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Received: 31 July 2025

Accepted: 20 February 2026

Published online: 27 February 2026

Cite this article as: Ahmadi P., Hosseinpanahi F., Siosemardeh A. *et al.* The effect of seed priming on yield and germination properties of quinoa (*Chenopodium quinoa* Willd). *Sci Rep* (2026). <https://doi.org/10.1038/s41598-026-41546-8>

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The effect of seed priming on yield and germination properties of quinoa (*Chenopodium quinoa* Willd)

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Abstract

Seed priming is a widely used pre-germination technique that enhances sprouting efficiency, synchrony, and the initial development of plantlets, particularly under suboptimal environmental conditions. This study aimed to evaluate the impact of different seed priming treatments on the germination, growth, and yield performance of quinoa (*Chenopodium quinoa* Willd.) through a series of laboratory, greenhouse, and field experiments conducted during the 2024 cropping season. The laboratory experiment was arranged in a completely randomized design (CRD) with four replications. Treatments included potassium nitrate (5% w/w), potassium chloride (1% w/w), zinc sulfate (6% w/w), gibberellic acid (30 mg.kg⁻¹), polyethylene glycol 6000 (10% v/v), salicylic acid (200 mg. L⁻¹), humic acid (54 mg. L⁻¹), hydropriming (distilled water), and a non-primed control. The same treatments were evaluated in a greenhouse trial (CRD with four replications) and a field trial (randomized complete block design with three replications). The overall results of the first experiment showed that treatments of potassium chloride, hydropriming, potassium nitrate, and gibberellic acid had positive effects on the germination characteristics of quinoa seeds. The greenhouse experiment also clearly demonstrated the superiority of potassium chloride and gibberellic acid treatments. In the field experiment, salicylic acid and potassium chloride treatments led to the highest economic yield. Based on the combined results of the experiments in this study, priming quinoa seeds with potassium chloride and salicylic acid is recommended.

Keywords: Germination, Hormonal Priming, Osmopriming, Quinoa yield, Seed priming

1. Introduction

The global population is projected to reach about 9.8 billion by 2050 and 11.2 billion by 2100. This rapid growth necessitates a significant increase in food production to ensure global food security ¹. However, climate change—alongside population expansion—is increasingly compromising crop productivity by exerting stress on agricultural systems ². Rising temperatures negatively impact crop development by reducing the soil's ability to retain water and maintain fertility. Unchecked population growth and ongoing climate change have worsened drought stress and accelerated the decline of soil fertility. To maintain agricultural productivity under these pressures, it is essential to prioritize climate-resilient crops. *C. quinoa* Willd., commonly known as quinoa, is a stress-tolerant pseudo-cereal with significant potential to meet global food demand and alleviate poverty in a warming world ³. Its inherent tolerance to salinity and drought enables quinoa to substitute for more sensitive crops under future climate scenarios. Nonetheless, successful cultivation is constrained by small seed size, which complicates germination and seedling establishment ⁴.

The global production rate of quinoa (*Chenopodium quinoa* Willd.) varies widely by country and environmental conditions ⁵. In the Andean region, quinoa yields have been reported according to the region's specific conditions ⁶. Other quinoa-growing countries also show varied yields ⁵. The global production trend of this crop over different years has been studied ⁷. The share of different countries in global quinoa production and the significance of the Andean region as the primary cultivation area have also been confirmed ⁸.

The production rate of quinoa (*C. quinoa* Willd.) in Iran varies depending on genotype, location, and cultivation conditions. Several studies report quinoa seed yield under diverse and often stressful Iranian climatic conditions, indicating a range of performance across different environments ⁹⁻¹¹. Research in various locations, including Karaj, Shahrekord, Ahvaz, and Iranshahr, has evaluated the performance of different genotypes, with some showing notably higher yields in trials ¹¹. Studies have also investigated the effects of sowing date and nitrogen fertilization on seed yield in Ahvaz ⁹. Sowing date experiments in Yazd have contributed to understanding production potential in that region ¹⁰.

Seed germination plays a fundamental role in seedling establishment, vigor, and overall plant health ¹². Traits such as uniform emergence and a high seedling emergence rate are key indicators of seed efficiency, directly influencing early plant development and stand establishment ¹³. Seed priming improves quinoa germination by promoting faster and more synchronized sprouting. Seeds that germinate quickly move into the seedling phase sooner, allowing them to utilize environmental resources more effectively. This leads to better establishment and reduced susceptibility to abiotic stresses. As a result, seed priming is widely recommended to enhance germination performance and seedling vigor, ultimately improving early plant establishment ². By accelerating germination and promoting uniform emergence, priming contributes to enhanced seedling development, higher yields, and improved crop quality. Moreover, it represents a cost-effective strategy for increasing agricultural productivity by stimulating the accumulation of bioactive compounds during early growth stages ¹⁴. Numerous studies have highlighted the benefits of seed priming across various crops. For instance, it has been demonstrated

¹⁵ that priming significantly improved the leaf area index, 1000-seed weight, and overall yield of the *Titicaca* quinoa variety.

Research indicates that salinity stress caused by sodium chloride decreases quinoa seed germination. However, priming seeds with gibberellic acid can counteract this negative effect and improve germination rates ¹⁶. Osmotic priming has also been reported to alleviate the adverse impacts of salt stress on germination traits, shoot length, and root length ¹⁷. In addition, priming with chitosan and potassium nitrate has been shown to mitigate the metabolic costs associated with the synthesis of soluble sugars, proline, and antioxidant enzymes, thereby preserving dry matter accumulation in quinoa plants ¹⁸. It has been studied ¹⁹ the effects of salicylic acid priming on two quinoa hybrids (*Giza1* and *Titicaca*) under salt stress and found that elevated salinity levels reduced photosynthetic pigment content and germination indices. However, salicylic acid treatment improved germination percentage, seedling vigor, and longitudinal growth, ultimately supporting better plant establishment under saline conditions.

In a separate study, priming quinoa seeds with potassium nitrate was shown to increase germination percentage and rate, shoot length, chlorophyll a and b contents, carotenoid content, protein levels, and catalase enzyme activity, while reducing electrolyte leakage from the plasma membrane ²⁰. Similarly, it has been investigated ²¹ the effects of hydropriming and biopriming with *Bacillus subtilis* on quinoa plants under drought stress. Their results showed that both treatments mitigated the negative effects of drought stress and improved traits like root dry weight, proline content, superoxide dismutase activity, and anthocyanin content. Furthermore, osmopriming and hormonal seed priming of rice using potassium nitrate and salicylic acid enhanced seed germination, plant growth, and antioxidant enzyme activities in drought-stress conditions ²².

It has been reported ²³ that hormonal priming with salicylic acid helps maintain cytokinin and auxin levels, enhances germination, reduces average germination time, promotes plant cell division, and improves corn plant growth and yield. In a separate study, it has been demonstrated ²⁴ that hormonal priming with gibberellin, auxin, and cytokinin increased germination traits and seedling growth in *Bromus*, and additionally noted that gibberellin elevated chlorophyll content in these plants. Similarly, it has been found ²⁵ that hormonal priming with gibberellin and kinetin decreased the mean germination time and improved greening in wheat seeds. Furthermore, it has been reported ²⁶ that hydropriming of chickpea seeds significantly increased seedling length, seed vigor, germination percentage, and germination rate. Another study reported that priming treatments increased grain yield in sesame, with hydropriming exhibiting the most pronounced effects ²⁷.

