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Research Article

Effect of Zinc Seed Priming on Growth, Yield, and Agronomic Biofortification of Wheat (*Triticum aestivum* L.)

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ABSTRACT

Zinc deficiency is a major constraint to wheat productivity and grain nutritional quality, particularly in South Asia. Therefore, a field experiment was conducted during the Rabi season of 2023–24 at the Student's Experimental Farm, Sindh Agriculture University, Tandojam, to evaluate the effects of zinc seed priming on the growth and yield of wheat varieties. The experiment was conducted using a randomized complete block design (RCBD) with a 3 × 2 factorial arrangement and three replications. The treatments comprised three zinc seed priming levels (0%, 0.25%, and 0.50%) and two wheat varieties, Imdad-2005 and Benazir-13. The results revealed that zinc seed priming significantly improved growth and yield attributes. They found that the highest plant population (344.83 m⁻²), plant height (82.50 cm) and grain yield (6458.20 kg ha⁻¹) were obtained with 0.50% zinc priming rate when compared with the control. In the varieties Benazir-13 gave the superior grain yield (6235.60 kg ha⁻¹) as compared to Imdad-2005. Zinc priming at 0.50% with Benazir-13 was also superior as shown by significant interaction effects. Finally, zinc seed priming at 0.50% is an effective and cost-efficient approach to improve wheat productivity and could be helpful for agronomic biofortification in zinc deficient areas.

Keywords: Zinc seed priming, Agronomic biofortification, Wheat, Grain yield, Micronutrient deficiency, Sustainable wheat production.

INTRODUCTION

Wheat (*Triticum aestivum* L.), an essential cereal, is produced in the world at the level of about 756.7 million tons, consumed by almost 40% of the world's population (FAO, 2018). Wheat is a key crop, cultivated on more than 17% of the world's arable land and is a staple food for billions of people providing a major source of carbohydrates, protein, dietary fiber and micronutrients (FAOSTAT, 2021). With the rapid growth of the world's population, the requirement to increase the production of wheat, both in quantity and quality, is growing. One of the different ways of improving both yields and nutritional quality of the crop is the micronutrient fortification particularly Zinc fortification of wheat.

Zinc is not only essential for human health but it also has a significant contribution towards enhancing wheat yield and grain quality, with implications for food security and human nutrition (Shewry, 2009). Zinc (Zn) is a micronutrient that is vital to human health and plays a significant part in metabolic processes and gene



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expression. (Chasapis et al., 2020; Wessels et al., 2022). The deficiency of zinc can cause various physiological dysfunctions, diseases and even death particularly in vulnerable groups like children and old people where the absorption and intake are low, making it more susceptible to "hidden hunger". Approximately 17.1% of the global population is believed to be at risk for insufficient Zn consumption (Wessells & Brown, 2012). The global impact of zinc deficiency (Wessells et al., 2022) can be worsened due to some of the following factors: rapid population growth, climate change, pandemics such as COVID-19, and geopolitical conflicts. In low- and middle-income countries, lack of access to foods rich in Zn, low food variety, and consumption of cereal-based diets with low bioavailability of Zn because of phytate binding are key drivers of the problem, especially in these countries (Gupta et al., 2020). Additionally, low levels of Zn in soil have been linked to Zn deficiency in soils worldwide, particularly in developing nations (De Groote et al., 2021). While Zn deficiency is an issue in low- and middle-income areas it also poses a challenge in developed nations. For example, about 15% of the adult population in the USA is at or below the estimated average requirement for Zn (Reider et al., 2020). In developed countries, the major source of Zn deficiency is the consumption of diets with low bioavailable Zn and high caloric density, typical of processed foods and foods that lack micronutrient-rich foods (Kruger et al., 2014). Zinc seed priming is an agronomic method, which includes seeding zinc solution before sowing and has been proved to be an effective method of wheat biofortification. This pre-sowing treatment leads to an improved rate of absorption of Zn by the seeds and hence to an increase in the level of Zn in the wheat grain. Zinc is a micronutrient essential for plant physiology, which is a cofactor for several enzymes that play important roles in plant metabolism, including photosynthesis, nitrogen metabolism and plant defense against environmental stresses (Cakmak, 2008; Hafeez et al., 2013). In wheat, Zn is essential for increasing photosynthetic efficiency and improving nitrogen use efficiency, and it also has an important role in reducing oxidative stress under stress conditions leading to better plant health and productivity (Marschner, 2012). Apart from its physiological role in plants, zinc is also essential for human nutrition and biofortification of wheat seeds by seed priming which demonstrates promise in improving the nutritional quality of wheat grains. Wheat is also a staple crop, and biofortifying wheat with zinc could help to alleviate the global zinc deficiency problem, affecting a significant proportion of the human population, which in turn causes a variety of health problems, including compromised immune system and stunted growth (White & Broadley, 2009). The benefits of biofortification strategies like Zn seed priming are also being widely recognized because of their ability to simultaneously enhance crop yields and nutritional profile, providing a viable and sustainable solution to address both agricultural and health challenges. Boosting Zn absorption and storage in wheat grains is vital to tackle Zn deficiency and improve human health, particularly in regions with low dietary intake. The production of zinc-enriched wheat can also help in global food security by delivering more balanced and nutritious diets (White and Broadley, 2009). Soil and foliar Zn application has proven to be effective for biofortification of durum wheat (Kutman et al., 2010; Gupta et al., 2024) and physiological experiments have revealed morphological and metabolic changes in cereals under Zn deficiency conditions, thereby improving knowledge of the mechanisms of Zn uptake (Cakmak et al., 1999).

