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RESEARCH

Seed Priming Boosts Plant Growth, Yield Attributes, Seed Chemical and Antioxidant Composition in Lentil under Low-Phosphorus Field Conditions

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Abstract
Although legumes can meet nitrogen requirements via symbiotic nitrogen fixation, they must acquire phosphorus from the rhizosphere through their roots. Additionally, the fixation of phosphorus with various cations in soils reduces its availability, thereby decreasing its effectiveness and increasing production costs. This study was conducted during the 2021-22 and 2022-23 growing seasons to investigate the effects of seed pre-treatment (priming) and phosphorus doses on plant growth, yield attributes, and seed chemical composition in lentil at Siirt, Türkiye. Six seed priming treatments and four phosphorus doses were used in the study. The research was laid out in split-plot randomized complete block design with four replications. According to the results, phosphorus fertilizer increased seed yield, but there was no statistical difference between 15 and 60 kg P_2O_5 ha^{-1}. Seed priming had a synergistic effect, allowing for higher seed yield when combined with phosphorus fertilizer, especially silicon priming resulting in high seed yield even at low phosphorus fertilizer doses. This result also indicated that seed priming improved phosphorus efficiency. The highest seed yield and net income were obtained by 6 kg P_2O_5 ha^{-1} with silicon priming treatment. Moreover, seed priming with salicylic acid, beneficial bacteria and silicon boosted growth and yield attributes, and seed chemical composition. Silicon priming increased the total antioxidant content in seeds while salicylic acid priming provided opportunities for both the increase of total antioxidants and phenolics. In conclusion, seed priming is an easy-to-implement and economical method for reducing phosphorus fertilizer and an effective way for higher profitability in lentil cultivation.

Keywords Antioxidant · *Brevibacillus choshinensis* · *Paenibacillus xylanilyticus* · Phenolic · Phosphorus efficiency · Sustainable agriculture

Introduction

Lentil (*Lens culinaris* L.) was recorded as the oldest cultivated grain legume on radiocarbon dating methods in archaeological excavations (Sonnante et al., 2009). According to Statpup (2024) data, 5.9 million tons of lentils on 5.5 million hectares were produced in the 2021-22 season, while it changed to 5.4 million tons on 5.2 million hectares in the 2022-23 season. Canada ranked first (1.606 million tons), followed by India (1.490 million tons) worldwide. Turkey produced 400 thousand tons on 290 thousand hectares of cultivated land in 2022 (FAO, 2023). The data underscores the significance of lentil in agriculture, human nutrition, and the global food chain.

Providing essential nutrients at optimum levels has a pivotal role in both yield and quality attributes in agricultural production. Nitrogen is the most critical nutrient for plants, however, legumes can meet their nitrogen requirement via symbiotic nitrogen fixation under suitable conditions including ecological, physio-chemical and biological ingredients. The availability of effective rhizobium strains (*Rhizobium leguminosarum*) in lentil cultivation areas or inoculation to

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seed before sowing enables to conversion of atmospheric nitrogen (N_2) into ammonia through root nodules (Ahmad et al., 2022). However, phosphorus has a critical role in lentil cultivation, since plants need to uptake it from the soil throughout their lifespan.

Phosphorus deficiency is a common phenomenon in agricultural areas due to fixation by some cations (Al, Ca, Fe, etc.), therefore it is converted into a non-available compound for plants (Ghodszad et al., 2021). MacDonald et al. (2011) indicated that more than 29% of agricultural soils (nearly 5.7 billion hectares) suffer from phosphorus deficiency and increasing by day worldwide. Therefore, the quantity of phosphorus fertilization in agricultural areas continues to increase each year. Inorganic phosphorus boosts yield attributes in the short term, however, the increased use of synthetic fertilizers substantially contributes to environmental pollution (Mallin and Cahoon, 2020). In addition, high addition of chemical fertilizers contaminates groundwater, reduces microbial activity and soil organic matter content, disturbs soil structure and increases soil erosion (Ji et al., 2023). Therefore, practices reducing chemical fertilizer without yield and quality loss have a pivotal role in agricultural production.

Seed priming facilitates seed germination and stand establishment of seedlings, boosts plant development, regulates physiological, biochemical, and molecular responses in plants, promotes nutrient uptake, and strengthens tolerance to stress factors. Seed priming is based on soaking seeds in a solution that has low osmotic potential for a certain period and drying to initial humidity again (McDonald, 2000; Reddy, 2012; Ceritoğlu et al., 2023). This process initiates various biochemical events in the seed such as activating antioxidant defense systems alongside the germination process (Mauch-Mani et al., 2017). The general objectives of seed priming are improving germination characteristics, enhancing seedling development and nutrient uptake, mitigating sensitivity to stress factors and improving crop yield (Paul et al., 2022). Sirisuntornlak et al. (2021) determined that seed priming with 1 mM silicon promoted nitrogen uptake in maize. Özyazıcı et al. (2023) reported that seed priming with 0.25 mM salicylic acid enhances germination characteristics and seedling growth in switchgrass (*Panicum virgatum* L.). Raza et al. (2024) indicated that seed priming with 6 mg L^{-1} selenium promotes quinoa yield under drought conditions. Mazhar et al. (2023) denoted that seed priming 75 ppm iron oxide nanoparticles increased superoxide dismutase (SOD) and catalase (CAT) activity by 13% and 38%, respectively. Freitas and da Silva (2024) reported that seed priming treatments enhance stress memory in plants.

The scenario of this experiment was built upon that seed priming with materials, that are related to phosphorus or acquisition of it, can reduce phosphorus fertilizer, directly or indirectly improve seed yield and quality and increase net income in lentil cultivation. The research holds an originality in examining the effects of the materials with seed priming technique on lentil under low-phosphorus field conditions. Furthermore, another original aspect of the study is to provide insight into the effects of seed priming on total antioxidant and phenolic compounds as well as the total protein and phosphorus content of lentil seed.

Materials and Methods

Experimental Materials

Tigris, a red lentil cultivar (*Lens culinaris* Medik.), which was developed via selection breeding by the GAP International Agricultural Research and Training Center (GAPUTAEM) in 2013, was used in the experiment. Triple superphosphate (43% P) and urea (46% N) were used for adjusting phosphorus levels and initial nitrogen for each plot, respectively. Inorganic phosphorus (Pi), silicon (Si), citric acid (CA), salicylic acid (SA), and phosphate-solubilizing bacteria (PSB) were used for seed priming. Monopotassium phosphate (KH_2PO_4) was used as the Pi source. *Brevibacillus choshinensis* (TV53D) and *Paenibacillus xylanilyticus* (KF63C) consortium were used for bio-priming. Certified reference material (Merck, Germany) was preferred for the chemical materials. The biological materials were isolated from the Van Lake Basin in 2008 (Çakmakçı et al., 2010) and from rural areas of the Siirt region in 2020 for TV53D strain within the scope of Scientific and Technological Research Council of Türkiye (TUBİTAK) project numbered TOVAG 108O147, and KF63C was isolated as a result of individual research conducted in rural areas of Siirt at 2018.

Ecological Conditions of Experimental Area

The research was conducted in the Faculty of Agriculture at Siirt University in the 2021-22 and 2022-23 seasons. Siirt is located in the Southeastern Anatolia Region at 41° 57' east longitude and 37° 55' north latitude. The elevation of the research area above sea level is 590 m.

