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Modulating Maize Productivity, Grain Quality and Economic Resilience through Conjoint Use of Phosphorus, Boron and Lime under Typic Hapludalf Soils

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Soil acidity is a pervasive obstacle to global crop productivity, profoundly restricting availability of essential nutrients especially, phosphorus (P) and boron (B). Addressing their deficiencies along with liming is the key to secure sustainable harvests. The present study explores the impact of graded applications of P, B and liming under maize in the *Typic Hapludalf* soils of Palampur region

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of Kangra valley, H.P. This endeavour tested graded doses of P (P_0: 0, P_1:45 and P_2: 60 kg P ha^{-1}) and B (B_0: 0, B_1: 1 and B_2: 2 kg B ha^{-1}) with 2 liming rates (L_0: no lime and L_1: 3.6 t ha^{-1}) in a randomized completely block design replicated thrice. The study assessed their impacts on nutrient acquisition, quality and monetary returns with the hypothesis that maximum doses would prove their superiority. Significant interactions (P × L, B × L, P × B) were evident only for plant height. Grain and stover yields increased notably with 60 kg P and 2 kg B ha^{-1}. Liming boosted yields by about 13.4 and 18.7%, respectively over controls. Likewise, total nutrient uptake (N, P, K and B), protein content and protein yield also enhanced under same treatments. Economic analysis identified T_{18} ($P_2B_2L_1$) as the highest yielding with net returns of ₹49681 but was, second in economic viability (B:C, 0.87), behind T_5 ($P_1B_1L_0$) with highest ratio (0.94).

Keywords: Soil acidity; productivity; nutrient uptake; quality; economic viability.

1. INTRODUCTION

Maize (*Zea mays* L.), a globally celebrated cereal, is acclaimed for its resilience and prolific yield potential, playing a seminal role in sustaining millions of livelihoods (Sharma *et al.,* 2025). Despite its promise, the pressure to amplify its quality production continues to intensify by shrinking arable land, and escalating input costs coupled with climatic vagaries. These setbacks are compounded by widespread soil degradation particularly in the resource constrained areas. Among the most formidable barriers to maize productivity is the prevalence of soil acidity, where low pH, poor nutrient retention, and high aluminium (Al) saturation create hostile environment for plant growth (Takala *et al.,* 2025). Such adverse edaphic conditions impair nutrient availability by fixation and increased toxic metal solubility, consequently leading to degraded crop quality, diminished yield and monetary returns. Despite decades of fertilizer research, responses in these soils remain suboptimal as a consequence of incomplete understanding of key limiting factors particularly the macro and micronutrient imbalances. Among essential plant nutrients, P and B are the most acutely limited under such soils. P plays exceptional role in phosphorylation reactions, ATP-driven energy transduction, nucleic acid synthesis and metabolism (Haokip *et al.,* 2019) while, B is equally vital, supporting cell wall integrity, membrane function, and reproductive development (Arunkumar and Srinivasa, 2018). However, in acid soils, solubility and bioavailability of both these nutrients is significantly diminished. P is rendered unavailable owing to fixation by iron and aluminium oxides whereas, B is highly prone to leaching due to highly weathered nature of these soils and high rainfall. Further, liming has long been recognized as a pragmatic amendment for ameliorating acid soils, that works by raising soil pH, reducing aluminium (Al) toxicity and improving availability and uptake of nutrients (Ao and Sharma, 2021). Conversely, failure to use lime, together with the increased use of acidifying fertilizers such as urea and diammonium phosphate to correct N and P deficiencies, has further increased acidity of such soils (Fageria *et al.*, 1995). Prior findings have reported conflicting outcomes of lime application on phosphate availability, with outcomes varying according to lime and P rates and their interaction. Thus, efforts to ameliorate the deleterious effects of soil acidity require simultaneous measures to increase available P and B. While, the sole impacts of P, B and lime in alleviating acid soil constraints are firmly documented, but there is a paucity of information on their conjoint effects, which hampers farmers' ability to determine optical application rates. This study hypothesized that applying their highest tested rates might produce significant outputs in terms of quantity as well as quality**.** To test this, a field experiment was carried out to evaluate the individual and interactive effects of varying rates of P, B and lime on maize growth, productivity, quality and economic viability.

