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Enhancing Drought Resistance in Spring Wheat (*Triticum aestivum* L.) Through Chelated Zinc Seed Treatment: An Experimental Study

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Abstract: Climate change-induced drought is a significant threat to global food security, particularly affecting wheat yields. Despite various strategies to enhance drought resistance in crops, the effectiveness of chelated Zinc (Zn) as a seed treatment agent remains underexplored, especially in the early stages of wheat ontogenesis. This study aims to fill this gap by evaluating the effectiveness of zinc as a seed treatment agent for drought resistance improvement in wheat seed varieties in the initial stages of development. The experimental setup involved treating seeds of seven spring wheat varieties with chelated Zn at concentrations of 10, 15, and 20 mg/L. Germination rates, shoot and root development, and various stability indices were measured under both natural and simulated drought conditions. Studies of seed germination showed a significant increase in germination, lengthening of the shoot and roots, and an increase in the area and mass of the shoot and the angle of appearance of roots when using chelated forms of zinc with a dose of 15 mg/L compared with other variants of the experiment under natural conditions and drought stress conditions. When zinc was used in stressful drought conditions, wheat genotypes stimulated intensive growth and development of root mass rather than the vegetative mass of wheat seedlings, that is, the root-to-shoot ratio increased compared to the control variant. Treatment of spring soft wheat variety seeds with a chelated form of zinc in a dose of 15 mg/L promoted the full growth and development of wheat seedlings and increased drought resistance (in terms of seedling viability stability index, plant height stability index, plant mass stability index, plant area stability index, root length stability index, root mass stability index, root number stability index, etc.,).

Keywords: Spring Soft Wheat, Variety, Seeds, Germination, Resistance

Introduction

Currently, one of the main factors threatening world food security is drought caused by climate change. In the next 20 years, due to the effects of high temperatures and drought, the yield of the wheat crop will decrease by 5.5-12% (Zulkiffal *et al*., 2021). Considering the possible increase in air temperature to 0.6-2.5°C by 2050 and to 1.4-5.8°C by 2100, the consequences of drought may increase even more (Birch, 2014).

Stress caused by drought negatively affects the water balance of the plant (Habib *et al*., 2022), the rate of transpiration, absorption, and movement of nutrients (Baidalina *et al*., 2023), photosynthesis processes (Dutbayev *et al*., 2021) and other metabolic processes (Nisa *et al*., 2019). Under the effects of drought, crops show a tendency to decrease seed germination (Faisal, 2016; Mahpara *et al*., 2022) and demonstrate deterioration of growth and development (Lukács *et al*., 2008), which also leads to a decrease in yield (Rakszegi *et al*., 2014) and quality of the crop (Umair Hassan *et al*., 2020) and sometimes their absence.

Plants have properties with various mechanisms of adaptation and response to drought stress, which cause physiological, biochemical, and morphological reactions (Reynolds and Tuberosa, 2008; Adl *et al*., 2020). The response of plants to drought stress is directly related to the level of moisture deficiency (Abdel-Motagally and El-Zohri, 2018; Bali *et al*., 2022). In case of short-term stress from drought, the plant limits the absorption of carbon dioxide.

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If the drought continues, then an average stress level occurs, at which the plant regulates the osmotic pressure of accumulated organic salts. Further, a prolonged drought stress is observed, where the plant triggers the processes of genetic information.

The reaction of the wheat plant to moisture deficiency directly depends on the susceptibility of the culture to the external environment and the reaction rate of the osmotic regulatory properties of the plant. The response to drought stress occurs at different levels of development depending on the crop and variety (Lukács *et al*., 2008; Rehman *et al*., 2021; Ashfaq *et al*., 2022). Under the influence of drought, the plant, for enhanced absorption of moisture from the soil, regulates osmotic pressure by increasing the volume of carbohydrates and proline (Pessarkli, 1999).

The most important problem faced by germinating seeds is the lack of moisture during germination. The assessment of drought resistance at the germination stage is very important since it affects all subsequent stages and ultimately grain yield (Basu *et al*., 2016; Kido *et al*., 2016; Nezhadahmadi *et al*., 2013). The amount of moisture in the nutrient medium and the duration of moisture regulate the process of seed germination. They cause a low level of response of germinating wheat seedlings to drought stress, which is just beginning to grow (Guo *et al*., 2017; Ahmed *et al*., 2022; Malko *et al*., 2022). Therefore, the focus of our study is aimed at solving this problem, since in the main grain-growing regions of Kazakhstan (in the central and northern regions), during the sowing and emergence of spring wheat, moisture deficiency constantly occurs (Baisholanov, 2017; Babkenov *et al*., 2023). If we do not address this problem, based on forecasts, the level of wheat yield in Kazakhstan may decrease significantly (Shaimerdenova *et al*., 2023). According to the United Nations, within the framework of the program for the development of spring wheat yields in the main grain-producing regions of Kazakhstan, a decrease in yield by 13-37% by 2030 and by 20-49% by 2050 has been predicted and substantiated (Zerno.ru, 2020). The change in weather conditions due to climate change is also observed in northern Kazakhstan. Over the past 31 years, in northern Kazakhstan, during the period of crop growth and development, the number of hot days has increased with a temperature background exceeding 32°C (Akshalov *et al*., 2022).

Researchers suggest various ways to increase the drought resistance of wheat at the germination stage, as an effective way to deal with drought stress (Zeng and Luo, 2012; Gholizadeh *et al*., 2022; Shaffique *et al*., 2023; Zhao *et al*., 2023). One of the effective ways to increase drought resistance in the initial periods of wheat development is the use of trace elements (Malakhov *et al*., 2022), which reduces the content of reactive oxygen species, increases the activity of antioxidant enzymes, and improves the drought resistance of wheat by increasing the ability to use water, antioxidant protection, and osmotic regulation (Nawaz *et al*., 2014; Wu *et al*., 2014).

While previous studies have explored various strategies to mitigate drought stress, the use of chelated forms of zinc specifically during the early stages of wheat ontogenesis remains under-researched. Trace elements improve physiological processes and plant growth and play a vital role in increasing plant resistance to various biotic and abiotic stresses (Keyvan, 2010; Silva Folli-Pereira *et al*., 2016). Zinc (Zn) is an important trace element for plants and plays a crucial role in various physiological processes during plant growth and development (Taran *et al*., 2017; Raeisi Sadati *et al*., 2022). Among the key points explaining why Zn supplementation is necessary to increase wheat productivity in ontogenesis, the researchers note the following:

1. Role in enzyme activation: Zn serves as an important cofactor for enzymes, crucial for processes such as photosynthesis, respiration, and DNA synthesis, which are vital for plant growth and development
2. Photosynthesis: Zn is necessary for the synthesis of chlorophyll (Samreen *et al*., 2017), the green pigment responsible for photosynthesis (it affects the plant's ability to produce energy and biomass)
3. Root development: A healthy root system is necessary for the absorption of nutrients and Zn deficiency can lead to a slowdown in root growth, limiting the plant's ability to obtain the necessary nutrients and moisture from the soil (Kondratenko and Soboleva, 2023)
4. Nutrient absorption: Zn facilitates the absorption of other essential nutrients by plants, such as iron (Fe) (Hasheminasab *et al*., 2023). This is especially important for wheat, as Fe deficiency can lead to a decrease in chlorophyll production and a decrease in photosynthesis
5. Protein synthesis: Zn is involved in protein synthesis and wheat plants need proteins for various functions, including the formation of structural components, enzymes, and transport proteins
6. Stress resistance: Zn plays a role in increasing plant stress resistance, including resistance to diseases and environmental stress factors (Babkenova *et al*., 2020; Hasanuzzaman *et al*., 2018) believe that strengthening the antioxidant defense system to mitigate oxidative stress is one of the effective strategies for increasing the drought resistance of wheat plants
7. Grain development: Zn contributes to the development of wheat grain and affects grain size and quality (Dashkevich *et al*., 2022)
8. Increasing wheat yields: Studies have shown that the application of Zn fertilizers can lead to an increase in wheat yields, especially in regions where Zn deficiency is common in the soil. This increase in yield is explained by improved nutrient uptake, improved photosynthesis, and overall improved plant health (Kenenbayev *et al*., 2023)

The study aims to experimentally determine the chelated form of Zn to reduce the effect of drought in the early stages of development of spring soft wheat (*Triticum aestivum* L.).