The primary focus of nutrient management in wheat has traditionally been on macronutrients: nitrogen, phosphorus, and potassium. But in recent times, the importance of micronutrients has been highlighted, and it is now understood that Zn deficiency is a serious yield and grain quality limiting factor (Alloway, 2008). Seeding priming of Zn is a relatively new research but has been found to be quite promising. These studies have demonstrated that, application of Zn priming will increase root development, yield and concentration of Zn in wheat grain (Cakmak et al., 1999; Rengel et al., 1999).

This study aims to build on recent advancements in Zn research and provide practical insights for wheat biofortification, contributing to sustainable agriculture and improved global nutrition (Singh et al., 2023). While zinc is recognized for its significant role in both wheat production and human nutrition, very little research has been done in the specific agro-ecological conditions of Sindh, Pakistan where soils are frequently alkaline, calcareous and have low zinc availability, which prevents plant uptake of zinc. Furthermore, the vast majority of earlier research have been conducted in soil and foliar application of zinc, and comparatively limited studies have been carried out for zinc priming of seeds as a farmer-friendly and cost-effective approach in this region. Lack of comparative evaluation of locally adapted wheat varieties under zinc seed priming condition is also observed. Thus, this research was conducted to evaluate the impact of zinc seed priming on the growth, yield, and biofortification of wheat varieties in the agro-climatic conditions of Tandojam. The findings of this research are expected to provide practical insights for improving wheat productivity and nutritional quality in zinc-deficient soils of similar environments. Therefore, the primary aim of this study was to assess the impact of varying levels of zinc seed priming on the growth, yield, and agronomic biofortification of wheat under the agro-ecological conditions of Tandojam. It was hypothesized that zinc seed priming would significantly enhance wheat

growth and yield attributes, and that an optimum concentration of zinc would produce superior performance compared to lower concentrations and control treatments. Additionally, the study aimed to determine the most responsive wheat variety to zinc seed priming for improved productivity under zinc-deficient soil conditions.

MATERIALS AND METHODS

The field experiment was conducted during the Rabi season 2023–24 at the Student's Experimental Farm, Department of Agronomy, Sindh Agriculture University, Tandojam, Pakistan. The crop was sown on 25th November 2023 and harvested on 10th April 2024. The study was structured using randomized complete block design (RCBD) featuring a factorial arrangement and conducted with three replications. Two wheat varieties, Imdad-2005 and Benazir-13, were assigned to factor A, while three zinc seed priming levels, namely 0.00% Zn (hydro-priming), 0.25% Zn, and 0.50% Zn, were assigned to factor B.

