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Conversion of pruning waste into biochar-based organomineral fertilizer to improve maize yield and phosphorus use efficiency

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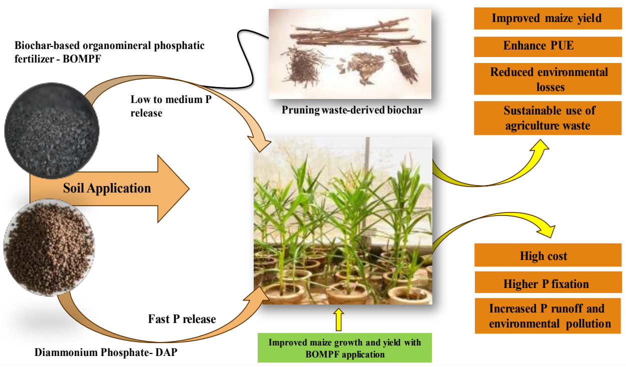
Graphical abstract



Abstract

Open burning and dumping of pruning waste into landfills is detrimental for environmental quality. This study was planned to convert pruning waste into biochar-based organomineral phosphatic fertilizer (BOMPF). A BOMPF with 20% P_2O_5 was prepared by enrichment of diammonium phosphate (DAP) in biochar of pruning waste. Five treatments (3 of BOMPF with 90%, 80% and 70% of recommended phosphorus, 1 of DAP and 1 as control with no phosphorus) were evaluated under pot trail using maize as test crop. Treatments were applied according to complete randomized design (CRD) with three replications of each treatment. Results demonstrated that BOMPF with 90% of the recommended phosphorus (P) significantly increased maize plant height, fresh shoot weight, root length, and fresh root weight by 20%, 76%, 25%, and 53%, respectively, as compared to the control. Likewise, treatment with 90% P as BOMPF also enhanced P contents (63%), P uptake (169%), K contents (34%) and K uptake (122%) and achieved 14.1% higher PUE as compared to DAP. It is concluded that application of P as BOMPF can significantly enhance PUE, maize growth and yield attributes than conventional DAP even with 10% less P. However, more field studies are needed for broader applicability of this technology.

Keywords: Environmental quality, biochar-based organomineral fertilizer, fertilizer use efficiency, phosphorus use efficiency, phosphorus uptake

1. Introduction

According to the prediction of the Food and Agriculture Organization (FAO), the global population may increase up to 9.7 billion in 2050 (FAO, 2017). The world demand for food production is growing rapidly in order to cope with population growth (Raza *et al.* 2023). Excessive use of chemical phosphatic fertilizers for crop production is damaging soil, water and environmental quality. Phosphorus (P) is the 2nd most essential primary element as it accounts for 0 .1 % to 0.5 % of the dry matter of plants. It is an essential component of energy metabolism, involves in biosynthesis of nucleic acids and membranes (Masood *et al.* 2011; Rafique *et al.* 2019). Being a central part of phospholipids, DNA, RNA, ATP, and photosynthesis, it plays significant functions in plants (Shen *et al.* 2011; Malhotra *et al.* 2018). Phosphorus is essential for food production, with no alternative, making its long-term availability crucial for global food security. In contrast to nitrogen (N), which is abundantly available in the atmosphere, rock phosphate (RP) has a limited supply. However, its reserves are rapidly depleting and are expected to be exhausted within the next 50 to 100 years (Cordell *et al.* 2009; Leghari *et al.* 2016). As the world's population continues to grow, there will be an increase in food demand, therefore, in order to ensure food production for future generations, more P will be required. (Wali *et al.* 2020).