Siirt has a climatic characterization as hot and dry in summers, predominantly experiencing a continental climate. There is a significant temperature difference between day and night throughout the province. Climate data for the 2021-22 and 2022-23 seasons, including monthly average temperatures and monthly total precipitation, along with the

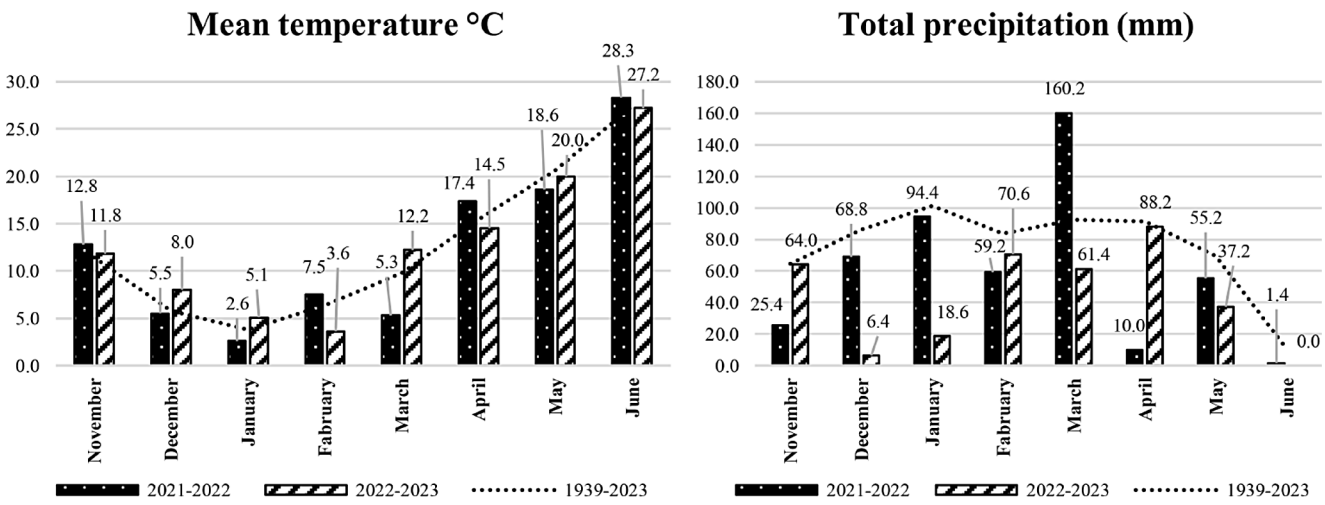

Fig. 1 The long-term (1939–2023) and research years (2021–2023) average temperature and total precipitation data for the province of Siirt

Table 1 Characteristic of experimental soil for 2021-22 and 2022-23 growing seasons

Year	Texture	EC (dS/m)	pH	Lime (%)	OM (%)	P_2O_5 (kg/da)	K_2O_5 (kg/da)
2021-22	Clay-loam	0.16	8.02	8.44	1.55	3.07	55.1
2022-23	Clay-loam	0.13	7.82	7.89	1.12	2.24	82.2

(OM: Organic matter)

long-term averages (LTA), are provided for the Siirt region in Fig. 1.

Total temperatures throughout vegetation period were 2940 °C and 3072 °C in the 2021-22 and 2022-23 seasons, respectively. In addition, the lowest air temperatures during 2021-22 for November, December, January, and February were 6.4 °C, -3.5 °C, -9.0 °C, and −0.8 °C, respectively, while they were determined as 5.5 °C, 0.7 °C, -2.2 °C, and −5.4 °C in 2022-23 season, respectively. Total precipitations during the entire vegetation period from stand establishment to harvest were recorded as 474.6 mm and 346.4 mm for the 2021-22 and 2022-23 seasons, respectively.

Soil Characteristics of Experimental Area

Soil samples were taken from A horizon at the experimental area before sowing in both years. Soil samples were analyzed for texture, pH, EC, lime, organic matter, available phosphorus, and potassium contents at Siirt University, Science and Technology Application and Research Center. The soil reaction (pH) and salinity (EC) were determined using the 1:2.5 soil-water mixture method. Lime was detected using the calcimeter method. The Bouyoucus hydrometer method was used for texture analysis. Soil organic matter was determined using the Walkley Black wet combustion method (De Vos et al., 2007). Available phosphorus was calculated by sodium bicarbonate method using a spectrophotometer (Schoenau & O'Halloran, 2007), and available potassium was determined using the ammonium acetate method with a flame photometer (Ferrando et al., 2020).

Soil texture and plant height were clayey-loamy (sand %20–40 and clay %27–40) and slightly alkaline in both years, respectively. The soil was non-saline and lime content was moderate in both seasons. Organic matter content and available phosphorus were low in 2021-22, while they were very low in 2022-23. Available potassium content was high in both seasons. Soil characterization is summarized in Table 1.

Preparation of Solutions and Seed Priming Process

Bio-priming or biological seed treatment includes beneficial microorganisms for seed priming to stimulate plant growth, increase yield attributes and protect against stress while maintaining environmental balance. Bio-priming is recognized as a low-cost and eco-friendly technique that is potent to encourage growth, enhance stress tolerance and increase crop yield (Chakraborti et al., 2022; Ceritoglu et al., 2024).

The bacterial strains were inoculated in petris including nutrient agar and were placed in an incubator at 28 ± 2 °C for 48 h to allow them to grow and form colonies. Nutrient broth (Merck, Sigma Aldrich, Germany) was mixed with distilled water and autoclaved at 121 °C for 20 min. Samples taken from sufficiently developed strains were transferred to the liquid nutrient broth. Colonies were added to the erlenmeyer flask containing nutrient broth until the

bacterial density reached 10^9 cfu, and then homogenized at 120 rpm using an orbital shaker. The density of the solutions was determined using the turbidimetric method. Chemical solutions, i.e., inorganic phosphorus, silicon, salicylic acid and citric acid, were set in concentrations at 1%, 4 mM, 0.2 mM and 100 ppm, respectively. Chemical-priming and bio-priming techniques were used in the experiment.

Seeds were treated for surface sterilization with 70% ethyl alcohol for 1 min and 10% sodium hypochlorite (NaOCl) for 5 min before seed priming process (Ceritoglu et al., 2023). Seeds were carefully washed with distilled water and then rinsed to remove surface water using sterile filter paper. Appropriate concentrations of Pi, Si, SA, and CA solutions were added at a seed: solution ratio of 1:1.5 (kg L^{-1}). Seed priming duration was set at 20 h for chemical materials, while it was set at 4 h for bio-priming. Chemical-primed seeds were washed with distilled water, however no bio-primed seeds. seeds were dried to the initial water content and stored at 4 °C.

Experimental Design and Layout of Two-Year Field Trails

The field trials were set up on November 19 and 21 for the 2021-22 and 2022-23 seasons, respectively. Sowing was done on slightly moist soil, and rainfall occurred within 48 h after planting in both seasons. The research was laid out in split-plot randomized complete block design with four replications. Main plots were assigned phosphorus levels, while subplots received seed priming treatments. Phosphorus levels were set as P0 (control), P1 (15 kg P_2O_5 ha^{-1}), P2 (30 kg P_2O_5 ha^{-1}), and P3 (60 kg P_2O_5 ha^{-1}). Phosphorus doses were applied under the seedbed with the planting using triple superphosphate (TSP) fertilizer. Nitrogen fertilization of 20 kg ha^{-1} pure nitrogen in urea form was treated in all plots (Dona et al., 2020).

The distance between plots and blocks was set at 1.5 m. Row spacing was set at 20 cm, and each plot consisted of 5 rows. With a plot width of 1 m and a plot length of 5 m, each plot was established as 5 m^2. Seeds were manually sown to avoid infection. The planting rate was adjusted to 250 seeds per square meter (Togay & Anlarsal, 2008).

Weed populations were managed to eliminate them before reaching the critical threshold that could cause damage to lentil (Erman et al., 2008). Herbicides or insecticides were not used within the scope of the study in both seasons. Crop harvesting was conducted in June during both growing seasons. One row from the edges of the plots and areas 50 cm away from the plot edges were left untouched to account for edge effects, and harvesting was carried out in the remaining central area.

Physiological, Agronomic and Yield Attributes

Shoot chlorophyll content was determined using a SPAD meter (SPAD-502 Konica Minolta Sensing, Inc., Japan) at flowering time. Measurements were taken between 10 and 12 am, and readings were taken from the youngest leaves of 5 randomly selected plants from each plot (Erman et al., 2022). Number of plants per square meter was determined near harvest time. Before harvest, 10 plants were randomly selected from each plot to achieve plant height, number of branches per plant and number of pods per plant. The harvested portion of the plot was dried in a well-ventilated area, and weighted to determine biological yield. After threshing, seed yield was calculated for the unit area (kg ha^{-1}).

Protein, Phosphorus, Total Antioxidant and Phenolic Content in Seed

Randomly selected seeds were taken and ground to prepare chemical analysis. A 0.5 g of the ground sample was weighed into porcelain crucibles, and after the pre-burning process, they were burned in a muffle furnace at 500 ± 20 °C. Total N content in seeds was determined using the Dumas method, and the obtained result was multiplied by 6.25 to determine total protein content in seeds (Wang & Daun, 2006). Seed phosphorus content was determined using the UV-spectrophotometric method (Wieczorek et al., 2022).

