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RESEARCH PAPER

Effect of Bulk Zinc and Nano Zinc on the Mineral Elements Content of Barley Plant under Salt Stress

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ABSTRACT

A field experiment was conducted on 8/11/2023 in one of the agricultural nurseries in Al-Salihiyah district, affiliated with Al-Shamiyah district/Al-Qadisiyah governorate, during the winter agricultural season (2023-2024) with the aim of studying the effect of bulk and nano zinc on some growth characteristics of the crop and the chemical content of barley plants under the influence of salt stress. Characterization of XRD and SEM were done in this work,. The experiment was designed according to a Randomized Complete Block Design (RCBD) with a factorial organization for a factorial experiment with three factors; the first factor included three concentrations of bulk zinc (0, 1 and 2 g L^{-1}), while the second factor included three concentrations of nano zinc (0, 1 and 2 mg L^{-1}), and the third factor included three levels of salt stress (0, 6 and 8 g NaCl L^{-1}) with three replications for each treatment. All combinations of the three factor treatments were distributed randomly within each block, including the entire experiment of 81 experimental units. The results were as follows: The significant effect of bulk zinc at a concentration of 1 g L^{-1} in recording the highest means nitrogen content of grains (1.75%), phosphorus content of grains (0.35%), zinc content of grains (27.64 µg g^{-1}). The significant effect of nano zinc at a concentration of 1 mg L^{-1} in recording the highest means of grain content of nitrogen (1.75%), grain content of phosphorus (0.36%), grain content of zinc (26.47 µg g^{-1}). The significant role of salt stress at a concentration of 8 g NaCl L^{-1} achieved the highest means grain nitrogen content (1.83%), grain phosphorus content (0.36%). The significant interaction between bulk zinc and nano zinc (AB) in combination (1 g L^{-1} bulk zinc × 1 mg L^{-1} nano zinc) achieved the highest means for grain phosphorus content (0.37%), grain zinc content (34.54 µg g^{-1}), While the double interaction in combination (1 g L^{-1} bulk zinc × 2 mg L^{-1} nano zinc) achieved the highest means for grain nitrogen content (1.89%).

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INTRODUCTION

Barley (Hordeum vulgare L.) is the fourth most important cereal crop in the world in terms of total production and consumption after wheat, rice, and maize [1]. About two-thirds of the global barley crop is used for animal feed, the remaining third is used for brewing and distilling. Besides, barley is an energy source in the human diet in many parts of the world. Barley is also considered one of the important grain crops in Iraq, as it is used mainly in most countries of the world as a fodder crop, either in the form of green fodder or as grains in a mixture of concentrated rations. It is also used in the manufacture of malt, in addition

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to many medical uses as a laxative, softener, and food for diabetics, and is used in the manufacture of vinegar. Yeast is characterized by its rapid growth, resistance to salinity, and tolerance to drought. Therefore, its cultivation can succeed in most regions of Iraq [2].

Barley is the most salt-tolerant of the cereal crops and is grown in a wide range of regions in the world, and is therefore an excellent model for studies of plant response to salinity stress [3]. Although it is one of the most salt-tolerant plants compared to other cereals, its growth and yield decrease under high-salt conditions in many parts of the world [4]. Salt tolerance in barley varies according to its growth stages and genotypes [5, 6]. The germination stage is one of the most sensitive stages to salinity stress in barley, as the salt tolerance of barley increases with increasing age [7].

Various environmental stresses cause negative effects on plant growth and development, which ultimately leads to reduced production and yields in crops. Salinity is considered one of the most destructive environmental stresses. Moreover, areas of saline soils are increasing in the world as a result of irrigation with poor and polluted water and low rainfall [8]. Salinity stress reduces agricultural yields by reducing seed germination and limiting plant growth and development [9]. Studies have shown that salinity stress reduces plant growth by inducing water and oxidative stresses, ion toxicity, reducing absorption of essential minerals, and nutritional imbalances [10, 11].

Micronutrients are important in agricultural production in terms of both quantity and quality and human health. Many studies indicate that there are more than 3 billion people in the world who suffer from a deficiency of micronutrients, especially zinc and iron, and that enrichment by adding supplements or salts is not the best way to solve the problem, especially in poor countries. Biofortification is a method that has been adopted, which includes, in one of its methods, adding these nutrients as fertilizers. It is known that natural micronutrients are mainly specific to plant growth and the quality of the product from a nutritional standpoint, despite the small quantities that crops need in comparison to macronutrients. Despite the availability of various mineral and chelated fertilizer sources (synthetic and natural-organic for these nutrients and the availability of different application methods) in addition to the soil and adding it sprayed on the leaves or both together (the efficiency of using these fertilizers does not exceed 5% of the additive. There is a recent trend To build micronutrient fertilizers manufactured using nanotechnology, which will hopefully solve part of the problem [12].

