Interaction of phosphorus chemical fertilizer and biochar application on wheat plant

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ABSTRACT Phosphorus (P) is one of the most important elements required for the physiological and biochemical functions of plants. It is well known that there are many limitations to the uptake of phosphorus from soil. In this study, the interaction between different doses of chemical P fertilizer and biochar application on wheat plants was investigated. In this greenhouse experiment, P fertility was studied in calcareous soil with a high pH in southern Türkiye. Wheat plants were grown for seven weeks with 3 biochar doses (0-20-40 tonnes ha^{-1}) and 4 P fertilizer applications (0, 50, 100, and 200 kg P_2O_5 ha^{-1}). Dry weight (DW), macro (nitrogen (N), P, potassium (K), magnesium (Mg), and micronutrient (iron (Fe), zinc (Zn), copper (Cu), and manganese (Mn)) concentrations were evaluated in post-harvest plant samples. The efficiency of P utilization (agronomic, physiological, and apparent recovery) was also determined. The dry matter yield increased significantly with increasing biochar dose and P application. The highest agronomic efficiency and apparent recovery efficiency of wheat plants were found to be 13.16 mg^{-1} and 12.52 % when BOP50 was applied. Increases in N, K, Zn, and Mn concentrations in wheat plants were determined depending on biochar and P dose applications.

KEYWORDS Phosphorus; Biochar; Wheat; Nutrient concentration; Phosphorus efficiency

In Türkiye, wheat (*Triticum aestivum* L.) is the most commonly grown cereal crop, with an average yield of 2566 kg ha^{-1} over 6.646,420 ha (TUIK, 2022). Soils in Türkiye (especially in the Mediterranean region) are generally calcareous, high in pH, low in organic matter, and low in P availability (Ortas et al., 2002). Due to P uptake problems, intensive P fertilization is applied in these regions. Long-term P fertilization has shown that P in the soil changes into a non-absorbable form (van der Bom et al., 2019). Türkiye is dependent on foreign sources of phosphorus raw materials, and P fertilizer prices are high. Approximately 29 % of agricultural soils in Türkiye are P-deficient (Eyupoglu, 1999). Since P is an important macronutrient, the importance of P fertilization for wheat nutrition is known worldwide (Batten, 1992).

P is an essential element for healthy plant growth and agricultural productivity (Stewart et al., 2005). Phosphorus is responsible for many processes, such as plant growth and development, energy transfer, protein metabolism (Fageria, 2009), promotion of shoot growth (Fageria, 2007; Fageria and Santos, 2008), and improvement of root development. With P deficiency, chlorophyll formation slows down, and photosynthetic efficiency decreases (Marschner, 1995). Many studies have shown that many factors such as clay, calcium carbonate and iron oxides affect the availability of P in the soil (Ryan et al., 1985); for this reason, 90 % of the phosphorus applied to the soil cannot be taken up by the plants (Rodríguez and Fraga, 1999; Gyaneshwar et al., 2002).

The major drawback of phosphorus is its low use efficiency (UE) in calcareous soils. Inorganic P applied to such soils is immediately precipitated with Ca^{+2} and Mg^{+2} (Pradhan and Sukla, 2009; Aziz et al., 2016) and turns into a form that is difficult to take up, affecting productivity. In addition, many mechanisms determine P efficiency in plants, such as root morphology, the rhizosphere (Batten, 1992), and mycorrhiza (Akpinar et al., 2019). Inorganic P also has a significant impact on productivity and its effective use is of great importance. Fertilizer use efficiency describes the ability of a plant to take up and use nutrients to produce biomass and grain (Gourley et al., 1993). Fertilizer use efficiency depends on soil, biological, plant, nutrient management, agronomic, and climatic factors (Fageria, 1992). Phosphorus efficiency can result from the ability of plants to take up or use P for dry matter production (Blair, 1993).

