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RESEARCH ARTICLE

Optimizing chickpea yield and profitability through phosphorus application and PSB inoculation in a custard apple (*Annona squamosa*) based agri-horti system

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Abstract

Agroforestry offers significant environmental, economic and social benefits by integrating trees into agricultural systems. Sometimes, horticultural crops are also added, leading to agri-horti systems. This study investigates the effects of phosphorus (P) application and phosphate solubilizing bacteria (PSB) inoculation on the growth, yield and economics of *Cicer arietinum* L. in an *Annona squamosa* L. based agri-horti system. The field experiment was conducted during *Rabi* season of 2018–19 at the Agroforestry Research Farm, Rajiv Gandhi South Campus, Banaras Hindu University, Mirzapur, under rainfed conditions. The trial followed a factorial randomized block design (FRBD) with 12 treatment combinations, consisting of four phosphorus levels (0, 20, 40 and 60 kg P_2O_5/ha) and three PSB inoculation levels (0, 5 and 10 mL/kg seed), replicated thrice. The results revealed that increasing phosphorus levels and PSB inoculation significantly enhanced growth attributes such as plant height, number of branches, root nodules and dry matter accumulation. The highest yield attributes were obtained with 60 kg P_2O_5/ha and 10 mL PSB/kg seed inoculation. Grain yield (16.70 q/ha) and biological yield (43.25 q/ha) were maximized at 60 kg P_2O_5/ha, while PSB inoculation at 10 mL/kg seed resulted in a grain yield of 14.40 q/ha. Economic analysis indicated that the highest net return (₹44195) and benefit-cost ratio (2.15) were achieved with 60 kg P_2O_5/ha and 10 mL PSB/kg seed. These findings highlight the potential of phosphorus application and PSB inoculation in optimizing chickpea production under agroforestry systems, ensuring better resource utilization and economic returns for farmers in rainfed regions.

Keywords: agroforestry; chickpea; custard apple; phosphorus; phosphate solubilizing bacteria (PSB)

Introduction

Climate change poses a major threat, requiring urgent action to reduce greenhouse gas emissions. Conventional agriculture contributes significantly to emissions, but large-scale agroforestry offers a sustainable solution by integrating trees and shrubs into farming systems (1, 2). Agroforestry enhances carbon sequestration, mitigates climate change and preserves natural values in agricultural landscapes (3). The combination of perennial and annual crops within an agroforestry system fosters nutrient cycling, reduces soil erosion and improves water retention, ultimately ensuring long term agricultural sustainability (4).

In rural areas, agroforestry systems not only enhance soil productivity but also generate employment opportunities and additional income sources for farmers (5). Horticulture based agroforestry plays a crucial role in enhancing agricultural productivity while addressing climate change through effective carbon sequestration. The strategic selection of compatible tree crop systems minimizes resource competition and enhances ecological interactions. This integrated approach fosters environmental sustainability and contributes to the overall well-being of the society (6). Agri-horticultural land use integrates fruit crop into croplands, offering farmers regular income, risk mitigation and aesthetic benefits. Intercropping enhances soil health, prevents erosion and generates additional income. This approach is particularly beneficial for improving productivity in low-input, small scale farming systems (7, 8).

A. squamosa, commonly known as sugar apple or sweetsop, is the most widely cultivated species of *Annona* genus. This small tropical tree is native to the New World Tropics, likely originating in the Caribbean region. It is also referred to by various regional names, including custard apple in India, anon in Portuguese speaking countries and noina in Thailand (9). Custard apple is widely cultivated across multiple states in India including Uttar Pradesh, Madhya Pradesh, Chhattisgarh, Andhra

Pradesh, Maharashtra, Bihar, Gujarat, Tamil Nadu, Rajasthan and Assam. According to ICAR, it covers a total area of 40000 hectares. This tropical fruit plays a significant role in the agricultural landscape of these regions (10). Being a small tree known for its edible fruit, it is used in various food applications, such as flavouring in ice cream and making juice. The tree has a height ranging from 3 to 8 meters with large, spread branches and thin leaves. Its fruit is rich in vitamin C, dietary fibre, vitamin B1 and potassium (11, 12).

