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ORIGINAL RESEARCH

Phosphorus Priming and Nitrogen Application Enhance Corn Yield and Nitrogen Availability in Alkaline Calcareous Soils

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ABSTRACT: Corn is a crucial crop for local communities and the global food system. Various amendments are used to increase corn yield in semi-arid climates, but the response to fertilization and seed priming at different moisture regimes is not well documented. An experiment was conducted at the University of Agriculture's research farm in Peshawar, Pakistan 2014, involving three variables: moisture regimes (low and high), seed priming (dry seed, water-soaked seed, and seed primed with 0.2 percent phosphoric acid solution), and nitrogen levels (0, 75, 150 kg ha^{-1}). The study found that seed priming and nitrogen levels significantly impacted plant height, leaf area, number of leaves per plant, grain cobs, 1000-grain weight, biological yield, stover yield, grain yield, and harvest index. The number of leaves in the normal irrigation area was lower than in a standardly irrigated field due to low irrigation. A higher moisture regime produced more leaves, more nitrogen uptake, and a maximum thousand-grain weight. A higher nitrogen level resulted in increased plant height, more leaves, grains cobs^{-1}, thousand-grain weight, nitrogen uptake, harvest index, maximum grain yield, biological yield, and stover yields. Priming seeds with P-primed seeds increased plant height, leaf area, grain weight, nitrogen uptake, harvest index, biological yield, grain yield, and stover yield at 150 N kg ha^{-1}. The minimum values of all parameters were noted for control plots. Based on the good crop yield in the Peshawar region, farmers are encouraged to use both high and low moisture regimes. The use of nitrogen at 150 kg ha^{-1} in combination with 0.2% P priming results in maximum corn yield and adequate nitrogen uptake when seedbeds moisture is high.

KEYWORDS: Corn, nitrogen, grain yield, moisture regimes, seed priming.

1. Introduction

Maize (*Zea mays* L.), an annual and cross-pollinated Kharif crop, is cultivated globally and holds significant economic and nutritional importance. In Pakistan, maize ranks as the fourth-largest crop after wheat, cotton, and rice. It is the third most important cereal crop worldwide and the second most significant cereal crop in Khyber Pakhtunkhwa (KPK) province, following wheat (Rajput et al., 2020). Based on grain structure, maize is categorized into several types, including popcorn, flour corn, pod corn, dent corn, and sweet corn. Popcorn is distinguished by its hard, fluffy kernels, while flour corn is characterized by hard, glassy, pest-resistant kernels (Patel et al., 2019).

Khyber Pakhtunkhwa contributes 56% of the total maize cultivation area and accounts for 63% of the country's maize production (Miller et al., 2021). After potatoes, maize is considered Pakistan's most dependable and lucrative crop, serving as a critical food source and industrial raw material (Khan et al., 2019). As a C4 crop, maize demonstrates a high potential for grain yield and is extensively utilized as food, livestock feed, and in industrial applications (Ledvinka et al., 2022). In addition, maize serves as a valuable oil crop, with an oil content of 3–6%, offering health benefits such as reducing blood cholesterol levels (Zhang et al., 2021).

Nitrogen plays a vital role in maize production by enhancing crop growth, promoting nutrient absorption, and supporting essential physiological functions, including protein synthesis and nucleic acid formation (Bobo et al., 2021; Grishin et al., 2020). Globally, approximately 80 million tons of nitrogen are used annually, with developing countries increasingly relying on fertilizers to meet the demands of growing populations (Ren et al., 2022). However, nitrogen efficiency in soil systems remains suboptimal, leading to limited nutrient uptake and reduced crop yields (Barłóg et al., 2022). Balanced nitrogen application is critical for achieving optimal plant growth, as excessive or insufficient nitrogen can negatively impact maize yields and nutrient utilization (Udvardi et al., 2021; Asibi et al., 2019).