Lentil seeds were first ground into flour using a 1 mm sieve to prepare the extractions for antioxidant and phenolic compounds. Then, 0.5 g of ground seeds were placed into centrifuge tubes. The 5 ml of acetone/water (1:1 v/v) extraction solvent was added to each tube. Subsequently, 5 ml of acetone/water/acetic acid (70:29.5:0.5 v/v/v) extraction solvent was added. The capped tubes were placed horizontally and shaken at room temperature at 300 rpm in an orbital shaker for 3 h. The mixtures were left overnight in the dark for an additional 12 h for further extraction. The extracts were centrifuged at 3000 rpm for 10 min. The residues were re-extracted with 5 ml of the respective extraction solvents, and two extracts were combined and stored in the dark at 4 °C. Extractions were performed in triplicate for each lentil seed obtained from each treatment (Xu et al., 2007). For the determination of seed total antioxidant, the ferric-reducing antioxidant power (FRAP method) was used (Parikh & Patel, 2018). The Folin-Ciocalteu method was utilized for the determination of seed total phenolic by the method of Xu et al. (2007).

Economical Analysis

Variable input costs and total revenue parameters were considered to calculate the economic analysis. The

differences in seed yield compared to the control were calculated based on the individual and interactive effects of each treatment. The costs of phosphorus fertilization (TSP) and seed priming materials (calculated based on Merck brand prices) for one hectare of land were calculated. When calculating the yield increase in USD ($) compared to the control, the price set by the Agricultural Products Office (TMO) for lentil purchases in June 2023 (Tonne: $500) was used as the basis (TMO, 2023). For calculating the income from straw, a market survey for June 2023 was conducted, and the price per ton was determined to be $85. Net income was calculated using the formulas provided by CIMMYT (1988).

Statistical Analysis

The data from a two-year experiment were subjected to Levene's test for homogeneity. Once homogeneity was confirmed, analysis of variance (ANOVA) was conducted based on the completely randomized split-plot design. Tukey's Honestly Significant Difference (HSD) test was used for the grouping of means for dependent variables using "*agricolae*" package *R* software (Mendiburu, 2010). Pearson correlation analysis was applied to the dataset to examine the relationships between traits using "*PerformanceAnalytics*" package (Peterson et al., 2014). Statistical calculations and graphics were performed using the *R* (V.4.4.1) software (R Core Team, 2018).

Results

Variance Analysis of Experimental Data

The effects of various seed priming treatments on the agronomic and yield characteristics, and seed composition of lentil depending on different phosphorus doses were investigated through two-year field trials. According to the ANOVA results, year (Y), phosphorus fertilizer (P), seed priming treatments (Pr) and their various interactions have led to statistically significant differences ($p < 0.05$ or $p < 0.01$) in traits. Experimental seasons were sharply different due to climatic indices (Fig. 1), therefore, it caused major differences in all traits but seed total antioxidant. Phosphorus fertilizer was statistically effective on shoot chlorophyll content, plant height, number of branches per plant, number of pods per plant, biological yield, seed yield, seed phosphorus content and seed protein content. Seed priming had no statistically significant differences in plant height and number of seeds per pod, however, they caused significant differences in other traits. Y×P and Y×Pr interactions exhibited nearly similar results i.e., they significantly affected biological yield, seed yield and seed phosphorus content. In addition, Y×Pr interaction also significantly affected number of plants per square meter and seed protein content. P×Pr interaction led to significant differences in shoot chlorophyll content, plant height, seed phosphorus content, seed total antioxidant and seed total phenolic. Finally, Y×P×Pr interaction had significant differences in number of seeds per pod, biological yield, seed yield, seed phosphorus content, seed total antioxidant and seed total phenolic. The ANOVA results are provided in Table 2.

Effect of Growing Seasons on Experimental Characteristics

Experimental years indicated a noteworthy variation in characteristics. Shoot chlorophyll content and seed protein content were higher in the first-year compared with second-one, while other characteristics were higher in the second growing season. Thus, growth and yield attributes, seed

Table 2 Analysis of variance for years and treatments on investigated characteristics

Traits/Factors	Tukey/F prob.						
	Year (Y)	Phosphorus (*P*)	Priming (Pr)	Y×*P*	Y×Pr	*P*×Pr	Y×*P*×Pr
Number of plants per square meter	7.56/**	14.41/ns	17.69/**	24.52/ns	28.71/*	45.35/ns	70.93/ns
Shoot chlorophyll content	0.32/**	0.59/**	0.93/**	1,02/ns	1,49/ns	2.38/**	3,67/ns
Plant height	0.92/**	1.76/**	2,34/ns	3,01/ns	4,79/ns	6,03/ns	9,37/ns
Number of branches per plant	1.95/**	0.37/**	0.41/**	0.65/ns	0.63/ns	1,00/ns	1,59/ns
Number of pods per plant	8.15/**	15.51/*	11.31/**	26.35/ns	18.38/ns	29,02/ns	45,04/ns
Number of seeds per pod	0.050/*	0.096/ns	0.084/ns	0.164/ns	0.137/ns	0.212/ns	0.331/*
Biological yield	19.3/**	37.0/**	32.5/**	62.9/**	52.7/**	83.3/**	129.3/**
Seed yield	5.65/**	10.75/**	8.82/**	18.35/**	14.32/**	22.58/ns	35.05/**
Seed protein content	0.040/**	0.074/*	0.064/**	0.126/**	0.107/**	0.167/**	0.257/**
Seed phosphorus content	102.1/**	199.5/*	165.0/**	331.1/ns	268.1/**	421.4/ns	656.9/ns
Seed total antioxidant	0.141/ns	0.276/ns	0.160/**	0.443/ns	0.256/ns	0.406/**	0.632/*
Seed total phenolic	0.043/**	0.082/ns	0.087/**	0.141/ns	0.139/ns	0.218/*	0.343/*

(*: $p < 0.05$, **: $p < 0.01$, ns: no significant difference)

phosphorus content and seed total phenolic were higher in the second experimental year. In contrast, seed protein content and shoot chlorophyll content were higher in the first-year, so it will be observed that there is a strong positive correlation between shoot chlorophyll content and seed protein content. Although seed total antioxidant was higher in the second-season, the difference among years was not significant (Fig. 2).

Effect of Phosphorus Fertilization on Experimental Characteristics

Increasing phosphorus levels promoted shoot chlorophyll content, plant height, number of branches per plant, number of pods per plant and shoot protein content, while plant per square meter, number of seeds per pod, seed total antioxidant and seed total phenolic were not affected by phosphorus fertilization. Also, phosphorus addition positively influenced biological yield and seed yield over control, however, gradually increasing doses had no statistically significant

