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EFFECT OF PHOSPHORUS AND FOLIAR APPLICATION OF GLYCINE ON THE GROWTH AND YIELD OF GARDEN PEA (*PISUM SATIVUM* L.)

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Abstract

Garden pea (*Pisum sativum* L.) is a nutritious crop whose productivity is limited by poor nutrient management, leading to delayed flowering and lower yields. This study examined the effects of phosphorus and foliar glycine application on the growth and yield of garden pea. It was carried out at the Horticulture Research Farm, University of Agriculture, Peshawar. The experiment used a Randomized Complete Block Design with two factors and three replications. Factor A was phosphorus levels (40, 60, and 80 kg ha^{-1}), while Factor B was glycine concentrations (0, 90, 180, and 270 mg L^{-1}). Both treatments significantly affected growth and yield traits, except for branches per plant. Applying phosphorus at 80 kg ha^{-1} resulted in maximum plant height, leaves per plant, pods per plant, pod length and diameter, seeds per pod, chlorophyll content, hundred seed weight, root fresh weight, and pod yield, while also significantly reducing days to flowering and first harvest. Most growth and yield parameters at 80 kg ha^{-1} phosphorus were similar to those at 60 kg ha^{-1}. Foliar applications of glycine at 270 mg L^{-1} were most effective, improving plant height, leaf number, pod characteristics, seed parameters, chlorophyll content, root biomass, and overall yield by promoting earlier flowering and harvest compared to lower concentrations and control treatments. The study recommends combining phosphorus at 60 kg ha^{-1} with foliar application of glycine at 270 mg L^{-1} for optimal growth, yield, and early harvest of garden pea.

Key words: Garden pea; Phosphorus; Glycine; Growth; Yield; Sustainability

Introduction

Garden pea (*Pisum sativum* L.) is an important leguminous crop belonging to the family Fabaceae and is widely cultivated in temperate regions worldwide. Beyond its agronomic value, peas play a significant role in sustainable agriculture by fixing atmospheric nitrogen, thereby improving soil fertility and reducing dependence on synthetic nitrogen fertilizers. As a nutrient-dense crop rich in carbohydrates, proteins, minerals, and vitamins (Santhiya *et al*., 2024), garden pea contributes substantially to plant-based protein supply and global food security. Its center of origin lies in the Near East and Central Asia, and it currently ranks third among grain legumes in global production, after soybean and common bean. China and Russia are the major producers, with China accounting for approximately 61% of global production (Li *et al*., 2017).

It is cultivated on approximately 27,000 hectares in Pakistan, with an annual production of approximately 178,200 tons (Ahmad *et al.,* 2025). Unfortunately, the quality and production of peas in Pakistan are significantly lower than in other countries, mainly due to inadequate nutrient management and environmental stresses. Pea is usually cultivated in mid-October, and harvesting begins in December and continues through April. Punjab is the leading producer of peas among the other provinces in Pakistan, with a total of 71% of the country's pea production, followed by Khyber Pakhtunkhwa, Sindh, and Balochistan (Khan *et al.,* 2025).

Pea production is highly dependent on soil pH, planting depth, and row spacing (Szczepanek *et al.,* 2024). Its flowering is sensitive to various factors, including humidity, temperature, and nutrition. To achieve higher yields, proper nutrient management is necessary. Nutrients like amino acids, phosphorus, etc., significantly improve the yield of pea (Powers & Thavarajah, 2019). Phosphorus is a well-known macronutrient and boosts ATP production, nucleic acid synthesis, and vigorous plant growth. It improves nodulation and enhances nitrogen fixation in leguminous crops, thereby ensuring sustainable pea production (Zhong *et al.,* 2023). Optimum supply of phosphorus enhances pea growth and development by improving the biomass, root, seed, and pod development. Lower phosphorus levels can reduce nitrogen fixation due to impaired nodule development, ultimately reducing plant growth and yield (Mitran *et al.,* 2018).

To improve the pea's productivity, the use of biostimulants like amino acids is rising due to their positive effects on plant health and their role against stress conditions (Ali *et al.,* 2019). Glycine is a simple amino acid that promotes

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chlorophyll synthesis, protein synthesis, and improves the antioxidant activities to suppress the ROS production (Basit *et al.,* 2025). Foliar application of glycine improves the vegetative growth and leads to higher photosynthetic activity due to its role in chlorophyll biosynthesis (Miri *et al.,* 2021). Glycine application results in elevated antioxidant enzyme activity, preparing the plant to combat harsh environmental stresses such as salinity, temperature, and drought. Recent studies have shown that phosphorus and amino acid applications can have synergistic effects on plant growth and production. Amino acids improve the plant's nutrient utilization and promote flowering, thereby increasing production (Abd-Elkader *et al.,* 2020). Despite numerous studies on phosphorus and amino acids, the synergistic role of these nutrients remains underexplored.