Rapid and uniform germination and early seedling establishment are key factors in realizing a crop's yield potential. In this regard, seed priming is recognized as a practical and effective strategy for improving germination indices and initial seedling vigor. While the positive effects of this method on quinoa seedling characteristics under controlled laboratory conditions have been well-documented, there is limited empirical evidence regarding the efficacy and sustainability of these effects under real field conditions, particularly in specific ecosystems such as the semi-arid climate of Iran. This

knowledge gap highlights the need for comparative studies in both controlled and field environments. Therefore, the main objective of this research is to comparatively evaluate the effects of different seed priming treatments on germination indices in the laboratory, as well as on seedling establishment, growth, and final yield under field conditions in the climate of Kurdistan Province, Iran. The results of this study can help identify the most effective priming method for improving establishment and increasing the sustainable yield of field-grown quinoa under similar conditions.

2. Materials and Methods

The quinoa seeds (*Chenopodium quinoa* Willd.) used in this study are of cultivated origin and were provided by the Kurdistan Agricultural and Natural Resources Research and Education Center. The center has granted permission for the research use of these seeds in accordance with the guidelines on the collection of plant material, ensuring full compliance with all relevant institutional, national, and international guidelines and legislation. . The experimental treatments included a control (without priming), hormonal priming with gibberellic acid (30 mg. L⁻¹), and salicylic acid (200 mg. L⁻¹), and various osmopriming treatments such as potassium chloride (1% w/v), potassium nitrate (5% w/v), polyethylene glycol 6000 (10% w/v), humic acid (54 mg.L⁻¹), zinc sulfate (6% w/v), and hydropriming with distilled water. The experiments were conducted on seeds of the quinoa variety "Titicaca."

This study was conducted through three experiments:

- Experiment 1 (laboratory): seed priming test in Petri dishes
- Experiment 2 (greenhouse): seed priming test in pots
- Experiment 3 (field): seed priming test in field condition

2.1. Experiment 1 (Laboratory): Seed priming test in petri dishes

First To prepare for the priming treatments, all equipment and germination papers were sterilized in an autoclave at 121°C for 20 min. Before priming, the seeds were surface-disinfected with 2% sodium hypochlorite for 5 minutes and rinsed several times with distilled water. Priming solutions were prepared by dissolving specific amounts of each priming agent in distilled water to the desired concentrations. Seeds were then immersed in the prepared solutions and incubated for 6 hours at 21–22°C, with continuous aeration provided by an air pump. After priming, seeds were dried at room temperature for 24 hours before being transferred to the germination and cultivation medium.

The selected treatments were initially evaluated under controlled conditions using a completely randomized design for preliminary assessment of the priming effects. Four Petri dishes were used as replicates for each treatment, with 100 seeds placed on Whatman No. 1 filter paper ²⁸ in each dish and moistened with 5 ml of distilled water. The Petri dishes were then transferred to a germinator set at 20 ± 1°C, with 70% relative humidity, and a photoperiod of 16 hours light and 8 hours darkness ²⁸.

The seeds were incubated in the germinator for ten days. During the experiment, the number of germinated seeds was recorded daily over one hour. Seed germination was defined by the emergence of a 2 mm root.

Germination percentage, germination rate, and mean germination time were calculated on the seventh day, while shoot and root lengths were measured on the tenth day.

The following equations were used to calculate germination percentage, germination rate, and mean germination time based on the number of germinated seeds recorded at the end of the counting period ²⁹:

$$(1) \quad FGP = (\sum n) / N \times 100$$

In this equation, $\sum n$ is the total number of germinated seeds, and N is the number of cultivated seeds.

$$(2) \quad R = \sum n_i / d_i$$

$$(2) \quad MGT = (\sum (n_i d_i)) / (\sum n_i)$$

In this equation, D is the time in days, n is the number of germinated seeds per day, and $\sum n$ is the total number of germinated seeds. After the experiment, shoot and root lengths for each treatment were measured using a ruler.

2.2. Experiment 2 (greenhouse): seed priming test in pots

The greenhouse experiment was conducted using a completely randomized design with four replications in the research greenhouse of Kurdistan University (latitude 35.19°N, longitude 46.59°E, altitude 1480 meters above sea level). The treatments applied were identical to those used in the laboratory priming experiment. A total of 36 plastic pots with drainage holes were prepared. The soil, sourced from Kurdistan University's research farm, was mixed in equal proportions (1:1:1) with sand and composted fertilizer. Before sowing, pots were saturated with water and allowed to drain to improve planting conditions. In each pot, 25 primed seeds were sown at a depth of 1 cm. The temperature inside the greenhouse was regulated by heating and cooling systems to maintain an optimal 25°C throughout the growing season. Light and temperature conditions were closely monitored, and irrigation was carried out manually once a day. After 45 days, the seedlings were harvested. Shoots and roots from each treatment were collected separately, placed in paper bags, and dried at 70°C for 72 hours. The dry weights of the shoots and roots were then measured using a digital scale.

2.3. Experiment 3 (field)

2.3.1. Farm Soil Characteristics

Prior to planting, random soil sampling was conducted from the experimental site. Subsequently, certain physical and chemical properties of the soil, such as soil texture, soil organic matter, soil nitrogen content, acidity (pH), and salinity (EC) were measured. Some physical and chemical properties of the soil at the experimental site are presented in the Table 1. The soil texture is clay loam.

Table 1. Soil Analysis Results of the Experimental Plot

Soil texture	Clay (%)	Silt (%)	Sand (%)	Organic Matter (%)	pH	EC (dS.m ⁻¹)	N (%)	K (mg.kg ⁻¹)	P (mg.kg ⁻¹)
Clay loam	29.30	40.23	30.47	1.21	7.65	0.82	0.10	450	16.20

2.3.2. Seed priming test in field condition

To validate the results obtained from the Petri dish and pot experiments, the selected priming treatments were evaluated under field conditions. The field experiment was carried out using a completely randomized block design with three replications at the research farm of Kurdistan University. This farm is situated in western Iran at approximately 35.18°N latitude, 46.35°E longitude, and an elevation of 1860 meters above sea level. The region experiences a Mediterranean climate, characterized by cold, moist winters and dry, moderate summers.

To prepare the planting bed, soil preparation operations—including plowing, disking, and leveling—were carried out to improve soil structure. Six planting rows were established in the field, and seeds were sown at a rate designed to achieve a final plant density of 50 plants per square meter. The seeds were thoroughly covered with soil. The planting date was recorded as May 8, 2019. Irrigation was applied weekly using a sprinkler system. During the growing season, manual weeding was performed three times to ensure effective weed control. At the 5-leaf stage, thinning was conducted to reduce intraspecific competition and maintain the desired plant density of 50 plants per square meter. Following thinning, the field was uniformly fertilized with urea at a rate of 200 kg.ha⁻¹ and subsequently irrigated. To manage pests, particularly shoot borers, Imidacloprid pesticide was applied at the 4–5 leaf and tillering stages at a concentration of 15 cc per 20 liters of water. Harvesting took place manually at physiological maturity on August 25, 2019, 109 days after planting. After harvesting, plants from each plot were dried under sunlight for ten days. At the end of the growing season, biological yield, grain yield, and harvest index were measured. The harvest index was calculated using the following formula: Harvest Index: After obtaining the biological yield and grain yield, the harvest index was obtained through Eq 4.

$$(4) \quad \text{Harvest index} = (\text{economic yield}) / (\text{biological yield}) \times 100$$

2.4. Statistical methods

Data normality was assessed using Minitab software (Ver 16.2.0). Variance analysis was performed using SAS software (Ver9.1), the LSD test was used to compare the data means and graphs were generated using Microsoft Excel (Ver 2016).

