

EFFECT OF PHOSPHORUS LEVELS, BIOFERTILIZERS AND BIOCHAR ON ENZYME ACTIVITIES AND NUTRIENT CYCLING OF SOIL IN CHICKPEA (*Cicer arietinum* L.)

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Abstract

The field experiment was conducted during rabi season of 2023-24 at Agronomy Research Farm, Acharya Narendra Deva University of Agriculture and Technology, Kumarganj, Ayodhya, Uttar Pradesh, to study the effect of phosphorous levels, biofertilizers and biochar on soil enzyme activities and nutrient cycling in chickpea (*Cicer arietinum* L.). The experiment was laid out in a randomized block design with ten treatments and three replications. Treatments consisted of 100% recommended dose of phosphorus (RDP), reduced levels (50 and 75% RDP), application of biochar @ 2.5 t ha⁻¹, inoculation of seed with phosphate-solubilizing bacteria (PSB) and Rhizobium. The available nitrogen (N), phosphorus (P) and potassium (K) were determined after harvest, along with dehydrogenase activity (DHA), acid phosphatase, alkaline phosphatase and soil microbial biomass carbon (SMBC). The integrated treatment, T₆ (75% RDP + biochar + PSB + Rhizobium) registered the highest available N (193.35 kg ha⁻¹), P (15.89 kg ha⁻¹) and K (264.88 kg ha⁻¹), as compared to the control T₁ (181.17, 11.67 and 247.62 kg ha⁻¹ respectively). T₆ recorded the maximum DHA (45.92 µg TPF g⁻¹ soil h⁻¹), acid phosphatase (15.81 µg PNP g⁻¹ soil h⁻¹), alkaline phosphatase (26.91 µg PNP g⁻¹ soil h⁻¹) and SMBC (235.32 mg C kg⁻¹ soil), compared to the lowest values in T₁. The integrated application of reduced dose of phosphorus with biochar and dual biofertilizers proved to be beneficial in terms of nutrient availability and microbial activity in soil. The treatment combination improved the microbial biomass and enzyme mediated transformations that enhance the nutrient cycling and fertility. Therefore, the application of 75% RDP along with biochar, PSB and Rhizobium proved to be a promising technique in improving the biological health of the soil and nutrient availability for chickpea crop.

1. INTRODUCTION

The chickpea (*Cicer arietinum* L.) is a plant of great nutritional, economic, and ecological value which is why it is widely grown in semi-arid and sub-tropical regions. Its seeds are a source of protein, carbohydrates, fiber, minerals, and bioactive compounds which in turn play a role in food and nutritional security (Jukanti et al., 2012; Kumar et al. 2025). Also we see that in cereal-legume cultivation systems chickpea's sustainability and fertility of the soil is improved by way of the symbiotic nitrogen fixation which is done by Rhizobium. What we find is that growth, energy production, root development, nodulation and reproduction of the chickpea are a function of phosphorus (P)'s presence in the soil. It also has the ability to improve nodulation, nitrogen fixation, biomass and yield although response does vary by agro climatic conditions (Idris et al., 1989; Parashar et al., 2024; Garg and Lilhare, 2024). In order to improve productivity and nutrient use it is key to put in place good P management. Rhizobium fixes atmospheric nitrogen, at the same time phosphate-solubilizing bacteria (PSB) transform unavailable P into plant available forms. Also some rhizobial strains have what it takes to solubilize phosphate and raise the availability of P (Alikhani et al., 2006). Rhizobium and PSB co-inoculation goes a long way in bettering the yield, biomass, and nodulation of chickpea (Tagore, 2013; Rudresh et al., 2005). Also we see that in many environments and low fertility settings chickpea productivity has been put forward via P fertilization and rhizobial inoculation (Wolde-Meskel et al., 2018; Ben Romdhane et al., 2022). Recently in

India we have reported that the use of P and PSB *Rhizobium* improved nutrient uptake, protein content, protein yield, and grain yield (Singh and Sharma, 2011; Parashar et al., 2024).