Farmers in salt-affected areas seek to find solutions to alleviate salt stress and increase crop production. Hence, the importance of nanofertilizers has emerged, which has been proven effective and effective in reducing salt stress. Nanoparticles (NPs) have gained more consideration in various applications. Due to its unique large surface area and physicochemical properties, it has been applied in many fields, including agriculture [13]. The use of nano-form of fertilizers may be a potential solution to control soil pollution, reduce agricultural productivity [14], and reduce abiotic stresses in plants [15]. The use of nanofertilizers in a foliar system has been identified as suitable for field use because it feeds plants gradually and in a more controlled condition than salt fertilisers, along with controlling the toxicity that may be caused by the soil after amending it with the same nutrients [16]. The research aims include: Know the effect of both nano- and bulk zinc fertilizer in reducing the effect of salinity on barley plants through

- Studying the response of barley plants to treatment with salinity and its effect on mineral elements content.

MATERIALS AND METHODS

Experiment site

A field experiment was carried out on 11/8/2023 in one of the agricultural nurseries in Al-Salahiya district of Al-Shamiya district, Al-Qadisiyah governorate, during the winter agricultural season (2023-2024) with the aim of studying the effect of bulk and nano-zinc on some yield growth characteristics and the chemical content of barley plants under the influence of salt stress. Soil samples were taken before planting and analyzed to reveal their physical and chemical characteristics in the U Science laboratory in the city of Diwaniyah, as shown in Table 1.

Experiment factors

The experiment included three factors. The first included three concentrations of bulk zinc (0, 1, and 2 gm L^{-1}) sprayed on the plant, and three concentrations of nano-zinc (0, 1, and 2 gm L^{-1}) by foliar spraying on the plant's vegetative system. The experiment also included stress. Saline solution at three concentrations (0, 6, and 8 g/L).

Scanning Electron Microscopy

Samples were investigated by Nova Nano FE-SEM 450 (FEI) Scanning Electron Microscope (SEM) to obtain topological, morphological and compositional information. Lens mounted DBS and LVD offer best selection of information and image optimization. Beam landing energy cam go down from 30 KeV to 50ev and resolution of 1.4 nm at 1 kV (TLD-SE) and 1 nm at 15 kV (TLD-SE). The entire sample was coated with gold before SEM analysis. Energy Dispersive X-ray spectroscopy (EDS) were also recorded in the SEM analysis (Fig. 1).

X- ray diffraction (XRD) analysis

XRD patterns were recorded on Philips PW 3050/10 model. The sample was recorded on a Philips X-Pert MMP diffractometer. The diffractometer was controlled and operated by a PC computer with the programs P Rofit and used a MoK (source with wavelength0.70930 A°, operating with Mo-tube radiation at 50 kV and 40 mA (Fig. 2).

Experiment design

The experiment was designed according to a Randomized Complete Block Design (RCBD) with a factorial organization for a factorial experiment with three factors. The first factor included three concentrations of regular zinc that represented the main panels, while the second factor included three concentrations of nano-zinc and three levels

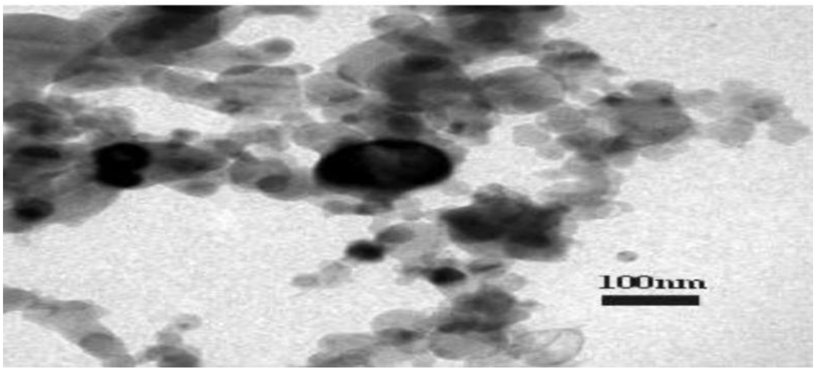

Fig. 1. SEM images of Zinc Nanoparticles.