Biochar is a charcoal-like product of high-temperature pyrolysis of biomass in the absence of oxygen and can be used as a soil conditioner to improve crop productivity and soil health (Lehmann and Joseph, 2009). Biochar has a large surface area (Chun et al., 2004) and a high cation exchange capacity (Liang et al., 2006), which is the most important reason for increasing soil fertility and enhancing soil retention capacity and especially the uptake of N and P (DeLuca et al., 2009; Major et al., 2009). In addition, biochar reduces soil bulk density and improves microbial structure owing to its highly porous structure and high carbon content (Xiao et al., 2017; Zhao et al., 2018). Biochar contains high amounts of carbon, nitrogen, phosphorus, magnesium, potassium, and calcium (Wang et al., 2014). The impact of biochar application on plants and soils is influenced by the type of crops grown, farming systems, plant species, climate (Gundale and DeLuca, 2006; Unger

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et al., 2011) and fertilization (Haefele et al., 2011). The large surface area of biochar provides a suitable habitat for soil microorganisms (Lehmann et al., 2011). The application of biochar to the soil has been found to increase the specific root length of the wheat plant (Olmo et al., 2015). The application of biochar increases the assimilation rate of the roots and causes an increase in root biomass (Hynšt et al., 2023). Biochar application has been reported to increase β-glucosidase and leucine aminopeptidase activities in silty soils, while suppression was noted in sandy soils (Bailey et al., 2011). It is known that pyrolysis temperature has an impact on the properties of biochar (Cantrell et al., 2012; Xu et al., 2016). The pyrolysis temperature at which biochar is produced can determine its acidic or alkaline character < 400 °C usually acidic > 600 °C produces alkaline biochar (Bista et al., 2019). Farrell et al. (2013) reported that biochar produced at 550 °C had low P content. Biochar application to soils allows more P to be retained in the soil (Glaser et al., 2002), thereby increasing P availability and microbiological activity (Xu et al., 2014; Zhai et al., 2014). P uptake in soils with low fertility has increased through the application of biochar (Biederman and Harpole, 2012; Subedi et al., 2016). On the other hand, Jeffery et al. (2011) reported in their study that biochar can prevent the uptake of nutritional elements such as manganese, iron, boron and phosphorus due to its high pH. The application of biochar to the soil can influence P dynamics by changing the pH of the soil (Xu et al., 2014). Chemical interactions begin six months after biochar is applied to the soil (Joseph et al., 2021). In addition to increasing soil fertility in the long term, biochar can also store carbon and nitrogen (Verheijen et al., 2019).

Global agricultural production is affected by the limiting effect of P, and it is estimated that global P resources will be very low by 2050 (Vance et al., 2003). Therefore, further studies are required to increase the efficiency of P use. The effect of organic matter such as biochar on the uptake of P and other nutrients into the plant body needs to be understood and well-studied to maximize the efficiency of its use and reduce production costs. Little is known about the interactions between P and biochar, particularly in wheat.

Biochar is believed to have a positive effect on P productivity due to its large surface area, cation exchange capacity and soil water holding capacity. The aim of this study was to use biochar in combination with phosphate fertilizers as an alternative technique to increase the efficiency of P fertilizers and to determine its effect on wheat plant growth.

1. Methods

1.1 Experimental design and applications

The study was conducted under greenhouse conditions at Osmaniye Korkut Ata University with 3 replicates between 14/03/2022-28/04/2022. Wheat (Adana 99 variety) was used as the test plant in the experiment. Peanut biochar used in the experiment was obtained by pyrolysis at 450 °C for 5 h without oxygen. Biochar was applied to the pots at a rate of 0-20-40 tonnes ha^{-1}. Triple superphosphate (TSP 43 % P_2O_5) was fertilized as a P source at a rate of 0-50-100-200 kg ha^{-1} TSP. The soils were air-dried, sieved to < 2 mm, and filled into 2.5 kg pots. At the beginning of the experiment, 5 seeds were sown per pot. After germination, three plants were left in each pot after thinning. During the experiment, the plants were irrigated with deionized water at the field capacity.

Table 1: Some properties of the used materials.

