



Optimization of Phosphorus Application Doses for Yield Enhancement in Bt. Cotton under Semi-Arid Conditions of Core Cotton in Punjab, Pakistan

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Abstract

This study evaluates the influence of varying phosphorus (P) application rates on seed cotton yield under semi-arid conditions in Punjab, Pakistan. Cotton is a vital cash crop for the national agricultural economy; however, its productivity is frequently constrained by phosphorus deficiency, particularly in alkaline soils prevalent in the region. The experiment was conducted across five distinct sites within the Bahawalpur division—Chistian, Haroonabad, Fort Abbas, Haroonabad-2, and Haroonabad-3—using a randomized complete block design (RCBD). Phosphorus was applied at eight levels (Control, 0, 25, 50, 75, 100, 125 and 150 kg ha⁻¹), and data were subjected to analysis of variance (ANOVA) to determine treatment effects. The results indicated that phosphorus application had a statistically significant impact on seed cotton yield. The highest yield, reaching up to 2800 kg ha⁻¹, was recorded at the 150 kg ha⁻¹ application rate in certain locations. Substantial yield improvements were observed at the 50 and 75 kg ha⁻¹ rates, with marginal gains noted beyond 100 kg ha⁻¹, suggesting a diminishing return trend at higher doses. The findings confirm the critical role of phosphorus fertilization in improving cotton yield, particularly in phosphorus-deficient soils. Although site-specific factors contributed to yield variability, phosphorus application consistently enhanced crop performance across all study sites. These results underscore the importance of efficient phosphorus management for achieving optimal cotton productivity and promoting sustainable agricultural practices in semi-arid environments.

Keywords: Plant Nutrition, Phosphorus Fertilizers, Seed Cotton Yield, Climate Change, Core Cotton Areas

Introduction

Cotton (*Gossypium spp.*) is one of the most important crops globally, playing a critical role in the agricultural sector. As the primary source of natural fiber, cotton is integral to the textile industry, which is one of the largest industries worldwide. It is also an essential raw material for various other industries, including the production of oil, food products, and biofuels (Hamawand et al., 2016). Cotton is cultivated in over 80 countries, and its production supports the livelihoods of millions of farmers around the globe. Additionally, the by-products of cotton, such as cottonseed, are used for producing oil, animal feed, and even biodegradable products (Mollae et al., 2019). With global demand for cotton rising due to the growth of the textile sector, its economic significance continues to grow across different regions.

In Pakistan, cotton holds immense importance as a staple crop, both economically and socially. Pakistan as the fourth-largest cotton producer globally and the third-largest exporter of cotton and its products (Ali et al., 2019; Own References). Cotton farming significantly contributes to the agricultural economy of Pakistan, accounting for around 2.9% of the total agricultural value-added and 0.7% of the national GDP (ESP, 2023-24). It is also a major source of employment, directly or indirectly supporting millions of people. Cotton is grown primarily in the provinces of Sindh and Punjab, with Punjab being the core cotton-growing region. The fiber produced is crucial for the country's textile industry, which is one of the largest sectors in terms of export revenue (Bhatti et al., 2020; Aslam et al., 2025). Moreover, the cottonseed industry, which provides oil and other by-products, further enhances the crop's economic value

Despite the significance of cotton cultivation in Pakistan, the country's cotton production has faced persistent challenges over the years, leading to relatively low yields compared to other major cotton-producing nations (Bhatti et al., 2020; Younas et al., 2025; Younas et al., 2025). Several factors contribute to this low productivity, including inadequate water management, pest infestations, and, notably, the improper or insufficient use of fertilizers (Younas et al., 2025; Younas et al., 2025). Fertilizer application in Pakistan is often inefficient, with farmers facing issues related to the availability, affordability, and proper utilization of nutrients (Khan et al., 2022). Phosphorus, one of the essential macronutrients for cotton plants, is particularly affected by soil depletion and poor fertilizer practices. Many cotton-growing regions in Pakistan suffer from phosphorus deficiency in the soil, which significantly impacts crop growth and productivity (Ahmed et al., 2020). Additionally, the excessive reliance on chemical fertilizers, coupled with inadequate knowledge of balanced fertilization techniques, further exacerbates nutrient imbalances, limiting the potential for optimal cotton yield (Blaise et al., 2006).