3. Results

3.1. Experiment 1 (laboratory): seed priming test in Petri dishes

3.1.1. Germination Percentage

Analysis of variance revealed a significant effect of the different priming treatments on germination percentage (Table 2; $p < 0.01$). The highest germination percentage was observed in seeds primed with potassium chloride (94.5%), while the lowest was recorded for polyethylene glycol treatment (65.5%) (Table 3, Figure 1). Potassium chloride priming increased

germination by 8% compared to the control. In contrast, treatments with potassium nitrate, zinc sulfate, gibberellic acid, polyethylene glycol, salicylic acid, humic acid, and hydropriming resulted in germination percentage changes of -13%, -13%, +1%, -25%, +4%, -19%, and -13%, respectively, relative to the control. Among these, only salicylic acid, gibberellic acid, and potassium chloride treatments showed increases in germination percentage compared to the control; however, these differences were not statistically significant.

Table 2. Analysis of variance for the effects of different seed priming treatments on germination characteristics of quinoa under Petri dish conditions.

Source of Variation	mean squares					
	df	Germination Percentage	Germination Rate	Mean Germination Time	Shoot Length	Root Length
Priming	8	393.62**	194.68**	0.094*	0.36**	0.47**
Error	27	50.50	61.66	0.020	0.069	0.052
Total	35	128.93	92.06	0.03	0.13	0.14
CV	-	8.85	11.87	9.44	4.51	5.72

ns, * and ** indicate non-significant, significant at the 5% level, and significant at the 1% level, respectively.

Table 3. Average comparison for the effects of different seed priming treatments on germination characteristics of quinoa under Petri dish conditions.

Treatment Priming	Germination (%)	Germination Rate (seeds per day)	Mean Germination Time (day)	Shoot Length (cm)	Root Length (cm)
Control (without priming)	87.50 a	69.24 abc	1.67 ab	5.50 d	3.70 ed
Potassium nitrate	76 b	63.10 dc	1.49 bcd	5.96 bc	4.63 a
Potassium chloride	94.50 a	77.84 a	1.53 bcd	6.35 a	4.15 bc
Zinc sulfate	76 b	63.35 bcd	1.43 cd	5.56 d	3.50 e
Gibberellic acid	86.50 a	74.71 ab	1.42 cd	5.70 cd	4.11 bc
Polyethylene glycol	65.50 c	55.88 d	1.41 cd	5.97 abc	3.90 cd
Salicylic acid	91 a	66.17 bcd	1.83 a	6.24 ab	4.24 b
Humic acid	70.75 bc	59.29 dc	1.54 ab	5.56 d	3.66 ed
Hydropriming	74.50 bc	65.71 bcd	1.33 d	5.85 cd	3.97 bcd

The values corresponding to the treatments examined in each column, which are marked with the same letters, do not have a statistically significant difference at the 5% probability level.

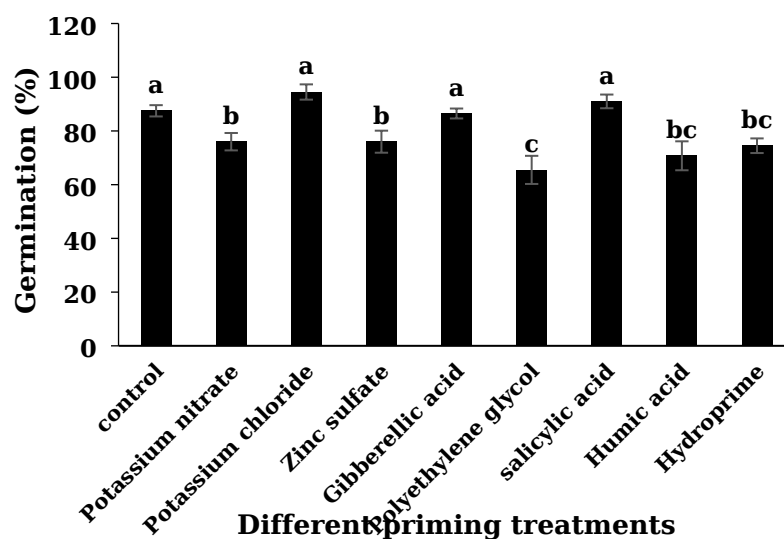


Fig. 1. Effect of different seed priming treatments on quinoa germination percentage under laboratory conditions.

3.1.2. Germination Rate

Analysis of variance showed that different seed priming treatments had a significant effect on germination rate (Table 2; $p < 0.01$). The highest germination rate was observed with potassium chloride treatment (77.84 seeds per day), while the lowest was recorded for polyethylene glycol treatment (55.88 seeds per day) (Table 3, Figure 2). The salicylic acid treatment resulted in an 8% decrease in germination rate compared to the control. Changes in germination rate relative to the control were as follows: potassium nitrate (-8.86%), potassium chloride (+12.42%), zinc sulfate (-8.50%), gibberellic acid (+7.90%), polyethylene glycol (-19.29%), humic acid (-4.37%), and hydropriming (-5.09%). While potassium chloride and gibberellic acid treatments enhanced the germination rate, these increases were not statistically significant. Among the treatments that reduced germination, only polyethylene glycol demonstrated a statistically significant decrease compared to the control.

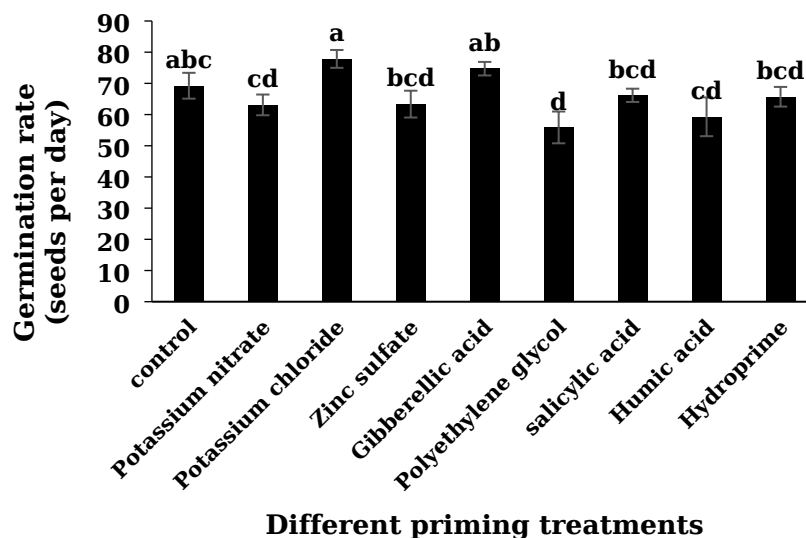


Fig. 2. Effect of different seed priming treatments on the germination rate of quinoa under laboratory conditions.

3.1.3. Mean Germination Time (MGT)

Analysis of variance indicated that the effect of different priming treatments on mean germination time (MGT) was significant ($p < 0.05$; Table 2). Potassium nitrate, humic acid, and potassium chloride treatments reduced MGT, although these reductions were not statistically significant compared to the control. Conversely, salicylic acid treatment was the only one to increase MGT, but this increase was also not statistically significant (Table 3, Figure 3). Mean germination time is a key indicator of seed quality, representing the average time required for complete germination of a seed lot. A longer MGT implies delayed germination, reflecting lower seed vigor. Thus, MGT is inversely related to seed quality.