The phosphorus levels used in this study were selected based on initial soil nutrient status and regional fertilizer recommendations, representing varying supply conditions relative to crop demand. Phosphorus is essential for energy transfer, root development, and nodulation in legumes, making graded levels important for evaluating plant responsiveness. The glycine concentrations were chosen based on previous evidence showing that foliar amino acid application can enhance chlorophyll synthesis and nitrogen metabolism. Foliar sprays were applied during the active vegetative and early reproductive stages to maximize physiological responsiveness, providing a sound agronomic and physiological basis for the treatment structure.

This study addresses the research gap by examining how varying glycine and phosphorus levels affect pea growth, flowering, and production. The study aims to determine the optimal levels of phosphorus and glycine and to assess whether they have synergistic effects on plant growth and production. The results will inform the sustainable management of its nutrients, thereby enhancing productivity, particularly in areas with nutrient-poor soils.

Materials and Methods

Experimental site and design: The study was carried out at Horticulture Research Farm, Peshawar, The University of Agriculture, Peshawar, Pakistan. The experiment was conducted in a Randomized Complete Block Design (RCBD) with two factors. Factor A was phosphorus, i.e., 40, 60, and 80 kg ha^{-1}, and Factor B was glycine levels, i.e., $G_0 = 0$, G1 = 90, G2 = 180, and G3 = 270 mg L^{-1}. There were twelve treatments, each replicated three times.

Preparation and application of glycine solution: Glycine solutions were prepared by dissolving the required amounts of glycine powder in distilled water, with 90 mg dissolved in one liter of distilled water for the 90 mg L^{-1} solution, and similar procedures followed for preparing 180 mg L^{-1} and 270 mg L^{-1} concentrations. Two foliar sprays were applied at seven-day intervals, with the first spray at the six-node stage of plant development.

Environmental conditions, field preparation, and crop management: The experiment was conducted during the 2024 winter season under semi-arid climatic conditions at the study site. The soil was slightly alkaline and well-drained, with low available phosphorus prior to treatment, which justified the selection of graded phosphorus levels. Seasonal rainfall was supplemented with controlled irrigation to maintain adequate and uniform soil moisture throughout the crop growth period. Prior to sowing, the experimental field was ploughed, leveled, and divided into plots measuring 0.60 m^2 each. Composite soil samples (0–20 cm depth) were collected before fertilizer application and analyzed for physicochemical properties (Table 1), including available phosphorus, to establish baseline fertility status.

Table 1. Analysis of the soil from experimental plots.

Soil characteristics	Values
Silt (%)	56.2
Sand (%)	17.5
Clay (%)	27.1
EC (ds/m)	0.47
pH	8.1
Phosphorous (mg/kg)	3.53
Nitrogen (%)	0.12%
Potassium (mg/kg)	113
Magnesium (%)	0.017%
Sulfur (%)	0.008%

Basal fertilizers were applied uniformly across all plots at 40 kg ha^{-1} nitrogen (as urea) and 60 kg ha^{-1} K_2O (as potassium sulphate) during final land preparation. Phosphorus was applied according to treatment levels (40, 60, and 80 kg ha^{-1}) using Single Super Phosphate as the source and incorporated into the soil before sowing. Seeds were sown at a depth of 2–3 cm with 10 cm intra-row spacing and 30 cm inter-row spacing. Irrigation was applied immediately after sowing and subsequently at 15-day intervals based on crop requirement and prevailing weather conditions to ensure uniform soil moisture across treatments. Pest and disease management was carried out uniformly, following recommended integrated crop management protocols to minimize confounding.

Data collection: Observations were recorded on five randomly selected plants from each plot for all growth and yield parameters. Growth parameters included plant height measured from base to tip using a measuring tape at final harvest, number of branches and leaves per plant counted at full maturity, days to flowering recorded when 50% of plants produced flowers, days to first picking counted from sowing to initial harvest, chlorophyll content measured using a SPAD meter on three fully expanded leaves, and root weight determined by carefully uprooting five plants and weighing washed roots using a digital balance. Yield parameters comprised the number of pods per plant counted from five randomly selected plants, pod length measured using a measuring tape, pod diameter measured using vernier calipers, number of seeds per pod determined from ten randomly selected pods, hundred seed weight recorded using a digital electronic balance, and pod yield calculated in tons ha^{-1} using the formula:

$$\text{Yield ha}^{-1}\text{ (tons)} = \frac{\text{Yield plot}^{-1}\text{ (kg) x 10000 m}^2}{\text{Plot area (m}^2\text{) x 1000 kg}}$$

Statistical analysis

Data were subjected to analysis of variance (ANOVA) using statistical procedures appropriate for a two-factor randomized complete block design to determine significant differences among treatments, and treatment means were compared using the Least Significant Difference (LSD) test at 0.05 and 0.01 probability levels (Ali *et al.,* 2024).