Moreover, P is the least mobile among the essential plant nutrients and is often unavailable under most soil conditions. (Ray *et al.* 2013). P has low solubility and is only available to plant uptake in inorganic forms as HPO_4^{2-} or $H_2PO^-_4$ and H_3PO_4 (Wang *et al*., 2022). When the soil is neutral or alkaline, organic P occurs in the form of insoluble calcium phosphate (Ca-P) or magnesium phosphate (Mg-P), while in acidic soil, P forms complex compounds with iron (Fe) and aluminum (Al) oxides (Xu *et al*., 2022). P also becomes unavailable in areas with low temperature and poor soil aeration (Amanullah *et al*., 2015). These conditions lead to a significant reduction in P use efficiency (Zhang *et al.* 2014). The P deficiency or unavailability through adsorption can result in reduced cell growth, yield, and overall crop production.

Extensive use of inorganic fertilizers is an emerging problem globally (Rehman *et al.* 2018). There is a high doses of P fertilizers are required in every production season. Fixation of P is one of the major factors which alleviate the efficiency of fertilizer, with only 10–20% being taken up by plants (Wang *et al.* 2012; Helfenstein *et al.* 2018). However, the high cost and low availability of chemical fertilizers is a major challenge (Sathish *et al.* 2011).

To enhance the efficiency of phosphatic fertilizers, several techniques were developed such as; coating of fertilizers with slow-release substances (Sanders *et al.* 2012; Sharma *et al.* 2013; Guelfi *et al.* 2018) and encapsulating granules to acidify the soil in alkaline environments help regulate P release according to crop needs (Mandal *et al.* 2019). Post-coating modifications, such as adding humic substances (Erro *et al.* 2016), use of phosphate solubilizing microorganisms (Sharma *et al.* 2013; Billah *et al.* 2019), and the enrichment of the compost with mineral P fertilizers (Sikora & Enkiri, 2000). But still, the benefits and the drawbacks of these techniques must be taken into account. Of all the methods, some might be time-taking or expensive particularly to the small-holder farmers. Therefore, one promising approach is to utilize natural resources, such as biochar enriched with chemical fertilizers, which can be used to create organomineral fertilizer (OMF) (Yaashikaa *et al.* 2020).

In recent years, the quantity of agricultural waste has been rising rapidly all over the world. Therefore, it is increasingly attracting attention because of its negative impacts on the environment (Xue *et al.* 2016). The conversion of pruning waste into biochar presents a sustainable approach to enhance maize yield and phosphorus use efficiency (PUE). This technique not only utilizes agricultural waste but also improves soil properties, leading to better crop performance (Kayikcioglu & Tepecik, 2022).

Biochar is a valuable byproduct derived from biodegradable agricultural waste. As a value-added product, it reduces environmental pollution by mitigating greenhouse gas emissions, volatile organic compounds, and leachates (Vigneshwaran *et al.* 2024). Biochar is a carbon-rich, fine-grained, porous substance formed by the thermal decomposition of biomass at relatively low temperatures (400-500 °C) and under oxygen-limited circumstances (Arif *et al.* 2023). When biochar is introduced into the soil, it improves soil structure by encouraging aggregate stability (Lehmann *et al.* 2006), increases porosity, reduces compaction, promotes soil aeration, and improves water and nutrient transport (Alkharabsheh *et al*., 2021). Biochar can positively impact the soil microbial community by providing a habitat and food source for beneficial microorganisms. Apart from increasing the fertility of the soil as well as yield of crops, biochar is one the practices used to increase the carbon stock in the soils, hence reduce the impacts of climate change (Lusiba, Odhiambo & Ogola, 2017).