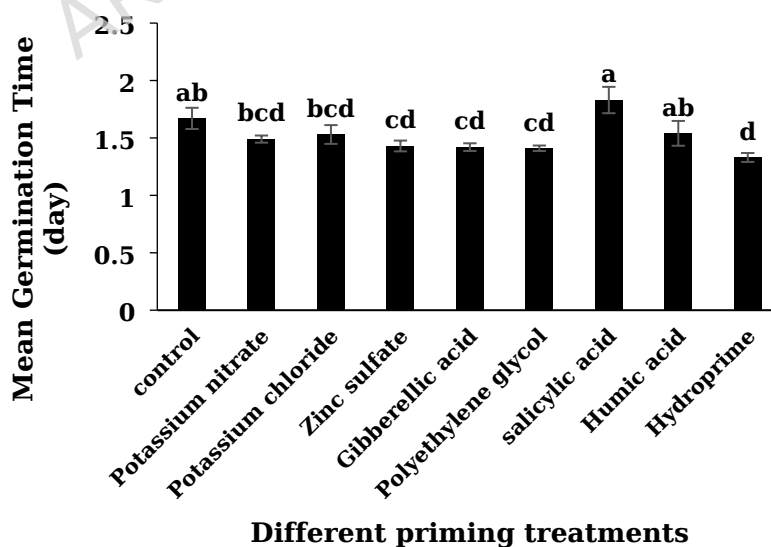


Fig. 3. Effect of different seed priming treatments on the mean germination time of quinoa under laboratory conditions.

3.1.4. Shoot Length

According to the analysis of variance, different priming treatments had a significant effect on shoot length (Table 2, $p < 0.05$). The highest shoot length was observed in the potassium chloride treatment, measuring 6.35 cm, while the lowest was recorded in the untreated control at 5.50 cm. Potassium chloride treatment resulted in a 15% increase in shoot length compared to the control (Table 3, Figure 4). Overall, potassium chloride, potassium nitrate, zinc sulfate, gibberellic acid, polyethylene glycol, salicylic acid, humic acid, and hydropriming treatments increased shoot length by 15%, 8%, 1%, 3%, 13%, 1%, and 6%, respectively, relative to the control. The potassium ions supplied during osmopriming play a crucial role in cellular potassium uptake and the activation of enzymes essential for germination and growth. Increasing shoot length in field conditions can enhance a plant's competitiveness against weeds. Among the treatments, gibberellic acid and potassium chloride stand out as strong candidates, as they have positively influenced several parameters, including germination rate, mean germination time, and germination percentage (Figures 1, 2, and 3).

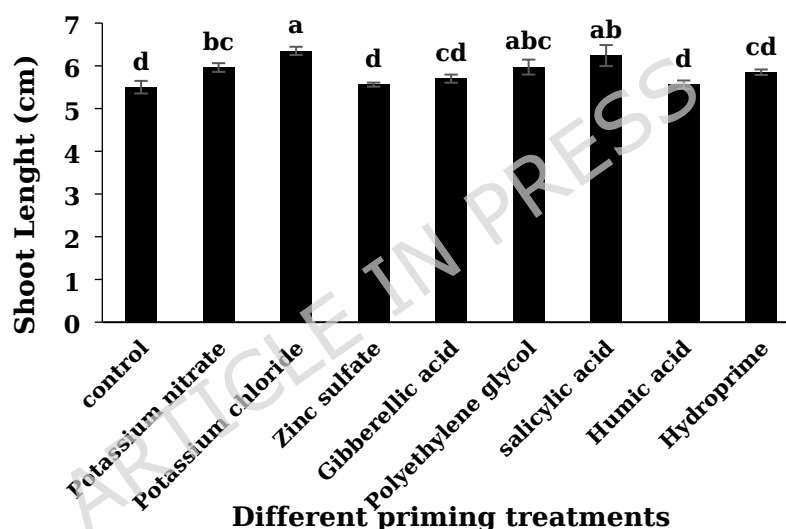


Fig. 4. Effect of different seed priming treatments on quinoa shoot length under laboratory conditions.

3.1.5. Root Length

According to the analysis of variance, different priming treatments had a significant effect on root length (Table 2, $p < 0.05$). The highest root length was observed in the potassium nitrate treatment, measuring 4.63 cm, while the lowest was recorded in the zinc sulfate treatment at 3.5 cm (Table 3, Figure 5). Compared to the control, potassium nitrate, potassium chloride, zinc sulfate, gibberellic acid, salicylic acid, humic acid, and hydropriming treatments resulted in changes in root length of +25%, +12%, -5%, +11%, +5%, +14%, and -7%, respectively.

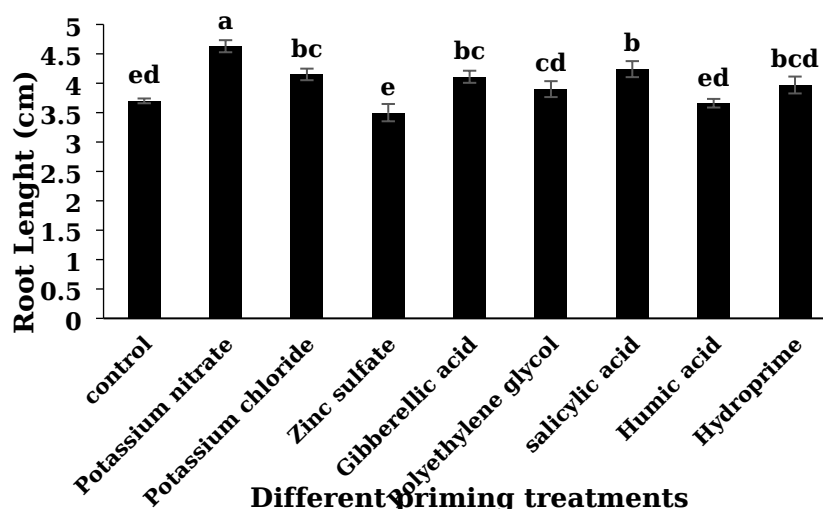


Fig. 5. Effect of different seed priming treatments on quinoa root length under laboratory conditions.

3.2. Experiment 2 (greenhouse): seed priming test in pots

3.2.1. Shoot dry weight

According to the analysis of variance, different priming treatments had a significant effect on shoot dry weight (Table 4, $p < 0.05$). The highest shoot dry weight was observed in the salicylic acid treatment (0.24 g per seedling), while the lowest was recorded in the zinc sulfate treatment (0.11 g per seedling). Although salicylic acid and hydropriming treatments increased shoot dry weight compared to the control, these differences were not statistically significant. Conversely, all other treatments resulted in a decrease in shoot dry weight relative to the control (Table 5, Figure 6).

Table 4. Analysis of variance of the effects of different priming treatments on seedling characteristics of quinoa plants under greenhouse conditions.

Source of Variation	mean squares		
	df	Dry weight of shoot	Dry weight of root
Priming	8	0.0053**	0.00019**
Error	27	0.0012	0.000026
Total	35	0.0022	0.000062
CV	-	19.86	15.18

ns, * and ** indicate non-significant, significant at the 5% level, and significant at the 1% level, respectively.

Table 5. Comparing the average effects of different priming treatments on seedling characteristics under quinoa plants greenhouse conditions.

Treatment Priming	Shoot dry weight (gr)	Root dry weight (gr)
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Control (without priming)	0.19 b	0.024 d
Potassium nitrate	0.17 bc	0.024 d
Potassium chloride	0.19 b	0.039 ab
Zinc sulfate	0.11 d	0.033 b
Gibberellic acid	0.17 bc	0.027 cd
Polyethylene glycol	0.13 cd	0.032 bc
Salicylic acid	0.24 a	0.045 a
Humic acid	0.18 b	0.037 ab
Hydropriming	0.20 ab	0.037 ab

The values corresponding to the treatments examined in each column, which are marked with the same letters, do not have a statistically significant difference at the 5% probability level.

