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Interactive Effects of K-Humate, Proline and Si and Zn Nanoparticles in Improving Salt Tolerance of Wheat in Arid Degraded Soils

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Abstract

Silicon (Si) and zinc (Zn) nanoparticles (NPs) and foliar application of proline have been used in alleviating salt stress and enhancing wheat productivity, but the effectiveness of these materials may be enhanced when supplying the sandy degraded soil with organic amendments, e. g., potassium humate (KH). The response of wheat to spraying with a mixture of proline and NPs of Si and Zn in the presence of soil additions of KH needs further clarification, especially in low fertile sandy soils. A split-plot design with three replicates was used to carry out a two-season field experiment in a sandy saline soil (11 dS m^{-1}). The K-humate doses (0, 10, and 20 kg ha^{-1}) were placed in the main plots, while the foliar spraying of proline and NPs were placed in the subplots. The foliar spraying treatments were: water, proline, Si NPs, Zn NPs, Si + Zn NPs, and proline + Si + Zn NPs. The obtained results showed that the soil organic matter (SOM) significantly increased by 13% when K-humate was added at the dose of 20 kg ha^{-1}. The addition of 20 kg ha^{-1} of K-humate improved the soil's available N, P, and K by 38, 67, and 21% and enhanced the uptake of these nutrients by 6, 13, and 12%, compared to the non-amended soil. Wheat grain, straw, and biological yield increased by 26, 45, and 38%, respectively, when the K-humate increased from 0 to 20 kg ha^{-1}. The grain, straw, and biological yield increased by 21, 26, and 24%, respectively, as a result of foliar spraying of proline + Si + Zn NPs. The addition of K-humate (20 kg ha^{-1}) enhanced the leaf chlorophyll and boosted the K^+/Na^+ ratio by 36%, compared to the control. Chlorophyll and proline levels in wheat leaves were markedly raised by foliar application of proline and Si and Zn NPs. The soil application of K-humate and the exogenous application of proline improved the effectiveness of Si and Zn NPs in minimizing the adverse effects of salt stress. It is not recommended to only apply silicon and zinc nanoparticles via foliar spraying; an integrated parenteral management plan that depends on the addition of organic amendments to the saline sandy soils is also required.

Keywords*:* Salinity stress; Humic substance; Proline; Silicon nanoparticles; Zinc nanoparticles; Wheat.

1. Introduction

Wheat (*Triticum aestivum* L.) is considered the most important grain crop in the world (Igrejas and Branlard, 2020). The world's food supply needs to expand by 50% in 2050 as a result of the population's increase (Mora et al., 2020). In Egypt, 1.39 million hectares are cultivated with wheat, with annual production of 8.90 million tons in 2021 (Foreign Agricultural Service, USDA, 2021). Soil and water salinity significantly reduces wheat productivity, where the productivity of the crop decreases by 7% for each 1 dS m^{-1} increase if the salinity exceeds 6 dS m^{-1} (Ayers and Westcot, 1985). A variety of physiological, biochemical, and metabolic processes are negatively impacted by the salinity stress (Abd El-Hamid et al., 2020). Salinity causes high levels of oxidative stress and imbalance in nutrients and hormonal irregularities in plants (Yang and Guo, 2018; Kumar et al., 2019;). Under salt stress conditions, these adverse effects drastically reduce plant production (Abdrabou et al., 2022; Awwad et al., 2022).

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There are many methods for managing agriculture under saline conditions to deal with salt stress in order to minimize its adverse impacts on plants (Etesami and Glick, 2020). The use of humic compounds has both directly and indirectly stimulates plant growth and addition of humic materials a successful strategy for minimizing the negative effects of salinity stress (Elshaboury and Sakara, 2021; Sarhan et al., 2021). Humic materials can improve soil quality through enhancing the physical, chemical, and biological conditions of the soil (Desoky et al., 2019). Moreover, humic materials can directly improve the plant growth and metabolic activities (Turan et al., 2011). The humic compounds mitigate salinity and reduce soil sodium and pH, due to its high Ca, Mg, and K content (Turan et al., 2011; Desoky et al., 2018). Furthermore, the addition of humic compounds to saline soils improved cation exchange capacity (CEC) and accelerated the removal of exchangeable Na^+ from the soil surface (Khattak et al., 2013; Jiangkuan et al., 2015). Humic acid promotes plant growth through enhancing the cell membrane permeability causing an increase in water and nutrient uptake (Ali et al., 2021). The growth and productivity of wheat plants are enhanced by potassium humate addition (Kandil et al., 2016).

