fraction was decreased in most biochar treatments (SSB3, SSB5, SSB7, OPB3, OPB5, OPB7, and CMB3), suggesting that these particular types of biochars may have stimulated the conversion of soil organic P in NaHCO<sub>3</sub>-P fraction into other labile fractions [65].

The P fraction extracted with 0.1 M NaOH (NaOH-P) consists of inorganic P (NaOH-Pi) generally bound to Al and Fe and organic P (NaOH-Po) form associated with labile fraction of organic matter, and it is categorized as moderately labile P [53, 66]. The NaOH-P is usually found to be the dominant P fraction in acid soils [42, 66], and its response to biochar addition was more evident in acid soils due to the presence of freely exchangeable Al and Fe [42]. In the current study, the content of the total NaOH-P (both inorganic and organic) fraction was low, representing only a small percentage of total P (1.6 to 3.8%), and this is in agreement with the other studies where NaOH extractable P represented small portion of total P in calcareous soils [22, 25]. The significant increase in NaOH-Pi in the current study was limited to soil treated with biochar derived from sewage sludge and chicken manure. This can be related to this type of biochar having higher inherent Al and Fe content compared to plant-based biochar [28], resulting in Al- and Fe-P being formed in soil after biochar addition. Another



**Fig. 2** Effects of biochars derived from four different sources: sewage sludge (SSB), olive pomace (OPB), chicken manure (CMB), and date palm residues (DRB) averaged over the pyrolysis temperatures on soil inorganic (Pi) and organic P (Po) P fractions: **A** Resin-Pi, NaHCO<sub>3</sub>-Pi, and NaHCO<sub>3</sub>-Po; **B** NaOH-Pi and NaOH-Po; **C** HCl-Pi; **D** residual-P. For a P fraction, biochar feedstock sources sharing the same letter are considered not significantly different based on Student–Newman–Keuls (SNK) test at  $P < 0.05$ , LSD test ( $P < 0.05$ ). LSD least significant difference value

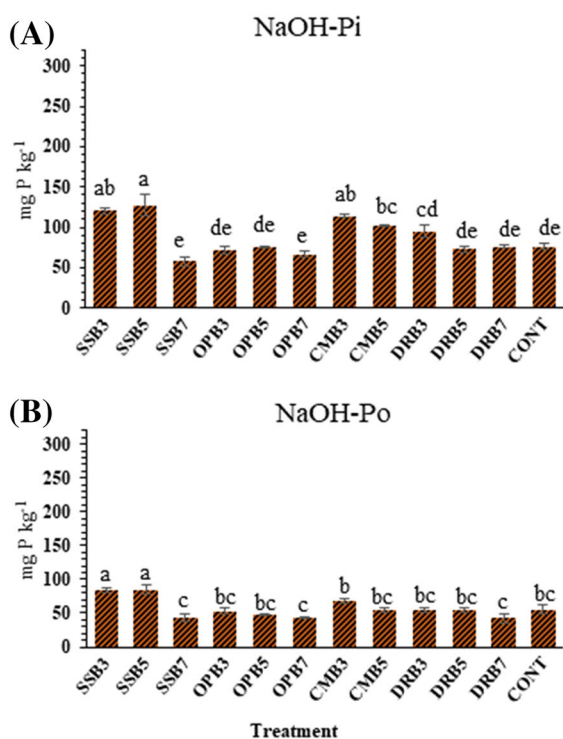


**Fig. 3** Soil P fraction percentage of soil total P in soil treated with biochars derived from sewage sludge (SSB), olive pomace (OPB), chicken manure (CMB), and date palm residues (DRB) produced at 300 (3), 500 (5), or 700 (7) in comparison to untreated soil (CONT)