Chickpea (*C. arietinum* L.), the second most widely consumed legume globally, is cultivated across more than 50 countries. It serves as a valuable dietary component, particularly for individuals with diabetes, due to its low glycemic index. Rich in essential nutrients, chickpea provides a diverse array of vitamins (A, C, E, K and B complex) and vital minerals (iron, zinc, magnesium and calcium), contributing significantly to human health and nutrition (13). Also known as garbanzo bean or Bengal gram, it is an important annual pulse crop from Fabaceae family. It ranks as the third largest food legume produced globally, following *Pisum sativum* L. and *Phaseolus vulgaris* L. (14, 15). With the global population projected to reach 9.9 billion by 2050, a 70 % increase in food production is essential (16).

Phosphorus (P) deficiency in soils significantly limits crop yields, threatening food security. P deficiency is a widespread issue affecting nearly 40 % of the world's arable soils, particularly in tropical and subtropical regions. This nutrient limitation hampers root development and crop productivity, posing a major challenge to global food security (17). Although abundant in the lithosphere, plant available inorganic orthophosphate (Pi) is insoluble and poorly absorbed. Inefficient P fertilizers further exacerbate the issue, with low uptake rates with only 15 %-25 % being taken up by plants and remaining amount is leached, leading to soil degradation and water eutrophication (18, 19).

The insoluble forms of phosphorus in soil can be solubilized by phosphate solubilizing bacteria (PSB), which then makes the P available to plants, thereby enhancing crop productivity while promoting environmental sustainability (20). In recent years, the use of PSB as a bio-fertilizer gained attention as a potential way to increase the availability and uptake of P by crops (21). Late sowing of chickpeas exposes it to adverse environmental conditions, including elevated temperatures, insufficient moisture and reduced day length, which can negatively affect its yield (22, 23).

Therefore, it is essential to explore the potential of PSB in enhancing the growth and yield of late sown chickpea. While the influence of PSB on chickpea growth and production under different conditions has been studied extensively, limited information is available regarding its effects on late sown chickpea.

Materials and Methods

Experimental site

The field study was conducted in the Vindhyan region of District Mirzapur, Uttar Pradesh, at the Agroforestry Research Farm of Rajiv Gandhi South Campus, Banaras Hindu University, located in Barkachha, southeast of Mirzapur. The research area covered 750 m^2 at a latitude of 25°10' N and longitude of 82°37' E. The climate of the region is semi-arid, characterized by high summer temperatures, low winter temperatures, limited annual precipitation and moderate humidity. During the crop growth season, the average precipitation was 6.40 mm, with the highest rainfall of 4.2 mm occurring in the first week of February 2019. In the first week of April, temperatures peaked at 35.6 °C, while the second week of January recorded the lowest temperature at 4.2 ° C. The soil at a depth of 0-15 cm in the experimental field was classified as sandy loam, with a composition of 51.7 % sand, 36.5 % silt and 11.8 % clay and a pH of 6.74. The soil exhibited moderate fertility, with an organic carbon content of 0.38 % and an electrical conductivity of 0.26 ds/m.

Experimental design and treatment details

The levels of nitrogen (N), phosphorus (P) and potassium (K) in the soil. The available N was estimated using the alkaline potassium permanganate method, available phosphorus was determined using the Bray I method and available potassium was analysed using the 1 N ammonium acetate extraction method (24-26). The soil contained 162.63 kg/ha of available N, 20.55 kg/ha of available phosphorus and 231.75 kg/ha of available potassium. The experiment was conducted using a 3 × 4 factorial randomized block design, which included three levels of PSB inoculation (0, 5 and 10 mL/kg seeds) and four phosphorus levels (0, 20, 40 and 60 kg P_2O_5/ha). A total of 36 plots were established, each with a gross plot size of 3 m × 3 m, encompassing 12 treatment combinations and three replications.