Results

Tables 2 and 3 summarize the effects of phosphorus and glycine on vegetative growth, phenology, yield components, physiological traits, and productivity of garden pea.

As presented in Table 2, phosphorus significantly increased plant height from 85.72 cm at 40 kg ha^{-1} to 91.70 cm at 80 kg ha^{-1}, representing an approximate 7% increase. Glycine application produced a stronger response, with 270 mg L^{-1} increasing plant height by approximately 25% compared with the untreated control. In contrast, the number of branches per plant remained statistically non-significant under both phosphorus and glycine treatments (Table 2), indicating limited responsiveness of branching architecture.

Leaf production showed a consistent upward trend (Table 2). Increasing phosphorus from 40 to 80 kg ha^{-1} enhanced leaf number by approximately 24%, while glycine at 270 mg L^{-1} increased leaf count by more than 100% relative to the control. Days to flowering were significantly reduced by both treatments (Table 2). Plants receiving 80 kg ha^{-1} phosphorus flowered about six days earlier than those at 40 kg ha^{-1}. Glycine at 270 mg L^{-1} advanced flowering by approximately 12 days compared with untreated plants. Similarly, days to first picking decreased with increasing treatment levels (Table 2), with phosphorus at 80 kg ha^{-1} reducing maturity time by approximately 5% and glycine at 270 mg L^{-1} by nearly 13% relative to the control.

Yield components were significantly influenced. Pod number increased from 41.33 at 40 kg ha^{-1} to 48.16 at 80 kg ha^{-1} phosphorus, representing a 17% improvement (Table 2). Glycine at 270 mg L^{-1} increased pod number by approximately 75% compared with the control. Pod length (Fig. 1A) improved from 9.44 cm at 40 kg ha^{-1} phosphorus to 10.85 cm at 80 kg ha^{-1} ($\approx$15% increase), while glycine at 270 mg L^{-1} enhanced pod length by approximately 48% relative to the control. Pod diameter (Fig. 1B) increased by nearly 13% under 80 kg ha^{-1} phosphorus and by approximately 62% under 270 mg L^{-1} glycine compared with untreated plants. The number of seeds per pod (Fig. 1C) also improved steadily, increasing by about 16% under the highest phosphorus level and by approximately 48% under the highest glycine treatment compared with the control.

Physiological and seed traits followed similar trends (Table 3). Chlorophyll content (SPAD) increased by about 17% under 80 kg ha^{-1} phosphorus compared with 40 kg ha^{-1}, while glycine at 270 mg L^{-1} improved SPAD values by approximately 41% over control, indicating enhanced photosynthetic capacity. Hundred-seed weight increased by approximately 17% under the highest phosphorus level and by nearly 45% under 270 mg L^{-1} glycine relative to untreated plants. Root biomass responded strongly, increasing by about 27% under 80 kg ha^{-1} phosphorus and by more than 240% under 270 mg L^{-1} glycine compared with the control.

Physiological and seed traits followed similar trends (Table 3). Chlorophyll content (SPAD) increased by about 17% under 80 kg ha^{-1} phosphorus compared with 40 kg ha^{-1}, while glycine at 270 mg L^{-1} improved SPAD values by approximately 41% over control, indicating enhanced photosynthetic capacity. Hundred-seed weight increased by approximately 17% under the highest phosphorus level and by nearly 45% under 270 mg L^{-1} glycine relative to untreated plants. Root biomass responded strongly, increasing by about 27% under 80 kg ha^{-1} phosphorus and by more than 240% under 270 mg L^{-1} glycine compared with the control.

Pod yield exhibited the most agronomically significant response (Table 3; Fig. 1D). Increasing phosphorus from 40 to 80 kg ha^{-1} improved yield by approximately 19%. Glycine at 270 mg L^{-1} increased pod yield by approximately 114% relative to the control. Moreover, the significant phosphorus × glycine interaction for pod yield (Table 3; Fig. 1D) indicates synergistic effects of combined application beyond the contributions of individual treatments.

Overall, treatment responses were consistent across vegetative, reproductive, and physiological parameters, demonstrating that the observed improvements were not isolated statistical differences but rather biologically meaningful and agronomically relevant enhancements in garden pea performance.

Table 2. Plant height (cm), no. of branches, no. of leaves, days to flowering, days to first picking, no. of pods, and pod length (cm) as influenced by phosphorus and glycine application.