Plants subjected to salt stress respond when osmoprotective molecules e. g., proline are applied exogenously (Ali et al., 2007; Ashraf and Foolad, 2007). The accumulation of compatible compounds (osmolytes) is related to an increase in a plant's tolerance to salt due to its ability to resist osmotic stress, maintain nutritional homeostasis, and maintain ion compartmentalization (Nazar et al., 2011; Khan et al., 2012). When exposed to salt stress, proline acts as an osmolyte for intracellular osmotic adjustment, and its accumulation is essential for maintaining photosynthetic activity (Silva-Ortega et al., 2008). Proline enhanced the antioxidant genes, decreased reactive oxygen species (ROS) and lipid peroxidation, and prevented NaCl-induced cell death due to the increase in membrane integrity (Banu et al., 2009).

Nanoparticles (NPs) are effective tool in enhancing salt stress resistance and plant growth (Ghazi et al., 2022). NPs (1 to 100 nm) have efficient physicochemical properties than larger particles (Cele, 2020). NPs are more reactive and may have increased biochemical activity because of their high surface-to-volume ratio (Das and Das, 2019). NPs enhance antioxidant defense and ion homeostasis, and gene expression (Zulfiqar and Ashraf, 2021). Silicon (Si) is considered a beneficial element because it can influence plant growth and production favorably under a variety of environmental conditions (Liang, 1999; Ma 2004). Under salt stress conditions, Si application improved chlorophyll and proline accumulation in plant tissues, enhancing photosynthetic capacity as well as decreasing transpiration rate (Ahmad, 2014). Increasing Si concentrations in leaves increased the proline concentrations and reduced shoot Na^+ and Cl^-, which prevents cell membrane damage (Sapre and Vakharia, 2017).

Zinc (Zn) is an essential micronutrient in the plant cells, it performs a number of crucial functions, e. g., participates in DNA transcription, intracellular and extracellular signaling, and cellular communication (Caldelas and Weiss, 2017). Zn is thought to has a vital role in plants, especially those are exposed to stress conditions like salinity and drought (Sofy et al., 2020). Plant morphological, physiological, and biochemical traits under salinity stress were improved by the foliar spraying with Zn NPs (Alabdallah and Alzahrani, 2020).

Therefore, the present research aimed to study the effect of the soil application of K-humate and the foliar spray of proline as well as Si and Zn nanoparticles to overcome the salinity stress on wheat plants grown on saline sandy soils. Another aim of the study was to investigate how K-humate affects soils' chemical characteristics and availability of nutrients. We hypothesize that the addition of K-humate to the saline sandy soil will contribute to raising the level of organic matter and regulating Na uptake under saline conditions. Also, reducing Na uptake by plant tissues will increase the effectiveness of spraying with proline and Si and Zn NPs in reducing the effect of salinity.