Fertilizers play a critical role in enhancing the growth and development of cotton plants by supplementing essential nutrients that are often lacking in the soil. The primary macronutrients required for cotton growth are nitrogen (N), phosphorus (P), and potassium (K), commonly referred to as NPK. Nitrogen is essential for promoting leaf and stem growth, while potassium aids in water regulation and disease resistance (Wang et al., 2013). Phosphorus, however, is the key nutrient for root development, energy transfer, and flowering. It supports the formation of strong root systems that enhance nutrient and water absorption, which is particularly important in regions with water stress (Khan et al., 2023).

Phosphorus also facilitates the production of ATP, a molecule crucial for cellular energy, and contributes to the development of healthy seeds and fruiting bodies (Malhotra et al., 2018). As a result, proper phosphorus management is necessary for maximizing cotton yield, especially in areas with soils that are naturally low in this nutrient.

The role of phosphorus in plant growth and development cannot be overstated, as it is involved in several critical biological processes. Phosphorus is a major component of DNA, RNA, and phospholipids, which are vital for cellular functions (Khan et al., 2023). During early plant growth, phosphorus helps in the establishment of a robust root system, which is crucial for the uptake of water and other nutrients (Niu et al., 2013). In the reproductive phase, phosphorus is involved in energy transfer processes, promoting better flowering, fruit setting, and seed production. In cotton, sufficient phosphorus levels lead to improved boll formation and a higher seed cotton yield (Saleem et al., 2010). However, in regions like Pakistan, where phosphorus deficiencies are common, the application of phosphorus fertilizers is essential to meet the crop's demand, ensuring optimal growth and enhancing overall productivity.

This study aims to evaluate the impact of varying phosphorus application levels on cotton yield in the semi-arid conditions of Punjab, Pakistan, where phosphorus deficiency is a significant constraint to cotton production. The primary objective is to determine the optimal phosphorus dose that maximizes seed cotton yield while ensuring sustainable nutrient management practices. By assessing different phosphorus levels, from no phosphorus (control) to higher doses (up to 150 kg/ha), the study will provide valuable insights into how phosphorus influences cotton growth at various stages of development. Data collected from multiple locations in the Bahawalpur division, including Chistian, Haroonabad, and Hasilpur, will be analyzed to determine regional variations in response to phosphorus application. The findings of this research will not only help in formulating recommendations for phosphorus management in cotton farming but also contribute to improving overall agricultural productivity in the region. Given the vital role of phosphorus in enhancing plant growth and yield, optimizing its use is crucial for addressing the challenges faced by cotton farmers in Punjab and ensuring the long-term sustainability of cotton production in Pakistan.

Materials and Methods

Experimental Design and Treatments:

The study was conducted at five different locations within the Bahawalpur Division, Pakistan, to investigate the impact of varying phosphorus applications on the yield outcomes

of Bt cotton (variety SS-32) by the Soil Fertility (Field), Bahawalpur. The locations chosen for the experiment were;

1. Chak 56/F Chishtian
2. 136/6.R Haroonabad (Haroonabad-1)
3. 38/3.R Haroonabad (Haroonabad-2)
4. 164/M Hasilpur
5. 101/6.R Haroonabad (Haroonabad-3)

These locations were selected to represent a variety of agro-ecological conditions in the Bahawalpur Division, providing a comprehensive understanding of phosphorus management across different soil types and climatic conditions. The experimental design followed split-plot arrangements under Randomized Complete Block Design (RCBD) with eight phosphorus treatment levels (Sub-factor) and five locations (Main factor) applied at each of the five locations. The treatments were as follows:

Table 1: Treatments levels of Phosphorus in cotton crop at five different sites of Bahawalpur Region

Treatments	Nitrogen (N kg/ha)	Phosphorus (P ₂ O ₅ kg/ha)	Potassium (K ₂ O kg/ha)
Control (T-1)	0	0	0
P-0 (T-2)	250	0	100
P-25 (T-3)	250	25	100
P-50 (T-4)	250	50	100
P-75 (T-5)	250	75	100
P-100 (T-6)	250	100	100
P-125 (T-7)	250	125	100
P-150 (T-8)	250	150	100

Each treatment was applied during the growing season, following standard practices for cotton cultivation in the region. Nitrogen and potassium (K₂O) were applied at a constant rate of 250 kg/ha and 100 kg/ha, respectively, across all treatments. The experimental cotton crop received a uniform seed rate of 10 kg per acre. The cotton was sown during the third week of April. The sowing date was selected based on typical agricultural practices for the Bahawalpur region, ensuring optimal environmental conditions for crop growth. The crop was managed under typical local agricultural practices, including irrigation and pest management.