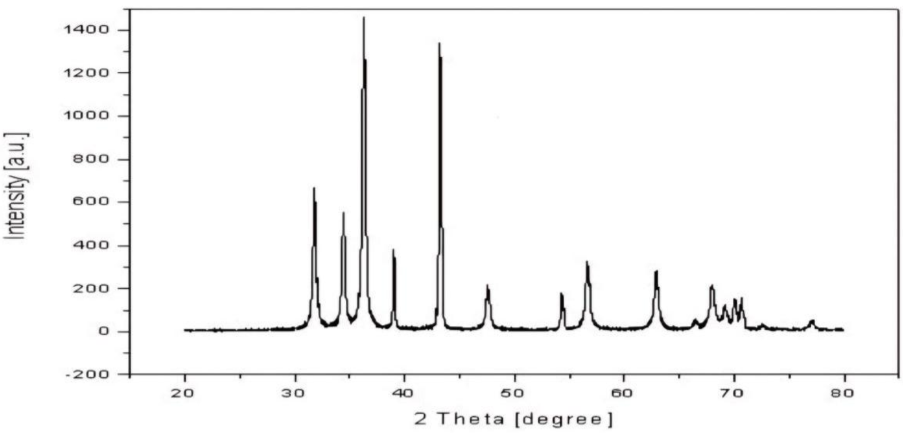

Fig. 2. XRD Spectra of zinc nanoparticles.

of salt stress that represented the secondary panels (Sub plot), with three repetitions for each treatment, and all combinations of the three factor treatments were distributed randomly within each. Sector, including the entire experiment, 81 experimental units.

Agricultural operations and experiment implementation

The experimental land was plowed using a rotary plow after carrying out the watering process. It was then smoothed using disc harrows and then leveled using a leveling machine. It was divided according to the design used into 81 experimental units (plates), each of which had an area of 4 m^2 (2 m × 2 m), and 1 m^2 was left between one experimental unit and another, as well as between one sector and another, to avoid overlapping of transactions. In addition, one experimental unit included ten agricultural lines in preparation for planting barley structures using the line method The seeds of the barley crop (Samir variety) were planted using the lines method and were covered with soil using hand rakes on 11/15/2022, at an amount of 100 kg ha^{-1} [17], and then the germination rate was given immediately after the completion of the planting process and with complete control. On the water stream to avoid seed drift, other irrigations were given according to field need, while the barley plant was treated with different concentrations of bulk and nano zinc after it reached the 4-leaf stage, and the same was true of salt stress.

The fertilization process was carried out according to the addition of triple superphosphate fertilizer as a source of phosphorus in one batch at planting at a rate of 80 kg P ha^{-1}, and the addition of urea fertilizer (46% N as a source of nitrogen at a rate of 200 kg N ha^{-1} and in four equal amounts, the first was done at the Emergence, the second at the branching stage, the third at the elongation stage, and the fourth at the budding stage, while potassium sulphate fertilizer (K 42%) was added as a source of potassium at a rate of 60 kg K ha^{-1} in two equal batches, the first after emergence and the second at the branching stage [18].

Mineral Contents of Seeds

The plant samples of the grains were digested according to the method of [19] by weighing 0.2 g of the ground dry matter and placing it in a 100 ml glass digestion flask to which 5 ml of concentrated sulfuric acid H_2SO_4 and 1 ml of perchloric acid HCLO4 were added as a catalyst. The flask was placed on a hot plate and the temperature was gradually increased (until the solution became clear), then the flask was cooled and the volume was completed to 50 ml by adding distilled water. The elements were then determined according to the following methods.

Nitrogen Percentage in Seeds

The nitrogen percentage of the digested samples was measured according to the method

Table 1. physical and chemical characteristics.

The values	The units	The properties
7.61	-	The degree of soil reaction PH
5.77	Ds/m	Electrical conductivity EC
16.8		Nitrogen
52.6		Phosphorus
242.78		Potassium
693.70		Sodium
416		Calcium
185.44	Mg/Kg	magnesium
24.887		Iron
120.04		Manganese
2.685		Zinc
1.19	g/cm^3	Bulk density
	Soil separators	
73.75		Sand
6.09	%	Clay
20.14		Silt
Sandy loam		Soil texture

of [20] using a Microkjeldhal distillation apparatus.