The nitrogen fertilizer requirement for maize varies based on the variety and environmental conditions, typically ranging from 150–200 kg N ha^{-1}. Seed priming has emerged as a promising strategy to improve maize productivity by accelerating germination, breaking dormancy, and enhancing nutrient uptake (El-Maarouf-Bouteau, 2022; PEKŞEN, 2021). Research indicates that phosphorus-based seed priming can further improve water and nutrient absorption, leading to better emergence and early growth (Galindo et al., 2022). Additionally, drying seeds to achieve optimal moisture levels is essential for ensuring successful germination and growth (Sarolia et al., 2018). Priming also enhances root development, enabling plants to withstand adverse conditions more effectively (Mustafa et al., 2021).

Although the soil and climate of Pakistan are well-suited for maize cultivation, achieving high yields remains a challenge due to inconsistent irrigation and suboptimal nitrogen management. This study aims to evaluate the combined effects of nitrogen levels and seed priming on maize seedling emergence, plant growth, and yield. By addressing these factors, the research seeks to enhance maize productivity under semi-arid conditions, ultimately contributing to sustainable agricultural practices and improved crop performance.

2. Material and methods

2.1. Experimental location and design

Field experiments were conducted during the summer of 2014 at the Agronomy Research Farm of the University of Agriculture Peshawar. This subtropical site, located at 34°N latitude, 71.3°E longitude, and an altitude of 450 meters above sea level, experiences an average annual rainfall of 350 mm, primarily between August and December. The climate is characterized by average summer temperatures of 40°C and winter temperatures around 18°C. The soil at the site is a silty clay loam, alkaline in nature, with low organic matter content and limited plant-available nutrients. The study aimed to evaluate the effects of seed priming, nitrogen levels, and soil moisture regimes on maize yield components and overall yield. The experimental field soil had a silty loam texture with a pH of 7.8 and was deficient in nitrogen (0.02%) and organic matter (0.8%) (Table 1).

The experiment considered three factors: moisture regimes (low and high), seed priming methods (dry seed, water-soaked seed, and seed primed with a 0.2% phosphorus solution), and nitrogen levels (0, 75, and 150 kg ha^{-1}). Two randomized complete block design (RCBD) experiments were conducted, one under high moisture conditions and the other under low moisture conditions. In both cases, irrigation was withheld until 40 days after sowing. Soil moisture levels at sowing were 21% and 28% for low and high moisture regimes, respectively. The maize variety Azam was sown at a seeding rate of 150 kg ha^{-1}, with each subplot measuring 4.5 m × 5 m and containing six rows, each one meter long and spaced 30 cm apart.

Nitrogen fertilizers were applied in three equal splits: one-third at sowing, one-third at tillering, and one-third at the booting stage. For seed priming, 180 g of seeds per plot were placed in perforated polyethylene bags and treated with either distilled water or a 0.2% aqueous phosphorus solution for 12 hours. After priming, the seeds were drained, surface-dried in the shade for approximately 30 minutes to prevent clumping, and then sown. Phosphorus was applied at a rate of 90 kg ha^{-1} at sowing, supplied as single superphosphate (SSP), while nitrogen was supplied as urea. Throughout the experiment, standard agronomic practices, including weed control and pest management, were consistently followed to ensure uniform crop growth and reliable results.