Two harvesting/picking were done. The first harvest was conducted in the 1st-2nd week of September, when the majority of the cotton bolls had reached maturity. The second harvest took place in the second week of October, with any remaining cotton bolls being collected. A

total of 10 irrigations, on an average, were applied throughout the growing season, in accordance with the water requirements of cotton in the Bahawalpur region. The irrigation schedule was designed to maintain optimal soil moisture levels and avoid both water stress and waterlogging during key stages of crop development. The cotton variety SS-32 was selected for the experiment due to its high pest resistance (specifically to bollworm), good fiber quality, and adaptability to the local climate. The seed rate used was 10 kg per acre, which is standard for cotton cultivation in the region.

Soil samples were collected prior to planting to analyze the baseline nutrient content of the soil. Based on the soil test results, fertilizers were applied as per the treatments outlined above. Nitrogen was applied in the form of urea, Phosphorus in the form of DAP and potassium as SOP. Fertilizers were incorporated into the soil at sowing time using broadcast application methods.

The soil analysis from the five locations where the study on varying phosphorus levels was conducted reveals several important soil parameters that may influence phosphorus availability and cotton growth. The soil pH across all locations ranged from 8.0 to 8.5, indicating slightly alkaline soils, which is common in many regions of Punjab. This pH range can affect the availability of phosphorus, as phosphorus tends to become less available in highly alkaline soils. The organic matter (OM) content in the soils varied from 0.40% to 0.77%, with higher organic matter levels observed in Hasilpur and Haroonabad-2. Organic matter plays a crucial role in improving soil structure, water retention, and nutrient availability, which could positively influence cotton growth.

Phosphorus levels in the soils (expressed in parts per million, ppm) were relatively low, ranging from 5.7 ppm to 10.2 ppm across the locations. This indicates a phosphorus deficiency, which is a common issue in semi-arid regions. Phosphorus is often bound in the soil in forms that are not readily available to plants, making its management crucial for optimizing cotton yield. Additionally, potassium levels varied significantly across the locations, ranging from 118 ppm to 185 ppm, with higher levels found in Haroonabad-1. Potassium is essential for cotton plants as it helps in regulating water and nutrient movement and improving disease resistance. These soil parameters highlight the importance of appropriate phosphorus fertilization strategies to overcome deficiencies and improve cotton yield in these locations.

Table 2: Soil Analysis of five locations where study on variable phosphorus level was conducted

SOIL PARAMETERS	EC (dS m-1)	pH	OM%	P (ppm)	K (ppm)
Chishtian					
Depth (0 - 15) cm	3.00	8.2	0.41	8.6	128
Depth (15-30) cm	2.9	8.1	0.40	8.5	127
Haroonabad-1					
Depth (0 - 15) cm	1.5	8.2	0.56	10.2	129
Depth (15-30) cm	1.6	8.1	0.49	9.9	185
Haroonabad-2					
Depth (0 - 15) cm	2.8	8.3	0.66	8.2	120
Depth (15-30) cm	2.5	8.0	0.62	8.1	118
Hasilpur					
Depth (0 - 15) cm	2.4	8.5	0.77	6.0	169
Depth (15-30) cm	2.3	8.3	0.56	5.7	156
Chistian					
Depth (0 - 15) cm	1.5	8.2	0.56	10.2	129
Depth (15-30) cm	1.6	8.1	0.49	9.9	185

Results and Discussion

Analysis of Variance for Phosphorus Doses and Locations

The results presented in Table 3 revealed the analysis of variance (ANOVA) for the effect of phosphorus doses and locations on cotton yield. The results show significant effects of phosphorus treatments on cotton yield, with a high F-value (175.68) and a very low p-value (0.0000), indicating that phosphorus application significantly influences seed cotton yield. The interaction between locations and phosphorus doses did not show significant results (p = 0.8023), suggesting that the effect of phosphorus doses on yield was consistent across the different locations tested. Locations themselves showed a moderate F-value (2.83) with a p-value of 0.0982, which is not statistically significant at the 0.05 level, implying that location by itself has a minor effect on cotton yield compared to phosphorus application. The error variance indicates variability within the experimental data but does not significantly affect the overall results (Table 3).