Integrating biochar into mineral P fertilizers, referred to as biochar-based organomineral phosphatic fertilizers (BOMPFs). As a novel soil amendment, BOMPF combines biochar with mineral P to enhance phosphorus use efficiency (PUE) and soil health (Esmaeili *et al*., 2024). This combination minimizes P loss in calcareous soils, reduces dependence on synthetic fertilizers, and mitigates environmental impacts. (Liu *et al*., 2021). BOMPF's have been shown to enhance P absorption by plants, improves soil structure, and boosts microbial activity, leading to better nutrient accessibility, increased crop growth, and higher yields. BOMPF improves PUE by significantly reducing P fixation and leaching, issues commonly observed with conventional fertilizers (Borges *et al*., 2022). Unlike traditional fertilizers that often release P rapidly, resulting in immobilization in alkaline soils. The biochar component in BOMPF retains P within the root zone and releases it gradually, aligning with plant demand for optimal uptake (Gunes *et al.* 2014). Moreover, BOMPF improves soil physiochemical properties, promotes crop root development and stimulates the release of root exudates, makes it an effective phosphorus fertilizer (Gao *et al.* 2019; Cao *et al.* 2021).

Besides, it has influence on the improvement in the fertility status of the soil along with biomass and physiological parameters and yield of crops (Bouhia *et al.* 2023). Application of organic based fertilizers has lesser adverse effects to the environment as compared to the mineral fertilizer. Because it has a slower nutrient release due to organic fraction binding and absorption of inorganic elements (Zebarth *et al.* 2005).

Therefore, using BOMPF could increase the effectiveness of P fertilization by decreasing the rate of phosphate release and its interaction with the solid phase of the soil (Pogorzelski *et al.* 2020). However, the use of the mixed-wood biochar enriched with phosphate fertilizer under calcareous soil has been minimally explored. Thus, we hypothesized that application of BOMPF can increase the P availability in the soil and improving P nutrition in the spring maize, resulting to optimal crop yields with reduced fertilizer mineral inputs. The specific objectives of this study were (1) to evaluate the potential of BOMPF on P uptake, growth and yield of spring maize crop; (2) to determine the potential of BOMPF in reducing chemical fertilizer doses.

2. Materials and methods

2.1. Feedstock collection, Production and Characterization of biochar

For the preparation of biochar, pruning wastes of different trees were used as feedstock. These were obtained from the experimental site, located at MNS University of Agriculture, Multan, Pakistan. First, feed stock was air-dried before pyrolysis, and then all physical impurities were removed. The Kon-Tiki Flame Curtain Pyrolysis technique (Cornelissen *et al.* 2016) was used to produce biochar at a temperature of 400-500 °C under controlled conditions, ensuring low oxygen levels and high pressure. Then, the resulting biochar was allowed to cool by water spray to prevent it from turning into ash. The cooled biochar was air dried and ground to pass through 1 mm and 2 mm sieves to ensure uniform particle size. The water holding capacity of biochar was determined as the mass of water retained per mass of dry biochar (Mimmo *et al.* 2014). The electrical conductivity (EC) and pH were measured by adding biochar in a distilled water at ratio of 1:10 *(w/v)*, followed by shaking on a mechanical shaker for 30 minutes (Rhoades, 1996). Furthermore, the digestion of biochar was done using hydrogen peroxide (H_2O_2) and sulfuric acid (H_2SO_4), for the estimation of P, K, Zinc (Zn), Copper (Cu), Iron (Fe) and Manganese (Mn) in the Soil and Water Testing Laboratory Multan, Pakistan (Wolf, 1982). The N determination was done with the help of Kjeldahl apparatus following the method explained by (Bremner & Tabatabai, 1972).

2.2. Preparation of BOMPF

BOMPF is produced by enriching biochar with a phosphorus solution. To prepare the phosphorus solution, 86.0 g of DAP fertilizer was thoroughly dissolved in 200 ml of distilled water. Once the solution was ready, 200 g of biochar was dipped into that solution for enrichment. The enriched biochar, now referred to as biochar-based organomineral phosphatic fertilizer (BOMPF), was then oven dried at 65 °C till the constant weight reached and stored in a plastic bag for future use. The characteristics of the biochar utilized in this experiment are presented in **Table 1**.