2.2. Measurement analysis

Plant height (cm) was measured at physiological maturity using a meter rod from the soil surface to the tip of the tallest leaf (excluding awns) for five randomly selected plants per plot, and the average value was calculated. The number of leaves per plant was counted for fully expanded leaves at the vegetative stage on five randomly selected plants per plot, and the average was recorded. Grains per cob were determined by harvesting cobs from five randomly selected plants per plot, shelling them, and manually counting the grains using a grain counter, with the average count recorded. Thousand-grain weight (g) was measured by randomly selecting 1,000 grains, weighing them using a precision digital balance, and repeating the process three times per plot to calculate the average. Nitrogen uptake was determined using the Kjeldahl method by oven-drying plant tissue samples (grains and stover) at 70°C to constant weight, grinding them to a fine powder, digesting them in concentrated sulfuric acid, and multiplying the nitrogen concentration by the corresponding biomass. Biological yield (kg ha^{-1}) was calculated by harvesting the entire above-ground biomass from each plot at physiological maturity, sun-drying it to a uniform moisture level, and weighing it. Grain yield (kg ha^{-1}) was obtained by threshing, cleaning, and drying grains to 12% moisture content, with the weight recorded per plot. Stover yield (kg ha^{-1}) was determined by subtracting grain yield from biological yield for each plot. The harvest index (%) was calculated as the ratio of grain yield to biological yield, multiplied by 100.

2.3. Statistical analysis

The collected data were subjected to statistical analysis using ANOVA (Analysis of Variance) under a randomized complete block design (RCBD). Means were compared using the Least Significant Difference (LSD) test at a 5% significance level to identify statistically significant differences among treatments. Standard errors and coefficients of variation (CV%) were calculated to ensure the reliability and precision of the experimental results. All statistical analyses were performed using statistical software (e.g., SPSS), with results presented as mean ± standard error.

3. Results and discussion

3.1 Plant height (cm)

Plant height was significantly influenced by seed priming (water or 0.2% P solution) and varying nitrogen levels. As shown in Table 2, statistical analysis confirmed that nitrogen levels and seed priming had a significant impact on maize plant height ($P \leq 0.05$). However, moisture levels and their interactions with other factors were not significant. An increase in plant height was observed with higher nitrogen levels and seed priming treatments. The tallest plants were recorded at 150 kg N ha^{-1} (196 cm), followed by 75 kg N ha^{-1} (173 cm). The shortest plants were observed at 0 kg N ha^{-1}, measuring 153 cm. Seed priming notably enhanced plant height, with P-primed seeds reaching 188 cm and water-soaked seeds measuring 180 cm, compared to dry seeds at 160 cm.

The growth pattern over five weeks is illustrated in figure 1a. During the initial week, plant height increased from 4.10 cm to 6.90 cm (a 40% rise). The second week saw a smaller growth, from 6.90 cm to 7.60 cm (4% increase). The third week exhibited a significant growth spurt, from 7.60 cm to 10.40 cm (32% increase). Growth slowed in the fourth week, moving from 10.40 cm to 12.00 cm (3% increase). By the fifth week, the plants reached 15.10 cm, representing a 26% increase.

These findings are consistent with the understanding that genetic factors primarily dictate plant height, although optimal environmental conditions are essential to achieve this potential. The variation observed between maize varieties is likely due to genetic differences rather than fertilizer effects (Hussain et al., 2023). Our results align with studies indicating that sufficient irrigation contributes to better heading and stem elongation (Alrajhi et al., 2024). Additionally, Amgai et al. (2023) reported increased maize height with nitrogen application, while Ahmad et al. (n.d.) noted taller plants from phosphorus-treated seeds.

3.2 Number of leaves plant^{-1}

The number of leaves was significantly influenced by seed priming (water or 0.2% P solution) and varying nitrogen levels. Data presented in Table 2 show that nitrogen levels, moisture conditions, and seed priming all significantly affected the number of leaves in maize ($P \leq 0.05$). However, interactions among these factors were not significant. High moisture plots showed fewer leaves (10) compared to low moisture plots (12). Both nitrogen and seed priming contributed to an increase in the number of leaves. The highest number of leaves (13) was observed at 150 kg N ha^{-1}, while the lowest (9) was at 0 kg N ha^{-1}. Seed priming treatments also improved the number of leaves, with P-primed seeds producing 13 leaves and water-soaked seeds yielding 12 leaves. Dry seeds had the lowest number of leaves at 10.