2. MATERIALS AND METHODS

Study Site: The present endeavour was undertaken at the experimental farm, Department of Soil Science, CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur, India, during *kharif* 2021. Soils were classified as *Alfisols* (*Typic Hapludalf*) under a Cwa (monsoon-influenced humid subtropical) climate (Peel *et al.,* 2007). The silty clay loam soil had a pH of 5.67 and an organic carbon content of 7.54 g kg^{-1}. Nutrient analysis showed low nitrogen (260 kg ha^{-1}), 1956), medium phosphorus (18.8 kg ha^{-1}) and potassium (197 kg ha^{-1}) and boron deficiency (0.37 mg kg^{-1}).

Experimental Details: The experiment comprised a factorial arrangement of three levels of P (P_0: 0, P_1: 45 and P_2: 60 kg P ha^{-1}) and B (B_0: 0, B_1: 1 and B_2: 2 kg ha^{-1}) and two of lime (L_0: 0 and L_1: 3.6 t ha^{-1}), arranged in eighteen treatment units in a randomized completely block design with triplicate replications. Basal application of N and K were 120 kg and 40 kg ha^{-1}, respectively. At sowing, half the N dose and full P and K doses were applied, remaining N was top dressed in two equal splits at the knee-high and pre-tasselling stages. Sources for N and K were urea and muriate of potash, B and P were applied at sowing through single super phosphate and borax, respectively. Finely ground lime ($CaCO_3$) as per the lime requirement of 3.6 t ha^{-1} was incorporated in the designated plots four weeks prior to sowing. Maize hybrid *Kanchan* was planted on 27th June, 2021 in 3.0 × 2.0 m plots with spacing of 60 × 20 cm and harvested on 17th October, 2021. Recommended cultural practices were followed throughout.

Plant Sampling, Processing and Analysis: Grain and stover yields were recorded at harvest. Samples (plot wise) were oven dried at 60 ºC for N, P and K analysis and ground in a Wiley mill. B content was determined following dry ashing in a blast furnace. Nutrient concentrations were quantified *via* micro kjeldahl for N (Jackson, 1973), colorimetry for P (Jackson, 1973), flame photometry for K (Black, 1965), and colorimetry for B (Datta *et al.,* 1998). Total nutrient uptake (grain + strover) was calculated by multiplying nutrient concentrations with respective yields. The total nutrient uptake was derived as the sum of uptake by grain and stover.

Economic Parameters were Computed Following the Expressions:

The cost of cultivation: Total expenditures associated with maize cultivation.

Gross returns: Yield (Grain and Stover) × Market selling price

Net returns = Gross returns - Cost of cultivation

B: C = Net returns / Cost of cultivation

3. RESULTS AND DISCUSSION

Plant Height: Maize height measured at various growth stages (30 days after sowing, tasselling and at harvest) demonstrated statistically significant differences. Significant interactions between B × L were observed at all three stages (Table 1). Treatments with maximum level of boron and lime (B_2L_1) elicited an increase of 47.9% at 30 DAS, 12.3% at tasselling and 14.8% at harvest, over controls. Further, P × B interaction was significant only at the harvest where peak tested levels (P_2B_2) yielded tallest plants (232.7 cm) compared to shortest (201.6 cm) in untreated plots (Table 2). Likewise, P × L interactions were found significant at all stages. At P_2L_1, height was found statistically equal to P_1L_1 (Table 3). Conversely, shortest heights of 45.1, 197.9 and 207.9 cm at the three respective stages were found in the plots lacking both P and lime.

Enhanced maize height under maximum levels of P, B and lime under present experimental conditions might be an outcome of improved nutrient availability and effective mitigation of soil acidity to some extent. Graded additions of P might have addressed their inherent deficiencies in these soils, enhancing energy metabolism and healthier root system that fueled vertical growth of the plant (Sankadiya and Sanodiya, 2021) while, B enhanced cell formation, sugar transport, photosynthetic and meristem activity, which led to stem elongation (Singh *et al.,* 2017). In contrast, the non- amended plots that received none of these inputs suffered from poor root activity and limited nutrient accessibility, resulting in stunted heights. Chowdhury *et al.,* (2015) and Kabir *et al., (*2013) attributed significant enhancement in plant height in lettuce and groundnut, respectively, in response to conjoint P and B application, suggesting a potential synergism between the two nutrients under field conditions. Further, lime likely neutralized exchangeable acidity and Al toxicity, fostering healthier root growth, thus the height (Ao and Sharma, 2021).