Each experimental plot measured 3 m × 5 m (15 m²). The crop was sown in rows spaced 22.5cm and with a seed rate of 125kg ha⁻¹ which is recommended for wheat under local conditions. Soil samples (0-15 cm depth) were taken and analyzed before sowing. The soil consisted of silty clay loam, pH 7.8, EC 1.2 dS m⁻¹, available P = 8.5 mg kg⁻¹, extractable K = 165 mg kg⁻¹ and available Zn = 0.62 mg kg⁻¹.

Zinc seed priming solutions were made by dissolving zinc sulfate heptahydrate (ZnSO₄·7H₂O). In the case of 0.25% and 0.50% treatments 2.5 g and 5.0 g of zinc sulfate were dissolved in 1 L of distilled water respectively. Seeds were soaked for 5 hours in the different solutions, and in the distilled water alone for control. Seed was dried in the shade for about 30-45 minutes until it was free flowing and contained the same moisture content as when it was taken from the seed bank. The primed seeds were sown on the same day immediately after drying.

Fertilizers were applied in the form of urea (120 kg N ha⁻¹), DAP (60 kg P₂O₅ ha⁻¹), SOP (60 kg K₂O ha⁻¹) and zinc sulfate (5 kg Zn ha⁻¹) at recommended rates. All phosphorus, potassium, and one-third of nitrogen was applied at sowing with the rest of the nitrogen added in two equal portions during the first and third irrigation.

Irrigation was done following standard agronomic practices, with irrigation applied at the critical growth stages (crown root initiation, tillering, booting, flowering and grain filling), providing optimal water availability throughout the crop cycle. All other agronomic practices were maintained consistently across all treatments.

The following growth and yield parameters were observed:

Plant Population (m⁻²)

At the mature stage of the crop, the number of plants in a frame of 1 m² was counted and the average value calculated in each plot.

Plant Height (cm)

Randomly selected plants were measured for plant height at maturity with a measuring tape from the ground to the tip of the plant. The height was measured for each plot and the average height was calculated in centimeters.

Spike Length (cm)

Each spike's length was measured from its base to the tip using a measuring tape, and spike length recorded.

Spikelets Per Spike

The number of spikelets on each spike was counted for the selected plants.

Grains Per Spike

The total number of grains from the selected plants was counted for each spike.

Grain Index (1000-grain Weight, g)

From each plot, one thousand grains were collected and weighed with a top-loading electronic scale.

Biological Yield (kg ha⁻¹)

At full maturity, wheat plants from each plot were harvested and collected. Biological yield/ha was determined by the following formula and the total above-ground biomass was weighed.

$$\text{Biological yield (kg ha}^{-1}\text{)} = \frac{(\text{Total yield per plot (kg)} \times 10,000 \text{ m}^2)}{\text{Plot size (m}^2\text{)}}$$

Grain yield (kg ha⁻¹)

At maturity, the crop of each plot was harvested and threshed. The yield of grain was calculated as grain yield per ha and was calculated as:

$$\text{Grain yield (kg ha}^{-1}\text{)} = \frac{(\text{Seed yield per plot (kg)} \times 10,000 \text{ m}^2)}{\text{Plot size (m}^2\text{)}}$$

Statistical Analysis

The collected data were analyzed statistically with Statistix 8.1 software (Statistix, 2006). The effects of treatments, wheat varieties and their interaction were evaluated using analysis of variance (ANOVA). The differences among treatment means were analyzed using Least Significant Difference (LSD) at 0.05 probability level.

RESULTS

The findings for the measured parameters on the present study are presented below.

Plant Population (m^{-2})

Table 1 displays the data and the corresponding analysis of variance regarding the effect of zinc seed priming (as an agronomic biofortification strategy) on the plant population (per square meter) of various wheat varieties. According to the ANOVA results, zinc seed priming, wheat variety, and their interaction each had a significant influence ($P < 0.05$) on plant population. The results showed that the highest (344.83 m^{-2}) plant population was observed when the crop was treated with the application of 0.50% zinc seed priming, followed by 0.25% zinc seed priming which was observed plant population (288.33 m^{-2}). However, the minimum plant population was noted from control treatment. In case of varieties Benazir-13 showed the maximum (308.33 m^{-2}) plant population, however, the minimum (290.89 m^{-2}) plant population was recorded in variety Imdad-2005. Among interactive effects 0.50% zinc seed priming variety Benazir-13 resulted in more plant population (347.67 m^{-2}), whereas the minimum plant population (247.00 m^{-2}) was recorded in the interaction of 0.00% zinc x variety Imdad-2005. The LSD test indicated that the zinc seed priming and varieties and their interaction were significant at the level of ($P < 0.05$).