By focusing on the early stages of plant development, this research adds valuable knowledge to the field, offering a practical and efficient solution to enhance drought resilience in wheat, which is crucial for ensuring food security in the face of climate change.

Materials and Methods

The experiment was conducted in the laboratory of the S. Seifullin Kazakh Agro Technical Research University in 2022-2023.

The objects of the study were seven varieties of spring soft wheat of midseason-ripening type Shortandinskaya 2014, Taimas, Karabalykskaya 90, Liskam, Aina, Granny, and Tselina 50.

The study variants were planted in three repetitions using the randomization method. To create artificial conditions of drought stress, a Polyethylene Glycol (PEG)-6000 solution with an atmospheric pressure of 1.0 bar was used. 78 g of PEG-6000 was used to prepare the solution and dissolved in 1,000 mL of distilled water according to the method proposed by Michel and Kaufmann (1973). Distilled water was used as a control variant of the study. The seeds of spring soft wheat were washed in running water before germination. Germination was determined by international seed testing rules (Introduction to the ISTA Rules, 2023). The filter paper was pre-disinfected with 70% alcohol and moistened with PEG-6000 solution.

The experimental variants were treated with pre-prepared chelated Zn forms with doses of 10-15-20 mg/L solution at a temperature of 25°C for 1 h and dried to standard humidity. To minimize contamination from Zn, all solutions, including the PEG-6000 solution used for creating drought conditions, were prepared using telex-treated water. The seeds of spring wheat brought to standard humidity were put on germination, with 20 seeds placed on each roll. For the germination of spring wheat seeds, a Ts-200 thermostat (1004 Stabilizer Bar (SB) model) was used at a temperature of 20°C (±2°C). 10 mL of PEG-6000 solution was poured into each roll daily.

On day 3, the seed germination energy was determined and on day 7, germination was determined. Along with the determination of germination, the plant length, mass, and area, as well as the root number, length, mass, and angle of emergence, were recorded. Based on the results of biometric indicators, the Shoot Viability Index (SVI) and the Root-to-Shoot Ratio (RSR) were determined according to the formula proposed by Hellal *et al*. (2018):

$$SVI = ((shoot\ length + rootstock\ length) \times germination)\ /100 \tag{1}$$

The Plant Stress Tolerance Index (PSTI) was determined by the formulas proposed by Ashraf *et al*. (2008) using Plant Height Stability Index (PHSI), Plant Mass Stability Index (PMSI), Plant Area Stability Index (PASI), Root Length Stability Index (RLSI), Root Mass Stability Index (RMSI) and Root Number Stability Index (RNSI):

$$PMSI = \ (plant\ height\ stress/plant\ height\ under\ control) \times\ 100 \tag{2}$$

$$PMSI\ =\ (plant\ mass\ under\ stress/plant\ mass\ under\ control) \times\ 100 \tag{3}$$

$$PASI\ = (plant\ area\ under\ stress/plant\ under\ control)\ \times\ 100 \tag{4}$$

$$RNSI = (root\ number\ under\ stress/root\ numberin\ the\ control\ \mathrm{variant}) \times 100 \tag{5}$$

$$RMSI = (root\ mass\ under\ stress/root\ mass\ in\ the\ control\ \mathrm{variant}) \times 100 \tag{6}$$

$$RNSI = (root\ number\ under\ stress/root\ numberin\ the\ control\ \mathrm{variant}) \times 100 \tag{7}$$

Statistical processing of the results of the study was carried out using the statistica 8.0 software. Differences in the results obtained are possible at a significance level of $p \le 0.05$ according to the student's t-test.

Results

The seed material of spring wheat varieties in terms of germination in natural conditions corresponded to the highest class (germination above 92.28%). As the study results showed, the use of Zn preparation in vivo with different doses of Zn contributed to an increase in germination of seed material by 0.12-2.49% (Table 1).

The control for these experiments was the untreated seeds germinated under the same conditions. When Zn was applied, germination rates increased slightly even under drought stress conditions. Specifically, using a 15 mg/L Zn solution under drought stress increased the germination rates to class 3 levels for several varieties: Taimas (91.05%), Karabalyk 90 (91.44%), Liskam (92.33%), Aina (92.2%), Granny (92.4%) and Tselina 50 (91.54%). Lower concentrations (10 mg/L) and higher concentrations (20 mg/L) of Zn also contributed to increased resistance, with germination rates improving by 5.4-8.9% compared to untreated controls.

The minimum value of the impact of stressful conditions on germination was characterized by the varieties of spring wheat Taimas (germination rate under stress 75.6%), Tselina 50 (germination rate under stress 76.3%), and Akmola 2 (germination rate under stress 72.7%). The use of a trace element of the chelated Zn form in various concentrations contributes to an increase in field germination. However, it is also necessary to note the varietal specificity of the studied varieties of spring wheat.

Table 1: The effect of drought stress and Zn on seed germination, root emergence angle, and RSR in spring wheat varieties