Seeds of chickpea variety Pusa-362 were inoculated with PSB according to the designated treatment combinations. After inoculation, the seeds were evenly spread, shade-dried and then sown in furrows made with a kudal, situated in an alley of 11-year -old custard apple trees planted at a spacing of 5 m × 5 m. The recommended doses of N and K were applied at a rate of 20 kg/ ha, while phosphorus was applied according to the respective treatment levels. Biometric data for growth parameters were recorded at regular intervals, such as 30, 60 and 90 days after sowing (DAS) and at the harvesting stage, from five randomly tagged plants. The crop was harvested when the grains were visually observed to be fully mature. After harvesting, yield parameters were determined following threshing, winnowing, cleaning and drying processes, with results expressed as quintals per hectare (q/ha).

Statistical analysis

The collected data were compiled and subjected to statistical analysis to derive reliable conclusions. Data analysis was performed using standard analysis of variance (ANOVA). Treatment effects were evaluated using the F-ratio test and the mean and standard deviation and correlation were calculated using the R-software. The critical difference (CD) at a 5 % probability level was used to determine significant differences between treatment means.

Results and Discussions

The growth attributes, including plant height, number of branches per plant, number of root nodules per plant and dry matter accumulation per plant, were recorded maximum with the application of 60 kg P_2O_5/ha (Table 1; Fig. 1). These values were significantly higher compared to the treatments with 40 kg P_2O_5/ha, 20 kg P_2O_5/ha and the control. Similarly, the highest dose of PSB inoculation (10 mL PSB/kg seed) resulted in the highest plant height (46.47 cm), number of branches per plant (25.99), number of root nodules per plant (25.94) and dry matter accumulation per plant (13.80 g/plant), which were significantly superior to the 5 mL PSB/kg seed inoculation and the control.

The application of PSB and varying phosphorus levels positively influenced soil microbial activity, which, in turn, promoted vigorous plant growth and enhanced root development. This resulted in significant improvements in all measured growth parameters (27). This aligns with established research, suggesting that adequate phosphorus application plays a critical role in stimulating plant growth through improved energy transfer, photosynthesis and metabolic processes. Phosphorus enhances root development, nutrient uptake and overall plant vigour, as evidenced by the observed increase in root nodulation and plant biomass (28).

Similarly, the inoculation of chickpea seeds with 10 mL PSB/kg seed resulted in superior growth characteristics compared to 5 mL PSB/kg seed and the un-inoculated control. PSB are known to enhance phosphorus availability in the rhizosphere by solubilizing insoluble forms of phosphorus, thereby promoting better nutrient uptake and fostering the growth of healthy root systems (29). The combination of phosphorus fertilization and PSB inoculation led to a synergistic effect on plant development, which is consistent with previous studies. Inoculation with PSB may have facilitated better microbial activity, supported nutrient cycling and led to improved plant health and growth (30).

The yield attributes, including the number of pods per plant, number of grains per plant, number of grains per pod and 100-seed weight, were maximized with the application of phosphorus at 60 kg P_2O_5/ha. This treatment significantly outperformed the lower phosphorus levels (40 kg P_2O_5/ha, 20 kg P_2O_5/ha) and the control treatment (Table 1). Similarly, number of pods per plant (47.63) and the number of grains per plant (59.43) were highest with 10 mL PSB/kg seed inoculation, which was significantly superior to the un-inoculated treatment but statistically comparable to the 5 mL PSB/kg seed inoculation.