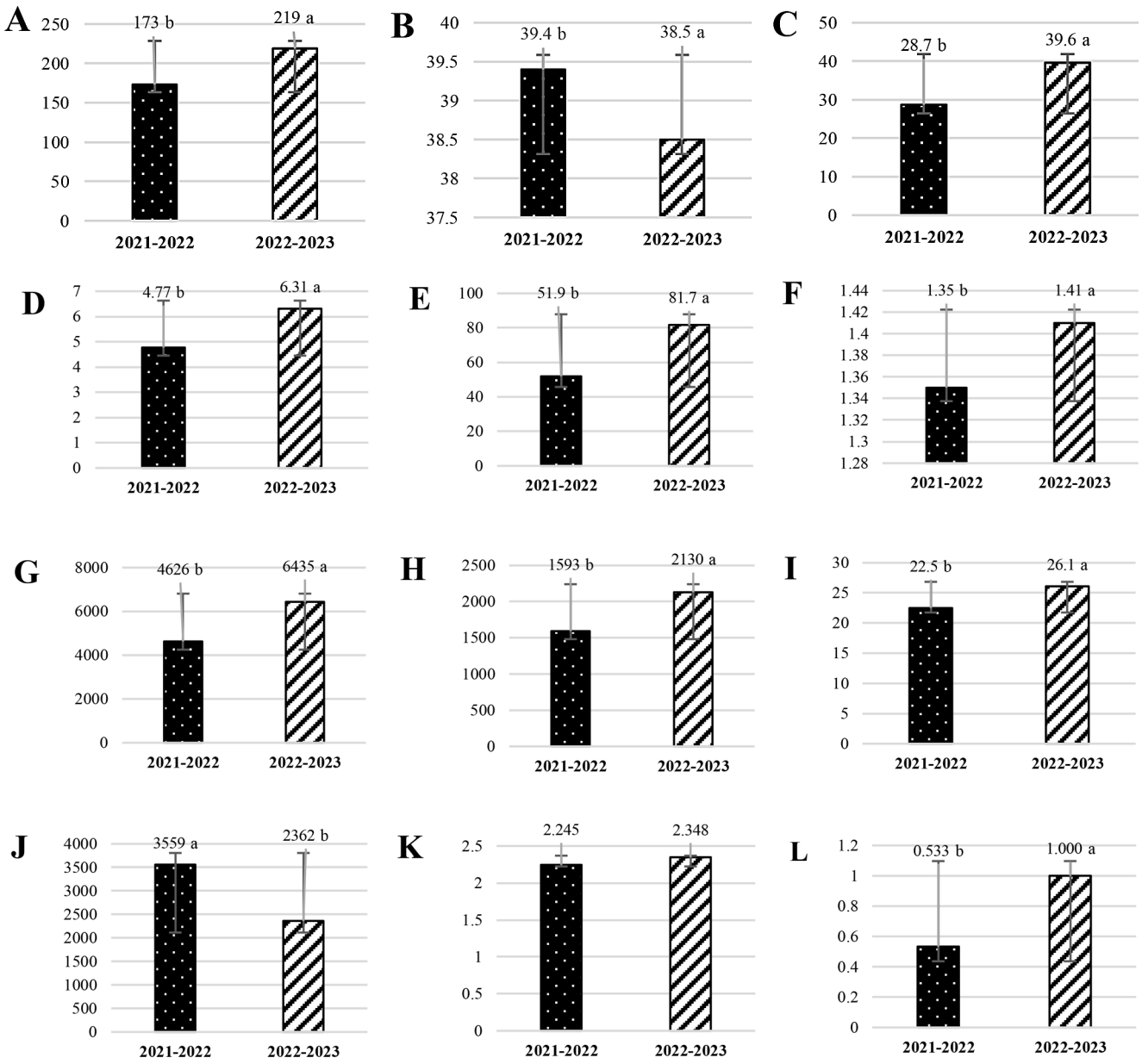

Fig. 2 Alteration of investigated parameters depending on experimental year [**A** Plant per square meter, **B** Shoot chlorophyll content (%), **C** Plant height (cm), **D** Number of branches per plant, **E** Number of pods per plant, **F** Number of seeds per pod, **G** Biological yield (kg ha^{-1}), **H** Seed yield (kg ha^{-1}), **I** Seed protein content (%), **J** Seed phosphorus content (mg kg^{-1}), **K** Seed total antioxidant (mg TE g^{-1}), **L** Seed total phenolic (mg GAE mL^{-1})]

difference. Seed phosphorus content exhibited a fluctuating response to phosphorus fertilization since it was lower in 15 kg P_2O_5 ha^{-1} treatment, whereas it was higher than the control in 30 and 60 kg P_2O_5 ha^{-1} treatments (Fig. 3).

Effect of Seed Priming Treatments on Experimental Characteristics

All seed priming applications increased the plant per square meter, however, most increase (21%) was determined in SA-primed seeds, following CA-priming (18%). Any seed priming treatment promoted shoot chlorophyll content up to 4.8% over control. Similarly, number of branches per plant was moved from 5.04 to 5.83 with SA-priming and other treatments increased it, too. SA-priming caused an increase in number of pods per plant by 31% compared to control plants and it was in the same statistical group as CA, PGPB and Si. Though all seed priming treatments increased biological yield and seed yield over control, in particular, Si-priming promoted them up to 14% and 20%, respectively. Pi- and PGPB-priming reduced seed phosphorus content, while other materials promoted nitrogen accumulation in seeds, thereby raising seed phosphorus content over control. Si-priming caused the highest seed protein content compared with control and other seed priming applications. Pi-, SA- and Si-priming promoted seed total antioxidant

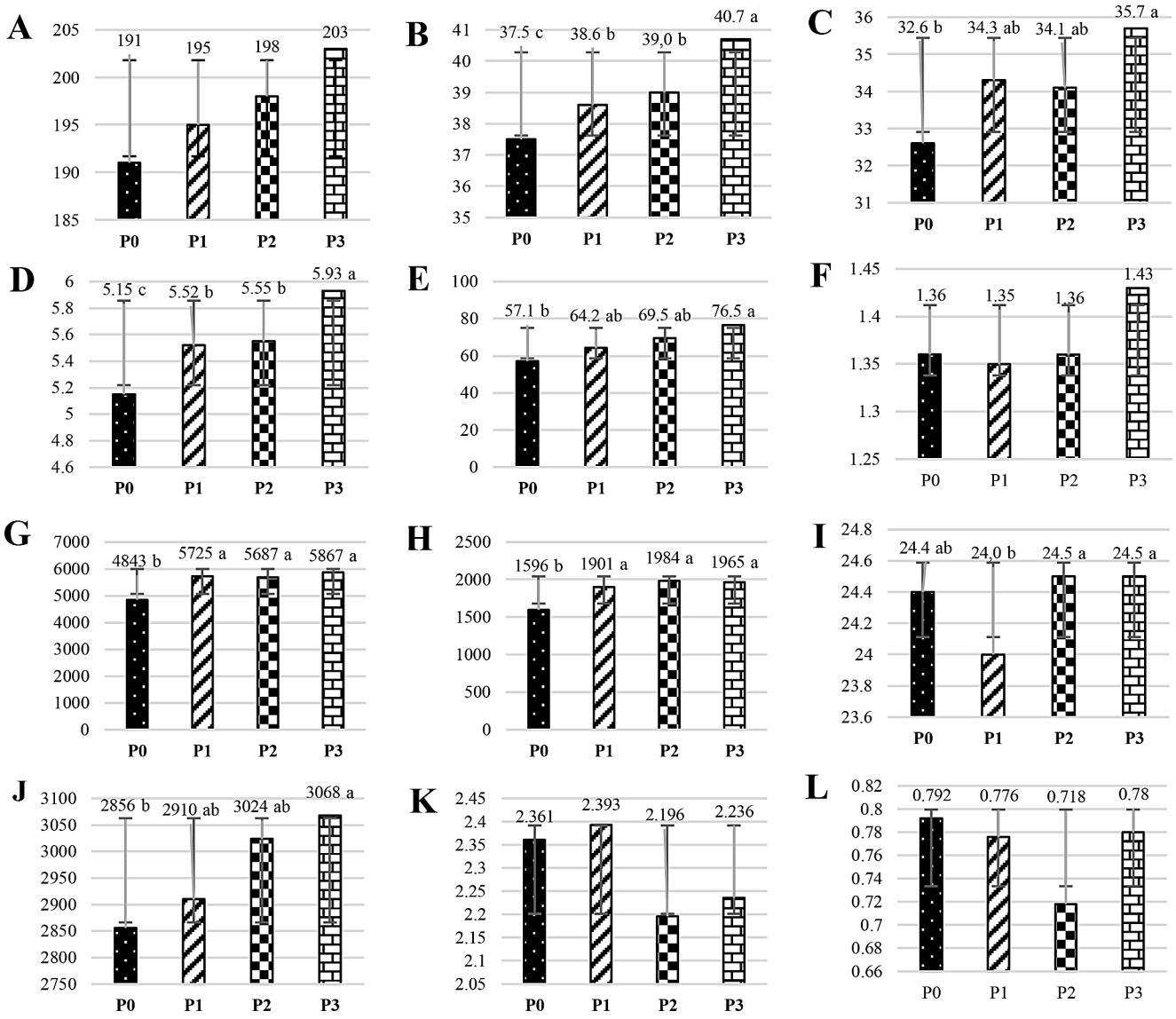

Fig. 3 Effect of phosphorus doses on agronomic and chemical characteristics [**A** Plant per square meter, **B** Shoot chlorophyll content (%), **C** Plant height (cm), **D** Number of branches per plant, **E** Number of pods per plant, **F** Number of seeds per pod, **G** Biological yield (kg ha^{-1}), **H** Seed yield (kg ha^{-1}), **I** Seed protein content (%), **J** Seed phosphorus content (mg kg^{-1}), **K** Seed total antioxidant (mg TE g^{-1}), **L** Seed total phenolic (mg GAE mL^{-1})]

and seed total phenolic, whereas CA- and PGPB-priming reduced their concentrations over control (Fig. 4).