Addition of biochar, the carbon-rich amendment, could improve the quality of the soil and the fertilizer use efficiency by its increases in the soil's porosity, carbon content, and the number of its surface functional groups (Dai et al., 2021; Singh et al., 2022). The effectiveness of this method depends on the properties of the soil, its application rate, the conditions of pyrolysis, and the type of feedstock (Sharma et al., 2023). The biochemical properties of the soil, together with nodulation, nitrogen assimilation, and biomass in chickpea, could be enhanced by the addition of the biochar. Moreover, its interaction with the phosphorus could affect the growth as well as nutrient uptake. It was noticed by Lusiba et al., 2018 and Liu et al., 2019 that it may increase the availability as well as uptake of the phosphorus, especially in the deficient soils, by changing the microbial communities as well as nutrient cycling as discussed by Tesfaye et al., 2021 and Zhang et al., 2025. A study was done on the basis of the above-mentioned points to assess the effectiveness of the phosphorus levels, biochar, and microbial inoculation in relation to the amounts of the available nitrogen, phosphorus, and potassium available as well as the soil enzyme activity after harvesting the chickpea crop.

2. METHODS AND MATERIAL

Study location

The field trial was conducted from month of October 2023 to march 2024 in the rabi season at Agronomy Research Farm, Acharya Narendra Deva University of Agriculture and Technology, Kumarganj, Ayodhya, Uttar Pradesh, India. The experimental site is located at location 26°47' N, 82°12' E longitude from the Ayodhya district headquarters on the university's main campus on the south-eastern side of Ayodhya Raebareli Road. It has a subtropical climate. The soil of the experimental site was silty loam in texture, with the Electrical conductivity (0.316 dS m⁻¹), Organic carbon (0.310%), available nitrogen (177.86 kg ha⁻¹), phosphorus (10.92 kg ha⁻¹), potassium (242.25 kg ha⁻¹) and pH (8.38), Dehydrogenase activity (27.05 µg TPF g⁻¹ soil h⁻¹) Alkaline Phosphatase (13.21 µg PNP g⁻¹ soil h⁻¹), Acid Phosphatase (µg PNP g⁻¹ soil h⁻¹), SMBC (162.31 mg C kg⁻¹ soil).

Experimental design and management

The experiment was laid out in a randomized block design (RBD) with ten treatments and three replications. The treatments consisted of different levels of phosphorus, biochar and biofertilizers viz., phosphate-solubilizing bacteria (PSB) and *Rhizobium*. The treatment combinations were: T₁: Control; T₂: 100% recommended dose of phosphorus (RDP); T₃: 75% RDP + biochar @ 2.5 t ha⁻¹; T₄: 75% RDP + biochar @ 2.5 t ha⁻¹ + PSB; T₅: 75% RDP + biochar @ 2.5 t ha⁻¹ + *Rhizobium*; T₆: 75% RDP + biochar @ 2.5 t ha⁻¹ + PSB + *Rhizobium*; T₇: 50% RDP + biochar @ 2.5 t ha⁻¹; T₈: 50% RDP + biochar @ 2.5 t ha⁻¹ + PSB; T₉: 50% RDP + biochar @ 2.5 t ha⁻¹ + *Rhizobium*; and T₁₀: 50% RDP + biochar @ 2.5 t ha⁻¹ + PSB + *Rhizobium*. The PSB and *Rhizobium* were applied as seed inoculants individually at 10 mL kg⁻¹ seed and the inoculants contained about 1.0 × 10⁹ CFU mL⁻¹. Similar crop management practices were followed in all the treatments, besides the implemented treatment differences. Fertilizers and biochar were applied as per the treatment schedule and all the recommended agronomic practices were followed uniformly during the crop season.

Soil samples collection

Soil samples were collected from the experimental plots after the crop harvest to evaluate the available nutrient status of the soil. The samples were then air dried under shade and were crushed and sieved through a 2-mm mesh before analysis. Fresh samples of soil were stored at 4 °C until enzymatic assays.

Available Nitrogen

The available nitrogen (N) in the soil was estimated by alkaline potassium permanganate method of Subbiah and Asija (1956). This method consists of taking 5 g of air-dried and sieved soil in distillation flask and treating it with alkaline KMnO₄ solution. The ammonia obtained was distilled and absorbed in boric acid containing mixed indicator and the volume of acid used for titration of ammonia was estimated against standard sulphuric acid solution. The amount of nitrogen present was calculated and expressed as kg ha⁻¹.

$$\text{Available N (kg ha}^{-1}\text{)} = \frac{(S - B) \times \text{NH}_2\text{SO}_4 \times 0.014 \times 100 \times 10^4 \times 2.24}{\text{weight of soil sample (g)}}$$

Where, S = burette reading of treated sample, B = reading of blank sample

Available Phosphorus

The available phosphorus (P) content in the investigated soil was extracted using an improved procedure developed by Olsen et al. (1954). In particular, 2.5 g of an air-dried and sieved soil sample was placed in a conical flask with 50 ml 0.5 M sodium bicarbonate (NaHCO₃) solution, adjusted to pH 8.5. The mixture was shaken for a certain time, and then filtered through the Whatman No. 42 filter paper. The amount of P was determined by spectrophotometrically measuring the intensity of the blue phosphor-molybdate complex. Subsequently, the P content was expressed in kg ha⁻¹.