Table 1. Pre and Post enrichment analysis of biochar

Parameters	Units	Pre-Analysis	Post-Analysis
EC	dS m^{-1}	2.36	2.45
pH	-	10.62	7.74
Total N	%	0.0278	8.154
Available P	mg kg^{-1}	8.5	21.8
Extractable K	mg kg^{-1}	38	35
Zinc	mg kg^{-1}	0.20	0.16
Copper	mg kg^{-1}	0.20	0.06
Iron	mg kg^{-1}	0.44	0.40
Manganese	mg kg^{-1}	0.24	0.29

Table 2. Physico-chemical characteristics of soil used for pot experiment

Parameter	Unit	Value
Textural class	-	Clay loam
Organic matter	%	0.588
EC	dS m^{-1}	1.58
pH	-	8.21
Total N	%	0.029
Available P	mg kg^{-1}	5.26
Extractable K	mg kg^{-1}	56
Zinc	mg kg^{-1}	0.13
Copper	mg kg^{-1}	0.05
Iron	mg kg^{-1}	0.19
Manganese	mg kg^{-1}	0.21
Boron	mg kg^{-1}	0.055

2.3. Plant material and Experimental design

A pot trial was conducted during spring season (2024), under greenhouse conditions near Academic Block-B (30°9'36'' N and 71°27'1'' E) of MNS-University of Agriculture, Multan, Pakistan. Total five treatments were evaluated in this experiment including control, recommended P from DAP, 90% BOMPF, 80% BOMPF, and 70% BOMPF. Treatments were arranged according to completely randomized design (CRD) with three replicates of each treatment. The P levels were determined by dividing the recommended dose (58 kg/acre) of inorganic P fertilizer (DAP) into four levels (100%, 90%, 80% and 70%). The recommended dose of nitrogen (92 kg/acre) and potassium (37 Kg/acre) was added to all the treatments. Each treatment was mixed in 11 kg soil and soil was then filled in earthen pot (1 feet in height and 8 inches in diameter). Maize (*Zea mays* L.) was used as a test crop. Nursery of maize was raised in peatmoss trays alongside and then seedlings were transplanted in each pot (one plant per pot). According to crop requirements and weather conditions, irrigation was performed throughout the experimental period. The other management practices were also kept constant throughout all treatments.

2.4. Sampling and Pre-Analysis of Experimental Soil

A soil sample was taken randomly at a depth of 0–15 cm from the experimental field area, of MNS University of Agriculture Multan, Pakistan. For the determination of selected physio-chemical properties of soil (**Table 2**), sample was air dried and ground to pass through a 2 mm sieve. The soil texture was analyzed using the hydrometer method (Bouyoucos, 1962), while EC and pH were measured using soil-water suspension of 1:1 *(w/v).* Organic matter was determined via the Walkley-Black method technique as outlined by (Walkley, 1947). Total nitrogen was measured using Kjeldahl distillation, and available P was estimated using method as stated by (Olsen *et al.* 1954). Extractable K was measured with ammonium acetate extraction method as described by Schollenberger and Simon, (1945). Additionally micronutrients (Zn, Cu, Fe, and Mn) were determined using DTPA extraction followed by Atomic Absorption Spectroscopy (AAS) (Lindsay and Norvell, 1978) (**Figure 1**).