Variety	Seed treatment	Germination, %		RSR		Root emergence angle, °	
		Control	Stress	Control	Stress	Control	Stress
Shortandinskaya 2014	No treatment	92.39	64.80	0.72	0.46	18.5	9.20
	Zn (10 mg/L)	92.51	71.38	0.70	0.51	23.25	11.78
	Zn (15 mg/L)	96.74	77.13	0.71	0.73	25.72	14.34
	Zn (20 mg/L)	92.07	73.46	0.68	0.71	23.07	11.50
Taimas	No treatment	93.02	75.61	0.88	0.89	22.82	9.78
	Zn (10 mg/L)	94.24	84.13	0.93	0.96	22.63	13.33
	Zn (15 mg/L)	94.41	91.05	0.97	1.02	24.33	15.58
	Zn (20 mg/L)	93.92	84.11	0.94	0.95	23.00	13.00
Karabalykskaya 90	No treatment	92.28	67.22	0.65	0.50	17.63	6.43
	Zn (10 mg/L)	92.64	76.58	0.66	0.70	18.43	8.50
	Zn (15 mg/L)	94.52	91.44	0.69	0.69	20.30	15.63
	Zn (20 mg/L)	92.67	85.87	0.66	0.69	21.00	13.00
Liskam	No treatment	94.40	65.90	0.78	0.44	19.17	6.93
	Zn (10 mg/L)	96.93	79.43	0.74	0.69	19.27	10.40
	Zn (15 mg/L)	97.83	92.33	0.73	0.69	21.67	7.67
	Zn (20 mg/L)	96.63	80.00	0.73	0.65	24.03	8.10
Aina	No treatment	93.38	72.50	0.74	0.76	26.50	5.87
	Zn (10 mg/L)	94.65	87.41	0.73	0.75	28.30	21.10
	Zn (15 mg/L)	95.90	92.20	0.81	0.89	28.00	24.43
	Zn (20 mg/L)	94.99	89.53	0.76	0.80	25.63	20.53
Granny	No treatment	95.01	71.64	0.77	0.70	30.10	11.50
	Zn (10 mg/L)	95.02	78.67	0.75	0.78	30.67	22.90
	Zn (15 mg/L)	96.51	92.40	0.73	0.77	30.83	25.03
	Zn (20 mg/L)	95.90	85.85	0.75	0.80	29.67	23.50
Tselina 50	No treatment	95.56	76.38	0.70	0.33	24.30	8.53
	Zn (10 mg/L)	95.69	83.62	0.68	0.53	25.04	16.23
	Zn (15 mg/L)	96.98	91.54	0.73	0.74	27.73	19.30
	Zn (20 mg/L)	96.51	86.30	0.72	0.74	25.27	16.53

A decrease in the germination rate under artificial stress from drought was observed from 18.96-39.98% depending on the studied varieties of spring wheat. The data presented in Table 1 represent the mean values obtained from three independent experiments (n = 3), each involving 20 seeds per roll and three rolls per treatment group, totaling 60 seeds per treatment condition

The varieties Karabalykskaya 90 (decrease by 44.16%), Lamis (52.78%), Liskam (49.22) Fantasia (48.55%), etc., were unstable to stress concerning the plant length. The varieties Taimas, Shortandinskaya 2014, and Tselina 50 were characterized by relatively high values of plant length. These varieties of spring wheat were also characterized by high plant mass and plant area values.

The formation of indicators of the number, length, and mass of germinal roots also changed when exposed to stressful conditions in comparison with the control variant. The recorded decrease in the number of germinal roots in the context of the studied varieties of spring wheat amounted to 28%, which is primarily due to low values of the length and mass of the wheat plant. Some spring wheat varieties showed no stress effect on the formation of the number of germ roots (Fantasia and Granny varieties) while using a dose of Zn (10 mg/L) reduced these values. The most optimal option is the Zn dose of 15 mg/L, which contributed to an increase in the number, length, and mass of germinal roots by an average of 9.3-18.6%.

Under the effects of drought stress, wheat seeds significantly reduced the growth and development of roots. Under natural conditions (control) and drought stress conditions, spring wheat seeds treated with Zn were characterized by more intensive development of roots than shoots. A particularly high RSR value was achieved with an increase in the concentration of the Zn element by more than 15 mg/L.

A high negative level of stress influence is noted in terms of the root emergence angle. In the context of the studied varieties of spring wheat, in comparison with the control variant, stress conditions reduced the indicator to 67.8%. Under artificial stress conditions, the root emergence angle in Zn-treated seeds increased by 3.47-15.9° compared with the control variant. As a result of the use of Zn for priming spring wheat seeds, the most pronounced increase in the appearance of roots was observed in the Aina (15.9°) and Granny (13.53°) varieties. The SVI decreased by 1.8-3.2 times in conditions of artificial drought stress depending on the genotype of spring soft wheat (Fig. 1). For wheat seeds treated with Zn, an increase in the SVI was achieved, reaching a high level (15.62-24.22%).

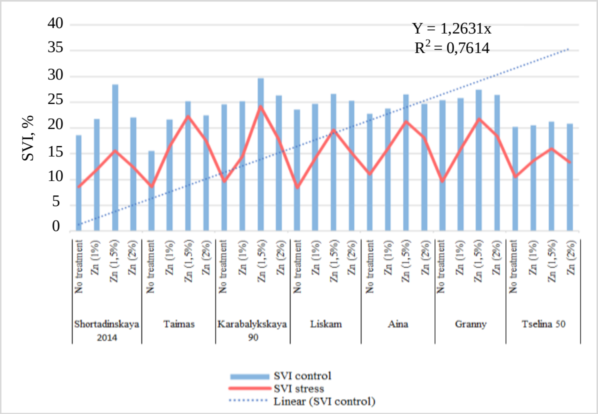

Fig. 1: The effect of drought stress and the Zn element on the SVI of various spring wheat varieties

Priming of seeds of spring soft wheat varieties with the Zn element showed different levels of the stability index in terms of Seedling Viability Stability Index (SVISI), PHSI, PMSI, PASI, RLSI, RMSI, and RNSI (Table 2). In all varieties of spring soft wheat, an increase in the germination stability index in natural and stressful conditions from drought was observed when using Zn as priming at a dose of 15 mg/L.

The maximum value of the SVISI, PHSI, PASI, and RLSI was recorded in seeds of the Taimas variety when treated with Zn at a dose of 15 mg/L. Besides, a high stability index was noted in the Tselina 50 variety (84.41%, PMSI) and the Granny variety (86.16%, RMSI).

The lowest value of the stability index in terms of SVISI, PHSI, PASI, and RMSI was found in seedlings of the Liskam variety in the untreated variant. Seedlings of the Karabalykskaya 90 variety (PMSI, 49.14%) and Granny (RLSI, 47.38%) had a low GSTI to drought stress. The GSTI for Zn applications with a dose of 15 mg/L is reached at maximum values and with an increase in the dose to 20 mg/L, the GSTI to drought stress decreases.

Various correlations were recorded under natural conditions and drought stress. When germinating seeds in natural conditions, a weak to negative relationship was found between the indicators of grain growth processes.

Table 2: The effect of spring wheat varieties seed treatment with Zn on drought stress resistance