Available potassium

The quantity of the readily available potassium (K) in the soil was evaluated by extracting the soil with neutral 1 N ammonium acetate (NH₄OAc) as described by black (1965). Specifically, a thoroughly mixed portion of 5 g of the air-dried and sieved soil was extracted with 25 mL of neutral 1 N NH₄OAc solution and shaken vigorously. The resulting clear solution was filtrated through the Whatman No. 42 filter paper. The content of

the K was determined by flame photometry after diluting the filtrate and measuring its optical density. The available potassium content was then calculated and expressed as kg ha⁻¹.

Soil health indicator enzymes

Dehydrogenase activity in soil

Dehydrogenase activity (DHA) as a parameter of microbiological activity and of the state of the soil was determined by the method of Casida et al. (1964) with slight modifications for chickpea rhizosphere soil. The substrate was 2,3,5-triphenyl tetrazolium chloride (TTC). TTC solution was adjusted to pH 7.4 and added to the fresh samples and they were incubated in a shaking water bath at an appropriated temperature. The reaction was stopped by adding acetone after incubation and then centrifuged at 4000 rpm for 15 min at 4 °C and filtered through Whatman No.1 filter paper. The amount of TPF formed was measured by spectrophotometer at 485 nm and expressed as dehydrogenase activity.

Acid and Alkaline phosphatase activity

Acid and alkaline phosphatases activities in the rhizosphere soil of chickpea were estimated by the method of Tabatabai and Bremner (1969) using p-nitrophenyl phosphate (pNPP) as a substrate. The action of acid and alkaline phosphatases on the soil was estimated by incubating the soil suspension with toluene and universal buffer (100 mM, pH 6.5) and universal buffer of pH 11.0, respectively at 37 °C for 1 h. The reaction was terminated by adding CaCl₂ and an alkaline solution. The amount of PNP released was determined spectrophotometrically at 400 nm after filtering the suspension. The enzyme activity was expressed as microgram of PNP released per gram of soil.

Soil microbial biomass carbon

Soil microbial biomass carbon (SMBC) was estimated from chickpea rhizosphere soil by chloroform fumigation-extraction method described by Vance et al. (1987). The fresh soil samples were separated into fumigated and non-fumigated treatments. The former was subjected to chloroform fumigation for 24 h prior to extraction with 0.5 M K₂SO₄. The organic carbon content was quantified and SMBC was estimated based on the differences in organic C content between fumigated and non-fumigated using a *k*_{EC} of 0.45. The data were expressed as Mg C g⁻¹ soil.

Statistical analysis

The experimental data were analyzed by ANOVA and the randomized block design (RBD) was used to examine the impact of treatments on available nitrogen, phosphorus, potassium, enzyme activity and SMBC. The treatment means were compared using the critical difference (CD) at the 5% level of significance. All statistical analyses were performed in the OPSTAT statistical software package (CCS HAU, Hisar, India; Sheoran et al., 1998).

3. RESULTS

Available Nitrogen

The effects of the treatment on the content of available nitrogen in the soil were statistically significant (Table 1; Fig 1). The highest content of available nitrogen was recorded in T₆ (75% RDP + biochar + PSB + Rhizobium) (193.35 kg ha⁻¹), followed by T₂ (191.78 kg ha⁻¹) and T₄ (190.98 kg ha⁻¹). The difference between T₆ treatment and T₂ treatment, as well as between T₆ treatment and T₄ treatment, was lower than the critical difference (CD = 3.05 kg ha⁻¹), which indicated that they were statistically comparable with each other. However, T₆ recorded significantly higher content of available nitrogen than T₅ (190.24 kg ha⁻¹) and all other treatments. The least available nitrogen was recorded in T₁ (control) with 181.17 kg ha⁻¹.

Available Phosphorus

Available phosphorus showed a distinct treatment response, and T₆ recorded the maximum value of 15.89 kg ha⁻¹ (Table 1; Fig 1). This was followed by T₂ (15.43 kg ha⁻¹) and T₄ (15.02 kg ha⁻¹). Based on the critical difference of 1.10 kg ha⁻¹, the phosphorus content under T₆ treatment was comparable with T₂ treatment and T₄ treatment. However, it was significantly higher than that of T₅ (14.60 kg ha⁻¹) and other treatments. The lowest available phosphorus content was recorded in T₁ (11.67 kg ha⁻¹). The results show that there is a distinct improvement of the soil phosphorus availability under an integrated treatment that includes reduced phosphorus fertilization, biochar and dual biofertilization.