Phosphorous levels (Kg ha^{-1})	PH	NOB	NOL	DTF	DTFP	NOP	PL
40	85.72B	3.36	187.17B	78.47A	97.86A	41.33B	9.44B
60	89.40A	3.47	205.19AB	75.76AB	95.20AB	43.20B	10.25A
80	91.70A	3.54	232.08A	72.44B	92.33B	48.16A	10.85A
LSD ($p \leq 0.01$)	3.37	NS	30.57	4.30	3.79	3.49	0.75
Glycine levels (mg L^{-1})							
0	77.10C	3.31	129.08C	81.64A	101.13A	32.04C	8.47C
90	89.04B	3.31	197.04B	78.11AB	97.78A	42.85B	8.54C
180	92.65AB	3.49	244.49A	73.47BC	93.40B	46.01B	11.17B
270	96.35A	3.71	261.98A	69.00C	88.21C	56.00A	12.53A
LSD ($p \leq 0.01$)	3.89	NS	35.31	4.97	4.38	4.04	0.87
Interaction	NS	NS	NS	NS	NS	NS	NS

PH= Plant height, NOB= No. of branches, NOL= No. of leaves, DTF= Days to flowering, DTFP = Days to first picking, NOP = No. of pods, PL= Pod length, NS = Non-significant

Table 3. Pod Diameter (cm), No. of seeds per pod, Chlorophyll content (SPAD), Hundred seeds weight (g), Root weight (g), and Pod yield (Tons ha^{-1}) as influenced by phosphorus and glycine application.

Phosphorous levels (Kg ha^{-1})	PD	NOSP	CC	HSW	RW	PY
40	0.95B	7.63C	46.70B	32.68B	3.65B	6.91B
60	0.96B	8.18B	51.87A	34.65AB	4.39A	8.03A
80	1.07A	8.82A	54.58A	38.20A	4.65A	8.24A
LSD ($p \leq 0.01$)	0.05	0.54	3.92	3.57	0.35	0.86
Glycine levels (mg L^{-1})						
0	0.81C	6.46C	43.01C	28.18C	1.83D	5.12D
90	0.82C	8.14B	47.09C	33.75B	3.60C	6.61C
180	1.05B	8.71B	53.58B	37.83AB	5.12B	8.21B
270	1.31A	9.53A	60.53A	40.98A	6.37A	10.97A
LSD ($p \leq 0.01$)	0.06	0.62	4.53	4.12	0.40	1.00
Interaction	NS	NS	NS	NS	NS	***

PD= Pod diameter, NOSP= No. of seeds per pod, CC= Chlorophyll content, HSW= Hundred seeds weight, RW= Root weight, PY= Pod yield, *** = Significant, NS = Non-significant