Interaction Effects of Experimental Factors on Statistically Significant Characteristics

The lowest biological yield (3908 kg ha^{-1}) was obtained from plots with no phosphorus and Pi-priming in 2021-22, while the highest one (7628 kg ha^{-1}) was determined with 15 kg P_2O_5 ha^{-1} and S-priming in 2022-23. The significance of the Y×P×Pr interaction arises from the fact that seed priming did not show a consistent increase in biological yield depending on phosphorus doses within the same or different production years, resulting in significantly lower biological yield values despite increases at some doses. The lowest seed yield (1364 kg ha^{-1}) was obtained from plots where no phosphorus and Pi-priming, while the highest seed yield (2653 kg ha^{-1}) was determined with 60 kg P_2O_5 ha^{-1} and Si-priming in 2022-23. The results also indicated that Si-priming boosts the efficiency of phosphorus fertilization. The significance of the Y×P×Pr interaction is caused to arise from the different responses of seed priming to phosphorus fertilization when compared across years. The PGPB-priming contributed to an increase in seed yield parallel to increasing phosphorus fertilizer doses during the 2021-22 season,

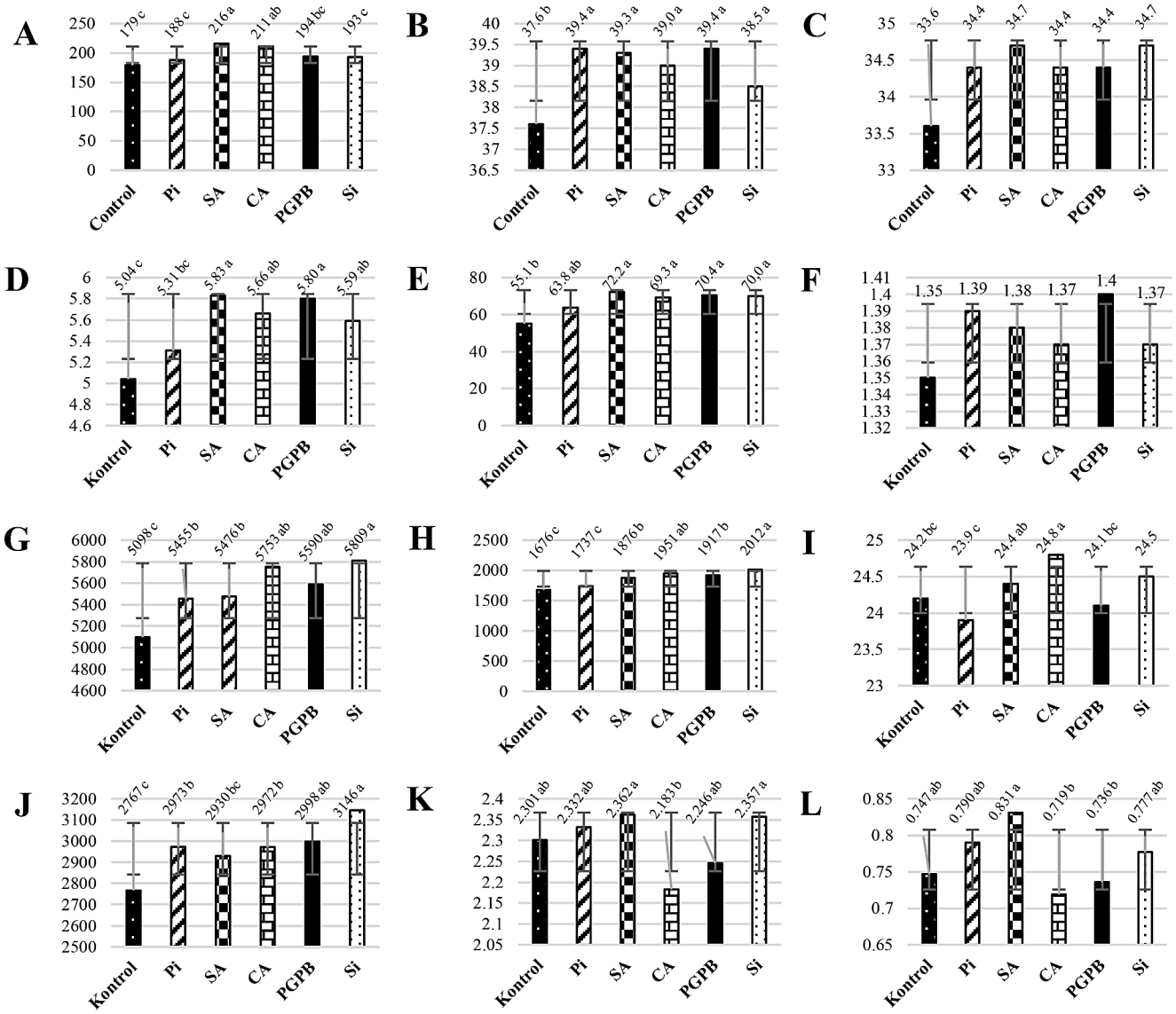

Fig. 4 Effect of seed priming treatments on agronomic and chemical characteristics [**A** Plant per square meter, **B** Shoot chlorophyll content (%), **C** Plant height (cm), **D** Number of branches per plant, **E** Number of pods per plant, **F** Number of seeds per pod, **G** Biological yield (kg ha^{-1}), **H** Seed yield (kg ha^{-1}), **I** Seed protein content (%), **J** Seed phosphorus content (mg kg^{-1}), **K** Seed total antioxidant (mg TE g^{-1}), **L** Seed total phenolic (mg GAE mL^{-1})]

providing an increase in yield up to the 30 kg P_2O_5 ha^{-1} dose, but causing a slight decrease with the 60 kg P_2O_5 ha^{-1} level in 2022-23 (Table 3).

The lowest SPC (21.2%) was determined from 30 kg P_2O_5 ha^{-1} and non-primed plants in 2021-22, while the highest seed phosphorus content (%27.3) was obtained from plots where 30 kg P_2O_5 ha^{-1} and S-priming were applied in 2022-23. The reason for the significance of the Y×P×Pr interaction is that 60 kg P_2O_5 ha^{-1} caused the highest seed phosphorus content in the first-year, while it was lower than control and other doses in the second experimental season. The lowest seed total antioxidant in seed (1.948 mg TE g^{-1}) was determined from plots where 30 kg P_2O_5 ha^{-1} was applied with S-priming in 2021-22, while the highest one (2.738 mg TE g^{-1}) was obtained from plots where 15 kg P_2O_5 ha^{-1} was applied with SA-priming in 2022-23. The reason for the statistically significant effects of the Y×P×Pr interaction on seed total phenolic is to show different effects on seed total antioxidant depending on the year and phosphorus fertilizer dose. The highest value was obtained in 2021-22 with Pi-priming and 15 kg P_2O_5 ha^{-1}, while the same application was found to be lower than other doses in 2022-23. The lowest seed total phenolic in seed (0.409 mg GAE mL^{-1}) was determined from plots where no phosphorus fertilizer and S-priming with 60 kg P_2O_5 ha^{-1} in 2011-22, while the highest seed total phenolic (1.154 mg GAE mL^{-1}) was obtained from no phosphorus with Pi-priming in the second year. The Y×P×Pr interaction's notable significance stems from the substantial rise in seed total phenolic in the P0 and Si-priming treatments during the 2021-22 season, contrasting with lower outcomes in the subsequent 2022-23 season, likely influenced by alternative seed priming applications and varying phosphorus doses. Additionally, the highest seed total phenolic was obtained with SA-priming with P1 in 2021-22, while the highest one was obtained with Pi-priming with P0 in 2022-23 (Table 4).

Economical Analysis of Experimental Data

The data regarding the economic analysis based on grain and straw yield attributable to the phosphorus fertilizer doses and seed priming applications used in the study are presented in Table 4. Changes arising from individual effects of phosphorus and seed priming and their interactive effects have been calculated, leading to the determination of a net income increase. Upon examination of Table 5, the lowest difference in seed yield compared to the control was found to be 140 kg ha^{-1} in Pi-priming, while the highest one was 810 kg ha^{-1} in the P3 + Si application. In terms of straw yield, the lowest difference compared to the control was 208 kg ha^{-1} in the PGPB-priming application, while the highest one was 1355 kg ha^{-1} in the P3 + S application. When calculating net income, the application costs were subtracted from the total value of seed and straw yield. Depending on increasing values, the net income ranged from \$930 to \$1370 per hectare after subtracting the application expenses. The lowest net income was obtained from the control, while the highest one was obtained from the P3 + Si application.