Properties	Unit	Soil	Biochar
pH	(1:1 H_2O)	7.4	8.7
Texture		CL	–
$CaCO_3$	%	36.7	–
Org. matter	%	1.29	–
Salt	%	0.001	–
C	%	–	42.3
N (Total)	%	0.09	0.61
P	kg ha^{-1}-%	18.2 (kg ha^{-1})	0.21
K	kg ha^{-1}-%	33.1 (kg ha^{-1})	0.41
Ca	%	0.08	2.27
Mg	%	0.05	0.11
Zn	mg kg^{-1}	0.27	19
Fe	mg kg^{-1}	1.11	447
Cu	mg kg^{-1}	0.41	1.4
Mn	mg kg^{-1}	1.51	88

1.2 Soil sampling and analysis

The soil used for this greenhouse experiment was taken from a depth of 0-30 cm in the research area of Osmaniye Korkuta Ata University, Kadirli Faculty of Applied Sciences. In addition to the P content, physical and chemical analyses of the soil samples were performed. The soils were clay loam textured with high calcium carbonate content (36.7 % $CaCO_3$), low organic matter (1.29 %), and pH of 7.4 (Table 1).

After harvesting, the plants were washed with distilled water in the laboratory and dried in an oven at 70 °C to constant weight. The concentrations of N, P, K, Mg, Fe, Zn, Mn and Cu were then determined in the ground plant samples. The P concentration was analysed according to Murphy and Riley (1962). N analysis was carried out according to the Kjeldahl distillation method recommended by Bremner (1965). The concentration of K, Mg, Ca, Fe, Cu, Zn and Mn was analysed according to Kacar and Inal (2010). P uptake per pot was calculated by multiplying the P concentration in the green parts by the dry weight.

1.3 P use efficiencies and statistical analysis

The use efficiency of P fertilizer and doses, physiological use efficiency (PE), agronomic use efficiency (AE), and apparent recovery efficiency (ARE) were calculated according to (Noor et al., 2017). All data were subjected to statistical post-hoc and Tukey test analyses using SPSS 20.0.

2. Results and discussion

2.1 Dry weight of wheat plants

When the effects of different doses of biochar and P fertilizer (P_2O_5) on the dry weight of wheat plants were studied, the application of biochar and P fertilizer increased the dry weight of wheat plants (Figure 1). The increase in biochar and P dosage generally resulted in an increase in the dry weight of wheat plants. The highest dry weight value was recorded at 5.23 g with B20P100 dosage, whereas the lowest value was recorded at 2.87 g with BOPO application. While the highest dry weight values were observed with the B20 and B40 dosages, higher dry weight values were obtained with the P100 and P200 dosages. Hamdani and Adil (2017) found that the application of biochar with different fertilizer rates significantly increased the growth and yield of wheat. Similarly, Blackwell et al. (2010) found that a lower fertilizer application with biochar increased wheat yield Korkmaz et al. (2009) reached the maximum DW at a P fertilization of 100 mg kg^{-1} P in different wheat genotypes, but it was found to start decreasing at higher levels.

2.2 P use efficiencies

Table 2 shows the results of the study comparing the effects of biochar and P fertilizer application (TSP) on fertilizer use efficiency in wheat crops. The data were analyzed in terms of physiological use efficiency (PE), agronomic use efficiency (AE), and apparent recovery efficiency (ARE) of biochar and P_2O_5 doses. An increase in PE was observed when the P level increased with biochar application. Although there was no statistical difference between treatments, the highest PE was found to be 1.93 mg^{-1} in treatment B20P100. When AE and ARE were analyzed, it was found that the values decreased as a function of biochar and P dose. The highest AE (13.16 mg^{-1} and the highest ARE (12.52 %) were obtained when the B0P50 dose was applied. In a study conducted by Noor et al. (2017), it was found that reduction of impregnated phosphate fertilizers in maize plants increased the agronomic and physiological efficiency of P, but reduced the efficiency of apparent P recovery. The P use efficiency was 465 kg kg^{-1} for upland rice, 492 kg kg^{-1} for maize, 229 kg^{-1} for dry beans, and 280 kg^{-1} for soybean (Fageria et al., 2013). Although increasing P doses significantly reduced the agronomic efficiency of fertilizer application in wheat, the highest agronomic efficiency was achieved with 50 kg ha^{-1} P_2O_5 application (Akpinar and Ortas, 2023). There was a statistically significant interaction between biochar and P fertilizer factors. This interaction was statistically significant for AE and ARE. Biochar alone had a significant effect on the PE, AE, and ARE. P fertilizer had a significant effect on AE and ARE, but had no effect on PE ($P < 0.065$). Mengel (1992) found that the addition of nutrients in the form of fertilizers leads to a decrease in nutrient-use efficiency. Oluleye and Akinrinde (2010) reported that increasing the nutrient dose causes a decrease in the P use efficiency of plants.