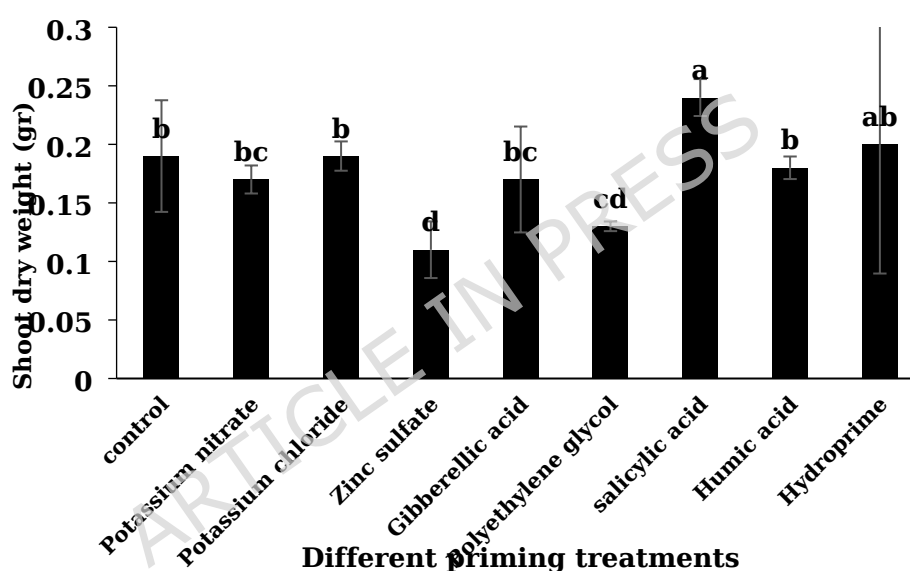


Fig. 6. Comparison of the effects of different priming treatments on quinoa shoot dry weight under greenhouse conditions.

3.2.2. Root dry weight

According to the original analysis of variance results, different priming treatments had a significant effect on root dry weight (Table 4, $p < 0.05$). The highest root dry weight was observed in the salicylic acid treatment (0.45 g per seedling), while the lowest values were recorded for potassium nitrate and control treatments (0.24 g per seedling). Treatments with potassium chloride, zinc sulfate, gibberellic acid, polyethylene glycol, hydropriming, and humic acid all increased root dry weight compared to the control (Table 5, Figure 7).

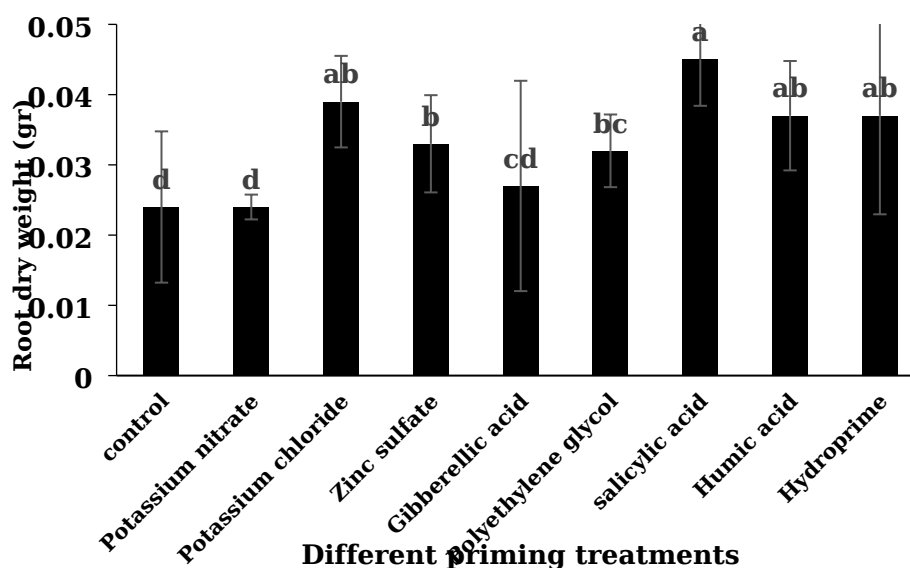


Fig. 7. Comparison of the effects of different priming treatments on quinoa root dry weight under greenhouse conditions.

3.3. Experiment 3 (field): seed priming test in field condition

3.3.1. Biological yield

According to the original analysis of variance, different priming treatments had a significant effect on biological yield (Table 6, $p < 0.05$). As shown in Table 7, Figure 8, the highest biological yield was recorded in the salicylic acid treatment, with 496 g.m^{-2} , while the lowest yield was observed in the control treatment (without priming), at 402.5 g.m^{-2} . Compared to the control, the biological yield changes for potassium nitrate, potassium chloride, zinc sulfate, gibberellic acid, polyethylene glycol, salicylic acid, humic acid, and hydropriming treatments were +8.11%, +3.22%, +0.78%, +17.59%, +1.98%, +23.22%, +21.42%, and +4.08%, respectively.

Table 6. Analysis of variance of the effects of different priming treatments on yield traits of quinoa plants under field conditions

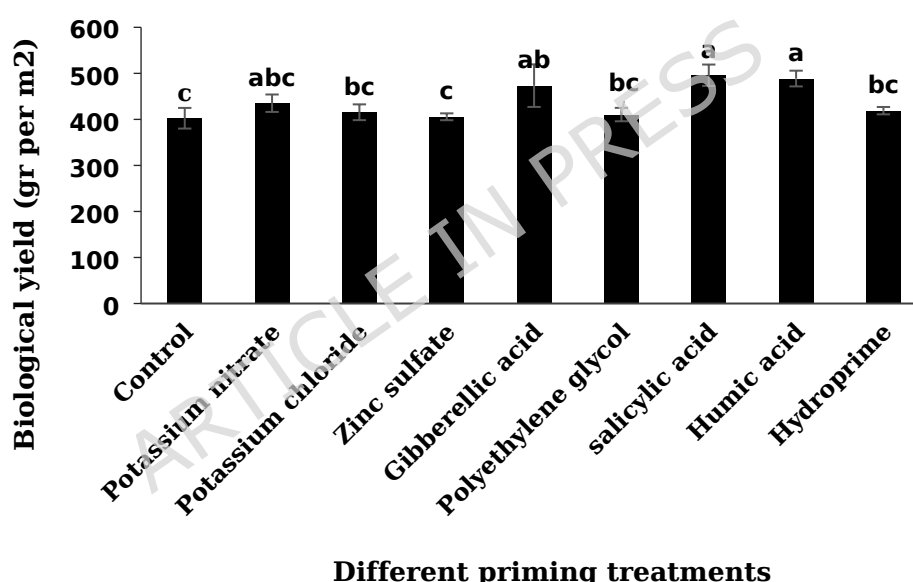
Source of Variation	mean squares				
	df	Biological yield	Inflorescence yield	harvest index	Grain yield
Rep	2	2321.69 ns	1826.37 ns	229.96 **	4236.74 **
Priming	8	4171.73*	2018.19 *	47.36 **	942.89 *
Error	16	1376.51	696.02	7.64	318.06
Total	26	2309.28	1189.80	36.97	811.73
CV	-	8.75	8.39	12.09	8.39

ns, * and ** indicate non-significant, significant at the 5% level, and significant at the 1% level, respectively.