Available Potassium

The content of available potassium was considerably affected by the treatment combinations (Table 1; Fig 1). T₆ recorded the highest available potassium concentration (264.88 kg ha⁻¹), followed by T₂ (261.80 kg ha⁻¹), T₄ (260.82 kg ha⁻¹) and T₅ (258.93 kg ha⁻¹). The observed differences among T₆ treatment, T₂ treatment, T₄ treatment and T₅ treatment were below the critical difference of 7.96 kg ha⁻¹, which indicated that they were statistically comparable with each other. In contrast, T₆ was significantly superior to T₃ (256.64 kg ha⁻¹) and treatments that had lower nutrient and microbial inputs. The minimum available potassium was recorded under T₁ (247.62 kg ha⁻¹).

Dehydrogenase Activity

There was a pronounced enhancement of the activity of dehydrogenase in the soil under the integrated application of phosphorus, biochar and biofertilizers (Table 1; Fig 2). T₆ recorded the highest dehydrogenase activity (45.92 µg TPF g⁻¹ soil h⁻¹), followed by T₂ (44.14 µg TPF g⁻¹ soil h⁻¹) and T₄ (42.95 µg TPF g⁻¹ soil h⁻¹). With a critical difference of 3.73 µg TPF g⁻¹ soil h⁻¹, T₆ treatment was comparable with T₂ treatment and T₄

treatment, but significantly higher than that of T₅ (41.86 $\mu\text{g TPF g}^{-1} \text{ soil h}^{-1}$) and other treatments. The lowest dehydrogenase activity was recorded under T₁ (30.11 $\mu\text{g TPF g}^{-1} \text{ soil h}^{-1}$). The substantially greater activity of enzymes under T₆ treatment reflects the enhanced biological activity in the soil under combined nutrient and microbial management.

Acid Phosphatase Activity

The activity of acid phosphatase was significantly affected by the imposed treatments (Table 1; Fig 2). The maximum acid phosphatase activity was recorded under T₆ (15.81 $\mu\text{g PNP g}^{-1} \text{ soil h}^{-1}$), followed by T₂ (15.10 $\mu\text{g PNP g}^{-1} \text{ soil h}^{-1}$) and T₄ (14.70 $\mu\text{g PNP g}^{-1} \text{ soil h}^{-1}$). The difference between T₆ treatment and T₂ treatment or T₄ treatment was lower than the critical difference of 1.38 $\mu\text{g PNP g}^{-1} \text{ soil h}^{-1}$, which indicated that they were statistically comparable with each other. However, T₆ exceeded T₅ (14.38 $\mu\text{g PNP g}^{-1} \text{ soil h}^{-1}$) by a magnitude greater than the critical difference and was therefore significantly superior to T₅ treatment and other treatments. The minimum acid phosphatase activity was registered under T₁ (9.26 $\mu\text{g PNP g}^{-1} \text{ soil h}^{-1}$).

Alkaline Phosphatase Activity

The treatment combinations had a significant influence on the activity of alkaline phosphatase (Table 1; Fig 2). T₆ recorded the highest activity (26.91 $\mu\text{g PNP g}^{-1} \text{ soil h}^{-1}$), followed by T₂ (25.70 $\mu\text{g PNP g}^{-1} \text{ soil h}^{-1}$) and T₄ (24.92 $\mu\text{g PNP g}^{-1} \text{ soil h}^{-1}$). The differences between T₆ treatment and T₂ treatment and between T₆ treatment and T₄ treatment were smaller than the critical difference of 2.36 $\mu\text{g PNP g}^{-1} \text{ soil h}^{-1}$, which indicated that they were statistically comparable with each other. In contrast, the value under T₆ treatment was significantly higher than that under T₅ (24.17 $\mu\text{g PNP g}^{-1} \text{ soil h}^{-1}$) and other treatments. The lowest alkaline phosphatase activity was observed under T₁ (14.31 $\mu\text{g PNP g}^{-1} \text{ soil h}^{-1}$).