Table 1. Effect of phosphorus and PSB inoculation on growth and yield attributes of chickpea under custard apple based agri-horti system

Treatment	Growth attributes of chickpea				Yield attributes of chickpea			
	Plant height (cm)	Number of branches /plant	Number of root nodules /plant	Dry matter accumulation (g) /plant	No. of pods /plant	No. of grains /pod	No. of grains /plant	Test weight-100 seeds (g)
Levels of PSB (mL/kg seed)								
0 mL	44.89	24.97	23.78	13.09	43.27	1.21	52.49	14.01
5 mL	45.75	25.36	24.48	13.48	44.82	1.23	55.53	14.12
10 mL	46.47	25.99	25.94	13.80	47.63	1.24	59.43	14.22
SEm ±	0.42	0.27	0.31	0.17	1.16	0.03	1.86	0.07
CD (p = 0.05)	1.25	0.79	0.90	0.50	3.39	NS	5.44	NS
Levels of phosphorus (in kg P_2O_5/ha)								
0 kg	42.03	23.04	21.65	11.81	38.58	1.16	44.54	13.61
20 kg	44.81	24.57	23.46	12.86	42.89	1.21	51.93	14.05
40 kg	46.73	26.38	25.36	13.98	46.71	1.26	58.76	14.37
60 kg	49.25	27.78	28.45	15.16	52.78	1.29	68.03	14.44
SEm ±	0.49	0.31	0.35	0.20	1.34	0.03	2.14	0.09
CD (p = 0.05)	1.44	0.92	1.04	0.58	3.92	0.09	6.28	0.25