Table 3: Analysis of Variance for studied phosphorous doses and five different locations in Cotton crop

Source	DF	SS	MS	F	P
Replications (A)	2	1243817	621909		
Locations (B)	4	2593411	648353	2.83*	0.0982
Error A*B	8	1831839	228980		
Treatments (C)	7	3.742E+07	5346187	175.68**	0.0000
B*C	28	636963	22749	0.75	0.8023
Error A*B*C	70	2130153	30431		
Total	119	4.586E+07			

Descriptive Statistics of Cotton Yield at Five Locations (Table 4)

Table 4 provides descriptive statistics for cotton yield at five different locations in the Bahawalpur Division. The mean seed cotton yield varied across locations, with the highest yield observed at Haroonabad-3 (2154.0 kg/ha) and the lowest at Haroonabad-1 (1743.5 kg/ha). The standard deviation (SD) indicates the spread of data points around the mean, with Haroonabad-1 showing the highest variation in yield (680.42), followed by Haroonabad-2 (684.01). The minimum and maximum yields also differed significantly, with Chistian showing the lowest minimum yield (725.00 kg/ha) and Haroonabad-3 having the highest maximum yield (2833.0 kg/ha). These variations suggest that while location plays a role in yield differences, the influence of phosphorus application is more pronounced (Table 4).

Table 4: Descriptive Statistics of cotton yield at five different locations in Bahawalpur Division

Locations	Mean	SD	SE Mean	Minimum	Maximum
Chistian	1910.8	512.65	104.65	725.00	2434.0
Haroonabad-1	1743.5	680.42	138.89	449.00	2636.0
Haroonabad-2	1764.9	684.01	139.62	455.00	2649.0
Haroonabad-3	2154.0	591.38	120.71	955.00	2833.0
Hasilpur	1860.2	581.16	118.63	698.00	2471.0

Descriptive Statistics of Cotton Yield at Eight Phosphorus Levels (Table 5)

Table 5 illustrates the descriptive statistics for cotton yield at different phosphorus application levels. The results show a clear positive correlation between phosphorus doses and seed cotton yield. The control group, which received no phosphorus, had the lowest mean yield (724.6 kg/ha). As the phosphorus levels increased, so did the yield, with the highest mean yield observed at the P-150 level (2450.7 kg/ha). The standard deviation (SD) also decreases slightly as the phosphorus dose increases, indicating more consistent yields at higher phosphorus levels. The minimum and maximum yields showed a similar trend, with higher yields being recorded at elevated phosphorus doses. This reinforces the significance of phosphorus fertilization in boosting cotton yield, with higher phosphorus applications leading to better yield outcomes

Table 5: Descriptive Statistics of cotton yield at eight different levels of phosphorus applications

Treatments	Mean	SD	SE Mean	Minimum	Maximum
Control	724.60	162.70	42.009	449.00	975.00
P-0	1297.7	265.44	68.535	923.00	1661.0
P-25	1778.9	181.01	46.736	1450.0	2016.0

P-50	2083.1	387.45	100.04	1212.0	2438.0
P-75	2150.5	397.96	102.75	1252.0	2504.0
P-100	2228.1	232.83	60.116	1891.0	2596.0
P-125	2379.8	208.68	53.882	1977.0	2688.0
P-150	2450.7	258.17	66.658	1911.0	2833.0