Variety	Seed treatment	Germination Stress Tolerance Index (GSTI) to drought stress, %						
		SVISI	PHSI	PMSI	PASI	RLSI	RMSI	RNSI
Shortandinskaya 2014	No treatment	46.21	69.74	65.42	80.08	62.85	42.11	83.33
	Zn (10 mg/L)	55.04	78.86	69.15	86.12	64.77	50.78	83.33
	Zn (15 mg/L)	54.85	69.89	74.05	89.98	67.87	76.29	85.00
	Zn (20 mg/L)	56.57	78.05	59.20	85.46	65.13	62.40	75.00
Taimas	No treatment	54.87	67.87	62.51	78.36	67.09	63.47	71.67
	Zn (10 mg/L)	76.30	88.87	67.70	86.65	82.43	69.97	100.00
	Zn (15 mg/L)	88.75	90.83	71.77	91.98	92.90	75.29	100.00
	Zn (20 mg/L)	78.04	87.85	69.53	92.08	86.05	70.62	78.33
Karabalykskaya 90	No treatment	38.86	55.59	49.14	55.76	51.45	37.21	80.00
	Zn (10 mg/L)	57.55	65.13	68.41	79.31	73.36	71.37	91.67
	Zn (15 mg/L)	81.55	84.61	79.45	90.10	84.11	78.79	100.00
	Zn (20 mg/L)	67.49	63.99	75.94	87.64	80.61	78.77	93.33
Liskam	No treatment	35.73	50.80	54.12	52.52	51.73	30.29	86.67
	Zn (10 mg/L)	57.52	61.05	63.80	69.13	79.17	58.43	86.67
	Zn (15 mg/L)	73.82	72.17	73.86	77.19	84.52	69.87	93.33
	Zn (20 mg/L)	60.24	61.10	74.41	73.44	84.07	66.40	93.33
Aina	No treatment	48.64	60.33	57.34	58.42	64.47	59.12	93.33
	Zn (10 mg/L)	67.33	66.56	68.57	88.88	78.47	70.60	100.00
	Zn (15 mg/L)	80.42	77.72	78.05	89.50	88.84	86.20	100.00
	Zn (20 mg/L)	73.46	66.93	74.68	88.17	87.27	79.26	93.33
Granny	No treatment	37.67	53.29	59.56	75.66	47.38	53.87	100.00
	Zn (10 mg/L)	62.10	70.33	69.34	86.51	78.93	71.48	100.00
	Zn (15 mg/L)	79.56	79.47	80.81	90.59	86.16	86.16	100.00
	Zn (20 mg/L)	70.00	70.48	76.21	87.34	84.69	81.55	91.67
Tselina 50	No treatment	52.03	64.75	83.16	77.55	65.82	38.85	86.67
	Zn (10 mg/L)	66.41	68.78	84.09	82.86	86.22	66.23	100.00
	Zn (15 mg/L)	75.41	75.36	84.41	82.13	86.56	85.64	93.33
	Zn (20 mg/L)	63.95	61.39	80.31	79.26	86.34	82.42	100.00
Variance, S^2		198.16	1.21	1.01	1.31	0.89	0.79	1.81
Standard deviation's		14.08	1.10	1.00	1.15	0.94	0.89	1.34
Coefficient of variation (V), %		22.39	15.70	14.20	14.20	12.40	13.40	14.70

There is a correlation between the indicators of plant area and germination (r = 0.76), root mass and germination (r = 0.72), SVI and plant length (r = 0.72), and SVI and the germinal root length (r = 0.88) and it is characterized as high. At the same time, it is necessary to highlight a close correlation between the RSR and the plant mass r = -0.90. In drought conditions, a close correlation was found between the germination index and the plant area (r = 0.85), the root mass (r = 0.80), and the SVI (r = 0.86). Under stressful conditions, a high correlation was found between the plant length and the SVI (0.83), the plant area and the root mass (0.72), the root emergence angle (0.7), and the SVI (0.74).

The root length (0.9) and the root mass (0.82) had a significant positive effect on the wheat SVI. According to the analysis of variance, the effect of the variety (factor A), seed treatment with Zn (factor B), and the effect of the interaction of factors A and B on germination are significant at all confidence levels (Table 4).

The actual Fisher's ratio test (F-test) for factor A under natural conditions (65.8) and drought stress conditions (123.6) turned out to be higher than the theoretical (3.13) values. The theoretical values of the F-test at a 5% significance level (2.75) for factor B turned out to be less than the actual F-test values under natural conditions (20.8) and under drought stress (213.5).

The interaction of factors A and B in the control variant and under stressful conditions was significant because the actual F-test for the interactions of factors A and B (F = 5.2 and 11.1) was higher than the theoretical values (F = 2.24). The relatively low experimental error (S_x 0.5-1.45%) of the experiment was shown in various conditions of germination of spring wheat seeds (Table 5).

Mathematical processing of the obtained data proves a sufficiently high accuracy of the experiment in natural conditions of germination (T = 99.5%) and under drought stress conditions (98.55%). The LSD_{05} criterion (0.82-4.1) proves the essential importance of varieties and the use of Zn on the germination level of spring wheat seeds (Table 3).

Table 3: Correlation coefficient between the studied signs in natural conditions and drought stress conditions

	Germination, %	Plant length, cm	Plant mass, g/100 pcs	Plant area, cm^2/100 pcs	Germinal roots number, pcs	Germinal roots length, pcs	Root mass, g/100 pcs	Root emergence angle, °	SVI
Germination, %	1.00	0.62	0.52	0.85	0.38	0.67	0.80	0.64	0.86
Plant length, cm	0.42	1.00	0.53	0.50	0.27	0.59	0.60	0.45	0.83
Plant mass, g/100 pcs	0.33	0.65	1.00	0.45	0.33	0.38	0.61	0.34	0.52
Plant area, cm^2/100 pcs	0.76	0.44	0.33	1.00	0.39	0.62	0.72	0.70	0.74
Germinal roots number, pcs	0.08	0.16	0.13	0.05	1.00	0.21	0.30	0.05	0.33
Germinal roots length, pcs	0.24	0.31	0.24	0.20	-0.13	1.00	0.75	0.52	0.90
Weight of roots, g/100 pcs	0.72	0.43	0.30	0.56	0.07	0.46	1.00	0.63	0.82
Root emergence angle, °	0.33	0.09	-0.06	0.43	-0.30	0.18	0.25	1.00	0.61
SVI	0.49	0.72	0.50	0.43	-0.01	0.88	0.61	0.21	1.00

Note:

🟧 - Natural conditions
🟩 - Drought stress conditions

Table 4: The results of the variance analysis of the two-factor 7×4 experiment conducted using the method of randomized blocks

Variance	Degree of freedom	Sum of squares		Mean square		Ff	F_{05}	Ff	F_{05}
		Control	Stress	Control	Stress	Control		Stress	
Total	83	307.2	6,464.4						
Repetitions	2	7.8	12.0						
Factor A	2	133.6	1,557.5	66.8	778.7	65.8	3.13	123.6	3.13
Factor B	3	63.2	4,035.7	21.1	1,345.2	20.8	2.75	213.5	2.75
Interaction of factors A and B	6	31.5	418.1	5.2	69.7	5.2	2.24	11.1	2.24
Excess	70	71.1	441.1	1.0	6.3				

Note: Factor A: Seeds of spring soft wheat varieties (Shortandinskaya 2014; Taimas; Karabalykskaya 90; Liskam; Aina; Granny; Tselina 50); Factor B: TFreatment of seeds with Zn in different doses (no treatment; Zn (10 mg/L); Zn (15 mg/L); Zn (20 mg/L))

Table 5: The results of the significance of particular differences in seed germination in natural and drought stress conditions

	Total		Factor A		Factor B	
Materiality assessment	Control	Stress	Control	Stress	Control	Stress
S_x	0.50	1.45				
Mean difference error (Sd)	0.82	2.05	0.41	1.02	0.47	1.18
Least significant difference $(LSD)_{05}$	1.65	4.10	0.82	2.05	0.95	2.37

Note: LSD_{05} is the least significant difference for a 5% significance level

Discussion

Based on the results of our study, we can draw theoretical and practical conclusions.

The theoretical conclusions are generally confirmed by the results of other studies on the need for Zn application, in particular at the stage of wheat ontogenesis. Foliar application of Zn increases grain yield, yield index, Fe, manganese, and copper content (Mehrinfar *et al*., 2023). It reduces drought stress by increasing the biometric parameters of wheat plants (Mahdy and Farghali, 2021). It increased the content of antioxidants (ascorbate, reduced glutathione, total phenolic, and total flavonoid composition), while simultaneously reducing the levels of lipid peroxidation and the H_2O_2 content (Ma *et al*., 2017).