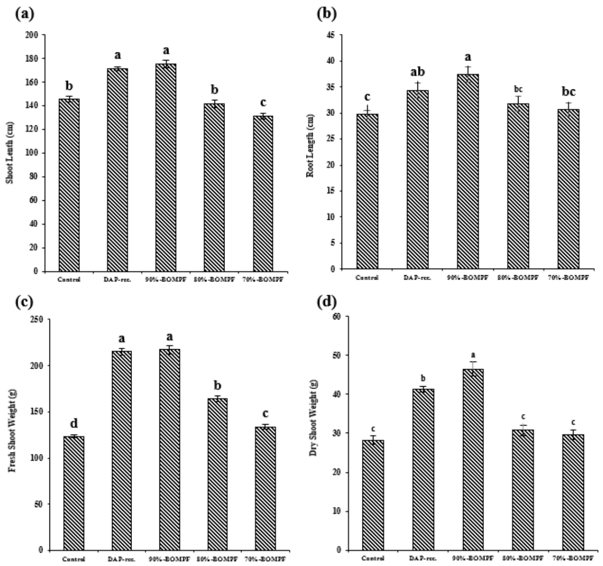


Figure 1. Effect of different BOMPF levels on (a) Shoot length (cm), (b) Root length (cm), (c) Fresh shoot weight (g), (d) Dry shoot weight (g). Mean ± SE (n = 3 biological replicates). Data labeled by different lowercase letters are statistically significant according to the LSD test at P < 0.05

2.5. Determination of Crop Parameters

The crop was harvested at the stage of maturity and the data regarding growth attributes were recorded. Chlorophyll content in maize leaves was measured using a SPAD meter 502 plus. The shoot length (cm) was determined from base to the top using a measuring tape. Similar procedure was also used for measuring the root length. A digital balance was used to determine the fresh weights of the roots and shoots (g). In order to determine their dry weights (g), samples were oven-dried at 60 ^{o}C for several hours until a constant weight was reached, and the dry weight was then measured with a digital balance. Moreover, the dried and ground plant leave samples were used to measure the elemental analysis. For the determination of P content in maize leaves, digestion was done in di-acid mixture (HNO_3 and $HClO_4$) followed by spectrophotometric measurement of P at the wavelength of 410 nm (Rashid, 1986). The digested sample was analyzed to detect extractable K content by using flame photometer and N content was determined by using the Kjeldahl apparatus (Kapellakis *et al.* 2015).

2.6. Calculations of phosphorus use efficiency (PUE)

P uptake by maize plants was calculated using following formula described by Kumar, (2015):

$$\text{P uptake}(\text{g / plant}) = \frac{\text{P content(\%) in grain/staw} \times \text{grain/straw yield(g/plant)}}{100} \quad (1)$$

Phosphorus use efficiency was, then, calculated by using following formula described by Fageria *et al.* (1997):

$$\text{PUE}(\%) = \frac{\text{Puptake in treatment pot}(\text{g}) - \text{Puptake in controlpot}(\text{g})}{\text{P dose applied}(\text{g})} \quad (2)$$

2.7. Statistical analysis

The recorded data was determined by using the analysis of variance (ANOVA) technique following CRD (Taylor-Powell and Steele, 1996). Means were compared by using the least significant difference (LSD) test at 5% level of significance. Statistix 8.1 software was used for statistical analysis of the data.

3. Results

3.1. Effect of BOMPF Application on Crop Growth Parameters

The application of BOMPF significantly influenced crop growth parameters, with varying impacts across treatments. The T2 treatment (90% BOMPF) resulted in the greatest improvements, particularly in shoot length, which reached an average of 180 cm, an increase of 20% over the control (T0). In comparison, T1 (DAP rec.) achieved a similar, yet slightly lower, increase of 18% with an average of 175 cm. However, T3 (80% BOMPF) and T4 (70% BOMPF) showed diminished performance, with T4 exhibiting the lowest average shoot length of 130 cm, marking a 9% decline relative to the control.

Regarding the root length, the results showed that 90% BOMPF gave the best results, with an improvement of 25% (38 cm), respectively. T1 achieved a moderate increase (34 cm), while T3 and T4 yielded 31 cm and 30 cm, respectively, with minimal improvements over the control. Therefore, in the case of BOMPF at 90%, the best production was obtained with the 90% BOMPF formulation, which led to a significant increase in the shoot and root biomass of 217 g fresh, 46 g dry, demonstrating improvements of 76% and 64%, respectively. T1 also performed well but was outpaced by T2. Conversely, T3 and T4 exhibited significantly lower shoot biomass, with T4 registering only marginal improvements over the control.