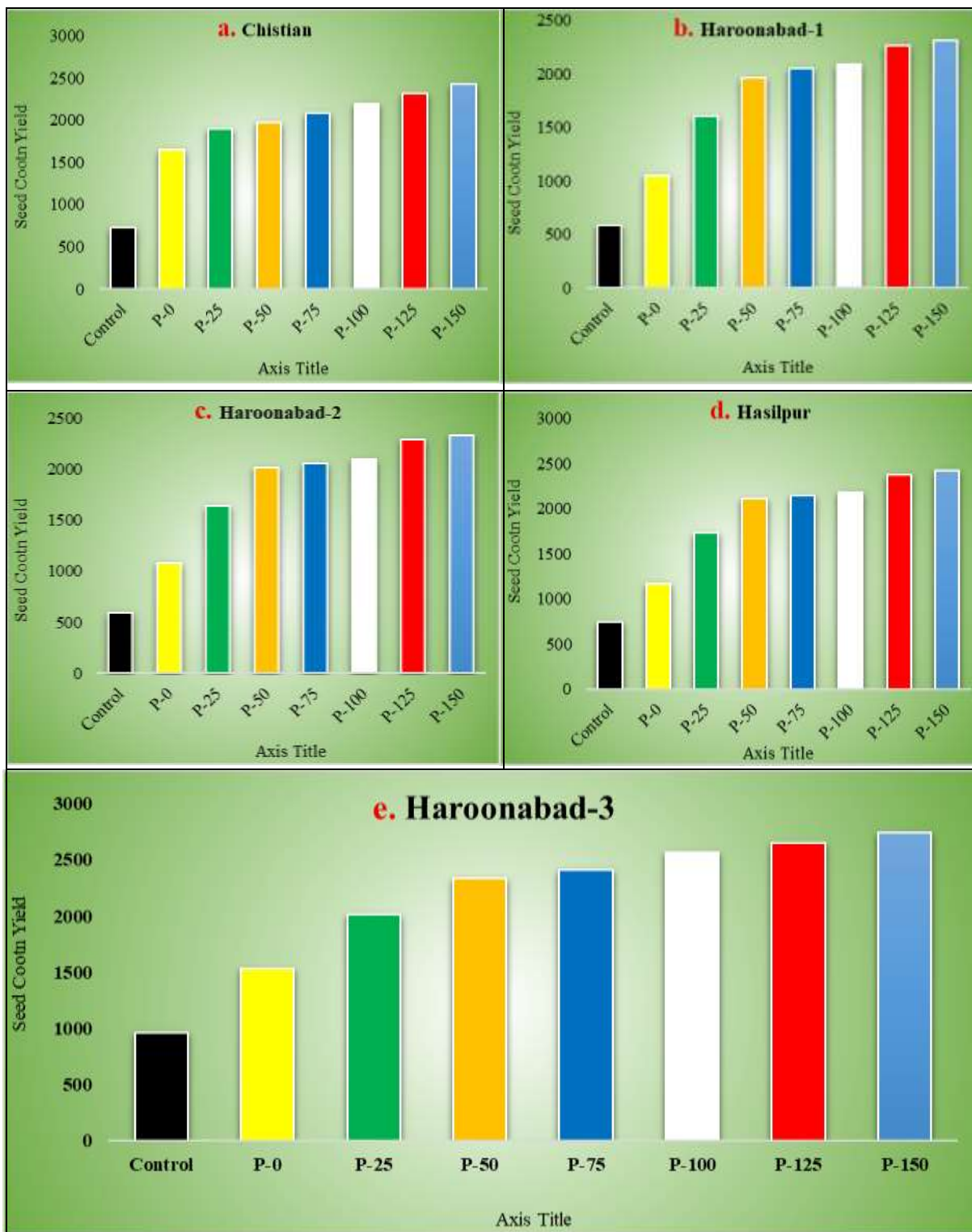


Figure 1(a-e): Impact of varying amount of phosphorus doses on seed cotton yield at **a)** Chistian **b)** Haroonabad-1 **c)** Haroonabad-2 **d)** Fortabbas **e)** Haroonabad-3

Figure 1(a-e) presents the impact of different phosphorus doses on seed cotton yield across five locations: Chistian, Haroonabad-1, Haroonabad-2, Fortabbas, and Haroonabad-3. The data in the figure clearly shows how varying phosphorus doses influence cotton yield, and it emphasizes the differences in yield response across locations.

The seed cotton yield at Chistian showed a gradual increase with phosphorus application. The control (P-0) group had the lowest yield, approximately 700 kg/ha. As phosphorus doses increased from P-25 to P-150, the yield consistently rose, reaching about 2400 kg/ha at the highest phosphorus dose (P-150). This result indicates that phosphorus application significantly improves cotton yield at this location. The trend in Haroonabad-1 followed a similar pattern, where higher phosphorus doses led to higher yields. The yield started at around 1100 kg/ha in the control group and increased to around 2500 kg/ha at the highest phosphorus dose. However, the yield increases were more pronounced after the P-50 dose, suggesting that a certain threshold of phosphorus is needed to see substantial yield improvement.