2. Materials and methods

2.1. Experimental site and soil characterization

Field experiments were conducted at the experimental farm of the Soil, Water and Environmental Research Institute, West Mania, Mania Governorate, Egypt, which is geographically located at 28.12^0 N latitude, 30.07^0 E longitude, and its elevation is roughly 123.98 m above mean sea level. Figure 1 depicts the climatic conditions of the experimental site during the two successive winter seasons (2019/20 and 2020/21). Table 1 displays the fundamental soil characteristics as well as the water's chemical constitution used in the experiment. The soil was classified as Aridisols: Typic Torri psamments according to Soil Survey Staff (2016). In both seasons, soil samples were taken from the study sites to investigate the basic soil properties. First sample was taken before planting, while the second sample was collected from each treated plot after harvesting the wheat plant. Soil samples (0-30 cm) were collected, air dried, crushed, and sieved to pass through a 2 mm sieve to measure the physical and chemical characteristics of soil. Particle-size distribution was detrimined by Bouyoucous hydrometer method (Bouyoucous, 1951). S soil organic matter (SOM) was detrimined by Walkley-Black method (Jackson 1973) Total carbonates were determined volumetrically using Collin's Calcimeter and calculated as $CaCO_3$ (Dewis and Freitas, 1970). Soil pH was measured in a suspension of soil and deionized water at a ratio of 1:2.5, using a pH meter (JENWAY Model 3510) (Jackson, 1973),. The electrical conductivity (EC) of the soil was measured in the soil paste extract, using an EC meter (JENWAY Model 4520 Conductivity meter) as described by Hesse, (1998). The available nitrogen was extracted with 1% potassium sulphate solution, and then determined using the micro-kjeldahl method described by Page et al. (1982). Available soil P was extracted by a 0.5 M sodium bicarbonate solution at pH 8.5 (Olsen et al., 1954). The extracted P was determined by spectrophotometer at 880 nm (JENWAY Model 6305 Spectrophotometer). Neutral ammonium acetate of 1 M was used to extract the available potassium by mixing 50 mL of ammonium acetate with 5 g of an air-dried soil sample (Knudsen and Peterson, 1982). Flame photometry was used to determine potassium in the extract according to (Jackson, 1973). Available zinc (Zn) was extracted by shaking 10 g of air-dried soil samples for 2 hours with 20 mL of DTPA (pH 7.3, 0.05 M). Available zinc was measured in the filtrate by atomic absorption spectrophotometry (Lindsay and Norvell, 1978).

The commercial potassium humate (K-humate) utilized in this investigation was provided by Bio Tec for the Bio-cids and Fertilizers Company, Al Sadat City, Egypt. Proline (M.w. 115.13 American) is a commercial product was supplied by Future Modern Lab for Chemicals Company, Ciro, Egypt. Nanoparticles (NPs) was supplied from Nano Gate Creating New Scientific Horizons Company, Nasr City, Ciro, Egypt. The general properties of nanoparticles are listed in Table 2, and Figure 2 shows the XRD pattern of the prepared SiO_2 and ZnO NPs.

TABLE 1. Pre sowing properties of the experimental site and ground irrigation water during two seasons

Experimental soil properties			**Some chemical properties of irrigation water.**		
Physical properties	Seasons		Chemical properties	Seasons	
	2019/20	2020/21		2019/20	2020/21
Sand (%)	83.3	85.4	EC (dS m^{-1})	3.41	3.40
Silt (%)	8.1	6.6	pH	7.84	7.80
Clay (%)	8.6	8.0	TDS (ppm)	2182.40	2176.00
Texture	Sandy	Sandy	Soluble cations (meq L^{-1})		
Saturation capacity	22.5	25.0	Ca^{++}	8.50	9.30
Chemical properties			Mg^{++}	8.00	9.00
$CaCO_3$ (g kg^{-1})	102.50	95.20	Na^{+}	15.00	13.60
Organic matter (g kg^{-1})	1.98	1.79	K^{+}	1.50	1.10
pH (1:2.5 suspension)	8.00	7.97	Soluble anions (meq L^{-1})		
EC_e (dS m^{-1})	11.8	10.4	CO_3^{--}	0.00	0.00
Available N (mg kg^{-1})	35	30	HCO_3^{-}	3.50	3.20
Available P (mg kg^{-1})	3.4	4.8	Cl^{-}	22.00	20.30
Available K (mg kg^{-1})	102	156	SO_4^{--}	7.50	9.50
Available Zn (mg kg^{-1})	0.16	0.26	Sodium adsorption ratio	5.22	4.50

Each value represents the means of three replicates.