Soil Microbial Biomass Carbon

Soil microbial biomass carbon (SMBC) was marked by a significant response to the integrated nutrient and biofertilizer treatments (Table 1; Fig 2). The maximum SMBC was recorded under T₆ (235.32 mg C kg⁻¹ soil), followed by T₂ (219.92 mg C kg⁻¹ soil) and T₄ (210.56 mg C kg⁻¹ soil). The difference between T₆ treatment and T₂ treatment was less than the critical difference of 22.18, which indicated that they were statistically comparable with each other. However, T₆ was significantly higher than T₄ treatment and other treatments. Among treatments that had biochar and reduced phosphorus levels, T₆ maintained the highest SMBC, demonstrating a substantial enhancement of the biologically active carbon pool of the soil. The minimum SMBC was observed under T₁ (168.23 mg C kg⁻¹ soil).

4. DISCUSSION

Available Nitrogen

The available nitrogen content in the soil was greatly influenced by the treatment combination (Table 1; Fig 1). The treatment T₆ (75% RDP + biochar + PSB + Rhizobium) recorded a higher amount of available N (193.35 kg ha⁻¹) which might be due to the combined effect of Rhizobium and PSB along with the nutrient retention ability of biochar. Rhizobium fixes atmospheric nitrogen while PSB helps in mobilizing the nutrients and increases the microbial activity in the rhizosphere. Biochar might have created conducive conditions for the microbial activity and nutrient retention. According to Verma et al., the co-inoculation of MesoRhizobium and PGPR helped in improving the N uptake and nutrient acquisition in chickpea from the field soils of eastern Uttar Pradesh. Similarly, Dubey et al., (2020) also reported an increase in the available nitrogen under biochar based management in chickpea from different agro-climatic regions of Uttar Pradesh. The higher available N recorded under T₆ over the control might also be due to the higher activity of rhizosphere microbes and nutrient cycling. The present finding is in conformity with the work of Egamberdieva et al., (2019) who reported that biochar amendment in chickpea improved the status of nutrients in the soil and enhanced the performance of MesoRhizobium ciceri.

Available Phosphorus

The available phosphorus content was also observed to be significantly influenced by the treatment T₆ which recorded the highest available P (15.89 kg ha⁻¹) while the lowest was recorded under T₁ (11.67 kg ha⁻¹) (Table 1; Fig 1). The higher availability of P under T₆ might be due to the phosphate solubilizing ability of PSB which mobilizes the insoluble P from the soil to its available form for plant uptake. Biochar might have also played a role in altering the P retaining capacity of the soil and maintaining a higher level of available P. Mudigiri et al. (2024) conducted a field experiment on chickpea at Hyderabad and reported that the inoculation of PSB along with P application was more effective in improving the fertility status of the soil (available N, P and K) over the sole application of P. The present finding is also in agreement with the study of Egamberdieva et al. (2019) who reported that biochar amendment in chickpea not only improved the microbial activity but also helped in modifying the biochemical properties of the soil including the phosphorus content. Recently Chaouki et al. (2026) demonstrated that the phosphate-solubilizing inoculants improved the rhizosphere interactions of chickpea under deficient P conditions and were effective in mobilizing P and increasing the acid phosphatase activity. Hence, the higher available P under T₆ can be attributed to the phosphate solubilizing activity of PSB and the beneficial role of biochar in modifying the P status of the soil.

Available Potassium

The available K content was also found to be significantly increased under the integrated treatment (Table 1; Fig 1). The treatment T₆ recorded the highest available K (264.88 kg ha⁻¹) over the control (T₁: 247.62 kg ha⁻¹). The

increased availability of potassium might be due to the nutrient conserving ability of biochar along with the enhanced microbial activity under the integrated treatment. Biochar can play a significant role in nutrient cycling which ultimately enhances the nutrient availability for plant uptake. Egamberdieva et al. (2019) in their study on chickpeas reported that biochar amendment helped in increasing the nutrient acquisition including K; however, the response was found to be dependent on the type of biochar and soil. Similarly, Dubey et al. (2020) while working on chickpea based cropping systems in Uttar Pradesh reported that the integrated application of biochar and organic manures improved the available K along with the available N and P under sustainable management practices. The available K was also found to be maintained under the integrated treatment along with the improved P availability which can be due to the nutrient conserving ability of biochar.