The fresh and dry root weights showed similar patterns, with T2 producing the highest fresh weight (25 g) and dry weight (7 g), representing increases of 53% and 130% over the control, respectively. Lower concentrations of BOMPF showed diminished effects, with T4 performing the worst, even falling below the control in fresh root weight.

Chlorophyll content was highest in the T4 treatment, which increased by 32% over the control, followed by T2 and T1. The lowest improvement was observed in T3, highlighting the differential response of chlorophyll content to BOMPF application (**Figure 2**).

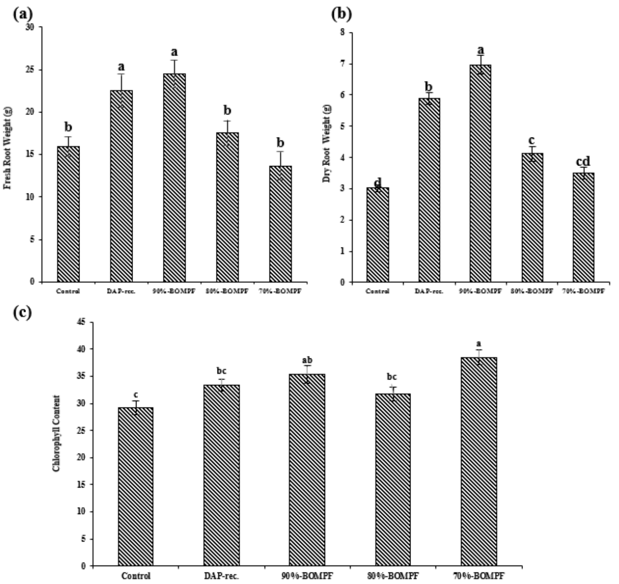


Figure 2. Effect of different levels of BOMPF on (a) Fresh root weight, (b) Dry root weight, (c) Chlorophyll content. Mean ± SE (n = 3 biological replicates). Data labeled by different lowercase letters are statistically significant according to the LSD test at P < 0.05

3.2. Effect of BOMPF Application on Nutritive Parameters

3.2.1. Effect on N, P, and K (%) Content in Leaf

Our investigation revealed that the BOMPF formulation significantly affected plant nutrient concentrations. The highest N content was observed in the T4 treatment (70% BOMPF), with a 26% increase over the control. T2 (90% BOMPF) also performed well, with a 23% increase, followed by T1 and T3, which showed more modest improvements. For P content, T2 was the most effective, with a 63% increase, while T3 (80% BOMPF) achieved 55%. The smallest improvements were recorded in T1 and T4, with increases of 29% and 28%, respectively. Potassium content peaked with the T2 treatment (34% increase), followed by T4 (26%). T1 showed the least increase, with only a 10% improvement over the control.

3.2.2. Effect on Phosphorus Use Efficiency (PUE)

The phosphorus use efficiency (PUE) was maximized in the T2 treatment (BOMPF at 90%), with an increase of 26.7%, indicating its superior ability to utilize phosphorus effectively. In comparison, T1 (DAP rec.) and T3 (80% BOMPF) exhibited moderate increases (12.6% and 12.2%, respectively), showing no significant difference between them. The lowest PUE increase was observed in the T4 treatment, which reached only 7.1%, indicating that higher BOMPF concentrations were more effective in improving PUE.

3.2.3. Effect on N, P, and K Uptake (g/plant)

The T4 (70% BOMPF) resulted in the highest N uptake, reaching 0.36 g/plant (26% increase), with T2 (90% BOMPF) closely following at 0.32 g/plant (23% increase). T1 (DAP rec.) and T3 (80% BOMPF) also showed increased N uptake but to a lesser extent, with 15% and 9% increases, respectively. Phosphorus uptake was maximized in the T2 treatment (0.31 g/plant), marking a 169% increase over the control, while T1 recorded an 88% increase. The lowest phosphorus uptake was observed in T4, with a modest 34% rise. Potassium uptake followed a similar trend, with T2 achieving the highest uptake, representing a 122% increase. T1 also performed well (0.8 g/plant, 66% increase), while the lower concentrations of BOMPF (T3 and T4) resulted in modest potassium uptake compared to the higher concentrations.