At Haroonabad-2, the yield again showed a consistent increase with phosphorus application. The control yielded approximately 900 kg/ha, while the P-150 treatment resulted in a yield of nearly 2700 kg/ha. The data indicates that phosphorus is crucial for boosting cotton yields in this region, especially beyond the P-50 dose. The response at Fortabbas was slightly more variable compared to the other locations, but the general trend still showed an increase in yield with higher phosphorus doses. The control group started at around 1000 kg/ha, and with increased phosphorus application, yields peaked at about 2300 kg/ha at P-150. The lower yield response at Fortabbas might be attributed to local soil conditions or other environmental factors that limit phosphorus uptake. Haroonabad-3 showed the highest overall yield among all locations. The control group still produced relatively high yields (around 1300 kg/ha), but the yield increased significantly with phosphorus application, reaching a peak of approximately 2800 kg/ha at the highest phosphorus dose. This indicates that Haroonabad-3 benefits most from phosphorus fertilization, likely due to favorable soil conditions or better phosphorus availability. All the figures show a clear positive relationship between phosphorus application and seed cotton yield across all five locations, with higher doses leading to better yields. However, the rate of yield increase varies depending on the location,

which suggests that local soil conditions and environmental factors play a role in phosphorus efficiency.

Impact of Varying Phosphorus Doses on Seed Cotton Yield (Grouped by Treatments)

Figure 2 presents a more detailed visualization of how seed cotton yield varies with different phosphorus doses across the five locations, grouped by treatment levels (P-0, P-25, P-50, P-75, P-100, P-125, P-150).

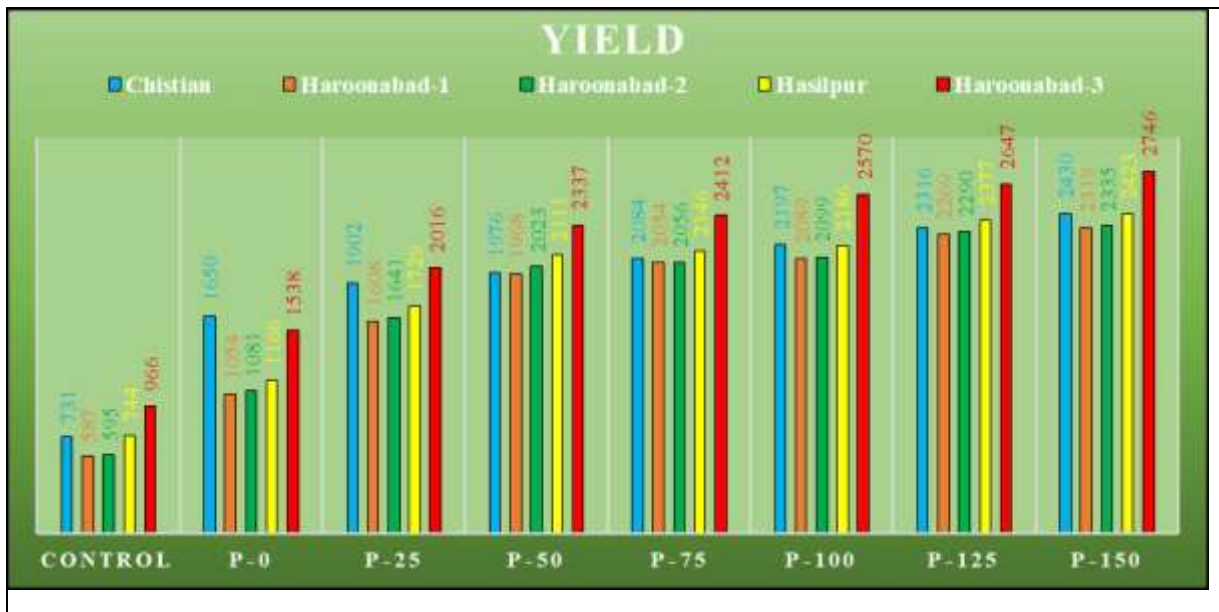


Figure 2: Impact of varying amount of phosphorus doses on seed cotton yield (grouped by treatments) at a) Chistian b) Haroonabad-1 c) Haroonabad-2 d) Fortabbas e) Haroonabad-3

The control group (P-0) consistently shows the lowest yields across all locations, with a range between 700 to 1300 kg/ha. This highlights the deficiency of phosphorus in the soil and the importance of phosphorus fertilization for enhancing cotton yield. As the phosphorus doses increase, there is a noticeable upward trend in cotton yield. The P-25 dose leads to a slight increase in yield, but the most significant improvements occur at the P-50 and P-75 levels. By the time the P-100 and P-150 treatments are applied, yields consistently reach the highest values observed in each location, with some locations showing peak yields exceeding 2500 kg/ha. The graph also indicates variability in how different locations respond to phosphorus. While Haroonabad-3 and Haroonabad-2 show relatively consistent increases across the treatments, Haroonabad-1 and Fortabbas display more moderate gains, particularly in the lower phosphorus doses. This variability might be due to differences in local soil fertility, water availability, or other agronomic practices that affect phosphorus availability and plant uptake.