Dehydrogenase Activity

Dehydrogenase Activity (DHA) was significantly increased under the integrated treatment (Table 1; Fig 2). The treatment T₆ recorded the highest DHA (45.92 µg TPF g⁻¹ soil h⁻¹) over the control (T₁; 30.11 µg TPF g⁻¹ soil h⁻¹). The increased dehydrogenase activity might be due to the combined effect of improved nutrient status and microbial activity under the integrated treatment. Biochar can provide suitable microsites which can help in maintaining and enhancing the microbial activity in the rhizosphere. The combined application of PSB and Rhizobium might have also contributed to the increased microbial activity which ultimately reflects in the higher DHA. The present finding is in consonance with the global analysis conducted by Pokharel et al. (2020) who showed that the application of biochar improves the microbial biomass C and dehydrogenase activity (DHA) in different soil types and experimental conditions. In addition, in a study conducted on chickpea, Bisht et al. (2024) found that the combined application of biochar and plant-beneficial rhizobacteria altered the soil properties, which enhanced enzymatic activity, including DHA. Thus, the increased DHA under the integrated treatment can be accredited to the improved microbial activity.

Acid Phosphatase Activity

Acid phosphatase activity was also significantly increased under the integrated treatment (Table 1; Fig 2). The treatment T₆ recorded the highest acid phosphatase activity (15.81 µg PNP g⁻¹ soil h⁻¹) while the control (T₁) recorded the lowest (9.26 µg PNP g⁻¹ soil h⁻¹). The increased activity might be attributed to the combined influence of PSB and biochar which enhanced the microbial activity and helped in mineralizing the organic phosphorus pool. Since, the combined application of PSB and biochar has been found to be more effective in improving the microbial activity; therefore, it might have also resulted in increased phosphatase activity for mobilizing the bound phosphate. This finding is consistent with the reports of Egamberdieva et al. (2019) who demonstrated that the biochar amendment in chickpea increased the soil enzyme activity including acid phosphomonoesterase. The enzyme activity was found to be dependent on the properties of biochar. Similarly, Chaouki et al. (2026) in their recent study on chickpea reported that the phosphate-solubilizing inoculants increased the acid phosphatase activity under low-P conditions. Hence, the increased acid phosphatase activity can be attributed to increased microbial proliferation under the integrated treatment which ultimately mineralized more organic phosphate.

Alkaline Phosphatase Activity

The alkaline phosphatase activity followed a similar trend as that of the acid phosphatase activity (Table 1; Fig 2). The treatment T₆ recorded the highest alkaline phosphatase activity (26.91 µg PNP g⁻¹ soil h⁻¹) while the control (T₁) recorded the lowest (14.31 µg PNP g⁻¹ soil h⁻¹). The increased alkaline phosphatase activity might be due to higher microbial biomass under the integrated treatment which demands higher P for its growth and survival. The phosphatase enzymes hydrolyze organic phosphate to release inorganic phosphate which can be used by the microbes and plants. The activity of these enzymes largely depends on the substrate availability and microbial biomass. According to the recent global meta-analysis conducted by Pokharel et al. (2020), biochar application increased the alkaline phosphatase activity along with the increase in microbial biomass C and dehydrogenase activity. Egamberdieva et al. (2019) also reported an increase in alkaline phosphatase activity in biochar amended soils under chickpea cropping system. Hence, the increased alkaline phosphatase activity under the integrated treatment can also be correlated with the improved microbial activity.

Soil Microbial Biomass Carbon

The microbial biomass carbon was greatly influenced by the treatment combination (Table 1; Fig 2). The treatment T₆ recorded the highest amount of microbial biomass carbon (235.32 mg C kg⁻¹ soil) while the lowest was recorded under T₁ (168.23 mg C kg⁻¹ soil). The increased microbial biomass carbon under the integrated treatment might be due to the combined influence of biochar, higher nutrient availability and enhanced microbial activity. Biochar acts as a stable C source and provides suitable niche for microbial colonization. The increased nutrient availability might have also favoured the microbial proliferation. The present finding is in accordance with the global analysis conducted by Pokharel et al. (2020) who demonstrated that biochar application significantly increased the microbial biomass C along with other enzymatic activities including dehydrogenase and phosphatases. Similarly, Dubey et al. (2020) in their study on chickpea based cropping system from different districts of Uttar Pradesh and conducted at Varanasi, Sultanpur and Gorakhpur, reported that biochar application improved the microbial properties of the soil. The present finding is in accordance with the global analysis performed by Pokharel et al. (2020) which demonstrated that the application of biochar increases the microbial biomass C and dehydrogenase activity (DHA) of different soils and experimental conditions. Similarly, Bisht et al. (2024) investigated the effect of combined application of biochar and plant-

beneficial rhizobacteria on chickpea and reported that the combined treatment altered the soil properties and increased the enzymatic activity including DHA.