The overall increase in the number of leaves over time was significant, as illustrated in figure 1b. During the first week, the count rose from 2.10 to 5.75, marking a 62.5% increase. The second week showed a smaller growth, from 5.75 to 7.45 (15.9% increase). The third week saw a substantial increase to 11.80 (38.6%), followed by a smaller rise from 11.80 to 13.00 in the fourth week (12% increase). Finally, in week five, the number of leaves grew from 13.00 to 14.90, representing a 2.1% increase.

Our findings align with prior research highlighting that seed priming and nitrogen application positively affect leaf development (Recalde et al., 2024). Seed priming activates a wider range of genes, enhancing plant defense mechanisms against stress and diseases (Aamir et al., 2019). Similar studies by Kuan-Hung et al. (2019) also demonstrated significant improvements in growth attributes like plant height, leaf number, and leaf area with nitrogen application.

3.3 Grains cob^{-1}

The number of grains per cob was significantly influenced by seed priming (water or 0.2% P solution) and varying nitrogen levels. As detailed in Table 3, data analysis indicated that nitrogen levels and seed priming had a significant effect ($P \leq 0.05$) on the number of grains per cob in maize. However, the moisture conditions did not exhibit a positive effect, and interactions among these factors were also non-significant.

Grains per cob increased with higher nitrogen levels and seed priming. The highest number of grains per cob (430) was recorded at 150 kg N ha^{-1}, followed by 398 grains at 75 kg N ha^{-1}. The lowest count (363) was observed at 0 kg N ha^{-1}. Seed priming enhanced grain production, with P-primed seeds yielding 420 grains per cob and water-soaked seeds showing 397 grains. Dry seeds produced the fewest grains per cob (365).

Overall, the number of grains per cob was maximized at the 150 kg N ha^{-1} nitrogen level, where 430 grains were recorded. These results align with previous studies that demonstrated the benefits of seed priming and nitrogen application on grain yield. For instance, Raza et al. (2023) reported similar findings for maize. Additionally, Rafiullah et al. (2020) found that wheat treated with a 0.3% phosphorus solution had a higher number of grains per spike, reinforcing the positive effect of phosphorus treatment. Choudhary et al. (2024) also noted that priming maize seeds with phosphate solutions boosted seedling growth and grain production, leading to increased yield.

3.4 Thousand-grain weight (G)

The weight of a thousand grains was significantly influenced by seed priming (with water or 0.2% P solution), nitrogen levels, and moisture conditions. As shown in Table 3, statistical analysis revealed that nitrogen levels, moisture, and seed priming had significant effects ($P \leq 0.05$) on thousand-grain weight, while interactions among these factors were not significant.

Table 1. Physio-chemical characteristics of the soil under study.

Property	Concentration
Sand (%)	38.4
Silt (%)	52.4
Clay (%)	9.2
Textural class	Silt loam
pH (1:5)	7.8
Electrical conductivity (EC) (d Sm$^{-1)}$	1.28
Lime (%)	16.2
Organic matter content (%)	0.8
Total nitrogen content (%)	0.2
Bulk density (gm cm$^{-3)}$	1.40
AB-DTPA extractable P (mg kg^{-1})	2.12

Table 2. Plant height (cm) and number of leaves of maize as influenced by moisture, nitrogen levels, seed priming.

Moisture	Plant height (CM)	Number of leaves
Low	162	10
High	178	12
Significance level	Ns	*
Nitrogen (kg ha^{-1})		
0	153c	9c
75	173b	10b
150	196a	13 a
LSD	*	*
Seed priming		
Dry seed	160c	10c
Water-soaked seed	180b	12b
P primed seed	188a	13a
LSD	*	*

LSD is used to group treatments based on their statistical differences. Treatments assigned the same letter (e.g., "a") are not significantly different from one another, whereas treatments assigned different letters (e.g., "a" and "b") indicate a statistically significant difference between them.