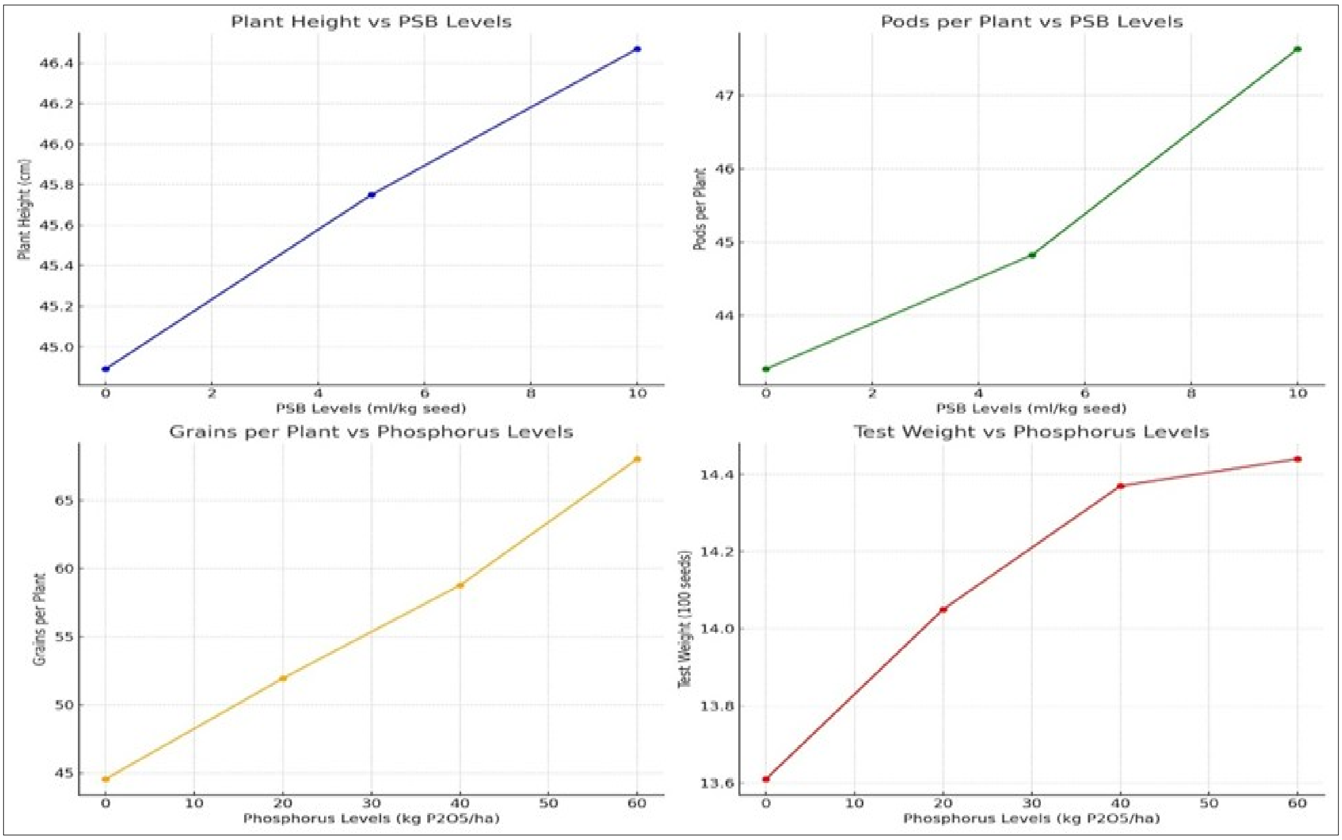

Fig. 1. Effect of PSB levels and phosphorus application on growth and yield attributes of chickpea.

The enhanced number of flowers that matured into pods under higher phosphorus levels and PSB inoculation may be attributed to the stimulation of meristematic activity, promoting tissue differentiation from somatic to reproductive stages and encouraging the development of floral primordia. Although the number of grains per pod and the 100-seed weight did not show significant differences across PSB inoculation levels, the increased number of pods and grains per pod during maturity contributed to the higher test weight. The results are in agreement with earlier findings that higher phosphorus levels positively affect the reproductive potential of legume crops, including chickpea (31, 32).

The highest grain yield, straw yield and biological yield were recorded with the application of phosphorus at 60 kg P_2O_5/ha, which was significantly superior to the lower phosphorus levels (40 kg P_2O_5/ha, 20 kg P_2O_5/ha) and the control treatment. Similarly, the maximum grain yield (14.40 q/ha), straw yield (22.76 q/ha) and biological yield (37.16 q/ha) were achieved with the application of 10 mL PSB/kg seed inoculation (Table 2 & Fig. 2). The increase in phosphorus levels likely enhanced the photosynthesis process, thereby improving the plant's ability to produce carbohydrates, sugars, starch, amino acids and proteins. This, in turn, supported fruiting and seed production, ultimately boosting the biological, grain and straw yields. The positive impact of phosphorus application and PSB inoculation on chickpea yield has also been reported previously (33, 34).

The highest harvest index was observed in the control treatment, followed by 60, 20 and 40 kg P_2O_5/ha. Regarding PSB inoculation, the harvest index was highest with 5 mL PSB/kg seed inoculation, followed closely by 10 mL PSB/kg seed inoculation and the un-inoculated treatment. A lower biomass can lead to higher harvest index as the plant allocates a greater proportion of its limited growth to grain production rather than vegetative parts. As a result, the ratio of grain yield to total biomass increases, even if the absolute yield is lower (35-38). Nonetheless, the improved productivity from phosphorus application and PSB inoculation is noteworthy, particularly given the significant improvement in grain yield and the economic returns associated with the higher phosphorus dose and PSB inoculation levels (33, 34, 39).

Table 2. Effect of phosphorus and PSB inoculation on yield and economics of chickpea under custard apple based agri-horti system

Treatment	Yield				Economics			
	Grain yield (q/ha)	Straw yield (q/ha)	Biological yield (q/ha)	Harvest index (%)	Cost of cultivation ₹/ha	Gross return ₹/ha	Net return ₹/ha	B:C ratio
Levels of PSB (mL/kg seed)								
0 mL	12.56	20.31	32.87	38.20	36565	62086	25521	1.69
5 mL	13.37	21.25	34.62	38.74	36945	66032	29087	1.78
10 mL	14.40	22.76	37.16	38.73	37076	71100	34024	1.91
SEm ±	0.46	0.66	1.07	_	_	2233.44	2233.44	0.06
CD (P = 0.05)	1.35	1.95	3.13	NS	_	6550.39	6550.39	0.18
Levels of phosphorus (in kg P_2O_5/ha)								
0 kg	10.32	15.97	26.29	39.18	35291	50871	15580	1.44
20 kg	12.41	19.86	32.27	38.46	36508	61305	24797	1.68
40 kg	14.35	23.38	37.73	38.03	37386	70991	33604	1.90
60 kg	16.70	26.55	43.25	38.57	38262	82457	44195	2.15
SEm ±	0.53	0.77	1.23	_	_	2578.95	2578.95	0.07
CD (p = 0.05)	1.56	2.25	3.62	NS	_	7563.74	7563.74	0.20