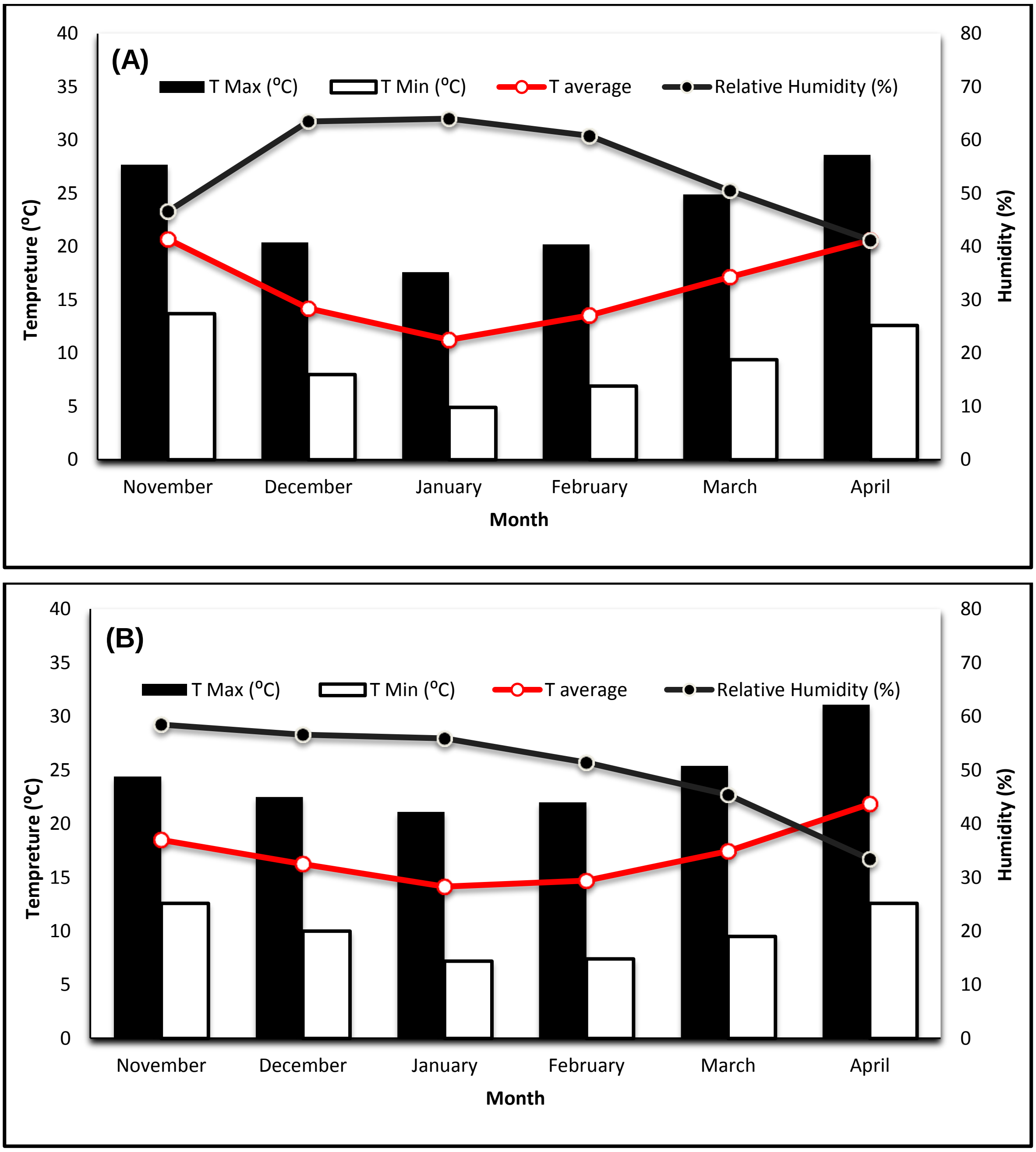
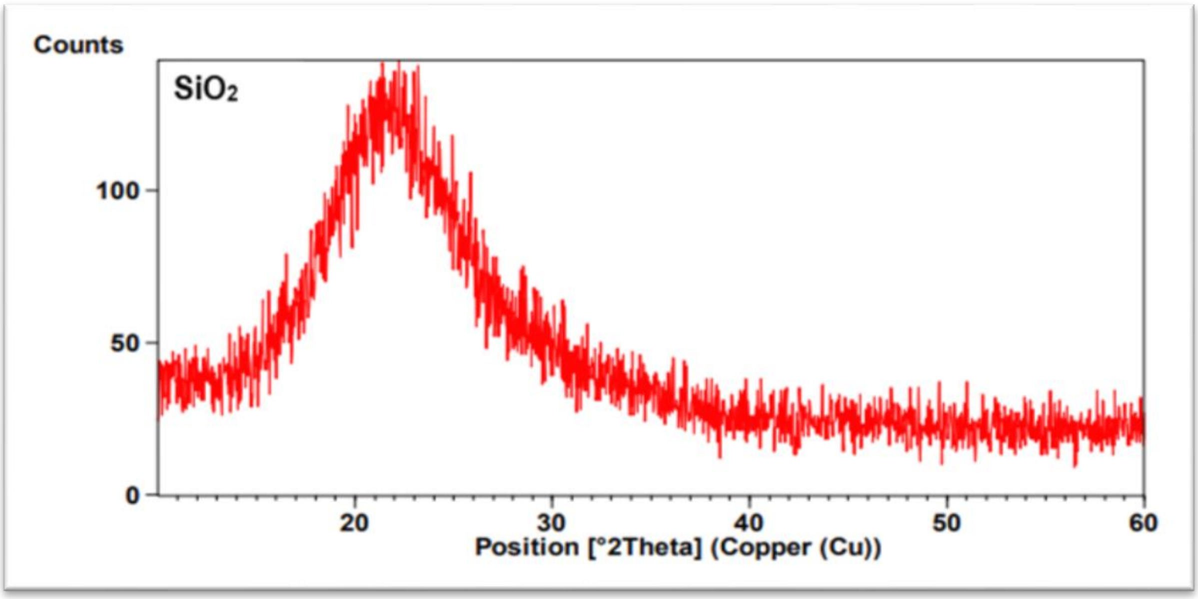