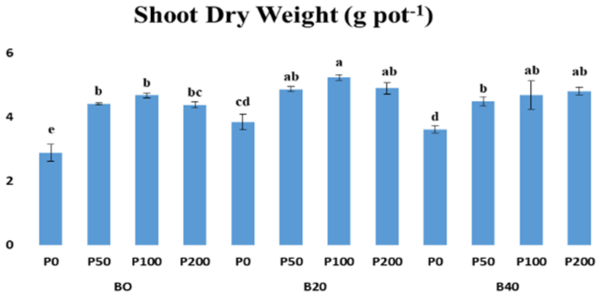

Figure 1: Effect of biochar and P applications on dry weight.

2.3 Macro nutrient concentrations

When the results of the study were evaluated by analyzing the data in terms of macro element concentrations of the wheat plant, the N concentration of the plant generally showed an increasing trend with the increase in biochar and P fertilizer application (Table 3). The highest N concentration was found to be 3.36 % with the application of B40P50. This was followed by the B40P100 application (3.17 %). According to the ANOVA results, the effects of biochar ($P < 0.001$) and P application ($P < 0.003$) on N concentration were statistically significant. The highest levels of N, P, and K were obtained with reduced fertilizer application with biochar to wheat plants (Hamdan et al., 2017). Phosphorus promotes plant growth and improves plant nutrient uptake, such as N (Deraoui et al., 2014). The K concentration in wheat plants increased as a function of biochar and P fertilizer application. The most effective dose application was determined to be B40P200 dose application at 6.71 %. The biochar dose applied to the plants had an effect on K concentration at $P < 0.001$, whereas the P fertilizer had an effect at $P < 0.059$. The application of biochar to pecan resulted in an increase in nutrients such as Ca, Mg, Zn, Cu and Mn as well as K concentration in the seedlings (Hou et al., 2020). The Mg concentration showed a decreasing trend with increasing biochar and P doses. The most effective dosage was 0.66 % Mg in the B0P0/P50 dosages. The lowest Mg concentration was observed in the B40P200 treatment with 0.21 % Mg. The effects of P and biochar application on plant Mg concentration were statistically significant. However, the BXP interaction had an effect on the Mg concentration at P level < 0.464. Biochar has a positive effect on soil properties by favorably affecting wheat plant growth and increasing soil organic matter, soil pH, and P, K, and S contents (Bista et al., 2019).

2.4 Micro nutrient concentrations

Table 4 shows the effects of different doses of biochar and P fertilizer application on the microelement concentrations of wheat plants. Analysis of Zn concentration showed a decreasing trend with increasing P dose, whereas the effect of biochar application was not significant. The highest Zn concentration was found when B40P100 was applied at 87.9 mg kg^{-1} Zn, and the lowest when the B0P50 dose was applied at 20.4 mg kg^{-1} Zn. The highest Fe concentration was determined at 260.8 mg kg^{-1} Fe

Table 2: Comparison of the fertilizer use efficiency of biochar and P fertilizer (TSP) in wheat under pot conditions.