5. CONCLUSIONS

The present study revealed that integrated management of phosphorus, biochar and biofertilizers significantly influenced the soil nutrient availability and biological properties after chickpea harvest. In this context, the integrated treatment, i.e., T₆ (75% RDP + biochar @ 2.5 t ha⁻¹ + PSB + Rhizobium) consistently recorded the maximum values of available N (193.35 kg ha⁻¹), P (15.89 kg ha⁻¹), K (264.88 kg ha⁻¹), dehydrogenase activity (45.92 µg TPF g⁻¹ soil ha⁻¹), acid phosphatase (15.81 µg PNP g⁻¹ soil ha⁻¹), alkaline phosphatase (26.91 µg PNP g⁻¹ soil ha⁻¹) and SMBC (235.32 mg C kg⁻¹ soil) among all the treatments. For several parameters, T₆ was statistically comparable with 100% RDP, suggesting that the integrated treatment could maintain the soil nutrient availability and biological activity with reduced phosphorus input. The combined application of biochar, PSB and Rhizobium probably enhanced the microbial activity, nutrient transformation and phosphorus mobilization, leading to improved soil fertility. Thus, the application of 75% RDP with biochar and dual microbial inoculation seems to be a promising nutrient-management strategy for maintaining the soil biological functioning and nutrient cycling in chickpea-based cropping systems.

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Conflict of Interest

No potential conflict of interest was reported by the author(s).

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Contribution of each author

Nempal Verma carried out the conduction of the experiment, enzyme activities and nutrient cycling of soil and preparation of manuscript draft as the part of his Ph. D. thesis research work. Suresh Kumar carried out the design of experiment and editing of the manuscript draft, Prashant Narayan carried out the editing of manuscript. Devendra Singh carried out the interpretation of data. Durgesh Kumar Maurya carried out the preparation of the manuscript. Mohd Yahya carried out the editing of the manuscript. All authors read and approved the final manuscript.

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Table: 1 Effects of phosphorus levels, biofertilizers and biochar on enzyme activities and nutrient status of soil in chickpea.

Treatments	Available Nitrogen (kg ha ⁻¹)	Available Phosphorus (kg ha ⁻¹)	Available Potassium (kg ha ⁻¹)	DHA (µg TPF g ⁻¹ soil h ⁻¹)	Acid Phosphatase (µg PNP g ⁻¹ soil h ⁻¹)	Alkaline Phosphatase (µg PNP g ⁻¹ soil h ⁻¹)	SMBC (mg C kg ⁻¹ soil)
T ₁	181.17	11.67	247.62	30.11	9.26	14.31	168.23
T ₂	191.78	15.43	261.80	44.14	15.10	25.70	219.92
T ₃	189.51	14.25	256.64	40.67	13.99	23.49	196.28
T ₄	190.98	15.02	260.82	42.95	14.70	24.92	210.56
T ₅	190.24	14.60	258.93	41.86	14.38	24.17	202.36
T ₆	193.35	15.89	264.88	45.92	15.81	26.91	235.32
T ₇	185.25	13.25	249.83	36.72	11.84	20.21	174.11
T ₈	187.95	13.72	252.41	38.36	13.03	22.16	184.06
T ₉	187.02	13.61	250.74	37.21	12.65	21.57	189.66
T ₁₀	188.75	13.96	254.55	39.45	13.38	22.85	191.33
SEm±	1.02	0.37	2.66	1.24	0.46	0.79	7.41
CD (p=0.05)	3.05	1.10	7.96	3.73	1.38	2.36	22.18