BOMPF application significantly enhanced both crop growth and nutrient uptake, with the 90% BOMPF treatment generally outperforming other treatments in most parameters, particularly in biomass and P uptake. While T4 (70% BOMPF) excelled in N content but generally underperformed in other parameters, emphasizing the importance of optimizing BOMPF concentrations for enhanced plant growth and nutrient absorption (**Table 3**).

Table 3. Effect of different levels of BOMPF on N, P and K concentration, uptake and P use efficiency of maize

Treatment	N content (%) in leaf	N uptake (g/pot)	P content (%) in leaf	P uptake (g/pot)	K content (%) in leaf	K uptake (g/pot)	PUE (%)
Control	1.04 c	0.28 c	0.39 c	0.11 d	1.74 c	0.49 c	0.0
DAP	1.20 ab	0.32 ab	0.51 b	0.21 b	1.93 bc	0.80 b	12.6 b
90%-BOMPF	1.28 ab	0.35 ab	0.65 a	0.30 a	2.35 a	1.09 a	26.7 a
80%-BOMPF	1.14 bc	0.31 bc	0.61 a	0.19 b	2.09 ab	0.64 bc	12.2 b
70%-BOMPF	1.32 a	0.36 a	0.51 b	0.15 c	2.20 ab	0.65 bc	7.05 b
LSD	0.1550	0.0425	0.0527	0.0379	0.3264	0.1749	6.8360

Mean values having different letters are statistically significant according to the LSD test at P < 0.05.

4. Discussion

The effective utilization of P in agricultural systems is essential for sustainable crop production, especially for maize, a vital cereal crop in Pakistan. However, conventional P fertilizers often demonstrate low efficiency due to factors such as rapid fixation, immobilization, and leaching in the soil. To address this issue, this study aimed to investigate the potential of BOMPF as a novel soil amendment to improve P availability and uptake by maize plants. The study evaluated the effectiveness of BOMPF in improving P nutrition in maize and its potential as a sustainable replacement to conventional P fertilizers. The research focused on assessing the impact of BOMPF on key parameters, such as maize growth, P uptake, nutrient cycling, and soil health. The change noted in almost all the parameters was fairly high as demonstrated by the results of the research.

4.1. Effect of BOMPF on growth parameters

We have observed a significant improvement in different growth parameters of maize plant with the use BOMPF as compared to conventional DAP fertilizer. Specifically, T2, with 90% P as BOMPF demonstrated the most significant increase, showing a 20% rise in plant height. The enhancement in crop growth can likely be attributed to several factors. First, biochar's highly recalcitrant nature ensures consistent P availability throughout the crop growth period (Dotaniya *et al.* 2014). Second, biochar application has been shown to reduce soil P sorption capacity, thereby increasing P availability to crops (Hematimatin *et al*., 2024) Deb *et al.* 2016). This result also supports other studies signaling that higher P doses lead to taller plants in several crops (Satya & Swami, 2020). It is quite noteworthy that P treatment consistently enhances growth parameters in maize, including plant height (Liaqat *et al*., 2018).

On the other hand, formulation of 90% BOMPF also showed better result on the other plant growth parameters including fresh and dry shoot and root weight, emphasizing its impact on overall plant biomass, which is crucial for healthy plant structure and potential grain yield. Additionally, different P levels were influenced the variations in chlorophyll content, with T4 showing a remarkable 32% increase. It appears that the increased uptake of C, N and P associated with enriched biochar had a significant impact on chlorophyll content in plants (Agegnehu *et al.* 2015; Lusiba *et al.* 2017). Many research studies have displayed the positive impact of BOMPF on plant growth and development. For instance, Chew *et al.* (2020) compared the effect produced by BBPF on rice crops to the results produced by chemical fertilizer alone and it stated that the former show higher biomass yield than the latter.