When only considering chemical fertilizer applications, the net income increase compared to the control was calculated as \$230, \$220 and \$200 for the P1, P2, and P3 applications, respectively. When evaluating net income only from phosphorus fertilizer, it was observed that despite the increased fertilization amount due to rising fertilizer prices, there was a decrease in net income due to the higher application cost. Moreover, applying

Table 3 Effect of seed priming under different phosphorus levels on biological and seed yield during 2021-22 and 2022-23 growing seasons

	Treatment	2021-22				2022-23			
		P0	P1	P2	P3	P0	P1	P2	P3
Biological yield (kg ha^{-1})	Control	404.0 k	441.0 jk	470.0 i-k	477.0 i-k	437.8 jk	644.5 a-e	608.5 c-h	595.5 d-i
	Pi	390.8 k	484.0 h-k	476.0 i-k	480.0 h-k	557.5 e-j	659.0 a-e	652.5 a-e	664.0 a-e
	SA	442.0 jk	470.0 i-k	495.0 g-k	514.0 f-k	503.3 g-k	669.0 a-e	670.0 a-e	617.8 b-g
	CA	464.0 j-k	448.0 jk	455.5 jk	553.0 e-j	562.3 e-j	762.8 a	675.3 a-e	681.8 a-e
	PGPB	416.0 k	412.5 k	443.0 jk	491.8 g-k	503.8 g-k	724.0 a-d	744.3 ab	736.5 a-c
	Si	493.0 g-k	470.0 j-k	453.0 jk	474.3 i-k	636.8 a-f	700.8 a-d	681.5 a-e	754.3 ab
	Mean	435.0 D	451.6 CD	465.4 CD	498.3 BC	533.5 B	693.3 A	672.0 A	675.0 A
Seed yield (kg ha^{-1})	Control	137.2 qr	143.1 p-r	154.3 o-r	159.5 n-r	143.2 p-r	203.5 f-k	197.8 f-l	202.0 f-k
	Pi	136.4 r	149.0 o-r	153.4 o-r	160.7 n-r	171.8 j-q	205.0 e-j	216.0 d-g	197.4 g-m
	SA	154.6 o-t	160.3 n-r	166.2 l-r	173.3 j-p	174.4 i-p	218.0 b-g	245.2 a-c	208.7 d-i
	CA	158.9 n-r	164.8 l-r	162.7 m- r	191.3 g-n	172.5 j-p	243.7 a-d	255.6 a	211.0 c-h
	PGPB	143.4 p-r	150.1 o-r	157.0 n-r	179.0 h-o	173.4 j-p	242.3 a-d	256.2 a	232.5 a-f
	Si	159.0 n-r	162.5 m-r	168.7 k-r	177.1 h-p	190.6 g-n	239.0 a-e	247.7 ab	265.3 a
	Mean	148.3 D	155.0 CD	160.4 BD	173.5 B	171.0 BC	225.2 A	236.4 A	219.5 A

(Pi: Inorganic phosphorus, SA: Salicylic acid, CA: Citric acid, PGPB: Plant growth promoting bacteria, Si: Silicon, P0: Phosphorus control, P1: 15 kg P_2O_5 ha^{-1}, P2: 30 kg P_2O_5 ha^{-1}, P3: 60 kg P_2O_5 ha^{-1})

Table 4 Effect of seed priming under different phosphorus levels on seed protein, total antioxidant and phenolic contents during 2021-22 and 2022-23 growing seasons

	Treatment	2021-22				2022-23			
		P0	P1	P2	P3	P0	P1	P2	P3
Seed protein content (%)	Control	22.1 hi	22.8 g-i	21.2 i	24.9 ef	26.0 a-e	23.9 f-g	27.0 a-c	25.9 a-e
	Pi	22.2 g-i	21.3 i	22.1 hi	22.0 hi	25.6 c-e	25.5 c-f	26.9 a-c	25.6 b-e
	SA	22.2 hi	22.1 hi	22.7 g-i	23.0 gh	26.1 a-e	26.7 a-d	27.2 ab	26.6 b-e
	S	22.6 g-i	22.2 hi	22.2 hi	23.9 fg	26.6 a-d	27.0 a-c	27.3 a	25.6 c-e
	PGPB	23.2 gh	22.1 hi	21.8 hi	22.2 hi	25.6 c-e	25.8 a-e	26.8 a-c	25.2 d-f
	Si	23.0 gh	22.3 g-i	22.3 hi	22.6 g-i	26.9 a-c	26.1 a-e	26.4 a-e	26.1 a-e
	Mean	22.6 CD	22.1 D	22.0 D	23.1 C	26.1 B	25.8 B	26.9 A	25.7 B
Seed total antioxidant (mg TE $g^{-1)}$	Control	2.339 a-d	2.021 cd	2.383 a-d	2.117 a-d	2.572 a-d	2.634 a-c	2.119 a-d	2.219 a-d
	Pi	2.252 a-d	2.276 a-d	2.308 a-d	2.246 a-d	2.542 a-d	2.537 a-d	2.287 a-d	2.207 a-d
	SA	1.959 d	2.738 a	2.062 b-d	2.290 a-d	2.387 a-d	2.659 ab	2.200 a-d	2.598 a-c
	S	2.049 b-d	2.142 a-d	2.203 a-d	2.005 cd	2.555 a-d	2.411 a-d	1.948 d	2.148 a-d
	PGPB	2.245 a-d	2.022 cd	2.296 a-d	2.374 a-d	2.274 a-d	2.549 a-d	2.117 a-d	2.093 b-d
	Si	2.598 a-c	2.291 a-d	2.361 a-d	2.303 a-d	2.565 a-d	2.433 a-d	2.065 b-d	2.237 a-d
	Mean	2.24	2.248	2.269	2.222	2.243	2.538	2.123	2.25
Seed total phenolic (mg GAE mL^{-1})	Control	0.502 h-j	0.487 h-j	0.474 jj	0.591 d-j	0.985 a-c	1.034 a-c	0.877 a-g	1.023 a-c
	Pi	0.506 h-j	0.487 h-j	0.583 e-j	0.491 h-j	1.154 a	0.979 a-c	1.048 a-c	1.073 ab
	SA	0.409 j	0.900 a-f	0.482 i-j	0.568 f-j	1.134 ab	1.072 a-c	0.987 a-c	1.093 ab
	S	0.498 h-j	0.441 j	0.507 h-j	0.409 j	1.086 ab	0.968 a-c	0.807 b-i	1.037 a-c
	PGPB	0.541 g-j	0.502 h-j	0.551 g-j	0.528 h-j	0.988 a-c	0.923 a-e	0.826 a-h	1.027 a-c
	Si	0.729 c-j	0.559 f-j	0.541 g-j	0.507 h-j	0.975 a-c	0.964 a-c	0.930 a-d	1.014 a-c
	Mean	0.531	0.563	0.523	0.516	1.054	0.99	0.912	1.044

(Pi: Inorganic phosphorus, SA: Salicylic acid, CA: Citric acid, PGPB: Plant growth promoting bacteria, Si: Silicon, P0: Phosphorus control, P1: 15 kg P_2O_5 ha^{-1}, P2: 30 kg P_2O_5 ha^{-1}, P3: 60 kg P_2O_5 ha^{-1})

Table 5 Economical analysis of treatments according to gain from seed and straw yield

Treatment	Increasing in seed yield (kg ha^{-1})	Income from seed ($ ha^{-1})	Increasing in straw yield (kg ha^{-1})	Income from straw ($ ha^{-1})	Treatment cost ($ ha^{-1})	Net income ($ ha^{-1})	Net income over control ($ ha^{-1})
Control	-	700	-	230	-	930	-
P1	330	870	888	310	15	1160	230
P2	360	880	826	300	30	1150	220
P3	410	900	749	300	60	1140	200
Pi	140	770	393	270	2	1040	100
SA	240	820	274	260	2	1080	140
S	260	830	667	290	2	1120	180
PGPB	180	790	208	250	2	1040	110
Si	350	870	1094	330	2	1200	260
P1-Pi	370	890	1138	330	17	1200	260
P1-SA	490	950	997	320	17	1250	310
P1-S	640	1020	1205	330	17	1340	400
P1-PGPB	560	980	914	310	17	1270	340
P1-Si	610	1000	960	310	17	1300	370
P2-Pi	450	920	989	320	32	1210	270
P2-SA	660	1030	961	310	32	1310	380
P2-S	690	1050	756	300	32	1310	380
P2-PGPB	660	1030	1063	320	32	1320	390
P2-Si	680	1040	784	300	32	1310	380
P3-Pi	390	900	1123	330	62	1160	230
P3-SA	510	960	942	310	62	1210	270
P3-S	610	1010	1355	350	62	1290	360
P3-PGPB	660	1030	1276	340	62	1310	370
P3-Si	810	1110	1124	330	62	1370	440

60 kg ha^{-1} phosphorus, despite obtaining higher seed yield, led to higher net income from plants without phosphorus and with Si-priming due to lower application costs. Furthermore, when Si-priming was applied along with the P1, P2, and P3 doses, it was determined to provide an extra income of $370, $380 and $440 per hectare, respectively.

In summary, although increasing phosphorus doses can increase seed and straw yield per unit area, considering the application costs, there is no difference in terms of net income. Nearly an income increase compared to the control could be achieved with Si-priming without phosphorus fertilization. However, low phosphorus fertilizer (15 kg ha^{-1}) with seed priming (especially S, Si, and PGPB), could increase net income and reduce chemical fertilizer input to agricultural soils (Table 5).