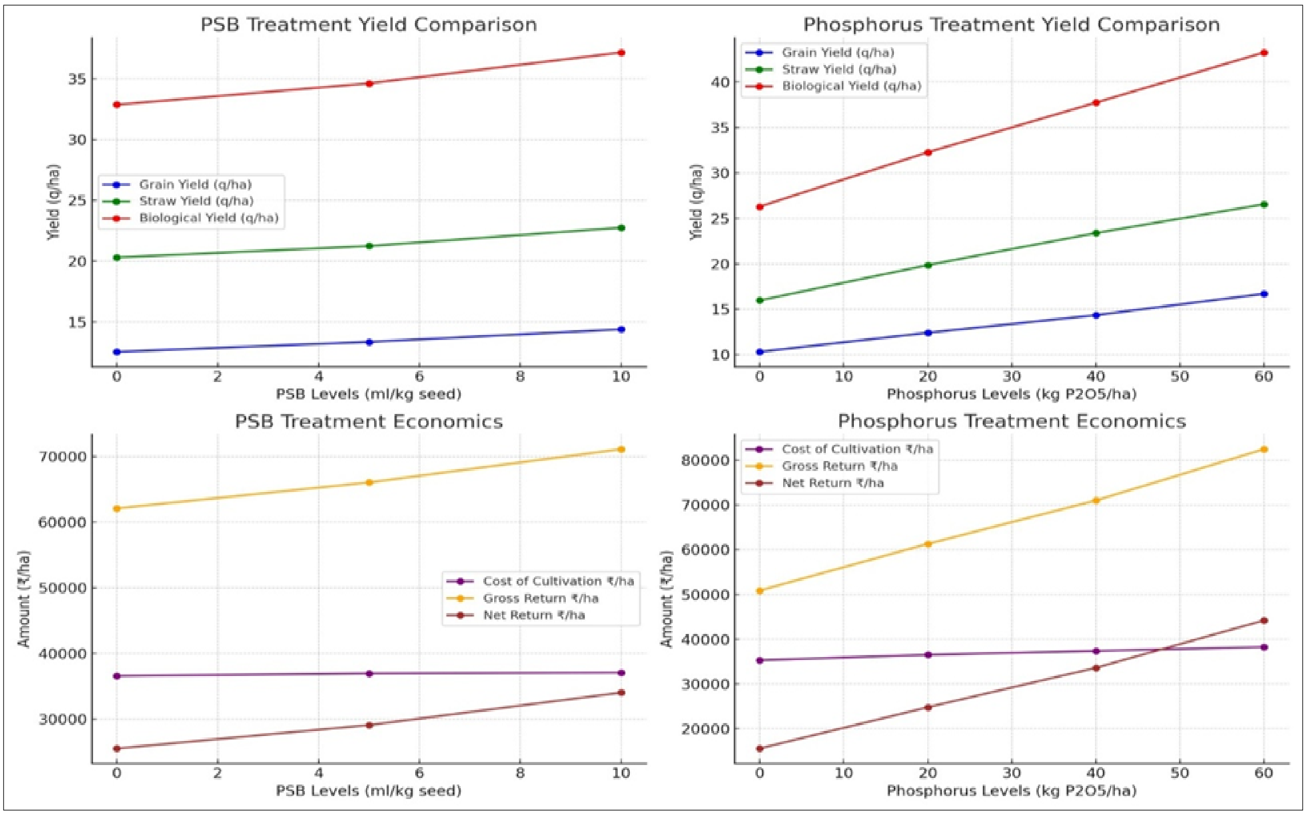

Fig. 2. Effect of PSB and phosphorus levels on yield and economics in crop production.