High moisture plots yielded a higher thousand-grain weight (270 g) compared to low moisture plots (260 g). The weight of a thousand grains increased with higher nitrogen levels and seed priming. The highest thousand-grain weight (285 g) was observed at 150 kg N ha^{-1}, followed by 272 g at 75 kg N ha^{-1}, while the lowest weight (235 g) was recorded at 0 kg N ha^{-1}. Seed priming also significantly improved thousand-grain weight. The highest weights were noted for P-primed seeds (280 g) and water-soaked seeds (267 g), while dry seeds had a lower thousand-grain weight (252 g).

Our findings are in line with previous studies, indicating that maize grain weight is a complex trait influenced by genetic and environmental factors (Choukri et al., 2022). The application of nitrogen significantly boosts maize yield, with different varieties responding variably to nitrogen levels. Larger leaf areas that capture more sunlight contribute to higher grain weight and overall yield (Gu et al., 2017). The activation of seeds through priming appears to enhance their growth and productivity, leading to higher grain weight and biomass production (Ali et al., 2007). Additionally, Wang et al. (2016) reported that plots receiving four irrigations achieved higher grain weight compared to those with fewer irrigations, suggesting that increased water availability supports better grain development.

3.5 Nitrogen uptake (kg ha^{-1})

Total nitrogen uptake was significantly influenced by seed priming (with water or 0.2% P solution), nitrogen levels, and moisture conditions, with all interactions found to be significant (*$P \leq 0.05$*).

Table 3. Grains cob-1, thousand-grain weight (g), and nitrogen uptake of maize as influenced by moisture, N levels, and seed priming.

Moisture	Grains cob^{-1}	Thousand-grain weight (g)	Nitrogen uptake
Low	380	260	136
High	395	270	150
Significance level	NS	*	*
Nitrogen (kg ha^{-1})			
0	363c	235c	82c
75	398b	272b	134 b
150	430a	285a	198a
LSD	*	*	*
Seed priming			
Dry seed	365c	252c	118c
Water-soaked seed	397b	267b	142b
P primed seed	420a	280a	163a
LSD	*	*	*

Note: Mean values followed by different letters in each category are significantly different at a 5% level of probability using the LSD test, ns = non-significant.

Table 4. Biological yield (kg ha $^{-1}$), grain yield (kg ha $^{-1}$), Stover yield (kg ha $^{-1}$), and harvest index (%) of maize as influenced by moisture, Nitrogen levels, and seed priming.

Moisture	Biological yield (kg ha $^{-1}$)	Grain yield (kg ha $^{-1}$)	Stover yield (kg ha $^{-1}$)	Harvest index %
Low	6645	2115	4530	31.3
High	7286	2385	4901	32.7
Significance level	Ns	Ns	Ns	Ns
Nitrogen (kg ha^{-1})	--	--	--	--
0	5419c	1542c	3877c	28.4c
75	6943b	2436b	4507b	35 b
150	9775a	3592a	6183a	36.7a
LSD	*	*	*	*
Seed priming	--	--	--	--
Dry seed	6394c	1908c	4486c	29.8c
Water-soaked seed	7848b	2426b	5422b	30.9b
P primed seed	8164a	2565a	5599a	32.2a
LSD	*	*	*	*

Note: Note: Mean values followed by different letters in each category are significantly different at a 5% level of probability using the LSD test, ns = non-significant.