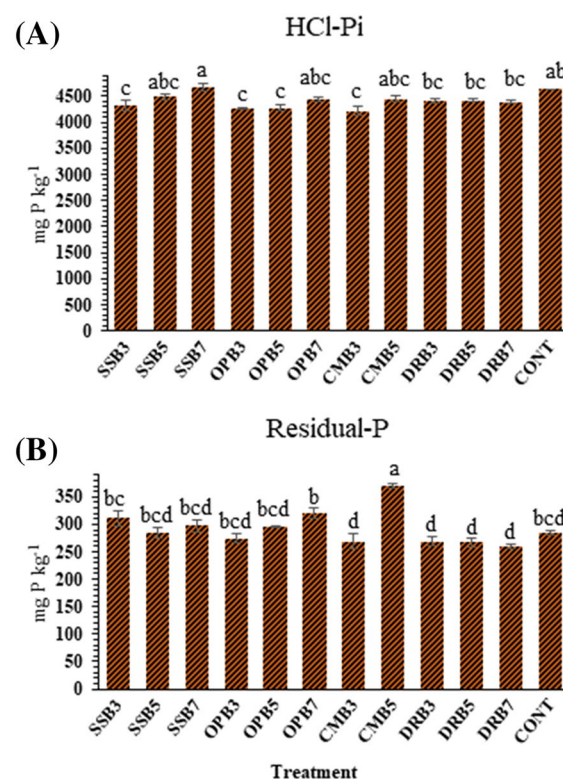
possible explanation is that these specific biochars have the highest total P content, and possibly, they also contain a higher amount of intrinsic Al- and Fe-bound P species that may have directly increased soil Na-OH-Pi fraction. A previous study on alkaline soils also found increases in Al- and Fe-P fractions' content [25]; however,

another study found no significant change in this fraction following addition of biochar to three alkaline soils varying in their texture and CaCO<sub>3</sub> content [67]. The NaOH-Po content remained much lower in all treatments compared to the NaOH-Pi fraction, and it only increased in soil treated with sewage sludge-derived biochar at the low temperature. The lack of increases in NaOH-Po in the current study with most of the biochar treatments is likely related to the low content of organic P added with these biochars [63].

The HCl-Pi and Residual-P fractions are generally the dominant P fractions in alkaline and calcareous soils [23, 25, 66]. The HCl-Pi represents mainly Ca-associated P compounds and is considered non-labile P that is sparingly available for plant uptake, whereas the Residual-P constitutes the most stable and recalcitrant P [53, 66]. The HCl-Pi was also found to be the dominant P fraction in the current study, representing across all the treatments 76% of total P which is much higher than that in Residual-P fraction that represented approximately 5% of total P. Most of the biochar types used in the current study made no significant change in HCl-Pi content, with the exception of sewage sludge and chicken manure produced at 300 °C and olive

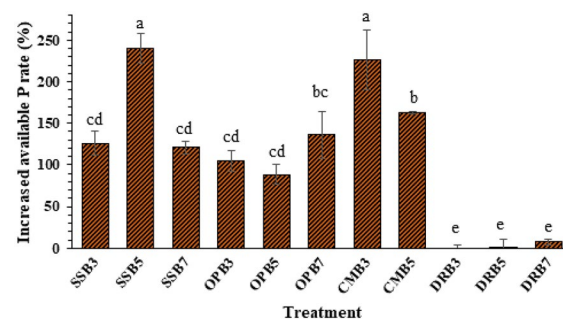


**Fig. 4** Effects of biochars derived from sewage sludge (SSB), olive pomace (OPB), chicken manure (CMB), and date palm residues (DRB) produced at 300 (3), 500 (5), or 700 (7) °C in comparison to a control treatment (CONT) on soil moderately labile inorganic (Pi) and organic P (Po)P fractions: **A** NaOH-Pi and **B** NaOH-Po. For a P fraction, treatments sharing the same letter are considered not significantly different based on Student–Newman–Keuls (SNK) test–LSD test (at  $P < 0.05$ ). Errors bars represent standard error of treatment mean ( $n = 3$ )



**Fig. 5** Effects of biochars derived from sewage sludge (SSB), olive pomace (OPB), chicken manure (CMB), and date palm residues (DRB) produced at 300 (3), 500 (5), or 700 (7) °C in comparison to a control treatment (CONT) on soil non-labile P fractions: **A** HCl-Pi, and **B** Residual-P. For a P fraction, treatments sharing the same letter are considered not significantly different based on Student–Newman–Keuls (SNK) test–LSD test (at  $P < 0.05$ ). Errors bars represent standard error of treatment mean ( $n = 3$ )