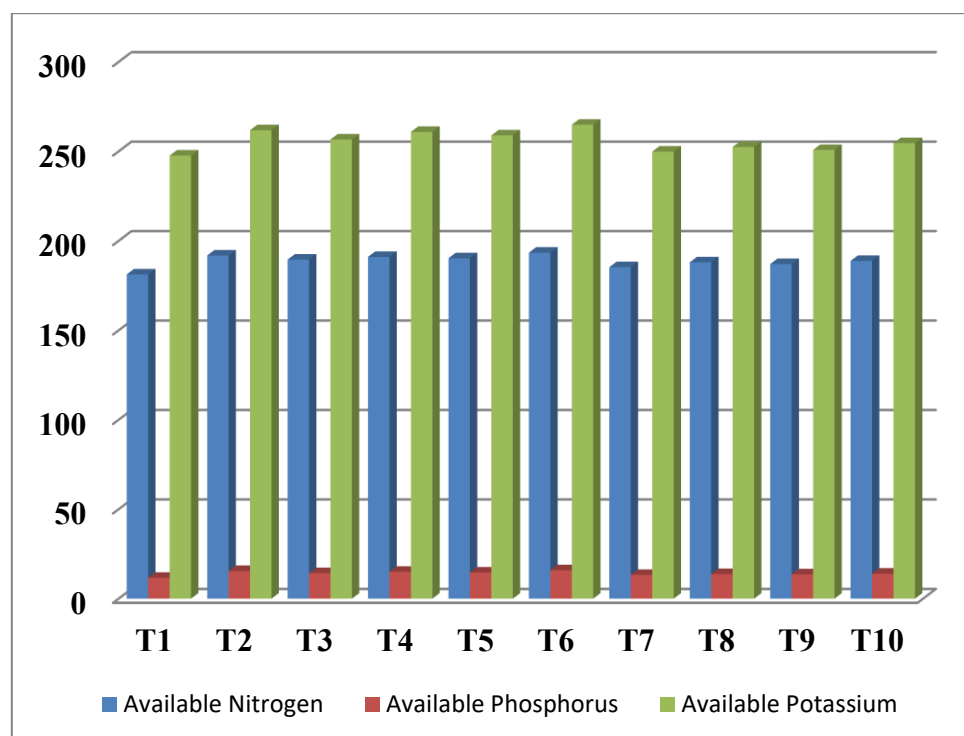


Fig. 1 Effect of phosphorus levels, biofertilizers and biochar on nutrient status of soil in chickpea.

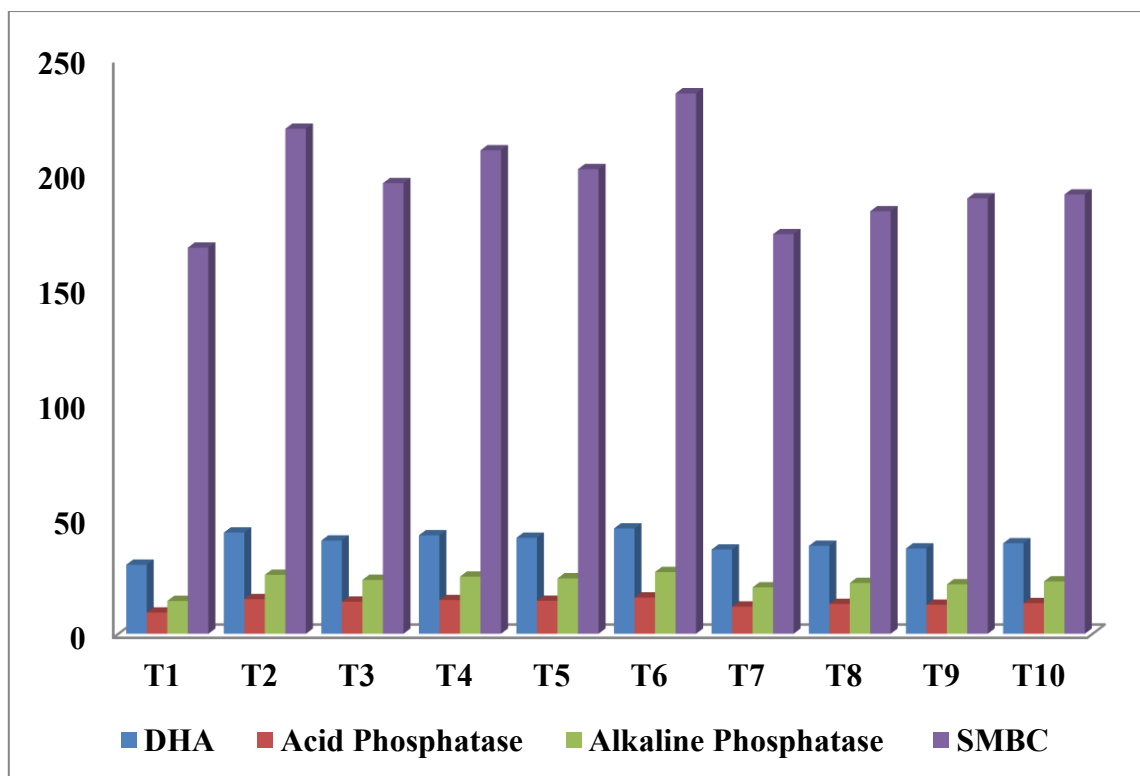


Fig. 2 Effect of phosphorus levels, biofertilizers and biochar on enzyme activities of soil in chickpea.