Fig. 1. Climatic characteristic of the experiential site at West El-Mania Governorate, Egypt in 2019/2020 (A) and 2020/2021 seasons (B)

TABLE 2. General properties of SiO_2 and ZnO nanoparticles

Properties	SiO_2 nanoparticles	ZnO nanoparticles
Appearance (color)	white	white to yellow color
Appearance (form)	Powder	Powder
Shape (TEM)	Spherical like shape	Spherical like shape
Size	20 ± 4 nm	30 ± 5 nm
Molecular weight	60.08 g/mol	81.408 g/mol



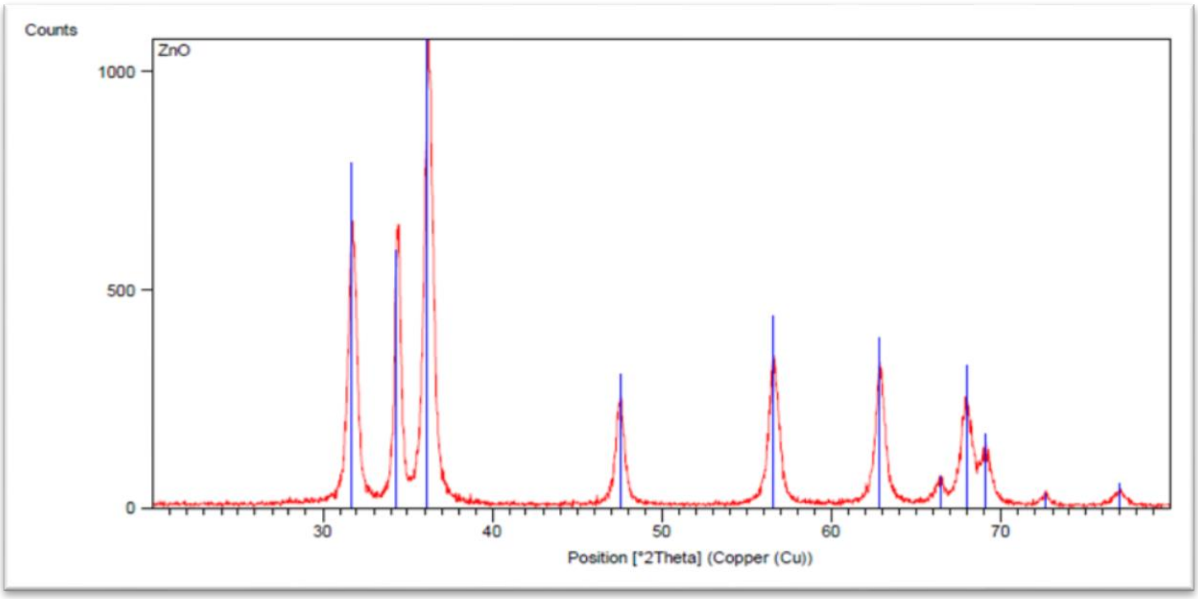


Fig. 2. XRD pattern of SiO_2 and ZnO nanoparticles

2.2. Filed Experiments

The study had two factors; the first was K-humate with three levels (0, 10, and 20 kg ha^{-1}) and was applied to the soil in the main plots. The second factor was the foliar spraying treatments with proline and nanoparticles of Si and Zn, which were belonged to the sub-plots. The experiments were designed in a split-plot within a randomized complete block design (RCBD), with three repetitions. The treatments used for foliar spraying were water, proline, Si NPs, Zn NPs, Si + Zn NPs, and proline + Si + Zn NPs. Wheat grains (*Triticum aestivum* L. variety Shandaweel-1) were acquired from the Wheat Crop Research Department at the Field Crop Research Institute, Agriculture Research Center, Giza, Egypt. Wheat was planted on November 3rd 2019 and November 4th 2020. Sowing was done by machine at 3 cm depth, 20 cm between the lines at a grain rate of 120 kg ha^{-1}. The plot area was 10.5 m^2 (3 m length x 3.5 m width). Wheat plants were irrigated with a drip irrigation system (4 L h^{-1} discharge and 25 cm between dippers). Nitrogen fertilizer was applied in the form of urea (46.5%) at a rate of 238 kg N ha^{-1}. Phosphorus fertilizer was supplied at a rate of 72 kg P_2O_5 ha^{-1} as phosphoric acid (85%). Potassium fertilizer was added at a rate of 114 kg K_2O ha^{-1} in the form of potassium sulphate (48% K_2O). Fertilizers including nitrogen, phosphorous, and potassium were applied using fertigation. K-humate (KH) was applied to the soil twice during the wheat growth season at 15 and 30 days after planting, at rates of 10 and 20 kg KH ha^{-1}. Foliar spraying treatments with proline (50 mM), as well as Si NPs (2 mM) and Zn NPs (2 mM) were carried out twice at 30 and 45 days of planting.

2.3. Plant analysis