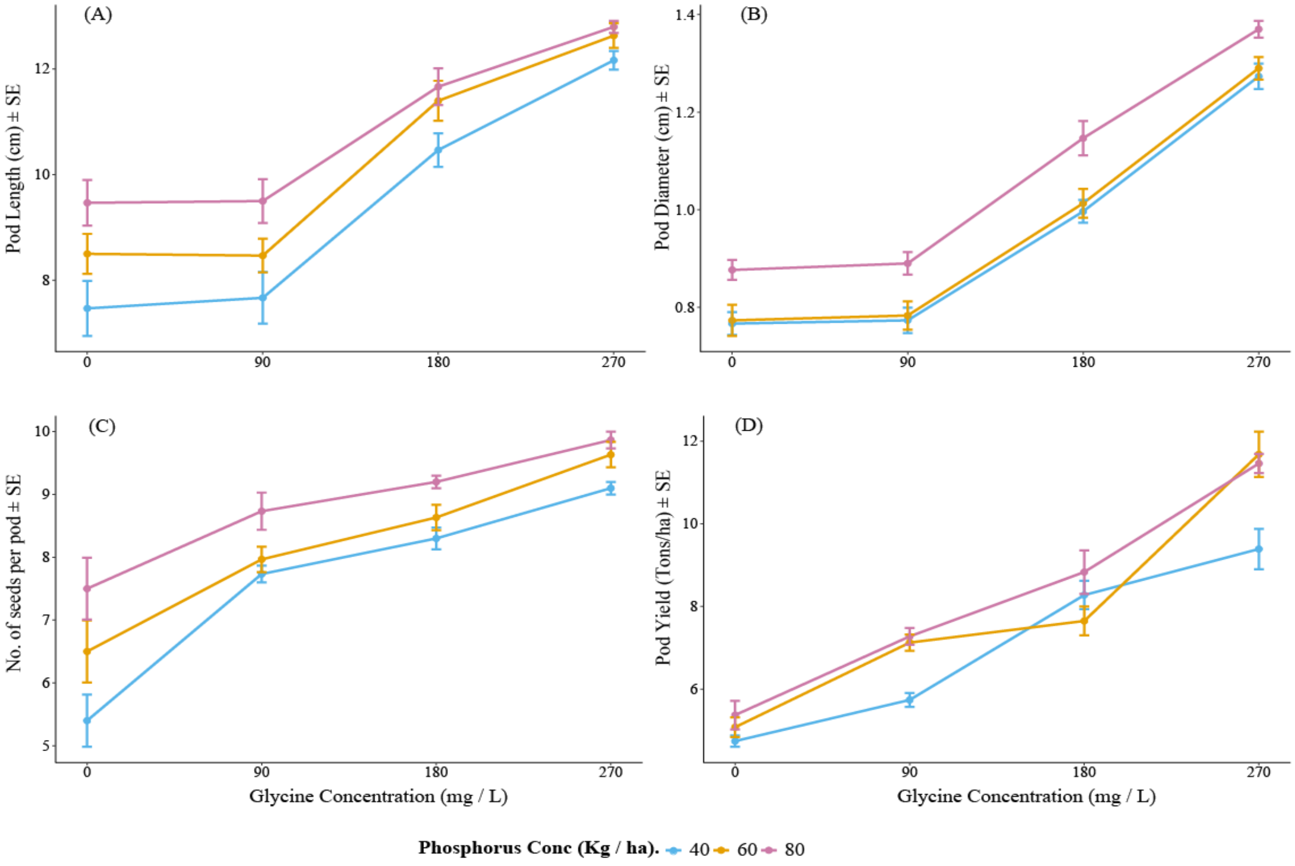

Fig. 1. Pod length (A), Pod diameter (B), No. of seeds per pod (C), and pod yield (D) of garden pea as affected by different phosphorus and glycine levels.

Principal component analysis: Principal component analysis (PCA) revealed a highly structured pattern of trait coordination among the measured garden pea attributes, with the first two principal components explaining 85.9% of the total variance (PC1: 79.5%, PC2: 6.4%) (Fig. 2). The dominance of PC1 indicates that most of the variability across treatments is governed by a single underlying productivity axis. Traits contributing strongly and positively to PC1 included pod yield (PY), pod diameter (PD), pod length (PL), number of pods (NOP), number of seeds per pod (NOSP), hundred-seed weight (HSW), chlorophyll content (CC), root weight (RW), plant height (PH), and number of leaves (NOL). This clustering confirms the univariate findings (Tables 1 and 2), in which improvements in vegetative growth and physiological capacity consistently translated into enhanced yield components.

In contrast, days to flowering (DTF) and days to first picking (DTFP) were positioned in the opposite quadrant of the biplot (Fig. 2), indicating strong negative loadings on PC1. This inverse association supports earlier results showing that higher phosphorus and glycine levels reduced phenological duration while simultaneously increasing productivity. Thus, PCA demonstrates that earliness and yield formation are functionally linked under improved nutrient management, rather than being independent responses.

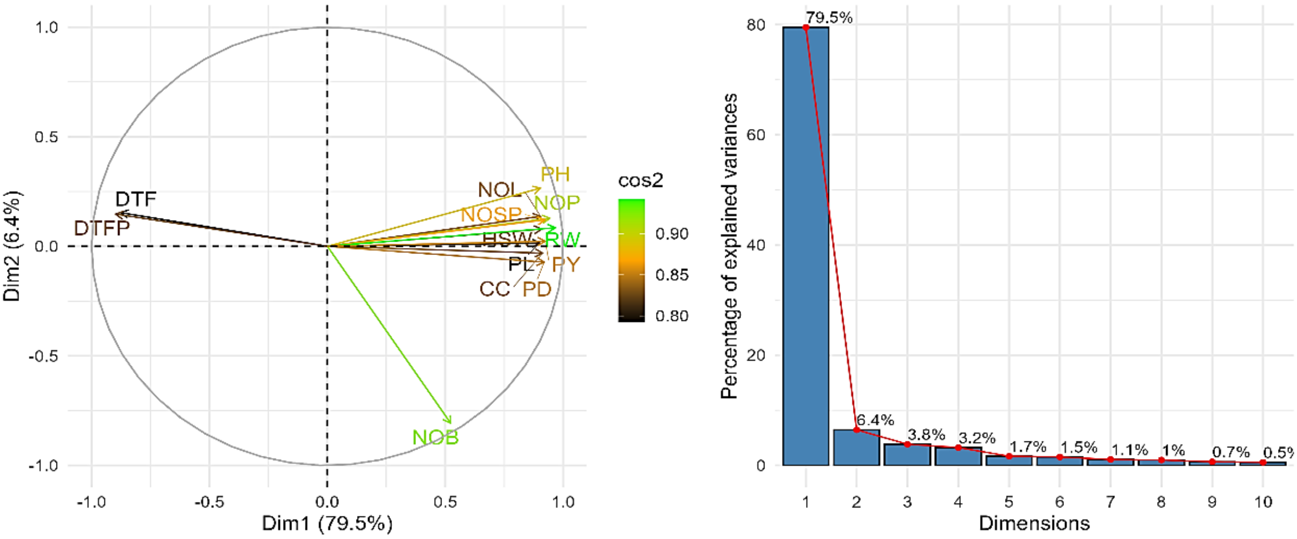

Fig. 2. Principal component analysis of the studied attributes of the garden pea.