Plant Height (cm)

The agronomic biofortification by zinc seed priming and its impact on wheat height was investigated across various wheat varieties. The data and results of the ANOVA for this trait are presented in Table 1. The ANOVA revealed that plant height was significantly ($P < 0.05$) affected by zinc seed priming, wheat variety and its interaction. The results showed that the tallest plants (82.50 cm) were observed in the 0.50% zinc seed priming treatment while the 0.25% treatment resulted in a plant height of 80.33 cm. However, the minimum (69.50 cm) plant height was noted from control. Regarding varieties Benazir-13 showed the highest plant height (79.66 cm), however, the lowest (75.22 cm) plant height was recorded in variety Imdad-2005. The interactive effect of varieties and zinc seed priming, the variety Benazir-13 and 0.50% zinc seed priming resulted in the more plant height (84.00 cm), whereas minimum plant height (67.00 cm) was observed in Imdad-2005 and control. LSD results indicated that the effect of zinc seed priming, varieties and interaction among the two were statistically significant ($P < 0.05$).

Table 1. Effect of zinc seed priming on plant population (m^{-2}) and plant height (cm) of wheat varieties.

Plant population (m^{-2})				Plant height (cm)		
Seed priming levels	Varieties		Mean	Varieties		Mean
	Imdad-2005	Benazir-13		Imdad-2005	Benazir-13	
$P_1 = 0.00\%$ Zinc	247.00	283.67	265.33 C	67.00	72.00	69.50 B
$P_2 = 0.25\%$ Zinc	283.67	293.00	288.33 B	77.66	83.00	80.33 A
$P_3 = 0.50\%$ Zinc	342.00	347.67	344.83 A	81.00	84.00	82.50 A
Mean	290.89 B	308.33 A		75.22 B	79.66 A	
	<i>Priming levels (P)</i>	<i>Varieties (V)</i>	<i>P x V</i>	<i>Priming levels (P)</i>	<i>Varieties (V)</i>	<i>P x V</i>
<i>P value</i>	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
<i>SE</i>	5.5973	4.5702	7.9158	2.0620	1.6836	2.9161
<i>LSD@ 5%</i>	12.472	10.183	17.637	4.5944	3.7513	6.4975

Spike Length (cm)

The impact of zinc seed priming (as an agronomic biofortification technique) on spike length (cm) across various wheat varieties was studied. The relevant data and analysis of variance for this parameter are given in Table 2. ANOVA

revealed that zinc seed priming, wheat variety and the interaction of zinc seed priming with wheat variety significantly ($P < 0.05$) affected spike length. It was revealed that 0.50% zinc seed priming produced the longest spikes (12.74 cm) while 0.25% was the second longest spike (12.11 cm). However, the minimum (9.77 cm) spike length was noted from control. Among the varieties, Benazir-13 produced the highest spike length (11.60 cm), however, the minimum (9.22 cm) spike length was recorded in variety Imdad-2005. The interactive effect of varieties and zinc seed priming, the variety Benazir-13 and 0.50% zinc seed priming resulted in the more spike length (13.27 cm), whereas the minimum spike length (cm) was recorded in Imdad-2005 and control. LSD results indicated that the effect of zinc seed priming, varieties and interaction among the two were statistically significant ($P < 0.05$).

Spikelet Per Spike

Table 2 contains the data and analysis of variance regarding the effect of zinc seed priming (agronomic biofortification) on the number of spikelets per spike in different wheat varieties. The ANOVA showed that spikelet per spike was significantly ($P < 0.05$) influenced by zinc seed priming, wheat variety, and their interaction. The findings indicated that the maximum number of spikelets per spike was (45.70) was observed zinc seed priming 0.50%, followed by 0.25% zinc seed priming which was observed spikelet per spike (43.03). However, the minimum (39.56) spikelet per spike was noted from control. Regarding varieties Benazir-13 showed the highest spikelet per spike (44.52), however, the lowest (41.86) spikelet per spike was recorded in variety Imdad-2005. The combined influence of varieties and zinc seed priming, the variety Benazir-13 and 0.50% zinc seed priming resulted in the more spikelet per spike (44.66), whereas the minimum spikelets per spike (37.27) was recorded in Imdad-2005 and control. LSD results indicated that the effect of zinc seed priming, varieties and interaction among the two were statistically significant ($P < 0.05$).