After 60 days of planting, samples of wheat plants at the booting stage were taken from every experimental plot. The sample consisted of 30 to 35 plants plot^{-1}. Chlorophyll (SPAD) was determined in blades of wheat flag leaves at the heading stage by Chlorophyll Meter (SPAD-502-m Konica Minolta, Inc., Tokyo, Japan) as reported by Dash et al. (2007). Each plot was harvested at to estimate the biological, grain, and straw yields. Plant samples were washed with distilled water, air-dried, and then the plant samples were oven-dried at 70 ^oC for 24 hours. The leaves of wheat plants were digested with a mixture of concentrated H_2SO_4 and H_2O_2 30% to determine nutrient content (Cottenie et al., 1982). Nitrogen content was determined by the micro Kjeldah method using 5% boric acid and 40% NaOH as described by Jones et al. (1991). Phosphorus content was determined using chlorostannnous reduced molybdophoshoric blue color method in H_2SO_4 as described by Peters et al. (2003). Silicon and zinc content in leaves were estimated by an atomic absorption spectrophotometer (AAS). Proline content in leaves (mmol g^{-1} DWt) was determined by sulphosalicylic acid method (Bates et al. 1973).

2.4. Statistical analysis

The MSTAT-C program was used to run a two-way analysis of variance (ANOVA). The Duncan multiple range tests were used to identify the significant differences between the means of the different treatments at a 5 % level of probability according to Gomez and Gomez (1984). The displayed parameter values represent an average of the two seasons.

3. Results

3.1. Soil available nutrients and chemical properties

Applications of K-humate to soil improve the availability of N, P, and K (Table 3). The availability of N, P, and K significantly increased as the rate of K-humate increased from 0 to 20 kg ha^{-1}. At the highest rate of K-humate (20 kg ha^{-1}), available N, P, and K increased by 38, 67, and 21%, respectively, as compared with the control. Concerning the soil chemical properties, K-humate significantly improved the studied soil characteristics. The soil addition of K-humate at the highest rate (20 kg ha^{-1}) produced a considerable increase in the soil organic matter (SOM) by 13% as compared with the control. The addition of 20 kg ha^{-1} of K-humate significantly decreased the soil pH from 8.24 to 8.11 (Table 3).