Percentage in Seeds Phosphorus

After digestion of the samples, phosphorus was estimated according to the method of [19] using ammonium molybdate and ascorbic acid using a spectrophotometer at a wavelength of 882 nm.

Determination of zinc content of grains (μg g^{-1})

The zinc element of the digested samples was determined using an atomic absorption spectrometer at a wavelength of (213.9) nanometers, and it was calibrated with a standard solution of zinc, according to [21].

RESULTS AND DISCUSSION

Nitrogen content of grains (%)

The results presented in Table 2 showed the effect of bulk and nano-zinc on the average grain nitrogen content (%) of barley plants under the influence of salt stress. The average nitrogen content of grains increased significantly ($p \leq 0.05$) with the effect of treatment with bulk zinc from 1.68. % when compared to the control treatment (0 gm L^{-1}) to 1.75% when treated with a concentration of 1 gm L^{-1}, compared to a significant decrease in the nitrogen content of grains to 1.63% at the highest concentration of bulk zinc (2 gm L^{-1}). As for the treatment with nano-zinc, it had a significant effect ($p \leq 0.05$), as it recorded at the lower concentration (1 mg L^{-1}) the highest significant average for the nitrogen content of grains, amounting to 1.75%, compared to what was recorded at the highest concentration (2 mg L^{-1}) of The average nitrogen content of grains was 1.67%, as compared to what was recorded by the comparison treatment, which had a significantly lower average for the trait, 1.63%. The significant double interaction between bulk zinc and nano zinc achieved with its combination of (1 g L^{-1} bulk zinc × 2 mg L^{-1} nano zinc) the highest significant mean of grain nitrogen content of 1.89% compared to all other combinations including the comparison combination with a content of 1.72%.

The significant double interaction between bulk zinc and salt stress increased significantly ($p \leq 0.05$) the grain nitrogen content, as the combinations (0 g L^{-1} bulk zinc × 8 g NaCl L^{-1}) and (1 g L^{-1} bulk zinc × 6 g NaCl L^{-1}) recorded the highest mean of the trait in each of them, reaching 2.02% compared to 1.53% for the comparison combination.

The significant double interaction between nano zinc and salt stress significantly increased ($p \leq 0.05$) the grain nitrogen content in all combinations

Table 2. Effect of bulk and nano zinc on the average nitrogen content of barley grains (%) under the influence of salt stress.

Interaction between regular zinc and nano zinc (AB	Salt stress (g NaCl L^{-1}) C			Nano zinc (mg. L^{-1}) B	Bulk zinc (g.L^{-1}) A
	8	6	0		
1.72	2.07	1.58	1.51	0	
1.74	2.27	1.45	1.50	1	0
1.58	1.72	1.43	1.58	2	
1.60	1.58	1.72	1.51	0	
1.76	1.70	2.05	1.52	1	1
1.89	1.79	2.30	1.57	2	
1.57	1.86	1.79	1.07	0	
1.77	1.79	1.86	1.65	1	2
1.55	1.72	1.77	1.17	2	
	1.83	1.77	1.45	Average effect of salt stress (C)	
Interaction between regular zinc and salt stress (AC)					
Average effect of bulk zinc)A(	Salt stress (g NaCl L^{-1}) C			Bulk zinc (g.L^{-1})	
	8	6	0		
1.68	2.02	1.49	1.53	0	
1.75	1.69	2.02	1.53	1	
1.63	1.79	1.81	1.30	2	
Interaction between nanozinc and salt stress (BC)					
Average effect of nano-zinc)B(	Salt stress (g NaCl L^{-1}) C			Nano zinc (mg. L^{-1})	
	8	6	0		
1.63	1.84	1.70	1.36	0	
1.75	1.92	1.79	1.56	1	
1.67	1.74	1.83	1.44	2	
LSD $_{(P \leq 0.05)}$:A 0.006 = B 0.006 = C 0.006 = AB 0.011 = AC 0.011 = BC 0.011 = ABC0.018 =					

compared to the control combination with the least significant mean for the trait (1.36%), as the combination (1 mg L^{-1} nano zinc × 8 g NaCl L^{-1}) recorded the highest significant mean for the trait, reaching 1.92% compared to all other combinations of the interaction. The significant triple interaction between bulk zinc, nano zinc and salt stress achieved, with its combination (1 g L^{-1} bulk zinc × 2 mg L^{-1} nano zinc × 6 g NaCl L^{-1}), the highest significant mean for the grain nitrogen content, reaching 2.30%, with a significant difference with all the triple interaction combinations recorded in Table 2.