pomace produced at 300 and 500 °C treatments that significantly reduced HCl-Pi content compared to the control. This is generally consistent with the positive impact of these treatments on the labile P pool, especially the NaHCO<sub>3</sub>-Pi fraction, indicating that these biochars may have stimulated the release of P through organic matter decomposition and dissolution of non-labile Ca-associated P forms to labile P forms [55]. Xu et al. [26] reported a slight decrease in the concentration of Ca-P fraction extracted with 0.5 M H<sub>2</sub>SO<sub>4</sub> in alkaline soil treated with 1% biochar, but almost no changes in higher rates of biochar treatments. These authors also found biochar to decrease P sorption and increase P desorption in alkaline soil where the opposite results were found with acid soils. Other studies found limited biochar effects on HCl-Pi content in alkaline soils [30, 65]. In the current study, biochar had no significant effect on Residual-P content, with the exception of chicken manure produced at 500 °C treatment which tended to increase Residual-P content. Similarly,



**Fig. 6** Phosphorus availability response (PAR) rate in soil treated with biochars derived from sewage sludge (SSB), olive pomace (OPB), chicken manure (CMB), and date palm residues (DRB) produced at 300 (3), 500 (5), or 700 (7) °C. Treatments sharing the same letter are considered not significantly different based on Student–Newman–Keuls (SNK) test–LSD test (at  $P < 0.05$ )



Mukherjee et al. [30] found that wheat straw biochar produced at various temperatures had no significant impact on Residual-P content in alkaline soil.

## Conclusion

The results of the current study indicate that biochar can be a possible option to enhance soil legacy P mobility and therefore increase its bioavailability. However, P fractions response to biochar addition varied among biochar type, with those produced from sewage sludge and chicken manure at low pyrolysis temperatures generally showing consistent effects across most of the P fractions. Irrespective of pyrolysis temperature, both SSB and CMB were the most effective in enhancing soil P availability through increasing the content of Resin-Pi by 77 and 206% and  $\text{NaHCO}_3$ -Pi by 200 and 188%, respectively. This is probably related to the high content of P in these particular biochars. With the exception of date palm residues' biochar (DRB), most of biochar treatments decreased  $\text{NaHCO}_3$  extractable organic P fraction, possibly related to the transformation of this fraction into other labile P forms. The SSB, CMB, and OPB produced at low temperature reduced HCl-Pi content, indicating that these biochars may have stimulated the organic matter decomposition and thereby dissolution of non-labile Ca-associated P forms to labile P forms.

The soil used in the current study contains a large amount of total P and also available P, and this indicates that soil sorbing sites may be saturated with P, minimizing this soil's fixing capacity, and making added P with biochar become more available in soil solution. The findings of this study may not be generalized in case of other alkaline soils with lower legacy P content. Therefore, further studies evaluating the effectiveness of biochar use in soils varying in their contents of initial P need to be carried out. Furthermore, such studies in the presence of plants can provide more information about the potential use of biochar in enhancing the availability of soil legacy P, as plants' interaction with soil constituents may influence soil P transformations response to biochar addition.

## Abbreviations

SS: Sewage sludge; OP: Olive mill pomace; CM: Chicken manure; DR: Date palm residues; PAR: P availability response; BFS: Biochar feedstock source; PT: Pyrolysis temperature.

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## Authors' contributions

Conceptualization: KA, MA, and NZ; funding acquisition: KA and NZ; methodology: KA and MA; investigation: KA; writing—original draft preparation: KA; writing—review and editing: MA and NZ. All authors have agreed to the

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## Availability of data and materials

All data obtained from the current study are available from the corresponding author on a reasonable request.

## Declarations

### Ethics approval and consent to participate

Not applicable.

### Consent for publication

Not applicable.

### Competing interests

The authors declare no conflict of interest.

## Author details

<sup>1</sup>Department of Soil Science, King Saud University, P.O. Box 2460, Riyadh 11451, Saudi Arabia. <sup>2</sup>Department of Soil Science, University of Saskatchewan, Saskatoon, 51 Campus Drive, Saskatoon, SK S7N 5A8, Canada. <sup>3</sup>Agriculture and Agri-Food Canada, Quebec Research and Development Centre, 2560 Hochelaga Blvd., Québec, QC G1V 2J3, Canada.

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