TABLE 3. Effect of K-humate soil application on nutrients availability and soil chemical properties

Treatments	**Available nutrients (mg kg^{-1})**			**Chemical properties**		
	Nitrogen	Phosphorus	Potassium	pH (1: 2.5)	EC_e (dS m^{-1})	Soil organic matter (g kg^{-1})
KH0	83.3±0.4^c	7.5±0.1^c	124.1±1.9^c	8.24±0.04^a	4.7±0.1^c	3.1±0.0^c
KH10	103.8±0.3^b	10.0±0.1^b	140.3±2.2^b	8.16±0.03^b	5.2±0.1^b	3.3±0.0^b
KH20	114.9±0.0^a	12.6±0.4^a	149.6±1.1^a	8.11±0.03^c	5.6±0.1^a	3.5±0.0^a

Means denoted by the same letter indicate no significant difference according to Duncan's test at p<0.05.

3.2. Nutrient's content in wheat shoot

The soil application of K-humate and the foliar spraying of proline and nanoparticles of Si and Zn significantly enhanced the nutrient content in wheat plants (Figure 3 and 4). The N, P, K, Si, Zn, and K^+/Na^+ ratio in the wheat plants at the booting growth stage were significantly increased by the soil application of K-humate at 10 and 20 kg ha^{-1}, while Na significantly decreased. The highest rate of K-humate (20 kg ha^{-1}) increased the N, P, K, Si, Zn, and K^+/Na^+ ratio by 6, 13, 12, 85, and 36%, respectively, on the other hand, it decreased the Na^+ content by 8% as compared with the control. Concerning the foliar spraying of proline and nanoparticles of Si and Zn, the foliar spraying significantly affected the nutrient content of wheat. The foliar spraying of proline and nanoparticles of Si and Zn significantly increased the N, P, K, Si, Zn, and K^+/Na^+ ratio by 11, 17, 13, 146, and 51%, respectively, compared with the control. However, the foliar spraying of proline and nanoparticles of Si and Zn significantly declined the Na^+ content in the wheat plants by 11%. The interaction between the soil application of K-humate and foliar spray of proline and nanoparticles of Si and Zn significantly affected the nutrient content of wheat. The soil addition of 20 kg ha^{-1} K-humate along with the foliar application of proline and nanoparticles of Si and Zn had the highest values (Figures 3 and 4). The highest value of Na^+ content in wheat plants at the booting stage was recorded in the control, while the lowest one was found in the treatment of 20 kg ha^{-1} K-