In terms of economic performance, the maximum gross return, net return and benefit-cost ratio were recorded with the application of 60 kg P_2O_5/ha. Among the PSB inoculation treatments, inoculation with 10 mL PSB/kg seed inoculation showed a significant improvement in gross return, net return and benefit-cost ratio compared to the un-inoculated treatment but was statistically at par with the 5 mL PSB/kg seed inoculation. This increased economic return was observed despite the higher cost of cultivation with 60 kg P_2O_5/ha and 10 mL PSB/kg seed inoculation, the increase in grain yield led to higher gross returns, net returns and a better benefit-cost ratio compared to lower phosphorus doses and the un-inoculated control. This finding underscores the economic viability of integrating phosphorus fertilization with PSB inoculation to achieve optimal productivity and profitability in chickpea cultivation (30, 40, 41).

Additionally, the correlation analysis in chickpea conducted under the agri-horti system highlighted key agronomic and economic traits influencing productivity and sustainability (Fig. 3). Strong positive correlations between plant height (PH), number of branches per plant (NOBPP), number of pods per plant (NPPP) and grain yield (GY) indicated that structural and reproductive traits significantly impact yield potential (42). Economic traits like gross returns (GR), net returns (NR) and benefit -cost (BC) ratio show a strong association with yield-related parameters, suggesting the profitability of high-yielding genotypes in integrated farming systems (43). The moderate correlation of harvest index (HI) with yield components suggests that optimizing biomass partitioning is crucial for efficient resource utilization (44). Additionally, the cost of cultivation (COC) correlates positively with most yield traits, indicating that strategic input management can enhance productivity while ensuring sustainability. These findings emphasize the importance of selecting high-yielding and resource-efficient chickpea genotypes for successful integration into agri-horti systems, ensuring both agronomic stability and economic viability.