4.2. Effect of BOMPF on nutritive parameters

Furthermore, this present study also assessed the impact of BOMPF on the nutrient contents, uptake and efficiency of the maize plant. Therefore, T2 with 90 % P as BOMPF was statistically on a higher level in relation to the other treatments where the contents of the P and K in the plant raised by 26% and 34%, respectively. Similarly, the PUE having significant enhancement of 14.1% under T2 as compared to T1. It was also determined in the previous studies that the application of biochar enhanced the supply of soil P (Xu *et al.* 2013). In addition, it can also improve soil physical properties, which may increase P uptake leading to higher P content (Deb *et al.* 2016). As for N content found in maize plant and its interaction with uptake level of the element was observed most significant at T4 with 70 % P as BOMPF. This is primarily due to biochar's ability to improve soil nutrient dynamics by enhancing soil organic matter and microbial activity, which creates a favourable environment for N mineralization and retention. The porous structure of biochar helps to reduce N leaching by adsorbing ammonium and nitrate ions, thus making N more available for plant uptake over time (Lehmann & Joseph, 2015; Hematimatin *et al*., 2024). Furthermore, biochar may promote the proliferation of beneficial soil microbes, such as nitrogen-fixing-bacteria, which contribute to increase N availability in the rhizosphere (Arif *et al*., 2017; Luo *et al*., 2024).

These findings highlight the potential of BOMPF to enhance the bioavailability and uptake of nutrient content in maize. Likely due to the mutual effects of biochar and mineral fertilizers in improving soil properties and nutrient retention. Biochar has shown promise in enhancing nutrient availability in soils. First of all, such characteristics of biochar as a high surface area and porosity enable the adsorption of nutrients, including P, on its surface. This leads to a slow release over time, minimizing leaching losses and optimizing plant uptake efficiency. In addition, the use of biochar enhances the CEC through ion exchange between the soil solution and root system of plants (Solaiman *et al.* 2019).

Several studies align with our findings such as Liu *et al.* (2022) study revealed that the combined treatment of BBPF had improved the absorption and application of nutrients in rapeseed by 21% as compared to the treatment without BBPF. While, Widowati and Asnah, (2014), showed that the 128% of potassium crop uptake is increased by the application of biochar (Xiang *et al.* (2017) described that biochar improved the soil environment thus endorsing crop root growth and soil nutrient absorption. These findings demonstrate that the application of BOMPF can recover the absorption and application of nutrients and contributes to the quality of crop production.

5. Conclusion

On the basis of this experiment the key findings was impregnation of biochar with DAP preformed as promising strategy in reducing the P inputs in the form of organic amendment. It was also found that this formula not only help in reducing the P dose by 10% but also functioned as slow-release fertilizer. Additionally, the one-time application of BOMPF can provide prolong availability of P in soil, promoting crop growth, yield, and development while addressing P deficiency. It can minimize the input costs incurred on fertilizer and offers an economical solution for small-scale farmers. Furthermore, BOMPF not only increases the availability of P for plant uptake, but also contributes to soil carbon sequestration, promoting long-term soil health and sustainability. Thus, using BOMPF could increase the effectiveness of P fertilization by decreasing the rate of phosphate release and its interaction with the solid phase of the soil. Collectively, our experiments align with the overarching hypothesis that BOMPF, particularly the 90% formulation, has the potential to enhance maize crop growth and productivity.

This study was focused on spring maize, limiting its generalizability to other crops and cropping systems. Additionally, the long-term effects of BOMPF application on soil health and nutrient dynamics were not assessed. Future research should focus on the expansive field trials conducted across diverse geographical regions and crop types will provide insights into the broader applicability of BOMPF in real-world farming scenarios.

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Data availability

The 1st corresponding author provide the data on demand.

Conflicts of interest

No conflict of interest declares by authors.

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