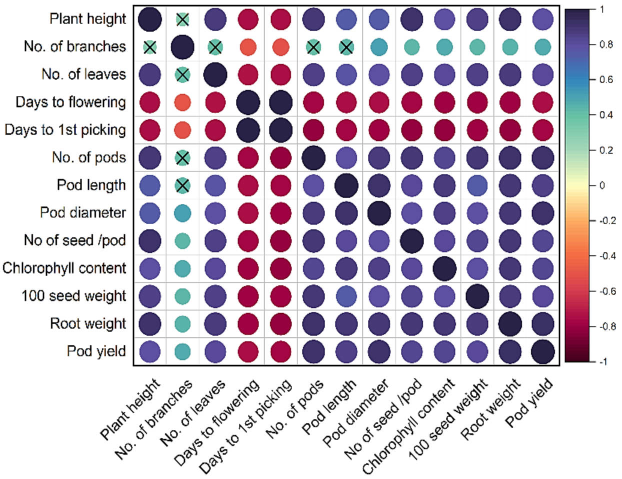

Fig. 3. Heat map of the studied attributes of the garden pea.

The scree plot (Fig. 2) showed a sharp decline in eigenvalues after PC1, with subsequent components contributing minimal variance (PC2: 6.4%, PC3: 3.8%, PC4: 3.2%). The cumulative variance exceeding 89% within the first three components suggests strong trait co-variation, reflecting coordinated physiological processes such as enhanced photosynthesis, assimilate partitioning, and reproductive development under phosphorus and glycine application.

The correlation heatmap (Fig. 3) further reinforced these relationships. Strong positive correlations ($r > 0.8$) were observed among yield-related parameters, particularly between pod yield and pod diameter, pod length, seed number, chlorophyll content, and root biomass. These findings align with the univariate yield improvements observed under higher phosphorus and glycine levels (Table 2). Conversely, days to flowering and days to first picking exhibited strong negative correlations with productivity traits, confirming that earlier maturity was associated with greater biomass accumulation and reproductive output.

The pairwise correlation matrix (Fig. 4) provided deeper insight into treatment-specific coordination patterns. Notably, pod yield showed very strong positive correlations with pod diameter ($r = 0.907^{***}$), seeds per pod ($r = 0.887^{***}$), and pod length ($r = 0.863^{***}$), indicating that pod morphology is a primary determinant of yield formation. Importantly, regression patterns across glycine levels (G0–G3) revealed steeper slopes and shifted distributions at higher glycine concentrations, suggesting enhanced efficiency of trait coupling under foliar amino acid application. This pattern indicates that glycine not only improves individual traits but also strengthens the structural integration among yield components.

Collectively, the multivariate analyses demonstrate that phosphorus and glycine application operate along a unified productivity axis, characterized by coordinated increases in vegetative growth, photosynthetic capacity, reproductive traits, and yield. Rather than merely confirming univariate results, these analyses reveal emergent patterns of trait integration and physiological coordination underlying yield formation in garden pea.

Discussion

The present study demonstrated that phosphorus and foliar glycine application significantly enhanced vegetative growth, physiological performance, reproductive development, and pod yield of garden pea. The consistent increases observed in plant height, leaf number, chlorophyll content, root biomass, pod traits, and final yield indicate that both treatments improved overall plant vigor and assimilate production. Since the number of branches was not significantly affected, yield enhancement appears to be associated primarily with improved biomass accumulation and reproductive efficiency rather than architectural modification.