The graph shows that after reaching a certain phosphorus level (P-100 or P-125), additional increases in phosphorus do not result in substantial yield increases for most locations. This

suggests that there might be a point of diminishing returns, where further phosphorus application does not significantly boost yield, likely due to soil nutrient saturation or other limiting factors. In conclusion, Figure 2 reinforces the message that phosphorus fertilization plays a critical role in improving cotton yield. However, the data also suggest that there is an optimal range of phosphorus application for each location, beyond which the benefits plateau. This insight is crucial for designing phosphorus management strategies that maximize cotton productivity while avoiding over-fertilization.

The role of phosphorus in promoting plant growth is well-documented in the literature. Phosphorus is integral to several essential plant functions, including root development, energy transfer, and flowering (Malhotra et al., 2018). In the context of cotton, phosphorus promotes the formation of strong root systems, which are crucial for nutrient and water uptake, particularly in semi-arid environments like Punjab (Rao et al., 2016). Iqbal et al. (2023) emphasized that phosphorus application significantly enhances root growth, which in turn improves the cotton plant's ability to withstand drought conditions and other abiotic stresses commonly found in semi-arid regions. Our findings support this notion, as the highest yields were observed at higher phosphorus doses, which likely contributed to better root development and overall plant health.

The results also suggest that while the benefits of phosphorus application were evident across all locations, the rate of yield improvement diminished beyond certain phosphorus levels (P-100 and P-125). This is consistent with the concept of nutrient saturation, where excessive phosphorus beyond the plant's requirements does not further improve yield and can even lead to environmental concerns such as nutrient leaching and soil pollution. Huo et al. (2023) noted that beyond a critical phosphorus level, the increase in cotton yield becomes marginal, and the risk of phosphorus buildup in the soil becomes a concern. Our study's findings, which show a plateau in yield response at the higher phosphorus doses, align with this concept, suggesting that optimal phosphorus management requires balancing phosphorus application with plant needs to avoid over-fertilization.

The results of this study are consistent with earlier research on the impact of phosphorus fertilization on cotton yield. For instance, Ahmad et al. (2020) found that phosphorus application significantly increased cotton yield in regions with phosphorus-deficient soils, similar to the conditions observed in the current study. Their study also highlighted that higher phosphorus doses led to greater improvements in yield, but the benefits diminished at higher doses, which is consistent with our findings. Similarly, Singh et al. (2015) reported

that phosphorus application improved seed cotton yield in Punjab, Pakistan, and emphasized the need for location-specific phosphorus management strategies. While our study suggests a relatively consistent response across locations, their research underlined the importance of tailoring phosphorus fertilization to local soil conditions.

Additionally, Li et al. (2022) found that phosphorus significantly influenced the number of bolls per plant, boll weight, and overall fiber quality, supporting the role of phosphorus in enhancing both quantitative and qualitative cotton yield. This reinforces the idea that phosphorus not only improves yield but also contributes to better fiber formation, which is critical for the textile industry.

Conclusion

In conclusion, the findings from this study demonstrate the significant role of phosphorus fertilization in improving cotton yield in Punjab's semi-arid regions. The positive response to phosphorus across all locations highlights its importance in overcoming phosphorus deficiencies commonly found in the soil. However, the diminishing returns at higher phosphorus doses emphasize the need for balanced fertilization practices to optimize yield while minimizing environmental impact. This study provides valuable insights for cotton farmers in Punjab and similar regions, suggesting that careful management of phosphorus application can significantly enhance cotton productivity and contribute to sustainable agricultural practices. Future studies should focus on refining phosphorus management strategies to ensure maximum yield with minimal environmental degradation.

Author's Contribution

Nazar, Farooq, Qamar, Rafiq, *Conceptualization, Validation, Supervision, Planning, Execution of Experiment*; Qamar, Shaheen, Rauf, Mehboob *Writing – original draft*; Hussain, Bashir, Javeed, Ghafoor, Khaliq *Writing – review & editing*; Raza, Ahmad, Latif, Saleem, Bilal, Murtaza, Hassan, Qamar *Formal analysis, Resources, Funding acquisition, Statistical Analysis, Graphic improvement*.

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