Table 1. Interaction effect of B and lime application on plant height (cm) of maize

Liming (t ha^{-1})	**30 DAS**			**Tasselling**			**Harvest**		
	B (kg ha^{-1})								
	0	**1**	**2**	**0**	**1**	**2**	**0**	**1**	**2**
0	42.8	45.6	51.8	197.5	209.0	214.8	206.1	218.4	222.0
3.6	55.4	62.0	63.3	208.3	217.9	221.8	221.8	229.6	236.6
P ≤ 0.05	2.2			7.2			7.6		

Table 2. Interaction effect of P and B application on plant height (cm) of maize at harvest

B (kg ha^{-1})	P (kg ha^{-1})		
	0	45	60
0	201.6	218.8	221.4
1	219.0	225.1	228.0
2	227.0	228.3	232.7
P ≤ 0.05	9.3		

Table 3. Interaction influence of P and lime application on plant height (cm) of maize

Liming (t ha^{-1})	30 DAS			Tasselling			Harvest		
	P (kg ha^{-1})								
	0	45	60	0	45	60	0	45	60
0	45.1	47.2	47.9	197.9	209.1	214.3	207.9	216.7	221.9
3.6	52.5	63.9	64.2	211.6	215.3	221.5	226.9	230.7	232.8
P ≤ 0.05	2.2			7.6			7.6		

Nutrient Uptake: Maize exhibited significant variations in nutrient uptake in response to varying rates of P, B and lime application (Table 4). The addition of 60 kg P ha^{-1} proved its superiority among all tested ones followed by 45 kg P ha^{-1} while, the lowest uptake was evidenced with P-deprived treatment. Compared to control, 60 kg P ha^{-1} led to increases of about 21, 37, 16 and 22% in N, P, K and B uptake, respectively. Whereas, application 2 kg B ha^{-1} yielded the highest N and P uptakes however, it showed statistical equivalence with 1 kg B ha^{-1}, while the minimum was recorded with B omission. On the contrary, increasing B levels from 0 to 2 kg ha^{-1} resulted in a proportionate increase in K and B uptakes. The application of 3.6 t ha^{-1} lime showed remarkable gains of about 25, 40, 24 and 25% in N, P, K and B uptakes, over their corresponding skipped treatments. The overall enhancement in nutrient uptake with graded P additions might have improved soil solution P levels, which likely stimulated root hair development and expanded root surface area, thereby improving nutrient absorption efficiency. Additionally, it might have formed stable alumino-phosphate complexes with toxic Al species, effectively reducing exchangeable acidity and creating a more conducive rhizosphere for nutrient uptake. A study by Zhao *et al.,* (2021) revealed that tailoring P fertilizer dose according to soil pH is critical for optimizing maize productivity and nutrient use efficiency. Whereas, B fertilization might have hastened the rhizosphere enzymatic activity and nutrient solubilisation, increasing nutrient availability (Singh and Kumar, 2018). It also strengthens cell wall and membrane structure, providing anchorage to root system and eventually causing efficient nutrient transport and better soil nutrient acquisition (Gupta *et al.,* 2015). Liming might have neutralized the toxic effects of predominant ions, such as aluminum and manganese, under acidic soil conditions that inhibit root growth, thereby improving root development and soil microbial activity. This process might have enhanced nutrient solubility particularly of nitrogen, phosphorus, potassium, and boron and significantly increased their uptake by maize (Fageria and Baligar, 2021).

Protein Content and Protein Yield: Graded additions of P and B exercised striking gains in both protein content and protein yield (Table 4). Peak protein content was found with 60 kg P ha^{-1} which was statistically equivalent to 45 kg P ha^{-1} and least under P omitted plots. Whereas, the protein yield increased progressively with higher P levels and was maximum under 60 kg followed by 45 kg P ha^{-1} and lowest under control. Although, B application did not result in statistically significant differences in protein content across doses, but the highest value was noted with 2 kg followed by 1 kg B ha^{-1} and least in absence of B. Whereas, protein yield was maximized at 2 kg which was statistically alike with 1 kg B ha^{-1}, with the former reflected a 9% increase over non-amended treatment. Lime amendment significantly increased both protein content and yield by 8.2 and 33% respectively, over the unlimed plots.

The observed enhancement in protein content and yield with graded applications of P, B and lime can be ascribed to improved N acquisition and assimilation, driven by improved soil conditions. P is integral for root growth, nodulation, ATP formation, efficient N metabolism and ribosomal activity; all these processes are essential for protein synthesis.