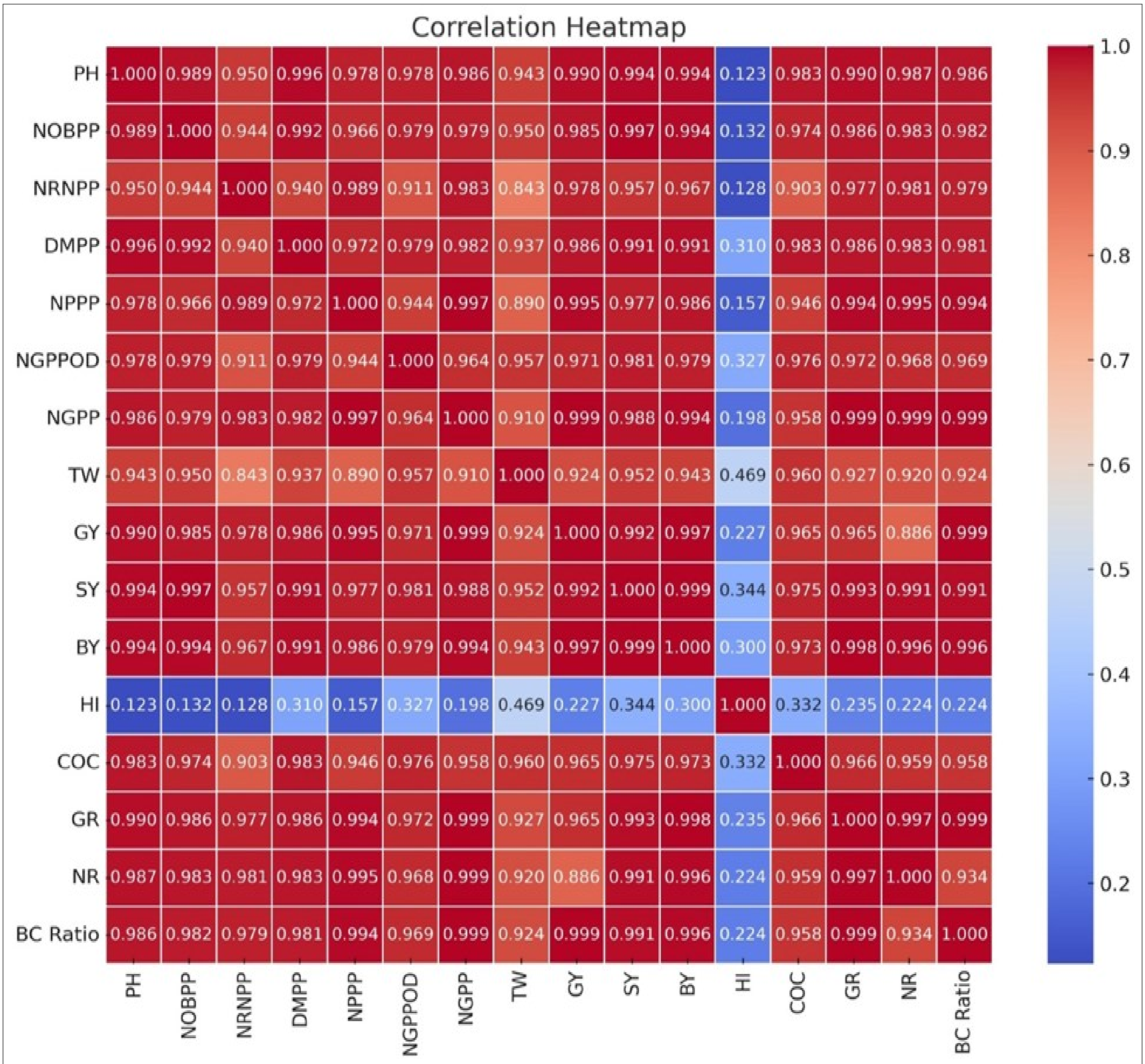

Fig. 3. Correlation matrix of key agronomic and economic traits in chickpea under agri-horti system.

PH: plant height; NOBPP: number of branches per plant; NRNPP: number of root nodules per plant; DMPP: dry matter accumulation per plant; NPPP: number of pods per plant; NGPPOD: number of grains per pod; TW: test weight; GY: grain yield; SY: straw yield; BY: biological yield; HI: harvest index; COC: cost of cultivation; GR: gross return; NR: net return; BC ratio: benefit cost ratio.

Conclusion

In conclusion, the study demonstrated that the application of 60 kg P_2O_5/ha in combination with 10 mL PSB/kg of seed inoculation significantly enhanced the growth, yield and economics of chickpea (*C. arietinum* L.) under a custard apple-based agri-horti system. This treatment led to notable increase in plant height (17.2 %), number of branches (20.65), root nodules (31.4 %) and dry matter accumulation (28.3 %) over the control. Yield parameters, including the number of pods, grains per plant, grain weight and overall grain yield, were also maximized under these conditions, showing significant superiority over other phosphorus and PSB inoculation levels. The results suggest that phosphorus and PSB inoculation effectively promote microbial activity in the soil, leading to improved plant growth, root development and nutrient uptake, particularly phosphorus, which is crucial for chickpea production. The combination of 60 kg P_2O_5/ha and 10 mL PSB/kg seed inoculation resulted in the highest biological yield, grain yield and net returns, making it a viable and economically beneficial practice for chickpea cultivation in semi-arid regions. Additionally, the custard apple-based agroforestry system offers an integrated approach to sustainable land use, contributing to soil fertility, biodiversity and economic stability in rural areas. Adoption of this nutrient combination is strongly recommended to enhance chickpea productivity and farm profitability in resource-limited environments.

Authors' contributions

MSK and AKS collected data and drafting and writing the original manuscript. SP and YS contributed to the conceptualization of the study and provided essential project supervision. RM, DA and BKS carried out necessary modifications and final draft preparation of this research framework. All the authors critically reviewed and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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