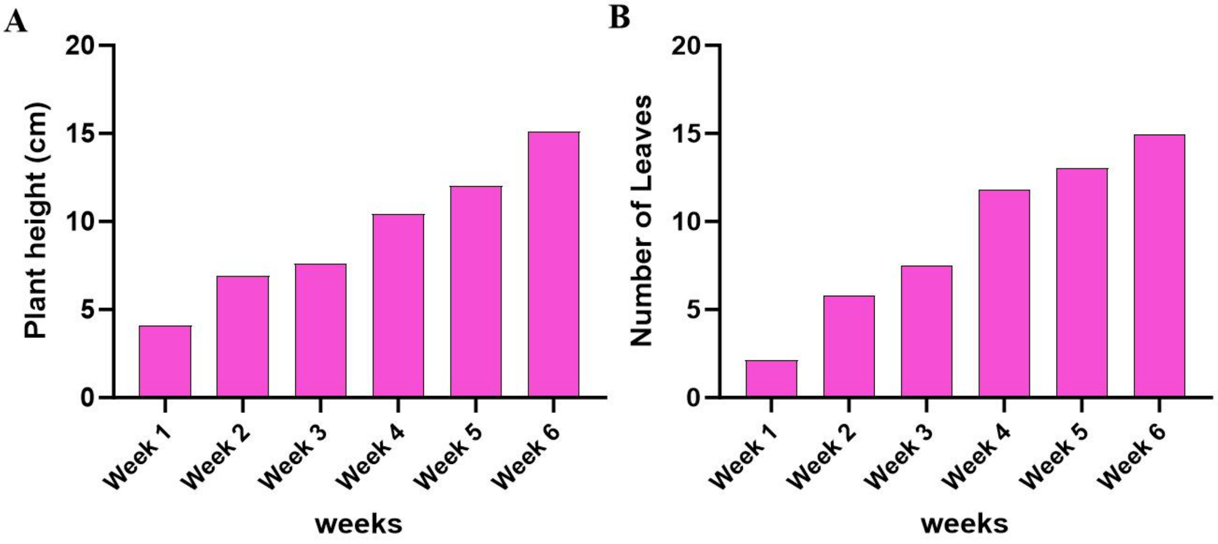

Figure 1. Weekly progress of (A) plant height and (B) leaves.

Data presented in Table 3 indicate that high moisture plots resulted in greater nitrogen uptake (250 kg ha $^{-1}$) compared to low moisture plots (136 kg ha $^{-1}$). The highest nitrogen uptake was recorded at 150 kg N ha $^{-1}$ (198 kg N ha $^{-1}$), followed by 75 kg N ha^{-1} (134 kg N ha $^{-1}$), and the control plot with no nitrogen application had the lowest uptake (82 kg N ha $^{-1}$).

Seed priming also played a crucial role in enhancing nitrogen uptake. The P-primed seeds showed the highest nitrogen uptake (163 kg N ha $^{-1}$), whereas dry seeds exhibited the lowest (118 kg N ha $^{-1}$). This improvement can be attributed to the increased vegetative growth fostered by priming, which enhances the plant's biological yield and overall nutrient uptake compared to the control (Mahmood et al., 2022).

The findings highlight the importance of nitrogen as a vital nutrient in maize production, as it significantly contributes to yield. However, it is also one of the most expensive inputs, making its efficient uptake crucial for cost-effective production. Nitrogen application accounts for an average of 18% and 13% of variable costs in corn and corn-soybean rotations, respectively (Foxhoven, 2022). Our study supports previous research indicating that seed priming can significantly improve nutrient uptake. For example, Guha et al. (2022) demonstrated that nutrient activation notably increased zinc uptake by seedlings, and similar improvements in phosphorus uptake were observed with seed activation using a phosphorus solution (source).

Overall, these results emphasize that seed priming, particularly with phosphorus solutions, along with optimal nitrogen application, enhances nutrient absorption and contributes to better plant growth and productivity.

3.6 Biological yield (kg ha $^{-1}$)

The study evaluated the biological yield of maize under different conditions, including seed priming (with water or 0.2% P solution) and non-primed seeds, across various nitrogen levels. The data, summarized in Table 4, illustrate how seed priming and nitrogen levels interact to influence the biological yield and overall productivity of maize. Data analysis revealed that both nitrogen levels and seed priming had significant effects ($P \leq 0.05$) on the biological yield of maize, whereas moisture had no significant impact. Similarly, interactions between these factors were not significant.