Assefa *et al.,* (2021) reported protein enriched wheat with conjoint P and S application. B facilitates N metabolism and the translocation of amino acids and accelerated enzymatic activity, directly influencing protein accumulation in grains. Work done by Singh *et al.,* (2025) in maize also demonstrated statistically sound results with B application compared to no additions. Lime reduces soil acidity and Al toxicity, thus improving root architecture and microbial activity, which collectively enhance N availability and uptake (Ao *et al.,* 2021). Increased uptake of N and P witnessed in the current study with liming might have improved N metabolism, increased nitrate reductase activity which stimulated protein biosynthesis in grain. The complementary effects of these amendments creates a favorable environment for efficient N use, culminating in higher protein content and yield of maize.

Yield: Significant augmentations in the maize yields were witnessed with graded doses of P, B and lime (Table 4). Grain yield responded incrementally across varied P treatments in the order 60 > 45 and 0 kg P ha^{-1}. The highest tested rate recorded an increase of about 14% over untreated control. Straw yield followed similar trend peaking at 60 kg P ha^{-1} followed by 75 kg P ha^{-1} which however, behaved statistically alike with the control. B fertilization showcased statistical equivalent effects on grain yield across treatments, indicating a plateaued response. Conversely, straw yield accrued proportionate gains with increased rates. Liming significantly improved both the yields by about 13 and 19%, relative to un-amended plots. These outcomes signify the complementary relation between added nutrients and soil amendments particularly, under the deficient conditions. Adequate P availability promotes foraging capacity of roots, early flowering, synchronizes reproductive development, bolstering pollination success and seed set. Chandrakala *et al.,* (2017) demonstrated eye catching improvements in fingermillet-maize system with higher doses of P relative no lower rates. The improvement with B is mainly attributed to its integral role in the vegetative improvement, sugar transport to growing parts and hastened reproductive development of plants (Kumar *et al*., 2019). Usually, micronutrients are required in very minute quantities but exhibit significant impacts on metabolism by working synergistically with hormones and enzymes for the normal functioning of plant system. Lime ameliorates soil acidity by neutralizing toxic Al ions and elevating pH, thereby improving root growth and nutrient uptake efficiency. Together, these inputs optimize physiological processes, boost photosynthetic activity and assimilate partitioning to reproductive structures culminating in superior grain yield and biomass accumulation. Research by Dugalić *et al.,* (2025) advocated that liming can be considered as a longer-term sustainability practice in maize production under the acid soils. Conversely, work done by Dwivedi *et al.,* (1992) on pea-maize demonstrated significant improvements in pea yield with conjoint use of 1.5 kg B ha^{-1} and liming at 3 t ha^{-1}, but was insufficient to meet B requirements of the succeeding corn.

Economic Viability: A critical evaluation of the economic data indicated that the cost of cultivation, gross and net returns were associated with T_{18} ($P_2B_2L_1$) followed by T_{17} ($P_2B_1L_1$) and the least under untreated control (Table 5). The elevated cost of cultivation (₹57349 ha^{-1}) might be a consequence of cumulative expenses incurred due to higher input levels of P, B and lime. Conversely, the least cost was recorded under T_1 ($P_0B_0L_0$) which resulted from absence of such amendments (₹44881 ha^{-1}). T_{18} also achieved the highest gross (₹107030 ha^{-1}) and net returns (₹49681 ha^{-1}) followed by T_{17} (₹103427 ha^{-1}) and (₹46649 ha^{-1}) respectively. In contrast, the control recorded the lowest gross (₹78840 ha^{-1}) and net returns (₹33959 ha^{-1}). The superior returns under T_{18} ($P_2B_2L_1$) and T_{17} ($P_2B_1L_1$) were primarily due to significantly higher yields realized, which outweighed the increased inputs costs. Prior findings by Sankadiya and Sanodiya (2021) reported conjoint use of 70 kg P ha^{-1} and 60 kg K ha^{-1} as the most economically feasible treatment in maize. Conversely, Thakur (2019) reported improved returns in cauliflower with foliar application of B over its soils application. A study by Ao *et al.,* (2021) witnessed improved economic returns with conjoint use of 26.8 mg kg^{-1} P, 0.90 mg kg^{-1} B and ¼ lime of LR for maize cultivation under pot study in acidic soils of Nagaland. The highest B: C was recorded in T_5 ($P_1B_1L_0$) (0.94) followed by T_{18} ($P_2B_2L_1$) (0.87) and T_9 ($P_2B_2L_0$) (0.86) and the lowest (0.75) in T_{10} ($P_0B_0L_1$). Despite higher net returns obtained under T_{18} ($P_2B_2L_1$), its comparatively lower B:C to T_5 ($P_1B_1L_0$) might be attributed to the additional expenditure on higher cost of liming (₹7200 ha^{-1}). Nonetheless, considering the residual effects of liming during the subsequent years, it would prove economically advantageous in the long run.