Table 7. Average comparison of the effects of different priming treatments on yield traits of quinoa plants under field conditions

Treatment Priming	Biological yield (gr per m ²)	Inflorescence yield (gr per m ²)	Harvest Index (%)	Grain yield (gr per m ²)
Control (without priming)	402.50 c	265.81c	47.45 cd	189.49 c
Potassium nitrate	435.17 abc	288.35c	46.38 d	203.04 bc
Potassium chloride	415.50 bc	302.30 abc	54.09 a	225.12 ab
Zinc sulfate	405.67 c	280.68 c	48.81 bcd	197.72 bc
Gibberellic acid	473.33 ab	300.88 bc	41.49 e	195.57 bc
Polyethylene glycol	410.50 bc	287.18 c	52.80 ab	215.35 abc
Salicylic acid	496 a	346.96 a	49.61 abc	245.45 a
Humic acid	488.75 a	336.53 ab	45.55 de	222.82 ab
Hydropriming	418.96 bc	303.23 abc	51.97 abc	218.05 abc

The values corresponding to the treatments examined in each column, which are marked with the same letters, do not have a statistically significant difference at the 5% probability level.

**Fig. 8.** Comparison of the effects of different priming treatments on the biological yield of quinoa under field conditions.

3.3.2. Inflorescence yield

According to the analysis of variance, different priming treatments had a significant effect on inflorescence weight (Table 6, $p < 0.05$). The highest dry inflorescence weight was observed in the salicylic acid treatment, with 346.96 g.m^{-2} , while the lowest was recorded in the control treatment, at 265.81 g.m^{-2} . Compared to the control, the percentage changes in inflorescence weight for potassium nitrate, potassium chloride, zinc sulfate, gibberellic acid, polyethylene glycol, salicylic acid, humic acid, and hydropriming treatments were +8.47%, +13.72%, +5.59%, +13.19%, +8.03%, +30.52%, +26.60%, and +14.07%, respectively. All treatments had a positive effect on inflorescence weight, with salicylic acid and humic acid treatments showing the most pronounced impacts (Table 7, Figure 9).

However, the increases observed with zinc sulfate, potassium nitrate, and polyethylene glycol treatments were not statistically significant compared to the control.

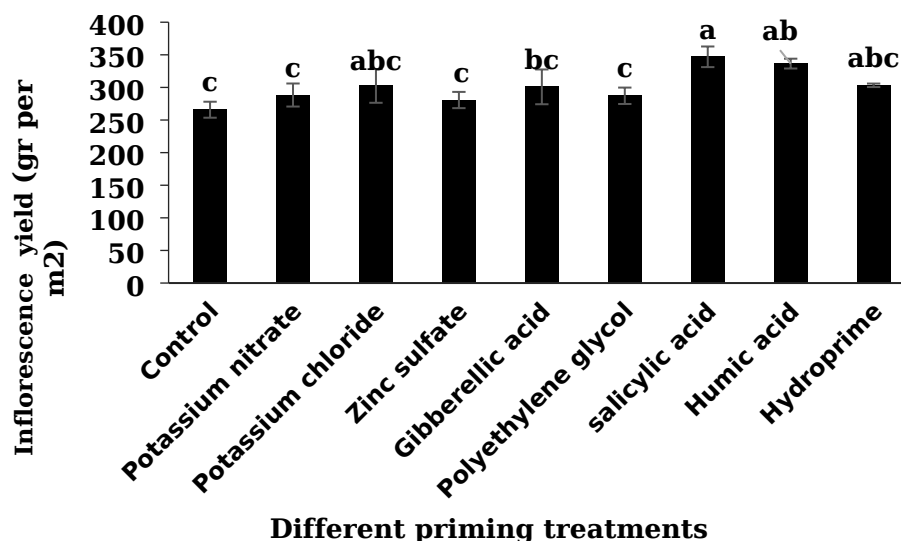


Fig. 9. Comparison of the effects of different priming treatments on quinoa inflorescence yield under field conditions.

3.3.3. Harvest index

According to the analysis of variance, the effect of different priming treatments on the harvest index was significant (Table 6, $p < 0.01$). The highest and lowest harvest indices were observed in the potassium chloride (109.54%) and gibberellic acid (49.41%) treatments, respectively. Compared to the control, the Harvest index changed by -2.25% (potassium nitrate), +13.99% (potassium chloride), +4.34% (zinc sulfate), -3.20% (gibberellic acid), +11.27% (polyethylene glycol), +29.53% (salicylic acid), +17.58% (humic acid), and +15.07% (hydropriming). Among these, potassium chloride, zinc sulfate, salicylic acid, polyethylene glycol, and hydropriming treatments improved the harvest index. However, only the differences between the potassium chloride and polyethylene glycol treatments and the control were statistically significant. In contrast, potassium nitrate, gibberellic acid, and humic acid treatments reduced the harvest index, with the reduction in the gibberellic acid treatment being significantly different from the control (Table 7, Figure 10).

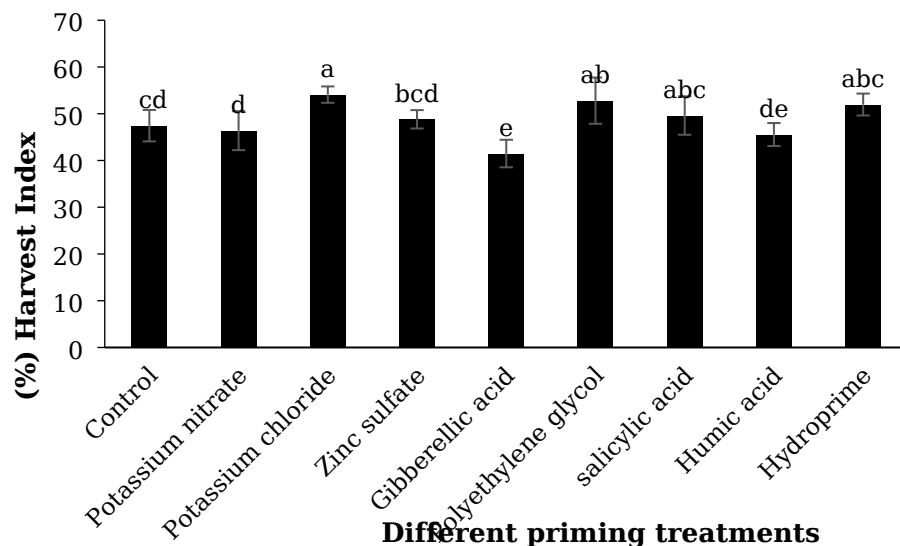


Fig. 10. Comparison of the effects of different priming treatments on quinoa harvest index under field conditions.

3.3.4. Grain yield

According to the analysis of variance, the effect of different priming treatments on economic yield was significant (Table 6, $p < 0.05$). The highest economic yield was observed in the salicylic acid treatment (245.45 g.m⁻²), while the lowest was in the control treatment (189.49 g.m⁻²). Compared to the control, the changes in economic yield for potassium nitrate, potassium chloride, zinc sulfate, gibberellic acid, polyethylene glycol, salicylic acid, humic acid, and hydropriming treatments were +7.15%, +18.80%, +4.34%, +3.20%, +13.64%, +29.53%, +17.58%, and +15.07%, respectively (Table 7, Figure 11).