For instance, Irmes *et al*. (2023) explored the effects of foliar zinc applications on winter wheat, focusing on leaf chlorophyll concentrations and grain yields over two seasons with different weather conditions. They found that foliar Zn treatments improved chlorophyll content and yield, particularly under drought conditions. The correlation between chlorophyll concentration and yield was stronger in the dry season, suggesting that Zn foliar applications are particularly beneficial under water-stressed conditions. This suggests that while both seed and foliar applications of zinc are beneficial, they target different growth stages and stress responses in wheat.

Also, Yahyaoui *et al.* (2017) investigated the effects of Zinc Oxide nanoparticles (ZnO NPs) on wheat, highlighting oxidative stress responses and potential toxicity. While the study underscores the significant impact of zinc-based treatments author emphasized the potential toxicity and oxidative damage at high ZnO NP concentrations, whereas our research showed the beneficial effects of moderate chelated zinc concentrations on drought resistance.

The practical conclusions of our study allow us to draw conclusions about methods that increase the efficiency of wheat cultivation. We agree with the researchers' conclusions that seed treatment with microelement nanoparticles helps to improve seed germination and seedling growth, ensuring plant resistance to various stresses (Nile *et al*., 2022).

The effectiveness of nanopriming wheat seeds depends on the concentration of nanoparticles, as well as the priming time. In wheat seeds, ZnO at a concentration of 10 mg/L with a treatment time of 18 h had the greatest positive effect on the level of seed germination, biomass, and seedling energy (Rai-Kalal and Jajoo, 2021). Using ZnO nanoparticles effectively mitigates the negative effects of drought during the emergence of wheat seedlings, increasing the fresh and dry mass of shoots and roots (Rukhsar-Ul-Haq *et al*., 2023).

Wheat seeds treated with ZnO (10 mg/L) showed a significant positive effect on seed germination and SVI compared with non-primed (control) and hydro-primed seeds (Rai-Kalal and Jajoo, 2021). As the results of our study showed, improper selection of Zn dosage for seed treatment causes greater harm to the roots of wheat seedlings and even destroys the antioxidant system (Zhu *et al*., 2019).

The main signs for assessing germination in drought-resistant conditions are the germination percentage, the plant length, the root length, and the RSR of germinated seeds (Arjenaki *et al*., 2012; Mohi-Ud-Din *et al*., 2021). To increase drought resistance in the early stages of development, especially during the emergence of wheat seedlings, it is necessary to consider the parameters of germination, their stability, and viability (Sallam *et al*., 2018). The objectives of the study were to assess the effects of drought stress on the germination parameters of spring wheat varieties and to reduce the negative effects of drought with the use of Zn.

All studied varieties showed a response to drought stress, reducing the germination rate to 64.8%. Stressful conditions also negatively affected the formation of the length, mass, and shoot area of spring wheat seeds. Under the influence of stress, the length of the shoot decreased from 30.4-52.7%. The use of Zn in various doses contributed to an increase in germination. However, the most optimal variant of the experiment was the use of Zn in the dose of 15 mg/L, which contributed to an increase in germination by an average of 20.2-29.4% in the context of the studied varieties.

In the case of drought, under the influence of stress, wheat shoots and roots are delayed in growth and the RSR in some varieties (Liskam) decreases to 0.44. Treatment of wheat seeds with Zn (15 mg/L) in drought stimulates the development of roots rather than shoots, increasing the RSR (Taimas variety) to 1.02. The study by Mahdieh *et al.* (2018) on pinto beans demonstrated that Zinc Oxide nanoparticles (ZnO NPs) significantly improved vegetative traits, yield, and zinc content. However, while

Mahdieh *et al*. (2018) highlighted the advantages of foliar application, our study focused on seed treatment, suggesting that the method of zinc application could influence the outcomes.

In natural conditions, the roots of wheat seeds grow somewhat sprawling, while under the influence of drought, the root emergence angle decreases from 9.3-20.3°. Using Zn at a dose of 15 mg/L under natural conditions (0.73-7.22°) and drought conditions (0.74-18.56°) leads to an increase in the root emergence angle.

A characteristic difference in all the studied varieties of spring soft wheat according to the GSTI to drought stress is that only when the seeds are treated with Zn (15 mg/L), the maximum value of drought resistance is achieved (Ivanov, 2021). Correlation studies between all the signs have shown that in natural conditions a close correlation is observed between the germination indices (r = 0.72-0.76) and the SVI (0.72-0.88). Under conditions of drought stress, many germination parameters positively and significantly correlated with each other, especially in terms of similarity (r = 0.8-0.86), plant area (r = 0.7-0.74), and SVI (r = 0.74-0.9).

The aina and granny varieties were characterized by a high rate of germination and resistance to stressful conditions (the germination rate was 92.2-92.4%, respectively).

It is also important to acknowledge some limitations of the research. The research is centered on wheat varieties from Kazakhstan, potentially limiting the generalizability to other regions with different climates and soils.

Nevertheless, the results of this study demonstrate significant advancements in the field of agricultural sciences, specifically in the area of drought resistance in crops. The findings that a 15 mg/L concentration of chelated zinc markedly improves germination rates, promotes root development over vegetative growth, and enhances various stability indices under drought conditions provide novel insights into the practical applications of micronutrient treatments.

These results contribute to the current body of knowledge by highlighting the specific benefits of chelated zinc in enhancing the early-stage drought resistance of spring wheat.

Conclusion

In case of drought under stress, soft wheat seeds include all germination parameters to ensure growth processes, which have a close correlation in similarity, plant area, and SVI.

The results of the study of the effects of drought stress showed a positive effect of the studied varieties, seed treatment with Zn, and the effect of the interaction of two factors on the germination of spring soft wheat. The relationship between varieties and variants of the use of Zn as seed priming has shown that the dominant role in the formation is played by the varietal feature and the dose of Zn.

It was found that the use of a chelated form of Zn with a dose of 15 mg/L contributed to an increase in field germination, lengthening of the shoot and root, increasing the area and mass of the plant, and leading to an increase in the root emergence angle. According to the results of the conducted studies, Zn increased the mass of primary roots rather than wheat shoots.

For further studies, the modeling method is planned to increase the germination rate and stress resistance of seeds of spring soft wheat varieties using trace elements to prevent and eliminate the effects of drought on the growth and development of crops.

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Author’s Contributions

Bekzak Amantayev: Led the research, conceptualized the study and contributed to the writing.

Gulden Kipshakbayeva: Conducted data analysis, developed the methodology, and contributed to the writing.

Arysgul Turbekova: Performed data analysis, created visualizations and contributed to the writing.

Yeldos Kulzhabayev: Edited the manuscript, created visualizations and managed the project.

Paul Lutschak: Conducted peer review, edited the manuscript, and secured funding.

Ethics

This article is composed of original content and does not include any material previously published elsewhere.

References

Abdel-Motagally, F. M. F., & El-Zohri, M. (2018). Improvement of wheat yield grown under drought stress by boron foliar application at different growth stages. *Journal of the Saudi Society of Agricultural Sciences*, *17*(2), 178–185. https://doi.org/10.1016/j.jssas.2016.03.005

Adl, S., Masoudian, N., Roodi, B., Ebadi, M., & Zadeh, M. H. K. (2020). Effect of drought stress on some morphological and physiological characteristics of low resistance and sensitive wheat cultivars. *Pakistan Journal of Medical & Health Sciences*, *14*(2), 1266–1275.