Discussion

Number of Plants per Square Meter

Mean temperatures in November during 2021-22 and 2022-23 are almost the same (12.8 °C and 11.8 °C, respectively), but the monthly total precipitation values are 25.4 mm and 64.0 mm, respectively (Fig. 1). In this case, the lack of sufficient rainfall on already dry soil after the summer season has caused some germination difficulties. Although there was enough rainfall for germination, the subsequent cessation of rainfall and the effect of wind may have prevented stand establishment due to the hard soil surface. The primary reason for variations in number of plants per square meter induced by seed priming is association with the germination process. It is known that seed priming involves the intake of a certain amount of water into the seed, activating the germination mechanism, and obtaining seeds where the germination mechanism is stimulated but no radical emergence (Paparella et al., 2015). Studies show that SA-priming, which resulted in the highest number of plants per square meter, exhibited positive effects on germination and seedling development in plants under various stress factors (Hongna et al., 2021). Sedláková et al. (2023) indicated that one of the major roles of SA in plants is to exert modulatory impact on seedlings via regulating seed dormancy, thereby providing more vigorous them against unfavorable environmental conditions. SA-priming empowered the seeds during the germination stage, promoted hypocotyl, and facilitated stand establishment under strong soil surface conditions. Thus promoting seed germination and stand establishment provided the higher number of plants per square meter.

Shoot Chlorophyll Content

Shoot chlorophyll content was determined using a SPAD meter at the beginning of flowering (between the end of March and the first week of April) in both years. Monthly total precipitation amounts were 408 mm and 220.8 mm in the first- and second-year, respectively (Fig. 1). Consequently, lower water availability reduced shoot chlorophyll content in the 2021-22 season since water is one of the primary components of photosynthesis (Stirbet et al., 2020).

Rising phosphorus increased shoot chlorophyll content. Mairura et al. (2007) stated that phosphorus addition leads to the formation of more vibrant plants and increases intense green color, indicating higher chlorophyll content and greater photosynthetic activity. The reason for the increased shoot chlorophyll content can be associated with the functional roles of phosphorus in processes such as sugar and starch utilization during plant growth, cell division and regulation, photosynthetic efficiency, and the formation of green pigments in plants (Mfilinge et al., 2014).

All seed priming applications are observed to be in the same group and significantly affect chlorophyll content compared to the control group. Anwar et al. (2020) found that seed priming with gibberellic acid and potassium nitrate increased shoot chlorophyll content and photosynthetic activity in peppers. Moradi and Mozafari (2020) reported that PGPB-priming increased chlorophyll-a and -b concentrations in lentil. Kashyap and Siddiqui (2021) observed that Si-priming increased chlorophyll and carotenoid content in pea. The increase in chlorophyll content due to seed priming is believed to be related to applied material as well as its ability to establish a faster and more effective root system during early seedling stages, better utilization of water and nutrients, and consequently higher chlorophyll production in leaves (Zhang et al., 2013). It is well-known that a portion of the products of photosynthesis are moved to root zones while uptaking water and minerals by roots are transported to upper organs and there is a positive correlation among them (Karthika et al., 2018; Melkikh & Sutormina, 2022). In other words, increased plant and root growth, leaf surface area, mineral and water uptake were promoted due to priming treatments, leading to increased chlorophyll content in the leaves and thus increased photosynthesis.

Plant Height and Number of Branches

Low precipitation and rapidly increasing temperatures forced the plants into a sudden transition to the generative phase, leading to restricted vegetative growth, i.e., plant height and number of branches per plant. Choukri et al. (2020) reported that low water availability and increasing temperatures promoted plants to early flowering in lentil.

Besides ecological factors, number of plants per square meter was determined as 173 and 220 plants in 2021-22 and 2022-23, respectively, and it might affect plant growth indicators due to light competition. However, Ezzat et al. (2004) reported that an increase in plant density from 200 to 300 plants per square meter resulted in a 6.5% decrease in number of branches per plant. Thus, it is thought that competition did not affect growth indices due to the low number of plants per square meter in both years.

Higher phosphorus fertilizer increased plant height and number of branches per plant. Phosphorus promotes root development in plants, and plants with effective root development not only utilize water and nutrients from the soil better but also tend to be more resilient against various stress factors. Additionally, phosphorus is an essential element involved in the process of converting solar energy into chemical energy during photosynthesis, as well as playing a role in cell division and growth processes (Lambers, 2022). Datta et al. (2013) and Sonet et al. (2020) reported that plant height and number of branches per plant increased with increasing phosphorus levels.

On the other hand, seed priming increased number of branches per plant compared to the control, in particular, SA- and PGPB-priming caused the highest number of branches per plant. Podile and Kishore (2006) indicated various mechanisms by which PGPBs promote plant growth, including increasing root hairs, improving seed germination, enhancing and expediting nodulation performance, increasing leaf area per plant, releasing specific phytohormones, enhancing nutrient and water uptake by plants, promoting greater vigor and biomass accumulation, and enhancing plant growth by stimulating the growth of plant species. Recent studies indicate that SA is a significant regulator of photosynthesis. According to research findings, SA affects leaf and chloroplast structure (Uzunova and Popova, 2000), stomatal closure (Melotto et al., 2006), chlorophyll and carotenoid content (Fariduddin et al., 2003), and the activity of enzymes such as RuBisCO (ribulose-1,5-bisphosphate carboxylase/oxygenase) (Slaymaker et al., 2002). Lhungdim et al. (2014) reported that Pi-priming increased the number of branches per plant in lentils by 88% compared to the control.

Yield Attributes

Several characteristics related to plant development have been found to have positive or negative relationships with each other through correlation analyses. Crippa et al. (2009) reported that plant height and number of branches per plant promote pod formation in plants based on correlation and path analysis. Therefore, the higher number of pods per plant in the second-year is directly related to characteristics such as plant height and number of branches per plant. Specifically, the approximately 41% higher number of branches per plant in the second-year increased number of pods per plant. Indeed, Pearson correlation analysis indicates a strong positive relationship between plant height and number of branches per plant with number of pods per plant in the experiment (Fig. 4). Besides, it exhibited the highest positive correlation with seed yield, biological yield, number of pods per plant, and number of plants per square meter. Additionally, there were approximately 27% more plants per unit area in 2022-23 compared to the 2021-22 season, therefore, it contributed to a higher biological yield and seed yield.

Phosphorus plays a significant role in stimulating biological activities such as nodulation, nitrogen fixation, and nutrient uptake in the soil and rhizosphere environment, leading to higher yields in grain legumes (Kayoumu et al., 2023). Singh et al. (2005) suggested that the increase in pod number and productivity in plants due to higher phosphorus levels may result from more efficient root development. Theologidou et al. (2023) determined that the addition of phosphorus fertilizer increased number of pods per plant in lentil grown in alkaline soils. While phosphorus fertilizer application led to an increase in biological yield and seed yield compared to control plants, there was no statistical difference among phosphorus doses. Anchra et al. (2023) examined the effects of 3, 4, and 5 kg P_2O_5 ha^{-1} applications in lentil cultivation and found that biological yield increased gradually. The lack of significant variation in biological yield and seed yield depending on increasing phosphorus doses in the study can be explained by two factors. Firstly, although the initial available phosphorus level in the soil may be low, phosphorus is not a limiting factor compared to other essential nutrients. Even low phosphorus fertilizer application (15 P_2O_5 ha^{-1}) provided sufficient supply to the plant along with the existing available phosphorus in the soil. In the second scenario, the application of seed priming leads to the dissolution and uptake by the plant of phosphorus compounds in forms that are not available in the soil. This process may have been caused by an increase in organic acid compounds synthesized by the roots due to priming treatments or directly by the ability of PGPB strains to solubilize phosphate. This phenomenon, which forms the basis of the study's hypothesis, supports the increase in yield that does not vary despite increasing doses.

Seed priming positively affected the number of pods per plant. Positive results regarding plant height and number of branches per plant have been emphasized in previous sections. Therefore, it can be concluded that the development of both underground and aboveground parts of the plant contributes to plant growth in terms of water and nutrient resources, thereby promoting number of pods per plant. Seed priming also appears to promote biological yield and

seed yield with Si, CA, and PGPB applications standing out. These materials are reported to promote water and mineral uptake in plants and increase the mineralization of nutrient complexes in the rhizosphere (Mallhi et al., 2019; Schaller et al., 2019; Fiodor et al., 2023).