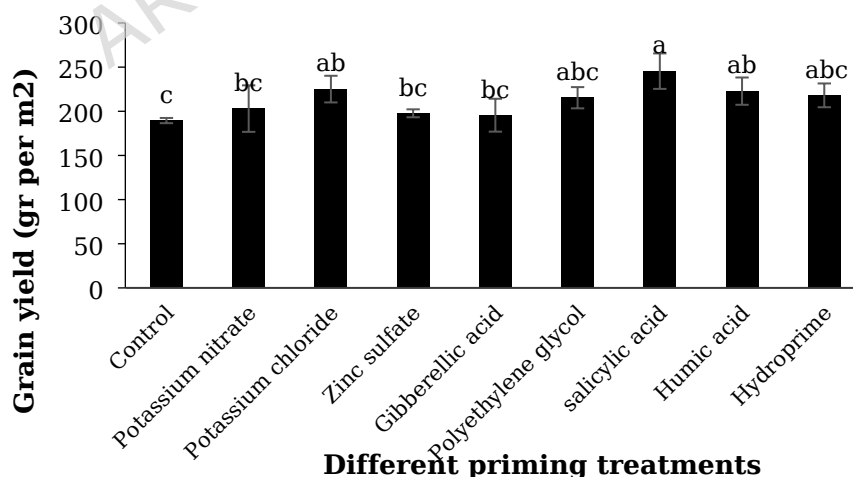


Fig. 11. Comparison of the effects of different priming treatments on quinoa grain yield under field conditions.

3.4. Correlation coefficients

The original correlation analysis results (Table 8) indicated several significant positive relationships among measured traits. Under laboratory conditions, seed germination percentage showed a significant positive correlation with germination rate ($p < 0.01$). Additionally, shoot length exhibited a significant positive correlation with root length ($p < 0.05$). Under greenhouse conditions, the dry weight of seedling shoots was significantly correlated with grain yield ($p < 0.05$). In field conditions, biological yield demonstrated a significant positive correlation with both grain yield and inflorescence yield ($p < 0.01$). Furthermore, grain yield was significantly and positively correlated with yield index and inflorescence yield ($p < 0.01$). These findings indicate that enhancements in early growth traits, such as shoot and root length or seedling dry weight, may lead to improved field performance and yield components.

Table 8. Correlation coefficients among measured traits of quinoa under laboratory, greenhouse, and field conditions in an experiment evaluating the effects of different priming treatments on germination characteristics, morphological traits, and yield.

	x1	x2	x3	x4	x5	x6	x7	x8	x9	x10
x2	0.875**	1								
x3	0.165 ^{ns}	-	1							
		0.314 ⁿ _s								
x4	0.236 ^{ns}	0.220 ⁿ _s	-	1						
			0.035 ⁿ _s							
x5	0.153 ^{ns}	0.231 ⁿ _s	-	0.544*	1					
			0.151 ⁿ _s							
x6	0.098 ^{ns}	-	0.300 ⁿ _s	0.123 ⁿ _s	0.237 ⁿ _s	1				
		0.010 ⁿ _s								
x7	0.262 ^{ns}	0.221 ⁿ _s	0.049 ⁿ _s	0.356 ⁿ _s	-	0.349 ^{ns}	1			
					0.154 ⁿ _s					
x8	-	-	0.344 ⁿ _s	-	0.132 ⁿ _s	0.189 ^{ns}	-	1		
	0.090 ^{ns}	0.239 ⁿ _s		0.085 ⁿ _s			0.026 ⁿ _s			
x9	-	-	0.183 ⁿ _s	0.220 ⁿ _s	0.056 ⁿ _s	0.478*	0.326 ⁿ _s	0.468*	1	
	0.171 ⁿ _s	0.247 ⁿ _s								
x10	-	-	-	0.317 ⁿ _s	-	0.334 ^{ns}	0.354 ⁿ _s	-	0.663*	1
	0.094 ^{ns}	0.047 ⁿ _s	0.095 ⁿ _s		0.038 ⁿ _s			0.343 ⁿ _s	*	
x11	-	-	0.226 ⁿ _s	0.123 ⁿ _s	0.110 ⁿ _s	0.339 ^{ns}	0.238 ⁿ _s	0.820*	0.640*	0.001 ^{ns}
	0.094 ^{ns}	0.186 ⁿ _s						*	*	

X1, X2, X3, X4, and X5 represent germination percentage, germination rate, average germination time, shoot length, and root length, respectively, under laboratory Petri dish conditions. **X6 and X7** denote shoot dry weight per seedling and root dry weight per seedling, respectively, under greenhouse pot cultivation. **X8, X9, X10, and X11** correspond to biological yield, grain yield, harvest index, and inflorescence yield, respectively, under field conditions. *ns*, *, and ** indicate non-significant, and significant at the 5% and 1% probability levels, respectively.

4. Discussion

Seed priming has become an important technique for improving germination and growth traits in a variety of plant species, including quinoa. It has been reported³⁰ that priming with potassium chloride enhances both physical and chemical activities within seeds, effectively reducing seed coat adhesion and facilitating root emergence without resistance. This observation aligns with the findings of previous research indicating that³¹ seed priming improves germination under saline stress by preventing cellular damage and inhibiting the absorption of harmful ions. In the context of quinoa seed priming, studies have found¹⁷ that gibberellic acid notably increased germination, while polyethylene glycol resulted in decreased germination rates, which is consistent with the results of the present study. However, a contrasting finding was noted regarding potassium nitrate treatment, which showed a decrease in germination percentage, differing from other work which documented¹⁸ an increase in germination percentage with potassium nitrate priming in quinoa seeds.

Furthermore it has been demonstrated³² that low concentrations of selenium priming enhanced quinoa seed germination. These discrepancies highlight that different quinoa genotypes may respond variably to priming treatments, emphasizing the need for genotype-specific approaches in priming protocols. The positive effects of seed priming on germination and growth characteristics of quinoa are evident, particularly when implemented and managed appropriately under field conditions, leading to improved crop performance. The favorable impact of potassium chloride on germination rate can be attributed to its osmotic benefits and its role as a cofactor in various enzyme activities, especially during radicle development and resource mobilization³³. In contrast, treatment with polyethylene glycol (PEG) has been shown to decrease both the percentage and rate of germination. Previous studies suggest that excessive priming, even at optimal PEG concentrations, can disrupt α -amylase activity, leading to reduced germination rates and abnormal growth of shoots and roots. Additionally, the effectiveness of seed priming is affected by several factors, including the concentration of the priming solution, the duration of treatment, and the temperature^{34,35}. Supporting these findings, research on barley has reported³⁶ that priming with salicylic acid, gibberellic acid, and calcium chloride enhanced both germination percentage and rate. Similarly, evidence shows³⁷ that saponin priming significantly improved quinoa seed germination rate. Overall, the results of this study suggest that treatments with gibberellic acid and potassium chloride effectively increase both germination percentage and rate, thereby identifying them as successful priming agents. Potassium enhances quinoa yield by improving seed germination, early seedling establishment, and tolerance to environmental stresses. This element ensures optimal plant density and robust early growth by increasing germination percentage, accelerating radicle and hypocotyl growth, and strengthening the antioxidant defense system, ultimately leading to enhanced grain yield and biomass. Studies indicate that optimal potassium application can significantly increase quinoa yield even under saline stress conditions. In addition to enhancing germination, previous studies have demonstrated that priming treatments reduce mean germination time (MGT) in quinoa seeds³⁷.

This is corroborated by findings that ³² low concentrations of selenium priming decreased MGT in quinoa. Uniform and rapid seedling emergence is crucial for achieving high-quality yields in field conditions. Priming, even if it does not significantly affect germination rates, can enhance plant growth by improving quality parameters like mean germination time (MGT). Recent studies have demonstrated that priming barley seeds with hydrogen peroxide, calcium chloride, salicylic acid, and succinic acid significantly increases both shoot and root length, particularly under low-temperature stress ³⁸. Similarly, studies on chickpea have reported ³⁹ that potassium chloride and hydrogen peroxide priming enhanced shoot and root length in chickpea plants under saline conditions. The increased root length observed in seeds primed with potassium nitrate may be attributed to faster germination, which promotes accelerated seedling growth and enhances both shoot and root development. Several studies have documented improvements in root and shoot length due to priming. For instance, reports indicate ⁴⁰ that seed priming with potassium nitrate increased shoot and root length in seedlings of various plant species under stress conditions. However, it is worth noting that other research has found ¹⁷ that polyethylene glycol priming reduced root length in quinoa, which contradicts the findings of the present study and may be attributed to differences in experimental conditions or genotype responses.