Table 4. Impact of graded doses of P, B and lime on total nutrient uptake, protein content, protein yield and productivity of maize

Treatment	Total nutrient uptake				Protein content	Protein yield	Grain yield	Stover yield
	N	P	K	B				
	kg ha^{-1}			g ha^{-1}	%	kg ha^{-1}	q ha^{-1}	
P (kg ha^{-1})								
0	86.7	24.4	61.1	63.4	7.97	351	43.9	59.1
45	97.3	29.6	67.3	71.9	8.19	390	47.5	64.5
60	105.1	33.4	70.9	77.1	8.29	408	49.1	65.7
$P \leq 0.05$	3.3	1.31	1.2	2.7	0.23	16	1.4	1.6
B (kg ha^{-1})								
0	92.6	27.7	63.8	66.1	7.98	366	45.7	60.4
1	96.7	29.2	66.6	70.6	8.18	385	46.9	63.5
2	99.8	30.4	69.0	75.8	8.29	398	47.9	65.5
$P \leq 0.05$	3.3	1.3	1.3	2.7	0.23	16	1.4	1.6
Liming (t ha^{-1})								
0	85.5	24.3	59.4	62.8	7.83	344	43.9	57.7
3.6	107.2	33.9	73.5	78.7	8.47	422	49.8	68.5
$P \leq 0.05$	2.7	1.1	1.1	2.0	0.19	13	1.1	1.3

Table 5. Effect of varied treatment combinations of P, B and lime on the monetary returns of maize

Treatments	Cost of cultivation	Gross return	Net return	B: C
	(₹ ha^{-1})			
T_1-$P_0B_0L_0$	44881	78840	33959	0.76
T_2-$P_0B_1L_0$	45453	79890	34437	0.76
T_3-$P_0B_2L_0$	46024	81272	35248	0.77
T_4-$P_1B_0L_0$	47975	85628	37653	0.78
T_5-$P_1B_1L_0$	45453	88300	42847	0.94
T_6-$P_1B_2L_0$	49118	89620	40502	0.82
T_7-$P_2B_0L_0$	49006	86270	37264	0.76
T_8-$P_2B_1L_0$	49578	90625	41047	0.83
T_9-$P_2B_2L_0$	50149	93462	43313	0.86
T_{10}-$P_0B_0L_1$	52081	90917	38835	0.75
T_{11}-$P_0B_1L_1$	52653	92902	40249	0.76
T_{12}-$P_0B_2L_1$	53224	95437	42213	0.79
T_{13}-$P_1B_0L_1$	55175	97738	42563	0.77
T_{14}-$P_1B_1L_1$	55746	100677	44930	0.81
T_{15}-$P_1B_2L_1$	56318	101357	45039	0.80
T_{16}-$P_2B_0L_1$	56206	98700	42494	0.76
T_{17}-$P_2B_1L_1$	56778	103427	46649	0.82
T_{18}-$P_2B_2L_1$	57349	107030	49681	0.87

4. CONCLUSION

This study delivers a breakthrough approach for managing crop production under acid stressed agro-ecosystems. Conjoint use of 60 kg P ha^{-1}, 2.0 kg B ha^{-1} along with liming at 100% lime requirement (3.6 t ha^{-1}) exercised significant impacts on maize productivity, protein content and quality. It imparted remunerative effects in terms of gross and net returns, though the B:C was comparatively lower owing to the higher cost involved in liming. Consequently, this study serves as a sustainable blueprint for improving agricultural output, economic viability and nutritional standards under nutrient constrained acid soils. These findings will not only help in refining nutrient management strategies but also contribute to sustainable agriculture by addressing soil health and crop productivity simultaneously. Such research is essential for guiding both policy decisions and field-level practices in resource-constrained farming systems.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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