Ahmed, H. G. M.-D., Zeng, Y., Shah, A. N., Yar, M. M., Ullah, A., & Ali, M. (2022). Conferring of drought tolerance in wheat (*Triticum aestivum* L.) genotypes using seedling indices. *Frontiers in Plant Science*, *13*, 961049. https://doi.org/10.3389/fpls.2022.961049

Akshalov, K. A., Baisholanov, S. S., Baimukanova, O. N., Aueskhanov, D. A., & Kuzhinov, M. B. (2022). Analysis of agrometeorological conditions of the growing season 2020 and 2021 in Northern Kazakhstan: features and measures of adaptation to climate change. *Herald of Science of S. Seifullin Kazakh Agrotechnical University*, *3*(114), 161–176. https://doi.org/10.51452/kazatu.2022.3(114).1166

Arjenaki, G. F., Jabbari, R., & Morshedi, A. (2012). Evaluation of drought stress on relative water content, chlorophyll content and mineral elements of wheat (*Triticum aestivum* L.) varieties. *International Journal of Agriculture and Crop Sciences*, *4*(11), 726–729.

Ashfaq, W., Brodie, G., Fuentes, S., & Gupta, D. (2022). Infrared Thermal Imaging and Morpho-Physiological Indices Used for Wheat Genotypes Screening under Drought and Heat Stress. *Plants*, *11*(23), 3269. https://doi.org/10.3390/plants11233269

Ashraf, M. Y., Hussain, F., Akhter, J., Gul, A., Ross, M., & Ebert, G. (2008). Effect of different sources and rates of nitrogen and supra optimal level of potassium fertilization on growth, yield and nutrient uptake by sugarcane crown under saline conditions. *Pakistan Journal of Botany*, *40*(4), 1521–1531.

Babkenov, A., Babkenova, S., Dashkevich, S., Kanafin, B., Shabdan, A., & Kairzhanov, Y. (2023). Resistance to Brown and Stem Rust in Spring Soft Wheat Varieties in the Arid Climate of Northern Kazakhstan. *OnLine Journal of Biological Sciences*, *23*(4), 411–417. https://doi.org/10.3844/ojbsci.2023.411.417

Babkenova, S. A., Babkenov, A. T., Pakholkova, E. V., & Kanafin, B. K. (2020). Pathogenic complexity of septoria spot disease of wheat in northern Kazakhstan. *Plant Science Today, 7*(4), 601–606. https://doi.org/10.14719/pst.2020.7.4.798

Baidalina, S., Baidalina, M., Khusainov, A., Kazydub, N., & Baiken, A. (2023). Photosynthetic activity, productivity, and nutritional value of mowing and grazing phytocenoses depending on the species composition of grasses. *SABRAO Journal of Breeding and Genetics*, *55*(3), 825–835. https://doi.org/10.54910/sabrao2023.55.3.18

Baisholanov, S. S. (Ed.). (2017). *Agroklimaticheskie resursy Akmolinskoi oblasti: Nauchno-prikladnoi spravochnik [Agroclimatic resources of Akmola region: A scientific and applied reference book*. TOO “Institut geografii” MON RK.

Bali, A. S., Sidhu, G. P. S., Grover, D., & Dahiya, B. (2022). Biological Trace Elements Confer Abiotic Stress Tolerance in Plants. In *Biostimulants for Crop Production and Sustainable Agriculture* (pp. 306–322). CABI. https://doi.org/10.1079/9781789248098.0019

Basu, S., Ramegowda, V., Kumar, A., & Pereira, A. (2016). Plant adaptation to drought stress. *F1000Research*, *5*, 1554. https://doi.org/10.12688/f1000research.7678.1

Birch, E. L. (2014). A Review of “Climate Change 2014: Impacts, Adaptation, and Vulnerability” and “Climate Change 2014: Mitigation of Climate Change.” *Journal of the American Planning Association*, *80*(2), 184–185. https://doi.org/10.1080/01944363.2014.954464

Dashkevich, S. M., Utebayev, M. U., Kradetskaya, O. O., Chilimova, I. V., Zhylkybaev, R. S., & Babkenov, A. T. (2022). The Genetic Potential of Spring Durum Wheat Grain Quality in the North of Kazakhstan. *OnLine Journal of Biological Sciences*, *22*(3), 347–355. https://doi.org/10.3844/ojbsci.2022.347.355

Dutbayev, Y., Tsygankov, V., & Kuldubayev, N. (2021). Photosynthesis response to leaf position of soybean genotypes in Western Kazakhstan. *Annals of Agri-Bio Research*, *26*(1), 33–36.

Faisal, S. (2016). Physiological Studies on Six Wheat (*Triticum aestivum* L.) Genotypes for Drought Stress Tolerance at Seedling Stage. *Agricultural Research & Technology: Open Access Journal*, *1*(2), 1–5. https://doi.org/10.19080/artoaj.2016.01.555559

Zerno.ru. (2020). *Kazakhstan riskuet v dva raza snizit urozhainost pshenitsy iz-za izmeneniya klimata [Kazakhstan risks halving wheat yield due to climate change]*. https://zerno.ru/node/13193

Gholizadeh, F., Janda, T., Gondor, O. K., Pál, M., Szalai, G., Sadeghi, A., & Turkoglu, A. (2022). Improvement of Drought Tolerance by Exogenous Spermidine in Germinating Wheat (*Triticum aestivum* L.) Plants is accompanied with Changes in Metabolite Composition. *International Journal of Molecular Sciences*, *23*(16), 9047. https://doi.org/10.3390/ijms23169047

Guo, Q., Wang, Y., Zhang, H., Qu, G., Wang, T., Sun, Q., & Liang, D. (2017). Alleviation of adverse effects of drought stress on wheat seed germination using atmospheric dielectric barrier discharge plasma treatment. *Scientific Reports*, *7*(1), 16680. https://doi.org/10.1038/s41598-017-16944-8

Habib, M. A., Mannan, M. A., Karim, M. A., Mamun, M. A. A., Dola, D. B., Miah, M. Y., Miah, M. M. U., Ferdous, J., & Singh, H. P. (2022). Water deficit stress tolerance assessment in barley cultivars using drought tolerance indices. *Journal of Agriculture and Crops*, *8*(4), 228–235. https://doi.org/10.32861/jac.84.228.235

Hasanuzzaman, M., Mahmud, J. A., Anee, T. I., Nahar, K., & Islam, M. T. (2018). Drought Stress Tolerance in Wheat: Omics Approaches in Understanding and Enhancing Antioxidant Defense. In *Abiotic Stress-Mediated Sensing and Signaling in Plants: An Omics Perspective* (pp. 267–307). Springer. https://doi.org/10.1007/978-981-10-7479-0_10

Hasheminasab, K. S., Shahbazi, K., Marzi, M., Zare, A., Yeganeh, M., Bazargan, K., & Kharazmi, R. (2023). A study on wheat grain zinc, iron, copper, and manganese concentrations and their relationship with grain yield in major wheat production areas of Iran. *Journal of Agriculture and Food Research*, *14*, 100913. https://doi.org/10.1016/j.jafr.2023.100913