Phosphorus plays a central role in plant growth through its involvement in ATP synthesis, energy transfer, and metabolic regulation (Khan *et al.*, 2023). The observed increases in plant height, leaf production, chlorophyll content, and root biomass under higher phosphorus levels may be explained by increased energy availability, which supports cell division, elongation, and nutrient transport. Phosphorus status has also been linked to the regulation of phosphate transporter genes, including members of the

PHT1 family, which enhance phosphorus uptake and redistribution within plants (Roch *et al*., 2019). Although gene expression was not measured in this study, the enhanced growth and yield components observed under 80 kg ha⁻¹ phosphorus are consistent with improved phosphorus acquisition and utilization efficiency. Furthermore, phosphorus has been associated with carbohydrate metabolism and assimilate partitioning through enzymes such as sucrose-phosphate synthase and ADP-glucose pyrophosphorylase (Wenqi, 2025), which may explain the improvements in seed number and hundred-seed weight. Reports linking phosphorus nutrition with floral regulatory pathways, including MADS-box transcription factors (Shah *et al*., 2022; Tripathi *et al*., 2026), provide additional context for the earlier flowering observed under adequate phosphorus supply; however, these mechanisms remain speculative within the scope of the present study.

Glycine application produced marked improvements in chlorophyll content, root biomass, pod characteristics, and yield. Glycine is directly involved in tetrapyrrole biosynthesis, where it contributes to δ-aminolevulinic acid formation, a precursor of chlorophyll (Harutyunyan *et al*., 2018). Regulation of chlorophyll biosynthesis has been associated with genes such as HEMA1 (Apitz *et al*., 2014), and enhanced glycine availability may support this pathway. While molecular activity was not quantified here, the substantial increase in SPAD values under higher glycine levels suggests enhanced chlorophyll accumulation and photosynthetic capacity (Huang *et al*., 2020). Glycine also participates in photorespiratory metabolism via the glycine cleavage system (Rosa-Téllez *et al*., 2024), which contributes to redox balance and metabolic stability. Additionally, glycine is involved in glutathione synthesis, supporting antioxidant defense mechanisms (Ali *et al*., 2020). These physiological roles may collectively explain the improvements in biomass accumulation, reproductive traits, and yield observed in the present study.