Seed Protein and Phosphorus Content

Leguminous plants meet their nitrogen requirement through symbiotic nitrogen fixation after nodule formation during the growth period, leading to increased protein accumulation in the seeds associated with the amount of ammonia bound to the root zone (Ahmad et al., 2022; Barbieri et al., 2023). However, biological nitrogen fixation is a highly complex process dependent on many factors. As known, sudden rises in temperatures and cessation of rainfall led plants to transition quickly to the generative phase in the 2021-22 season, resulting in insufficient development opportunities for parameters such as plant height, number of branches per plant, and possibly root growth. This situation resulted in low photosynthetic activity and nitrogen fixation in plants that did not grow sufficiently after entering the generative phase. In terms of seed phosphorus, higher phosphorus content in the 2021-22 season was associated with the transfer of more phosphorus compounds to the seeds during the grain formation period, resulting in increased phosphorus content in the seeds. Taliman et al. (2019) reported that phosphorus is transferred to the seeds from the grain formation period onward, depending on genetic traits and environmental factors.

Indeed, various researchers reported that the presence of nutrients in the soil is one of the critical factors affecting biological nitrogen fixation, and insufficient nutrients in the soil or increased competition among plants negatively affect nitrogen fixation. Phosphorus fertilization has positive effects on plant root development, increasing the structure of ATP, enhancing the energy produced in metabolism, and thus increasing the amount of fixed N_2, required for nitrogen fixation (Nicholls et al., 2023; Zhong et al., 2023). Niri et al. (2010) reported that the application of 4 kg P_2O_5 ha^{-1} in lentils increased the protein content in the grains. The available phosphorus content in the soil was found to be insufficient in both growing seasons. Although the available phosphorus and low doses of phosphorus fertilization seemed sufficient during the plant growth period, reserves were insufficient by the harvest period, leading to an increase in the phosphorus transported to the seeds with increasing doses. Urbano et al. (2000) found that phosphorus compounds taken up from the soil in legumes are first transported to the shoots during the growth period and then to the seeds during the grain formation period, where they are converted into phytates, which constitute approximately 80% of the phosphorus content in the seed, and are stored as reserves to be reused during germination.

Priming applications are considered a rapid, easily applicable, and economical way to enrich or improve product quality in terms of macro and micronutrient content (Barupal et al., 2022). Citric acid can function as a carbon source for soil microorganisms, affect microbial activity in the rhizosphere, and support nutrient uptake by plants (Heitkötter et al., 2017). Thus, CA application is suggested to increase soil mineral solubilization and uptake by plants, thereby promoting biological nitrogen fixation and increasing nitrogen content and protein content in seeds (Chen et al., 2023). Khan and Gupta (2018) stated that Si applications contribute to carriers that facilitate nutrient uptake and transport, thus contributing to an increase in the amount of nutrients transported from roots to leaves and seeds. Jinger et al. (2022) reported that Si application in rice increased the nutrient content of the grains. Lavakush et al. (2014) reported that bacterial strains capable of phosphate solubilization increased both phosphorus uptake and the concentration of phosphorus compounds accumulated in the grains in rice. In conclusion, the findings from our study are consistent with the results of various researchers regarding phosphorus content in seeds.

Seed Total Antioxidant and Phenolic Contents

Bibi et al. (2022) examined the effects of climatic conditions and soil properties on the variation of total phenolic compounds in different plant species and locations, therefore, they reported that both factors led to statistically significant differences in the accumulation of phenolic compounds. Orduna (2010) determined that secondary metabolites, especially phenolic and flavonoid contents, are influenced by various environmental factors such as day length, light intensity, temperature, nutrient concentration, and soil moisture. Similarly, different researchers have reported that environmental factors affect the formation of seed total phenolic in plants, but the variation is not consistent; rather, it varies depending on the response of the plant species to the growing environment (Liu et al., 2016; Holopainen et al., 2018).

The mechanism responsible for the accumulation of antioxidants and phenolics in seeds is not yet fully understood. It is observed that SA and Si-priming especially increase seed total antioxidant in seeds. Luyckx et al. (2023) stated that external Si applications in hemp plants led to increased seed total antioxidant in leaves via reduction of oxidative stress. Similarly, Belkadhi et al. (2013) reported that SA-priming application increased seed total antioxidant and reduced oxidative stress in flax plants. Bekker et al. (2007) reported that Si applications on avocado trees led to an increase in seed total phenolic in roots. Therefore, Si

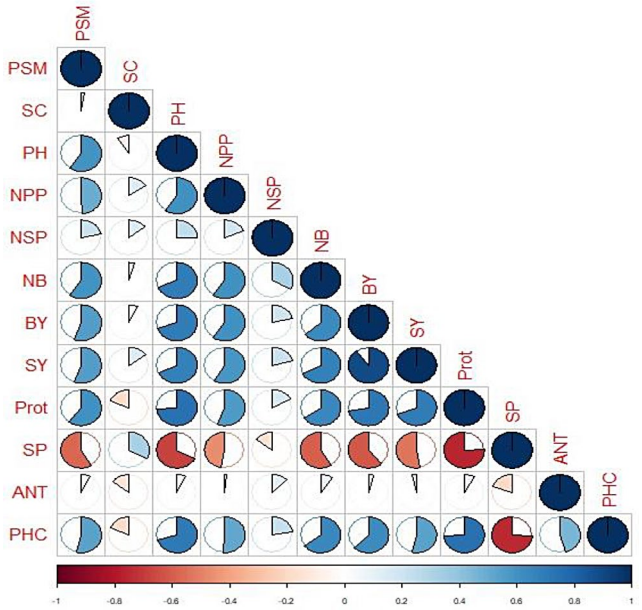

Fig. 5 Diagram showing Pearson correlation of investigated characteristics (The colors in the diagram represent the range from −1 to 1, where dark red corresponds to -1 and dark blue corresponds to 1. PSM: Number of plants per square meter, SC: Shoot chlorophyll content, PH: Plant height, NPP: Number of pods per plant, NSP: Number of seeds per pod, NB: Number of branches per plant, BY: Biological yield, SY: Seed yield, Prot: Seed protein content, SP: Seed phosphorus content, ANT: Seed total antioxidant, PHC: Seed total phenolic)

application may increase seed total phenolic in different tissues of the plant, although further investigation is needed. Although SA-priming mostly increased seed total phenolic in seeds in the experiment, Belkadhi et al. (2013) reported there is no significant effect of SA on the concentration of seed total phenolic in leaves. However, Grzeszczuk et al. (2018) recorded a significant increase in seed total phenolic in sage plants with SA treatment.

Pearson Correlation Analysis of Characteristics

The characteristics showing the highest positive correlation with seed yield were determined as biological yield, number of plants per square meter, plant height, number of branches per plant, and number of pods per plant. Additionally, seed yield is strongly positively correlated with the number of seeds per pod, seed phosphorus content, and seed total phenolic. Crippa et al. (2009) reported that plant height and number of branches per plant promote pod formation in plants. Sharma et al. (2014) reported a strong and positive correlation between number of pods per plant, plant height and number of branches per plant. Again, findings from various researchers suggest that the strongest positive characteristics of seed yield are number of pods per plant, number of seeds per plant and biological yield (Aghili et al., 2012; Sakthivel et al., 2019). Seed protein content exhibited significant negative correlations in all but shoot chlorophyll content since phosphorus has a critical role in chlorophyll and photosynthesis mechanisms (Bennett et al., 2021). It was found that seed total antioxidant and seed total phenolic in grains form a positive and significant correlation. Phenolic acids have been shown to exhibit strong antioxidant properties through research. Therefore, this emerging positive correlation is similar to findings from previous studies (Fig. 5).

Conclusion

Experimental years substantially influenced agronomical and chemical characteristics due to extreme climatic differences. Additionally, phosphorus fertilization and seed priming treatment promote growth, yield, and quality attributes in lentil. It was found that even at a dose of 15 kg ha^{-1}, significant yield and economic income were achieved at Siirt ecological conditions. In the scope of the research, it is recommended to apply Si-priming before sowing and to add 60 kg P_2O_5 ha^{-1} at the time of sowing to obtain the highest grain and straw yield as well as net income. Si-priming increased seed total antioxidant in seeds, while SA-priming application provided opportunities for both the increase of antioxidant substances and phenolic compounds. However, there is a need for new research at the molecular and genetic levels to elucidate the mechanisms of seed total antioxidant and phenolic compounds in seeds. In conclusion, seed priming is concluded to be a sustainable and applicable method for reducing the use of phosphorus fertilizers, improving yield and quality components, and increasing economic income in lentil cultivation.

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Author Contributions MC and ME conceptualized the idea and designed the experiment. MC laid out the field experiments and analyzed the data, and wrote the manuscript and visualization. FC contributed to the preparation of bacterial solutions and bio-priming process and reviewing of the results. All authors contributed to editing the manuscript and have approved the final version.

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Declarations

Conflict of interest Authors declare that there is no conflicts of interests.

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