Priming seeds under stress conditions has been shown to enhance the mobilization of seed reserves to the embryo, promoting better embryo growth and improving germination and related traits. This physiological process allows seedlings to utilize water and nutrients more efficiently, leading to greater growth compared to unprimed seeds. As a result, the dry weight of shoots and roots from primed seeds tends to increase ⁴¹. It has been demonstrated ⁴² that priming with humic acid, *Pseudomonas*, marlamin, and hydropriming led to increased shoot dry weight in barley under drought stress conditions. However, it is important to highlight that it has been reported ²¹ a contrasting finding, indicating that hydropriming decreased shoot dry weight in quinoa under similar drought conditions. These varying outcomes indicate that although priming treatments typically boost seedling growth by enhancing the plant's ability to absorb and utilize water and nutrients, the effectiveness of specific priming methods can vary based on the treatment type and plant species. This improved capacity for water and nutrient uptake through priming leads to greater dry matter accumulation in both shoot and root tissues. Supporting this notion, it has been reported ⁴² that priming with humic acid, *Pseudomonas*, marlamin, and hydropriming significantly promoted root growth in barley subjected to drought stress. Similarly, it has been demonstrated ²¹ that hydropriming increased root length in quinoa plants under drought stress, further indicating that priming can positively influence root development, which is critical for overall plant health and resilience.

Seed priming has been shown to significantly influence various aspects of plant growth and yield, contributing to enhanced biological yield and improved resource utilization. It has been attributed ⁴³ the increase in biological yield following priming to rapid plant establishment and more efficient resource utilization. This enhancement appears to be closely linked to improvements in seedling emergence percentage and rate. Similarly, it

has been reported ^{44,45} that the increase in biological yield due to priming can be associated with enhanced antioxidant activity, accelerated seedling growth, improved establishment, and more effective utilization of environmental factors such as light, soil moisture, and nutrients. Notably, it has been found ⁴⁶ that priming lentil seeds with zinc sulfate resulted in increases in grain and biological yields of up to 92%.

The impact of seed priming on chlorophyll activity and photosynthetic efficiency has also been documented. It has been indicated ⁴⁷ that seed priming influences chlorophyll activity, which subsequently enhances photosynthetic efficiency. This improvement is evident in the increased number of seeds per inflorescence after seed priming. This enhancement is due to improved photosynthetic activity resulting from earlier plant establishment and more efficient use of environmental resources ⁴⁸. Furthermore, the increased inflorescence weight resulting from seed priming is associated with improved germination and successful plant establishment. This enhanced early growth fosters vigorous vegetative development, which in turn contributes to better reproductive growth, including a higher inflorescence weight. Supporting this notion, it has been reported ⁴⁹ that priming with potassium chloride, calcium chloride, and potassium nitrate significantly increased inflorescence weight in rice plants, reinforcing the positive impact of seed priming on yield components. Despite the benefits associated with seed priming, the exact mechanisms behind the behavior of some priming treatments remain unclear. It has been reported ⁵⁰ an increase in the harvest index of chickpea seeds due to seed priming. Similarly, it has been found ⁵¹ that priming with salicylic acid and zinc sulfate increased the maize harvest index by 24%.

It has been also reported ⁵² improvements in the harvest index of wheat through priming with polyethylene glycol and hydropriming. Additionally, it has been observed ⁵³ an increase in the harvest index of quinoa plants following priming with potassium sulfate. Seed priming can also enhance plant growth rate, ultimately improving yield by shortening the greening period and reducing the base temperature required for germination ⁵⁴. It has been demonstrated ⁵⁴ that seed hydropriming can increase total chlorophyll content, including chlorophyll a and b, thereby enhancing photosynthetic activity and boosting organic matter production and nutrient availability. These physiological improvements contribute to increased crop performance. The overall enhancement in yield due to priming treatments can be attributed to faster and more uniform germination, rapid seedling growth, effective establishment, and better utilization of environmental and nutritional resources ⁵⁵. Further supporting this concept, it has been found ⁵⁶ that seed priming in spring canola improved both the quantity and quality of seed yield. Similarly, it has been reported ⁵⁰ that salicylic acid priming positively influenced chickpea yield. It has been demonstrated ⁵⁷ that priming mitigated the negative effects of salinity stress on wheat yield. Furthermore, it has been observed ²⁷ that priming—particularly hydropriming—increased sesame seed yield. It has been also reported ⁵⁸ a significant improvement in the economic yield of corn following seed priming with zinc sulfate.

Various seed priming treatments significantly influence the germination and growth parameters of quinoa, with potassium chloride and salicylic acid

proving to be particularly effective. Priming with potassium chloride notably enhanced the germination percentage and rate, shoot length, and biological yield, likely due to its osmotic benefits and its role as a cofactor in enzymatic activities during early seedling development. Similarly, salicylic acid positively impacted several growth parameters, including the dry weight of shoots and roots, as well as economic yield, indicating its potential as a beneficial priming agent under suitable conditions. In contrast, treatments such as polyethylene glycol and potassium nitrate often led to reduced germination rates and growth, suggesting that priming protocols must be carefully tailored to optimize seed performance. The variability in treatment effectiveness observed in this and other studies highlights the necessity for genotype-specific priming strategies, as quinoa cultivars may respond differently based on their genetic makeup and environmental conditions. Overall, these findings suggest that seed priming is a promising, low-cost strategy to enhance the germination, growth, and yield performance of quinoa. This has practical implications for improving crop establishment and productivity, especially in suboptimal or stress-prone environments. Implementing effective priming techniques in agricultural practices could strengthen quinoa cultivation and contribute to food security and sustainable agricultural systems. Further research is recommended to refine priming protocols and elucidate their physiological and biochemical mechanisms, particularly under diverse environmental stresses.

5. Conclusion

This study demonstrates that seed priming significantly enhances quinoa germination and yield. Potassium chloride (KCl) improved laboratory germination (94.5%) and shoot length (6.35 cm), while salicylic acid (SA) increased field biological yield (496 g.m⁻²) and grain yield (245.45 g.m⁻²). Conversely, polyethylene glycol (PEG) reduced germination (65.5%). Strong correlations between early growth traits and final yield suggest that optimized priming (e.g., KCl for germination, SA for yield) can boost quinoa productivity, particularly in stress-prone environments. Further research should refine protocols for diverse cultivars and conditions.

Conflict of Interests

All authors declare no conflict of interest.

Ethics approval and consent to participate

No human or animals were used in the present research.

Ethical issues

Ethical issues (including plagiarism, data fabrication, double publication) have been completely observed by the authors. The authors have adhered to ethical standards, including avoiding plagiarism, data fabrication, and double publication.

Consent for publication

All authors read and approved the final manuscript for publication.

Availability of data and material

The authors of this article are committed to ensuring that all data presented in this article was extracted based on sound scientific methods in the form of scientific experiments in an academic environment, and that all data is available for presentation upon request. The datasets generated and/or analyzed during this study are available from the corresponding author upon reasonable request.

Authors' contributions

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Writing-original draft: P. A.

Writing-reviewing & editing: All authors.

Informed Consent

The authors declare not used any patients in this research.

Funding Declaration

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Acknowledgement

This study was supported by the equipment of University of Kurdistan in the form of a student thesis, and the authors did not receive any support from any other organization for the submitted work.

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