Biological yield increased with higher nitrogen levels and seed priming. The maximum biological yield was recorded at 150 kg N ha $^{-1}$ (9775 kg ha $^{-1}$), followed by 75 kg N ha $^{-1}$ (6943 kg ha $^{-1}$). The lowest biological yield (5419 kg ha $^{-1}$) was obtained at 0 kg N ha $^{-1}$. Seed priming further improved the biological yield, with P-primed seeds yielding 8164 kg ha $^{-1}$ and water-soaked seeds yielding 7848 kg ha $^{-1}$. In contrast, dry seeds resulted in a lower yield of 6394 kg ha $^{-1}$.

The observed positive impact of seed priming on biological yield is consistent with findings in other research. Ya et al. (2021) also demonstrated that varying nitrogen levels significantly enhance the biological yield of maize, underscoring the importance of optimized nutrient management. This study aligns with Anas et al. (2020), who reported that increased nitrogen application promoted vegetative growth, resulting in higher biological yields. The findings confirm those of Ellouzi et al. (2024), who found that seed activation led to significant improvements in total biomass and dry weight, highlighting the benefits of seed priming for overall plant growth. Additionally, Pawar and Laware (2018) noted that primed seeds substantially increased total biomass and dry weight compared to unprimed seeds, further supporting the effectiveness of seed priming in boosting crop productivity.

These results emphasize that both seed priming, particularly with phosphorus, and optimal nitrogen fertilization are critical for maximizing the biological yield of maize. The increased biomass production observed in this study suggests that seed activation plays a key role in improving the efficiency of nutrient utilization and promoting robust plant growth.

3.7 Grain yield (kg ha $^{-1}$)

Table 4 presents the data on maize grain yield, indicating that both nitrogen levels and seed priming significantly ($P \leq 0.05$) affected the grain yield. The results showed that grain yield increased substantially with higher nitrogen levels and seed priming. Moisture, however, did not have a significant impact on grain yield. Additionally, all interaction effects were found to be insignificant.

The highest grain yield was recorded at 150 kg N ha $^{-1}$ (3592 kg ha $^{-1}$), followed by the nitrogen level of 75 kg N ha $^{-1}$ (2436 kg ha $^{-1}$). The minimum yield was observed at 0 kg N ha $^{-1}$ (1542 kg ha $^{-1}$). Seed priming also played a significant role in improving grain yield, with maximum yields of 2565 kg ha $^{-1}$ and 3246 kg ha $^{-1}$ achieved for P-primed and water-soaked seeds, respectively. Dry seeds showed the lowest grain yield at 1908 kg ha $^{-1}$.

The observed increase in grain yield due to nitrogen application and seed priming aligns with research findings that underscore the importance of these factors in boosting maize productivity. Huang et al. (2024) similarly reported that nitrogen application and seed treatment enhanced both biomass and grain yield in maize. The linear increase in grain yield with higher nitrogen levels corroborates previous studies that highlight the importance of adequate nitrogen supply for crop productivity. The highest grain yield achieved with 0.2% P seed activation further emphasizes the benefits of seed priming, as demonstrated by Gelaw et al. (2023).

Watering seeds as part of seed priming was also found to be an effective practice for improving maize yield, supported by Farooq et al. (2019), who demonstrated that adequate moisture contributes significantly to crop productivity. Moreover, Ali et al. (2023) found that seed activation with water alone led to a marginal increase in maize yields, highlighting the value of simple and cost-effective seed treatment methods for enhancing growth and yield.

These results suggest that combining seed priming—especially with phosphorus or water—and appropriate nitrogen application can significantly improve grain yield, emphasizing the importance of optimized agronomic practices for maize production.

3.8 Stover yield (kg ha^{-1})

Data on maize stover yield are presented in Table 4. The analysis demonstrated that both nitrogen levels and seed priming significantly (*P≤0.05*) influenced stover yield, while moisture did not show a significant positive effect. Additionally, all interaction effects were found to be non-significant.