Table 2. Effect of zinc seed priming on spike length (cm) and spikelets per spike of wheat varieties.

Seed priming levels	Spike length (cm)			Spikelet per spike		
	Varieties		Mean	Varieties		Mean
	Imdad-2005	Benazir-13		Imdad-2005	Benazir-13	
$P_1 = 0.00\%$ Zinc	10.31	9.22	9.77 C	37.27	41.86	39.56 C
$P_2 = 0.25\%$ Zinc	11.91	12.31	12.11 B	41.00	45.05	43.03 B
$P_3 = 0.50\%$ Zinc	12.21	13.27	12.74 A	44.75	46.66	45.70 A
Mean	11.48 B	11.60 A		41.01 B	44.52 A	
	<i>Priming levels (P)</i>	<i>Varieties (V)</i>	<i>P x V</i>	<i>Priming levels (P)</i>	<i>Varieties (V)</i>	<i>P x V</i>
<i>P value</i>	0.0000	0.0134	0.0000	0.0000	0.0000	0.0143
<i>SE</i>	0.0513	0.0419	0.0725	0.3886	0.3173	0.5495
<i>LSD@ 5%</i>	0.1143	0.0933	0.1616	0.8657	0.7069	1.2244

Grain Per Spike

The impact of zinc seed priming (agronomic biofortification) on grain per spike of different wheat varieties was investigated and the data in relation to this trait is presented in Table 3. The ANOVA showed that the grain per spike was significantly ($P < 0.05$) affected by the zinc seed priming agronomic biofortification, wheat varieties and by their interaction. The findings showed that the maximum grain per spike (47.41) was observed when the zinc seed priming 0.50%, followed by 0.25% zinc seed priming which was observed grain per spike (44.25). However, the minimum (39.62) grain per spike was noted from control. In case of varieties Benazir-13 showed the maximum grain per spike (45.18), however, the minimum (42.27) grain per spike was recorded in variety Imdad-2005. The interactive effect of varieties and zinc seed priming, the variety Benazir-13 and 0.50% zinc seed priming resulted in the more grain per spike (48.44), whereas the minimum grain per spike was recorded in Imdad-2005 and control. LSD results indicated that the effect of zinc seed priming, varieties and interaction among the two were statistically significant ($P < 0.05$).

Grain Index (1000-grain Weight, g)

The impact of zinc seed priming (agronomic biofortification) on grain index (1000-grain weight, g) of different varieties of wheat was analyzed and the data in relation to this trait is presented in Table 3. The ANOVA showed that the seeds index (1000 grain weight, g) was significantly ($P < 0.05$) affected by the zinc seed priming agronomic biofortification, wheat varieties and by their interaction. The findings indicated that the highest grain index (1000-grain weight, g) (47.20 g) was documented in zinc seed priming 0.50%, followed by 0.25% zinc seed priming which was observed grain index

(43.01 g). However, the minimum (41.90 g) grain index (1000-grain weight, g) was noted from control. Regarding varieties Benazir-13 showed the maximum grain index (44.46 g), however, the minimum (42.95 g) grain index (1000 grain weight, g) was recorded in variety Imdad-2005. The combined influence of varieties and zinc seed priming, the variety Benazir-13 and 0.50% zinc resulted in the more grain index (1000 grain weight, g) (48.44 g), whereas the minimum grain index (38.59 g) was recorded in Imdad-2005 and control. LSD results indicated that the effect of zinc seed priming, varieties and interaction among the two were statistically significant ($P < 0.05$).

Table 3. Effect of zinc seed priming on grains per spike and grain index of wheat varieties.