Hellal, F. A., El-Shabrawi, H. M., Abd El-Hady, M., Khatab, I. A., El-Sayed, S. A. A., & Abdelly, C. (2018). Influence of PEG induced drought stress on molecular and biochemical constituents and seedling growth of Egyptian barley cultivars. *Journal of Genetic Engineering and Biotechnology*, *16*(1), 203–212. https://doi.org/10.1016/j.jgeb.2017.10.009

Introduction to the ISTA Rules. (2023). *Rules Proposals for the International Rules for Seed Testing 2023 Edition*. https://www.seedtest.org/api/rm/35T6F556FRKANC7/ogm22-05-rules-proposals-for-ista-2023-edition-1.pdf

Irmes, K., Kristó, I., Szentpéteri, L., Rácz, A., Vályi-Nagy, M., Kassai, M. K., Valentinyi, K. V., & Tar, M. (2023). The Effect of Foliar Zinc Application on the Leaf Chlorophyll Concentrations and Grain Yields of the Winter Wheat (*Triticum aestivum* L.) in the Field Experiments of Two Seasons. *Agronomy*, *13*(6), 1640. https://doi.org/10.3390/agronomy13061640

Ivanov, D. I. (2021). The influence of the cultivar and foliar treatment with micronutrient preparations on the yield, economics and energy efficiency of grain production of spring soft wheat (*Triticum aestivum* L.). *Research on Crops*, *22*(3), 470–477. https://doi.org/10.31830/2348-7542.2021.093

Kenenbayev, S., Yessenbayeva, G., Zhanbyrbayev, Y., Bekturganov, A., Dutbayev, Y., & Toktay, H. (2023). Influence of Climate Conditions and Biofertilizers on Soybean Yield in Southeastern Kazakhstan. *International Journal of Design & Nature and Ecodynamics*, *18*(6), 1391–1398. https://doi.org/10.18280/ijdne.180612

Keyvan, S. (2010). The effects of drought stress on yield, relative water content, proline, soluble carbohydrates and hlorophyll of bread wheat cultivars. *Journal of Animal & Plant Sciences*, *8*(3), 1051–1060.

Kido, É. A., Ferreira-Neto, J. R. C., Pandolfi, V., de Melo Souza, A. C., & Benko-Iseppon, A. M. (2016). Drought Stress Tolerance in Plants: Insights from Transcriptomic Studies. In *Drought Stress Tolerance in Plants* (Vol. 2, pp. 153–185). Springer. https://doi.org/10.1007/978-3-319-32423-4_6

Kondratenko, E. P., & Soboleva, O. M. (2023). Features of the development of the primary roots of wheat seedlings after the removal of abiotic electromagnetic stress. *Journal of Global Innovations in Agricultural Sciences*, *11*(2), 127–133. https://doi.org/10.22194/jgias/23.1058

Lukács, A., Pártay, G., Németh, T., Csorba, S., & Farkas, C. (2008). Drought stress tolerance of two wheat genotypes. *Soil and Water Research*, *3*(10), S95–S104. https://doi.org/10.17221/10/2008-swr

Ma, D., Sun, D., Wang, C., Ding, H., Qin, H., Hou, J., Huang, X., Xie, Y., & Guo, T. (2017). Physiological Responses and Yield of Wheat Plants in Zinc-Mediated Alleviation of Drought Stress. *Frontiers in Plant Science*, *8*, 860. https://doi.org/10.3389/fpls.2017.00860

Mahdieh, M., Sangi, M. R., Bamdad, F., & Ghanem, A. (2018). Effect of seed and foliar application of nano-zinc oxide, zinc chelate, and zinc sulphate rates on yield and growth of pinto bean (*Phaseolus vulgaris*) cultivars. *Journal of Plant Nutrition*, *41*(18), 2401–2412. https://doi.org/10.1080/01904167.2018.1510517

Mahdy, R. E., & Farghali, K. A. (2021). Role of Zinc on Drought Tolerance in Some Wheat (*Triticum aestivum* L.) Cultivars under Reduced Soil Water. *Egyptian Journal of Agronomy*, *43*(3), 417–430. https://doi.org/10.21608/agro.2022.105221.1291

Mahpara, S., Zainab, A., Ullah, R., Kausar, S., Bilal, M., Latif, M. I., Arif, M., Akhtar, I., Al-Hashimi, A., Elshikh, M. S., Zivcak, M., & Zuan, A. T. K. (2022). The impact of PEG-induced drought stress on seed germination and seedling growth of different bread wheat (*Triticum aestivum* L.) genotypes. *PLOS ONE*, *17*(2), e0262937. https://doi.org/10.1371/journal.pone.0262937

Malakhov, D., Tskhay, M., Kalashnikov, A., Bekmukhamedov, N., Kalashnikov, P., & Baizakova, A. (2022). Features of Creating a System of Space Monitoring of Water-Supplied Territories for Irrigation in the South of Kazakhstan. *Journal of Ecological Engineering*, *23*(11), 202–216. https://doi.org/10.12911/22998993/153398

Malko, M. M., Khanzada, A., Wang, X., Samo, A., Li, Q., Jiang, D., & Cai, J. (2022). Chemical treatment refines drought tolerance in wheat and its implications in changing climate: A review. *Plant Stress*, *6*, 100118. https://doi.org/10.1016/j.stress.2022.100118

Mehrinfar, A. R., Rezaei Moradali, M., Mirmahmoody, T., Yazdan Seta, S., & Sharafi, S. (2023). The effect of foliar application of nutrients and humic acid on grain yield and quality of bread wheat cultivars under drought stress. *Environmental Stresses in Crop Sciences*, *16*(1), 1–18. https://doi.org/10.22077/escs.2022.4234.2000

Michel, B. E., & Kaufmann, M. R. (1973). The Osmotic Potential of Polyethylene Glycol 6000. *Plant Physiology*, *51*(5), 914–916. https://doi.org/10.1104/pp.51.5.914

Mohi-Ud-Din, M., Hossain, M. A., Rohman, M. M., Uddin, M. N., Haque, M. S., Ahmed, J. U., Hossain, A., Hassan, M. M., & Mostofa, M. G. (2021). Multivariate Analysis of Morpho-Physiological Traits Reveals Differential Drought Tolerance Potential of Bread Wheat Genotypes at the Seedling Stage. *Plants*, *10*(5), 879. https://doi.org/10.3390/plants10050879

Nawaz, F., Ashraf, M. Y., Ahmad, R., Waraich, E. A., & Shabbir, R. N. (2014). Selenium (Se) Regulates Seedling Growth in Wheat under Drought Stress. *Advances in Chemistry*, *2014*(1), 143567. https://doi.org/10.1155/2014/143567

Nezhadahmadi, A., Prodhan, Z. H., & Faruq, G. (2013). Drought Tolerance in Wheat. *The Scientific World Journal*, *2013*(1), 610721. https://doi.org/10.1155/2013/610721

Nile, S. H., Thiruvengadam, M., Wang, Y., Samynathan, R., Shariati, M. A., Rebezov, M., Nile, A., Sun, M., Venkidasamy, B., Xiao, J., & Kai, G. (2022). Nano-priming as emerging seed priming technology for sustainable agriculture recent developments and future perspectives. *Journal of Nanobiotechnology*, *20*(1), 254. https://doi.org/10.1186/s12951-022-01423-8

Nisa, W., Nisa, V., Nagoo, S. A., & Dar, Z. A. (2019). Drought tolerance mechanism in wheat: A review. *The Pharma Innovation Journal*, *8*(2), 714–724.