The highest stover yield was observed at 150 kg N ha^{-1} (6183 kg ha^{-1}), followed by 75 kg N ha^{-1} (4507 kg ha^{-1}). The minimum stover yield was recorded at 0 kg N ha^{-1} (3877 kg ha^{-1}). Seed priming significantly improved stover yield, with higher yields of 5599 kg ha^{-1} and 5422 kg ha^{-1} for P-primed and water-soaked seeds, respectively. In contrast, dry seeds produced the lowest stover yield (4486 kg ha^{-1}).

The results confirm that seed priming (with water or 0.2% P) and varying nitrogen levels contribute positively to stover yield. These findings are consistent with those reported by Ahmad et al. (2024), who also observed higher stover yields with treated seeds compared to untreated ones. Similarly, Saudy et al. (2020) highlighted that seed priming significantly increased stover yield, aligning with the current study's outcomes. Chakma et al. (2021) further supported these findings, noting that seeds treated with a 0.2% P solution showed an enhanced straw yield, and priming with a 1% P solution resulted in a 94% increase in dry matter compared to the control. These observations underscore the importance of seed priming and appropriate nitrogen management in boosting stover yield, which contributes to overall biomass and productivity in maize cultivation.

3.9 Harvest index (%)

The data on the harvest index of maize are presented in Table 4. The analysis revealed that nitrogen levels and seed priming had significant (*P ≤ 0.05*) effects on the harvest index, while moisture did not show a significant positive effect. Additionally, all interaction effects were non-significant. The highest harvest index (36.7%) was recorded in plots treated with 150 kg N ha^{-1}, followed by 35% for plots with 75 kg N ha^{-1}. The lowest harvest index (28.4%) was observed in plots that received no nitrogen (control). Seed priming also influenced the harvest index, with the highest value of 32.2% for P-primed seeds, followed by 30.9% for water-soaked seeds, and 29.8% for dry seeds. The harvest index increased with higher nitrogen rates, demonstrating that nitrogen application positively impacted the efficiency of biomass conversion to harvestable yield. High moisture plots exhibited a slightly higher harvest index (32.7%) compared to low moisture plots (31.3%), although the effect of moisture was not significant.

These findings align with similar studies that underscore the impact of nitrogen and seed priming on the harvest index. Ali et al. (2021) also reported significant improvements in the harvest index due to varying nitrogen levels. Chakwizira (2021) highlighted that nitrogen plays a crucial role in influencing the efficiency of biomass conversion, thereby affecting the harvest index. The significant positive impact of seed activation on the harvest index aligns with Waqas et al. (2021), who demonstrated that seed treatment with polyethylene glycol led to a 60% harvest index, illustrating its effectiveness in enhancing yield components.

Furthermore, Noreen et al. (2021) observed that phosphorus (P) priming increased the harvest index, reinforcing the benefits of nutrient-based seed treatments. In conclusion, both nitrogen application and seed priming can effectively enhance the harvest index of maize, contributing to better yield efficiency and productivity.

4. Conclusion

High moisture (seedbed) resulted in higher yield and yield components as compared to low moisture seedbed. Nitrogen at the rate of 150 kgha^{-1} produced higher yield and yield components as compared to other levels. Phosphorous-primed seed resulted in maximum grain yield and yield components as compared to water-soaked and dry seed. Phosphorous-primed seed resulted in maximum grain yield and yield components as compared to water-soaked and dry seed. P priming is recommended to the farmers based on good crop stand and yield performance.

Authors contributions: Abid Kamal contributed to conceptualization and methodology. Imran led the research, including conceptualization, methodology, data analysis, supervision, and manuscript drafting. Muhammad Irfan assisted with data collection and analysis. Sajid Ali contributed to fieldwork and data acquisition. Ahmad Naeem reviewed the literature and refined the manuscript. Abdul Bari supported the experimental setup and final review. Imran served as the corresponding author and ensured the study's overall quality. All authors reviewed and approved the final manuscript.

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