Grain Phosphorus Content (%)

The results in Table 3 show the effect of bulk and nano zinc on the average grain phosphorus content of barley plants under salt stress, as the treatment with a concentration of 1 g L^{-1} of bulk zinc achieved the highest average grain phosphorus content of 0.35% compared to the treatment with a concentration of 2 g L^{-1} of bulk zinc, which was equal to the control treatment, reaching 0.34%. As is the case with bulk zinc, the treatment with nano zinc significantly increased ($p \leq 0.05$) the grain phosphorus content of barley plants, as the average of the trait increased significantly from 0.33% in the control treatment (0 g L^{-1}) to 0.36 and 0.34% in the treatment with concentrations of 1 and 2 g L^{-1}, respectively, with a significant difference between them.

On the other hand, the treatment with salt stress at the highest concentration (8 g NaCl L^{-1}) was equal to the treatment without it (the comparison treatment) in effect, as they recorded the same average of the grain phosphorus content of 0.36% compared to a significant decrease to 0.30% in plants stressed with 6 g NaCl L^{-1}. The significant double interaction between bulk zinc and nano zinc produced plants with a significantly higher grain phosphorus content than in the comparison plants (0.36%), as it reached 0.37% in the plants of the combination consisting of (1 g L^{-1} bulk zinc × 1 mg L^{-1} nano zinc).

The significant two-way interaction between bulk zinc and salt stress produced plants with high grain phosphorus content of 0.40% by both combinations (1 g L^{-1} × 0 g NaCl L^{-1}) and (1 g L^{-1} × 8 g NaCl L^{-1}) compared to 0.31% for the control combination plants. As for the significant two-way interaction between nano zinc and salt stress, the combination (1 mg L^{-1} × 8 g NaCl L^{-1}) achieved the highest significant mean grain phosphorus content of 0.42% compared to 0.33% for the control combination plants. The triple significant interaction between bulk zinc, nano zinc and salt

Table 3. Effect of bulk and nano zinc on the average grain phosphorus content (%) of barley plants under the influence of salt stress.

Interaction between regular zinc and nano zinc (AB	Salt stress (g NaCl L^{-1}) C			Nano zinc (mg. L^{-1}) B	Bulk zinc (mg. L^{-1}) B
	8	6	0		
0.36	0.43	0.35	0.29	0	
0.35	0.41	0.29	0.35	1	0
0.32	0.31	0.34	0.30	2	
0.32	0.35	0.25	0.37	0	
0.37	0.47	0.23	0.40	1	1
0.36	0.39	0.25	0.44	2	
0.31	0.30	0.29	0.33	0	
0.36	0.38	0.35	0.34	1	2
0.34	0.21	0.39	0.43	2	
	0.36	0.30	0.36	Average effect of salt stress (C)	
Interaction between regular zinc and salt stress (AC)					
Average effect of bulk zinc (A)	Salt stress (g NaCl L^{-1}) C			Bulk zinc (g.L^{-1})	
	8	6	0		
0.34	0.38	0.33	0.31	0	
0.35	0.40	0.24	0.40	1	
0.34	0.30	0.34	0.37	2	
Interaction between nanozinc and salt stress (BC)					
Average effect of nano-zinc (B)	Salt stress (g NaCl L^{-1}) C			Nano zinc (mg. L^{-1})	
	8	6	0		
0.33	0.36	0.30	0.33	0	
0.36	0.42	0.29	0.36	1	
0.34	0.30	0.33	0.39	2	
LSD $_{(P \leq 0.05)}$:A 0.0002 = B 0.0002 = C 0.0002 = AB 0.0003 = AC 0.0003 = BC 0.0003 = ABC0.0006 =					

stress showed, in its combination of (1 g L^{-1} bulk zinc × 1 mg L^{-1} nano zinc × 8 g NaCl L^{-1}), the highest significant average of grain phosphorus content, reaching 0.47%, with a significant superiority over the averages of grain phosphorus content recorded by the triple interaction combinations, including the comparison combination with an average of 0.29%.