Biochar	P_2O_5	PE	AE	ARE
		mg mg^{-1}		%
B_0	P_0	–	–	–
	P_{50}	1.05 ±0.13^{a}	13.16 ±2.51^{a}	12.52 ±1.62^{a}
	P_{100}	0.87 ±0.08^{a}	7.70 ±0.82^{bc}	8.88 ±0.16$^{a\text{-}c}$
	P_{200}	0.62 ±0.10^{a}	3.20 ±0.41^{d}	5.21 ±0.20$^{b\text{-}d}$
B_{20}	P_0	–	–	–
	P_{50}	0.84 ±0.34^{a}	8.82 ±2.02^{b}	10.96 ±1.98^{ab}
	P_{100}	1.93 ±0.52^{a}	5.99 ±0.73$^{b\text{-}d}$	3.24 ±0.93^{cd}
	P_{200}	1.86 ±0.86^{a}	2.26 ±0.54^{d}	1.38 ±0.55^{d}
B40	P_0	–	–	–
	P_{50}	0.68 ±0.19^{a}	7.53 ±1.17^{bc}	11.93 ±4.76^{a}
	P_{100}	1.33 ±0.65^{a}	4.59 ±1.59^{cd}	4.24 ±2.64^{cd}
	P_{200}	1.49 ±0.68^{a}	2.56 ±0.09^{d}	2.00 ±0.95^{d}
B		0.021	0.001	0.004
P		0.065	0.001	0.001
BxP		0.096	0.051	0.437

Mean of three replicates and ± is a standard error.

Table 3: Effects of applying biochar and P at different doses on macroelement concentrations of the wheat plant.

Biochar	P_2O_5	N	K	Mg
			%	
B_0	P_0	1.55 ±0.29^{e}	4.78 ±0.32^{b}	0.66 ±0.05^{a}
	P_{50}	1.74 ±0.06^{e}	5.11 ±0.11^{ab}	0.66 ±0.19^{a}
	P_{100}	1.80 ±0.09^{e}	5.62 ±0.62^{ab}	0.57 ±0.08^{ab}
	P_{200}	1.89 ±0.09$^{c\text{-}e}$	4.99 ±0.13^{b}	0.53 ±0.06$^{a\text{-}c}$
B_{20}	P_0	1.86 ±0.22^{de}	5.06 ±0.05^{ab}	0.46 ±0.03$^{a\text{-}e}$
	P_{50}	2.40 ±0.35$^{b\text{-}e}$	5.94 ±0.83^{ab}	0.51 ±0.07$^{a\text{-}d}$
	P_{100}	2.89 ±0.24^{ab}	5.84 ±0.37^{ab}	0.43 ±0.11$^{a\text{-}e}$
	P_{200}	2.68 ±0.29$^{a\text{-}d}$	5.92 ±0.88^{ab}	0.22 ±0.02^{e}
B_{40}	P_0	2.74 ±0.39$^{a\text{-}c}$	5.84 ±0.35^{ab}	0.25 ±0.04$^{c\text{-}e}$
	P_{50}	3.36 ±0.41a	6.23 ±0.91^{ab}	0.31 ±0.19$^{b\text{-}e}$
	P_{100}	3.17 ±0.50^{ab}	6.30 ±0.77^{ab}	0.25 ±0.03^{de}
	P_{200}	2.78 ±0.25^{ab}	6.71 ±0.41^{a}	0.21 ±0.02^{e}
B		0.001	0.001	0.001
P		0.003	0.059	0.005
BxP		0.078	0.729	0.464

Table 4: The effects of biochar and P doses at different dosages on the microelement concentrations of the wheat plant.