Grain per spike				Grain index (1000 grain weight, g)		
Seed priming levels	Varieties		Mean	Varieties		Mean
	Imdad-2005	Benazir-13		Imdad-2005	Benazir-13	
P ₁ = 0.00% Zinc	38.36	40.88	39.62 C	38.59	43.21	41.90 C
P ₂ = 0.25% Zinc	42.27	46.23	44.25 B	44.91	41.12	43.01 B
P ₃ = 0.50% Zinc	46.39	48.44	47.41 A	45.35	49.06	47.20 A
Mean	42.34 B	45.18 A		42.95 B	44.46 A	
	<i>Priming levels (P)</i>	<i>Varieties (V)</i>	<i>P x V</i>	<i>Priming levels (P)</i>	<i>Varieties (V)</i>	<i>P x V</i>
<i>P value</i>	0.0000	0.0000	0.0266	0.0036	0.0320	0.4820
<i>SE</i>	0.3027	0.2472	0.4281	1.0714	0.8748	1.5152
<i>LSD@ 5%</i>	0.6745	0.5507	0.9539	2.3872	1.9492	3.3760

Biological Yield (kg ha⁻¹)

Table 4 presents the data related to the effect of zinc seed priming (agronomic biofortification) on the biological yield of various wheat varieties. According to the ANOVA results, biological yield (kg ha⁻¹) was significantly ($P < 0.05$) affected by zinc seed priming, wheat varieties, and their interaction. The maximum biological yield (12,414 kg ha⁻¹) was recorded with the 0.50% zinc seed priming treatment, followed by the 0.25% treatment, which yielded 11,417 kg ha⁻¹. In contrast, the minimum biological yield (10,342 kg ha⁻¹) was observed in the control treatment (no zinc priming). Among varieties Benazir-13 showed the maximum biological yield (11731 kg ha⁻¹), however, the minimum (11051 kg ha⁻¹) biological yield was noted in variety Imdad-2005. The interactive effect of varieties and zinc seed priming, the variety Benazir-13 and 0.50% zinc seed priming resulted in the more biological yield (12900 kg ha⁻¹), whereas the lowest biological yield (10287 kg ha⁻¹) was documented in Imdad-2005 and control. LSD results showed that the effect of zinc seed priming, varieties and interaction among the two were statistically significant ($P < 0.05$).

Table 4. Effect of zinc seed priming on biological yield (kg ha⁻¹) and grain yield (kg ha⁻¹) of wheat varieties.

Biological yield (kg ha ⁻¹)				Grain yield (kg ha ⁻¹)		
Seed priming levels	Varieties		Mean	Varieties		Mean
	Imdad-2005	Benazir-13		Imdad-2005	Benazir-13	
P ₁ = 0.00% Zinc	10287	10397	10342 C	5107.3	5560.00	5333.70 C
P ₂ = 0.25% Zinc	10937	11896	11417 B	5534.00	6241.30	5887.70 B
P ₃ = 0.50% Zinc	11928	12900	12414 A	6011.00	6905.30	6458.20 A
Mean	11051 B	11731 A		5550.80 B	6235.60 A	
	<i>Priming levels (P)</i>	<i>Varieties (V)</i>	<i>P x V</i>	<i>Priming levels (P)</i>	<i>Varieties (V)</i>	<i>P x V</i>
<i>P value</i>	0.0000	0.0002	0.0232	0.0000	0.0000	0.0000
<i>SE</i>	147.51	120.44	208.61	24.959	20.379	35.298
<i>LSD@ 5%</i>	328.66	268.35	464.80	55.613	45.408	78.648

Grain Yield (kg ha⁻¹)

Table 4 contains the data examining how zinc seed priming (as an agronomic biofortification strategy) affects the grain yield of different wheat varieties. The ANOVA revealed that grain yield (kg ha⁻¹) was significantly ($P < 0.05$) affected by zinc seed priming, wheat varieties, and their interaction. The findings showed that the maximum grain yield (6,458.20 kg ha⁻¹) was achieved when the crop was primed with 0.50% zinc, followed by the 0.25% treatment, which produced a grain yield of 5,887.70 kg ha⁻¹. However, the lowest (5333.70 kg ha⁻¹) grain yield was noted from control. Regarding varieties Benazir-13 showed the maximum grain yield (6225.60 kg ha⁻¹), however, the lowest (5534.00 kg ha⁻¹) grain yield was recorded in variety Imdad-2005. The interactive effect of varieties and zinc applications, the variety Benazir-13 and 0.50% zinc seed priming resulted in the more grain yield (6905.30 kg ha⁻¹), whereas the lowest grain yield (5107.3 kg ha⁻¹) was documented in Imdad-2005 and control. LSD results showed that the effect of zinc seed priming, varieties and interaction among the two were statistically significant ($P < 0.05$).