Zinc content of grains (µg g^{-1})

The results of Table 4 showed a significant effect ($p \leq 0.05$) on the zinc content of grains, as the average zinc content of grains increased under the effect of bulk zinc from 23.17 µg g^{-1} for the control plants to 27.64 µg g^{-1} under the effect of the treatment with 1 g L^{-1}, while the zinc content of grains decreased significantly under the effect of the treatment with 2 g L^{-1} to 19.79 µg g^{-1}. The treatment with nano zinc also achieved a significant superiority in the zinc content of grains, as the zinc content of grains increased significantly from 23.87 µg g^{-1} in the control plants to 26.47 µg g^{-1} with the effect of the treatment with a concentration of 1 mg L^{-1}, in addition to a significant decrease in the zinc content of grains to 20.27 µg g^{-1} with the effect of the treatment with 2 mg L^{-1}. As for salt stress, its significant effect was negative on the average zinc content of grains, as it decreased from 27.17 µg g^{-1} in the control plants to 21.63 and 21.80 µg g^{-1} in the plants stressed with salt at 6 and 8 g NaCl L^{-1}, respectively, with a clear significant difference between them and the control plants.

The significant two-way interaction between bulk zinc and nano zinc produced in its combination (1 g L^{-1} × 1 mg L^{-1}) the highest significant mean of zinc content in grains, reaching 34.54 µg g^{-1} compared to 23.46 µg g^{-1} for the control combination plants (0 g L^{-1} × 0 mg L^{-1}) and the rest of the other combinations, with a significant difference between them. The significant two-way interaction between bulk zinc and salt stress increased significantly ($p \leq 0.05$) the zinc content in grains, as the combination (1 g L^{-1} × 0 g NaCl L^{-1}) achieved the highest significant mean of zinc content in grains, reaching 34.05 µg g^{-1} compared to the averages achieved by all other combinations for the trait, including the control combination with an average of 26.75 µg g^{-1}. As for the significant double interaction between nano zinc and salt stress, the combination (1 mg L^{-1} × 0 g NaCl L^{-1}) recorded the highest significant mean for the grain zinc content, reaching 33.53 µg g^{-1}, compared to the averages achieved by all

Table 4. Effect of bulk and nano zinc on the average zinc content of grains (micrograms g-1) of barley plants under the influence of salt stress.

Interaction between regular zinc and nano zinc (AB)	Salt stress (g NaCl L^{-1}) C			Nano zinc (mg. L^{-1}) B	Bulk zinc (mg. L^{-1}) B
	8	6	0		
23.46	17.92	18.51	33.95	0	
26.44	19.88	31.67	27.78	1	0
19.60	25.47	14.82	18.51	2	
26.31	21.33	26.02	31.57	0	
34.54	33.43	20.54	49.66	1	1
22.08	18.75	26.57	20.92	2	
21.84	21.13	21.23	23.16	0	
18.42	18.44	13.65	23.16	1	2
19.13	19.88	21.68	15.82	2	
	21.80	21.63	27.17	Average effect of salt stress (C)	
Interaction between regular zinc and salt stress (AC)					
Average effect of bulk zinc (A)	Salt stress (g NaCl L^{-1}) C			Bulk zinc (g.L^{-1})	
	8	6	0		
23.17	21.09	21.67	26.75	0	
27.64	24.50	24.38	34.05	1	
19.79	19.82	18.85	20.71	2	
Interaction between nanozinc and salt stress (BC)					
Average effect of nano-zinc (B)	Salt stress (g NaCl L^{-1}) C			Nano zinc (mg. L^{-1})	
	8	6	0		
23.87	20.13	21.92	29.56	0	
26.47	23.92	21.95	33.53	1	
20.27	21.37	21.02	18.42	2	
LSD $_{(P \leq 0.05)}$:A 0.06 = B 0.06 = C 0.06 = AB 0.11 = AC 0.11 = BC 0.11 = ABC0.19 =					

other combinations for the trait, including the comparison combination with an average of 29.56 µg g^{-1}. As for the significant triple interaction between the study factors, the plants treated with the combination of bulk zinc (1 g L^{-1}) with nano zinc (1 mg L^{-1}) without salt stress (0 g NaCl L^{-1}) recorded the highest significant mean for the grain zinc content, reaching 49.66 µg g^{-1}, with a significant superiority over the averages achieved by the other combinations of the triple interaction for the grain zinc content, including the comparison combination, which recorded 33.95 µg g^{-1}.