Biochar	P_2O_5	Zn	Fe	Cu	Mn
			mg kg^{-1}		
B_0	P_0	44.4 ±3.1^{f}	228.2 ±8.3^{b}	7.2 ±0.2^{b}	55.0 ±1.0^{c}
	P_{50}	20.4 ±4.4^{g}	260.8 ±3.2^{a}	3.4 ±2.5^{b}	64.8 ±3.2^{c}
	P_{100}	77.8 ±6.4$^{a\text{-}c}$	191.2 ±1.8^{c}	28.0 ±5.1^{a}	54.7 ±4.1^{c}
	P_{200}	53.5 ±1.7^{ef}	115.1 ±2.7^{g}	19.4 ±6.9^{a}	60.8 ±6.1^{c}
B_{20}	P_0	75.5 ±6.4$^{b\text{-}d}$	143.2 ±6.2^{ef}	29.0 ±2.8^{a}	79.3 ±2.3^{b}
	P_{50}	71.6 ±5.9$^{b\text{-}d}$	181.7 ±4.6^{c}	31.4 ±4.1^{a}	66.1 ±6.5^{c}
	P_{100}	66.0 ±0.4^{cd}	143.1 ±3.0^{ef}	31.4 ±3.9^{a}	61.2 ±5.4^{c}
	P_{200}	72.8 ±1.3$^{b\text{-}d}$	151.9 ±6.0^{de}	26.8 ±7.0^{a}	80.8 ±5.0^{b}
B_{40}	P_0	63.7 ±4.8^{de}	132.3 ±6.1^{fg}	20.5 ±2.2^{a}	97.1 ±1.8^{a}
	P_{50}	82.3 ±3.8^{ab}	161.4 ±12.6^{d}	23.4 ±2.5^{a}	103.6 ±2.3^{a}
	P_{100}	87.9 ±1.6^{a}	146.3 ±5.4$^{d\text{-}f}$	20.4 ±3.6^{a}	106.4 ±2.7^{a}
	P_{200}	73.2 ±3.2$^{b\text{-}d}$	145.1 ±3.7$^{d\text{-}f}$	25.9 ±3.3^{a}	104.7 ±6.4^{a}
B		0.001	0.001	0.001	0.001
P		0.001	0.001	0.001	0.006
BxP		0.001	0.001	0.001	0.001

in the P50 dose without biochar application. A decrease in the Fe concentration was observed depending on the biochar dose. Biochar applications (BC20 and BC40) increased the Fe content of pecans by 20.79 % and 6.15 %, respectively (Hou et al., 2020). The Cu concentration increased with increasing P and biochar doses. The highest copper concentration was found in treatment B20P50/100 with 31.4 mg kg^{-1} Cu and the lowest in treatment with dose B0P50 with 3.4 mg kg^{-1} Cu. Mn concentrations increased as a function of the biochar dosage. The Mn concentrations varied between 54.7 (B0P100) and 106.4 (B40P100) mg kg^{-1} Mn. The addition of biochar and P fertilizer had significant effects on microelement concentrations ($P < 0.001$). Biochar is a source of many nutrients, and its complex reaction with the soil releases nutrients and makes them available for plant uptake over time (Biederman and Harpole, 2012; Lehmann et al., 2015). In addition, the BxP interaction had a significant effect on microelement concentrations ($P < 0.001$). In conclusion, biochar and P fertilizer application have different effects on microelement concentrations in wheat plants. It can be concluded that the use of biochar and P fertilizer at appropriate doses and combinations can be important for plant nutrition and microelement uptake. Chan et al. (2007) reported that the use of biochar in combination with inorganic fertilizers or organic material increases the efficiency of fertilizers.

3. Conclusions

This study was conducted to determine the P uptake, dry matter, macro and micronutrients, and P use efficiency (agronomic, physiological, and apparent recovery) of wheat plants with increasing P doses and biochar. There was an increase in PE and a decrease in AE and ARE as a function of biochar and P dosage. It was found that the content of dry matter, macronutrients (N and K), and micronutrients (Zn and Mn) in the plant samples taken after harvest increased as a function of P and biochar application.

Phosphorus is one of the nutrients limiting agricultural production in the calcareous soils and high pH soils of the Mediterranean region. Therefore, it is important to understand the interaction of wheat, a widely grown crop in this region, with biochar to reduce crop nutrition, production costs, and environmental impacts. It is expected that these results will be scientifically useful for future analyses with field trials and different biochar applications on different crop species.

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