Pessarkli, M. (1999). *Handbook of plant and crop stress* (2nd Ed.). Marcel Dekker Inc.

Raeisi Sadati, S. Y., Jahanbakhsh Godehkahriz, S., Ebadi, A., & Sedghi, M. (2022). Zinc oxide nanoparticles enhance drought tolerance in wheat via physio-biochemical changes and stress genes expression. *Iranian Journal of Biotechnology*, *20*(1), 12–24. https://doi.org/10.30498/ijb.2021.280711.3027

Rai-Kalal, P., & Jajoo, A. (2021). Priming with zinc oxide nanoparticles improve germination and photosynthetic performance in wheat. *Plant Physiology and Biochemistry*, *160*, 341–351. https://doi.org/10.1016/j.plaphy.2021.01.032

Rakszegi, M., Lovegrove, A., Balla, K., Láng, L., Bedő, Z., Veisz, O., & Shewry, P. R. (2014). Effect of heat and drought stress on the structure and composition of arabinoxylan and β-glucan in wheat grain. *Carbohydrate Polymers*, *102*, 557–565. https://doi.org/10.1016/j.carbpol.2013.12.005

Rehman, H. U., Tariq, A., Ashraf, I., Ahmed, M., Muscolo, A., Basra, S. M. A., & Reynolds, M. (2021). Evaluation of Physiological and Morphological Traits for Improving Spring Wheat Adaptation to Terminal Heat Stress. *Plants*, *10*(3), 455. https://doi.org/10.3390/plants10030455

Reynolds, M., & Tuberosa, R. (2008). Translational research impacting on crop productivity in drought-prone environments. *Current Opinion in Plant Biology*, *11*(2), 171–179. https://doi.org/10.1016/j.pbi.2008.02.005

Rukhsar-Ul-Haq, Kausar, A., Hussain, S., Javed, T., Zafar, S., Anwar, S., Hussain, S., Zahra, N., & Saqib, M. (2023). Zinc oxide nanoparticles as potential hallmarks for enhancing drought stress tolerance in wheat seedlings. *Plant Physiology and Biochemistry*, *195*, 341–350. https://doi.org/10.1016/j.plaphy.2023.01.014

Sallam, A., Mourad, A. M. I., Hussain, W., & Stephen Baenziger, P. (2018). Genetic variation in drought tolerance at seedling stage and grain yield in low rainfall environments in wheat (*Triticum aestivum* L.). *Euphytica*, *214*(9), 169. https://doi.org/10.1007/s10681-018-2245-9

Samreen, T., Humaira, Shah, H. U., Ullah, S., & Javid, M. (2017). Zinc effect on growth rate, chlorophyll, protein and mineral contents of hydroponically grown mungbeans plant (Vigna radiata). *Arabian Journal of Chemistry*, *10*, S1802–S1807. https://doi.org/10.1016/j.arabjc.2013.07.005

Shaffique, S., Imran, M., Kang, S.-M., Khan, M. A., Asaf, S., Kim, W.-C., & Lee, I.-J. (2023). Seed Bio-priming of wheat with a novel bacterial strain to modulate drought stress in Daegu, South Korea. *Frontiers in Plant Science*, *14*, 1118941. https://doi.org/10.3389/fpls.2023.1118941

Shaimerdenova, A., Agapitova, L. G., Bobrova, A. V., Akhmetov, Y., Sinyukov, V. A., Sharonin, P. N., Dobrovolsky, A. G., Ryakhovsky, D. I., Krasnovskiy, E. E., & Ten, A. D. (2023). Development of optimal crop production model considering existing natural-climatic risks increasing crop yields. *SABRAO Journal of Breeding and Genetics*, *55*(3), 778–795. https://doi.org/10.54910/sabrao2023.55.3.15

Silva Folli-Pereira, M., Ramos, A. C., Canton, G. C., Conceição, J. M., Souza, S. B., Cogo, A. J. D., Figueira, F. F., Eutrópio, F. J., & Rasool, N. (2016). Foliar application of trace elements in alleviating drought stress. In *Water stress and Ccrop plants: A sustainable approach* (pp. 669–681). John Wiley & Sons. https://doi.org/10.1002/9781119054450.ch38

Taran, N., Storozhenko, V., Svietlova, N., Batsmanova, L., Shvartau, V., & Kovalenko, M. (2017). Effect of Zinc and Copper Nanoparticles on Drought Resistance of Wheat Seedlings. *Nanoscale Research Letters*, *12*(1), 1–6. https://doi.org/10.1186/s11671-017-1839-9

Umair Hassan, M., Aamer, M., Umer Chattha, M., Haiying, T., Shahzad, B., Barbanti, L., Nawaz, M., Rasheed, A., Afzal, A., Liu, Y., & Guoqin, H. (2020). The Critical Role of Zinc in Plants Facing the Drought Stress. *Agriculture*, *10*(9), 396. https://doi.org/10.3390/agriculture10090396

Wu, S., Hu, C., Tan, Q., Nie, Z., & Sun, X. (2014). Effects of molybdenum on water utilization, antioxidative defense system and osmotic-adjustment ability in winter wheat (*Triticum aestivum*) under drought stress. *Plant Physiology and Biochemistry*, *83*, 365–374. https://doi.org/10.1016/j.plaphy.2014.08.022

Yahyaoui, A., Djebar, M. R., Khene, L., Bouarroudj, T., Kahli, H., & Bourayou, C. (2017). Assessment of exposure wheat *Triticum aestivum* L. To Zinc Oxide Nanoparticles (ZNO): Evaluation of oxidative damage. *Studia Universitatis Vasile Goldis Arad, Seria Stiintele Vietii*, *27*(4), 271–280.

Zeng, D., & Luo, X. (2012). Physiological Effects of Chitosan Coating on Wheat Growth and Activities of Protective Enzyme with Drought Tolerance. *Open Journal of Soil Science*, *02*(03), 282–288. https://doi.org/10.4236/ojss.2012.23034

Zhao, Q., Ma, Y., Huang, X., Song, L., Li, N., Qiao, M., Li, T., Hai, D., & Cheng, Y. (2023). GABA Application Enhances Drought Stress Tolerance in Wheat Seedlings (*Triticum aestivum* L.). *Plants*, *12*(13), 2495. https://doi.org/10.3390/plants12132495

Zhu, J., Zou, Z., Shen, Y., Li, J., Shi, S., Han, S., & Zhan, X. (2019). Increased ZnO nanoparticle toxicity to wheat upon co-exposure to phenanthrene. *Environmental Pollution*, *247*, 108–117. https://doi.org/10.1016/j.envpol.2019.01.046

Zulkiffal, M., Ahsan, A., Ahmed, J., Musa, M., Kanwal, A., Saleem, M., Anwar, J., Ur Rehman, A., Ajmal, S., Gulnaz, S., & Makky Javaid, M. (2021). Heat and Drought Stresses in Wheat (*Triticum aestivum* L.): Substantial Yield Losses, Practical Achievements, Improvement Approaches, and Adaptive Mechanisms. In *Plant Stress Physiology*. IntechOpen. https://doi.org/10.5772/intechopen.92378