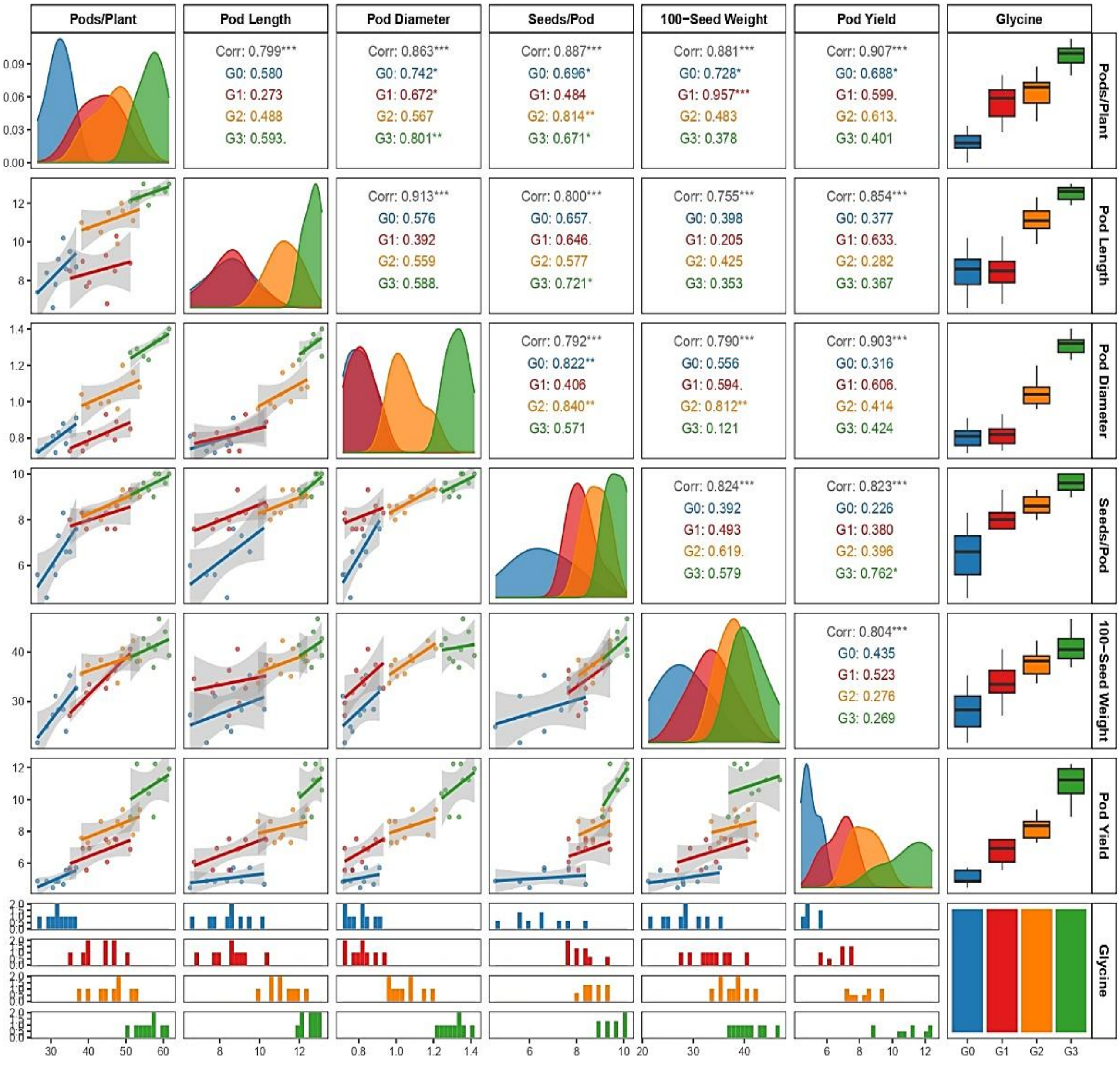

Fig. 4. Pairwise Correlation Matrix of the yield-related attributes of garden pea. Here, glycine concentration is given by G0= 0, G1=90 mg/l, G2=180 mg/l, G3=270 mg/l.

The significant phosphorus × glycine interaction for pod yield indicates a synergistic effect between soil nutrient supply and foliar amino acid application. Phosphorus likely enhanced energy availability and assimilate production, while glycine may have supported chlorophyll biosynthesis, protein stability, and metabolic efficiency (Shelly *et al*., 2010; Li *et al*., 2023). Improved source–sink dynamics, reflected in strong correlations among pod diameter, seed number, seed weight, and yield, suggest coordinated enhancement of reproductive development. Previous studies have reported that integrated nutrient management can influence signaling pathways associated with carbon–nitrogen metabolism and assimilate transport (Chen *et al*., 2022; Vadera *et al*., 2025). Although these molecular processes were not directly measured in this production-focused study, they provide a plausible framework for interpreting the coordinated physiological improvements observed.

Several previous studies have reported positive effects of foliar amino acids on growth and productivity in legumes and other crops, findings that align with ours. For example, foliar application of glycine and other amino acids has been shown to enhance chlorophyll content, photosynthetic efficiency, and yield in soybean, chickpea, and mungbean under field conditions, often resulting in improved pod number, seed weight, and total yield (Teixeira *et al*., 2018; Elahi *et al*., 2024; Shahzad *et al*., 2023). In many of these studies, amino acid treatments increased chlorophyll content by 15–40% and yield by 20–80% compared with untreated controls, which is consistent with the 41% increase in SPAD and 114% increase in pod yield observed under the highest glycine level in the present study. Similarly, research on foliar amino acid application in maize and wheat has demonstrated enhanced nutrient uptake and biomass accumulation, suggesting that amino acid supplementation can improve source–sink relationships across diverse crop types (Zhang *et al*., 2023). These comparative trends support the notion that glycine and related amino acids may act as effective biostimulants by improving physiological processes common to many plants, including enhanced chlorophyll synthesis, better stress resilience, and more efficient assimilate partitioning toward reproductive organs. However, the magnitude of responses can vary across species, environmental conditions, and application rates, indicating the need for crop-specific optimization.

Overall, optimized phosphorus fertilization combined with foliar glycine enhanced chlorophyll content, root development, reproductive efficiency, and yield formation in garden pea. This integrative nutrient management strategy represents a physiologically supported and agronomically practical approach for improving legume productivity under field conditions.

Conclusion

This study tested the hypothesis that integrated phosphorus fertilization and foliar glycine application would enhance growth, physiological performance, and yield formation in garden pea. The results confirm that improved phosphorus supply enhanced vegetative growth, chlorophyll content, reproductive development, and seed yield. Although 80 kg ha^{-1} phosphorus produced maximum values, 60 kg ha^{-1} performed comparably for most traits, indicating greater nutrient-use efficiency and supporting its recommendation as a resource-conservative rate. Foliar glycine at 270 mg L^{-1} further strengthened photosynthetic capacity, root biomass, and yield components, resulting in earlier flowering and increased pod productivity. Collectively, the findings highlight the importance of coordinated nutrient and biostimulant management in optimizing source–sink relationships and yield formation. The combined use of moderate phosphorus fertilization and foliar glycine offers a practical strategy to enhance productivity while improving input efficiency, supporting sustainable nutrient management in legume-based cropping systems.

Author's Contribution: F.A., Supervision, S.T., L.N. & K.T.K., Data collection, Literature review, Data analysis, H.A. & S.T., Initial Draft, S.T. & H.A., Final draft of manuscript & Graphical Analysis, M.A., S.N.M. & I.A., Manuscript Proofreading.

Declaration of Interest: All the authors declare no conflict of interest.

Data Availability: Data will be made available on a fair request to the corresponding author.

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