DISCUSSION

Zinc seed priming, an agronomic technique involving pre-sowing treatment of seeds with zinc solutions, significantly boosted the agronomic and yield-related traits of wheat in this experiment. Zinc plays a fundamental role in plant physiology as a cofactor of numerous enzymes essential for major metabolic activities namely, photosynthesis, protein formation, and carbohydrate utilization (Cakmak, 2008; Hafeez et al., 2013). The improvement in plant population observed under zinc priming may be attributed to enhanced seed vigor and germination, as zinc activates enzymes responsible for early seedling growth and establishment.

The enhanced plant height, spike length and spikelets per spike measured in this experiment are associated with the function of zinc during auxin biosynthesis, a plant development hormone involved with cell division and elongation (Marschner, 2012). Furthermore, zinc stimulates chlorophyll production and photosynthesis efficiency leading to higher biomass production. The findings are consistent to those investigated by Hassan et al. (2019) and Rehman et al. (2022) which stated a higher growth performance for wheat under zinc priming of seed conditions.

Similarly, grains per spike and grain index improvement might be a reproductive development and assimilate translocation effect. Zinc is important for pollen function, effective fertilization, and grain filling, which results in better yield components. The increased activity of enzymes and mobilization of nutrients within the plant also could lead to enhanced grain filling. Comparable findings have been stated by Rehman et al. (2018), who noted that zinc seed priming and its associated biological interactions showed significant improvement in wheat productivity and grain biofortification. More improved biological and grain yields were observed in the case of zinc seed priming at 0.50% suggesting that availability of zinc improves the overall productivity of the plants. This might result from enhanced nutrient acquisition, increased photosynthetic activity and increased tolerance to environmental stresses. Zinc also plays a role in stabilizing membranes and inducing antioxidant defense mechanisms in plants, which is essential for withstanding the stress conditions in semi-arid environments.

This study's findings support previous research on soil and zinc applied to foliage for enrichment of wheat for increased zinc absorption and yield gain (Kutman et al., 2010; Gupta et al., 2024). Furthermore, it is widely recognized that zinc deficiency is a significant factor limiting crop productivity and human nutrition, especially in developing and underdeveloped countries in which zinc-rich foods are scarce (Alloway, 2008).

Rehman et al. (2022) found that wheat seedling emergence, leaf growth, chlorophyll content and photosynthetic properties were significantly enhanced by zinc seed priming. In a related investigation, Rehman et al. (2018) showed that the use of zinc, in combination with endophytic bacteria, also led to an improved productivity of wheat and biofortification of the grains. Similarly, Hassan et al. (2019) reported that zinc priming of seeds had a positive influence on crop establishment, biological yield and grain productivity in crops. Besides this, Ali et al. (2018) found that crop establishment, yield components and wheat grain yield was markedly enhanced through the zinc micronutrient application with boron, which showed that micronutrient seed priming is economically and agronomically beneficial. The results of these investigations are consistent with the results obtained from the present research and validate the efficacy of zinc seed priming as a viable method for enhancing wheat yield and nutritional value.

CONCLUSIONS

It is concluded from the results that zinc seed priming significantly ($P \leq 0.05$) enhanced the growth and yield performance of wheat varieties. Seed priming with 0.50% zinc produced the highest grain yield (6458.20 kg ha⁻¹). Among the evaluated varieties, Benazir-13 recorded the maximum grain yield (6235.60 kg ha⁻¹). Furthermore, the

interaction of 0.50% zinc seed priming and Benazir-13 resulted in the highest grain yield (6905.30 kg ha⁻¹), indicating the superior response of this variety to zinc seed priming under the experimental conditions.

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AUTHOR CONTRIBUTIONS

All the authors contributed equally to this research.

COMPETING OF INTEREST

No conflicts of interest have been disclosed by the authors.

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