Zinc is an important micronutrient for plants, plays a vital role in many physiological and metabolic processes, and is involved in enzyme activation, protein synthesis, and regulation of plant growth hormones [22]. Zinc plays a key role not only in plant growth and development, but also helps plants increase yield quality. Zinc biofortification strategies, especially foliar application of zinc, can help farmers harvest higher grain yields with enhanced zinc content. This will later help in saturating Hidden hunger or zinc deficiency in humans. In this context, it is very important to understand how zinc is absorbed into different tissues, especially leaves, where it is remobilized and distributed to the grains, and the genetic makeup of varieties likely enables some plants to absorb more zinc content than others. Likewise, the timing of Zn application to barley plants also plays a role in increasing Zn accumulation in leaves and grains [23].

In this study, foliar application of zinc and its subsequent uptake and transport in grains were studied, based on the efficiency of zinc uptake by foliar spray, and other possible reasons could be protection from superoxidative radicals in the soil, improvement of zinc uptake by the plant, and differential utilization. It was reported [24]. Other reasons for these plant differences could be due to soil conditions and the environment where the plants were grown [25]. The greater zinc efficiency in some plants may be the result of a different genetic makeup, which may lead to increased zinc uptake, utilization, and transport [26,27] reported that nicotinamide efflux transporter genes (ENA1 and ENA2) played a critical role in Zn uptake and transport in plants, determining the efficiency of plant transport, and they reported that efficient transport of Zn and Fe in grains was supported by increased levels of DMA (de-oxymugeinic acid) and NA (Nicotinamide).

[28] and [29] showed that the concentration of zinc in grains increased significantly by foliar treatment with zinc, as was the case in this study, as [30] reported an increase in the concentration of zinc in grains of up to 28% during the first growing season and 89% during the second growing season with foliar spraying of zinc. Our results are consistent with those of [30\ who also found an increase of about 83% in grain yield with foliar zinc application at the grain formation stage.

The results indicated that foliar spraying of barley plants with zinc led to an increase in the nitrogen and phosphorus content of grains through several physiological mechanisms, including:

1. Zinc Absorption and Translocation: Zinc is absorbed directly through the leaf surface when sprayed on the leaves, then transported to the bark and transferred to the developing grains. This process improves the components of the crop by increasing the activity of photosynthetic enzymes [31].

2. Zinc and nitrogen metabolism: Foliar spraying with zinc oxide nanoparticles was found to significantly increase the activity of nitrate reductase and glutamine synthetase in the leaves. These enzymes play a fundamental role in nitrogen metabolism. The increased enzyme activity increases the nitrogen content in both leaves and grains [32].

Zinc and phosphorus interaction: While there is no direct evidence from scientific sources about the effect of zinc spraying on the phosphorus content of barley grains, it is known that zinc plays an important role in the phosphorus metabolism process in plants, as zinc is a component of many enzymes involved in the synthesis and decomposition of carbohydrates, which affects energy metabolism and phosphorus utilization [33]. Since zinc foliar application is a technology used in agriculture to enhance the nutrient content of crops, including barley, and involves applying zinc solution directly to the leaves of the plant, this method has been found to have significant effects on the nutrient content of barley grains, including zinc. Zinc foliar application has been shown to significantly improve the zinc concentration in grains [34-36]. [35] found that applying zinc fertilizer as a foliar application increased the zinc concentration in grains by 29% compared to the control treatment. Another study showed that foliar application of zinc significantly increased the zinc content in grains [36].

CONCLUSION

This study demonstrated the efficacy of foliar-applied bulk and nano-zinc fertilizers in mitigating salinity stress and enhancing nutrient content in barley grains. The results indicate that moderate concentrations of both bulk zinc (1 g L^{-1}) and nano-zinc (1 mg L^{-1}) significantly improved nitrogen, phosphorus, and zinc accumulation in grains, with the highest nutritional enhancement observed under controlled salt stress conditions. Notably, the triple interaction of bulk zinc, nano-zinc, and salinity yielded the most pronounced effect on grain micronutrient enrichment, especially in zinc biofortification. These findings reinforce the potential of nano-enabled fertilization strategies as a sustainable solution for improving crop resilience and nutritional value under abiotic stress, particularly in salt-affected soils. The enhanced uptake and translocation mechanisms associated with nano-zinc application highlight its promise in precision agriculture. Moreover, zinc biofortification through foliar application offers a practical pathway to address micronutrient deficiencies in human populations, supporting food security efforts in regions burdened by soil salinity.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript.

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