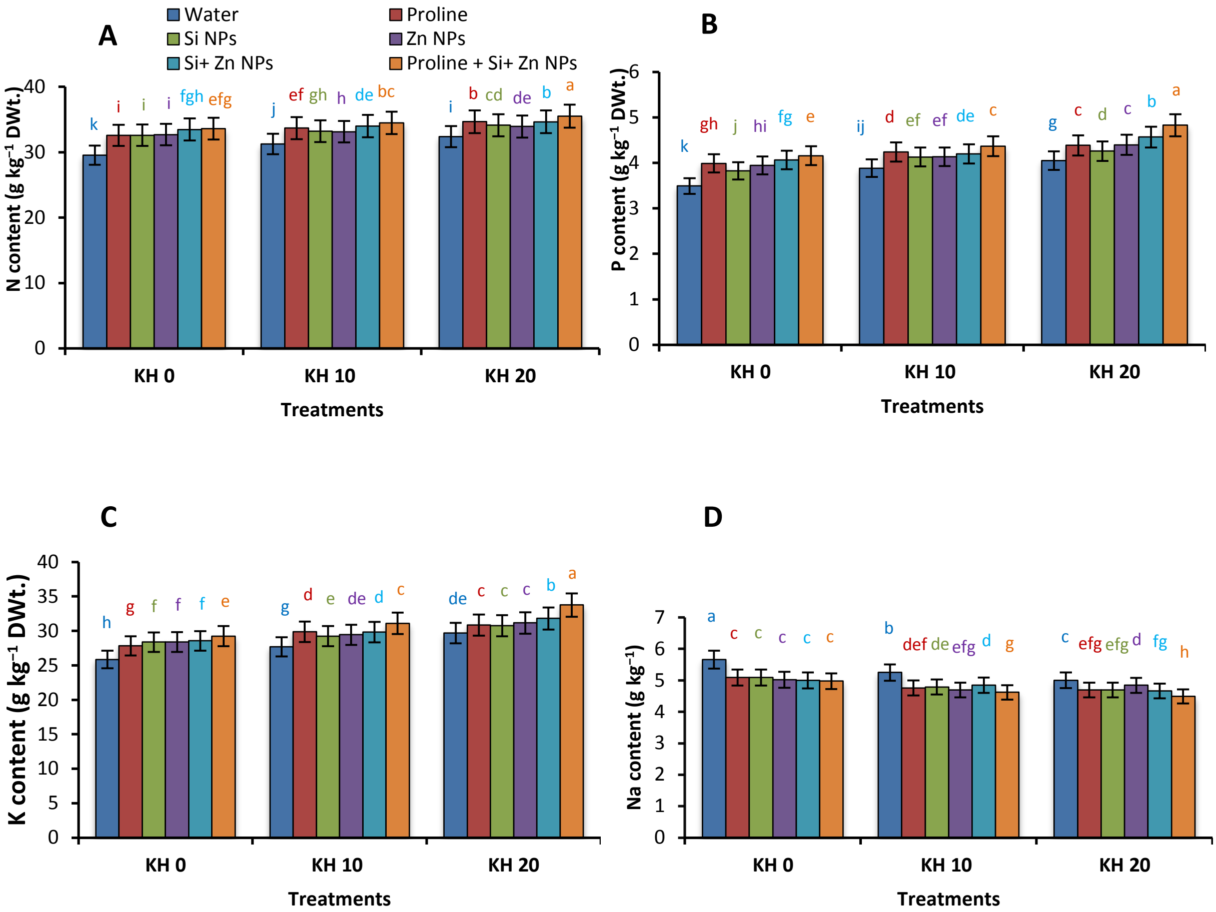


Fig. 3. Effects of K-humate soil application and foliar spray of proline and nanoparticles of Si and Zn on nitrogen (A), phosphorus (B), potassium (C), and sodium content (D) in wheat plant at booting stage. Means (± standard deviation, n=3) denoted by different letter are significantly different at P< 0.05

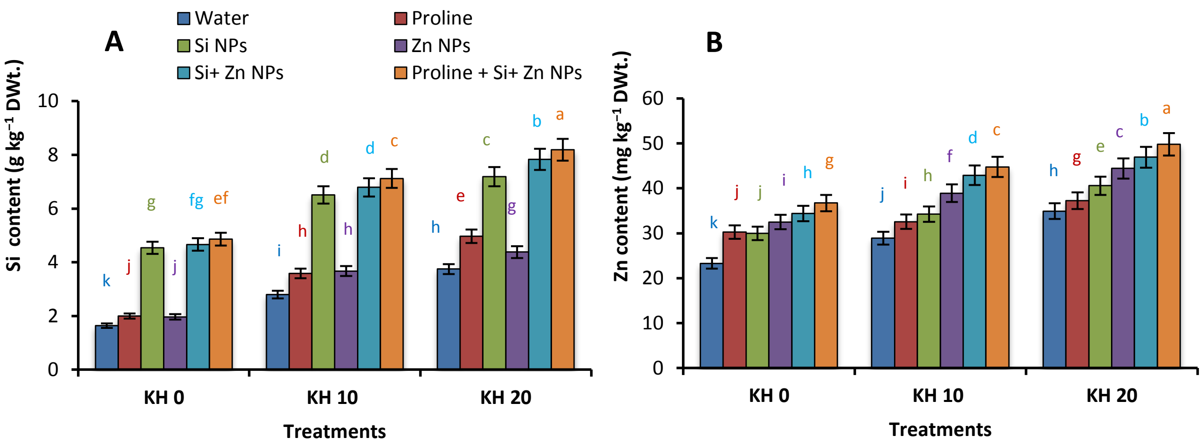


Fig. 4. Effects of K-humate soil application and foliar spray of proline and nanoparticles of Si and Zn on silicon (A) and zinc (B) in wheat plant at booting stage. Means (± standard deviation, n=3) denoted by different letter are significantly different at P< 0.05

3.3. Wheat growth, leaf-chlorophyll and proline

The soil amendment K-humate as well as the foliar spray of proline and nanoparticles of Si and Zn had a significant impact on wheat growth, leaf-chlorophyll, and proline levels (Figure 5). There was a significant and gradual increase in plant height and leaf-chlorophyll when K-humate was increased from 0 to 20 kg ha^{-1}. In comparison to the control treatment, the highest rate of K-humate (20 kg ha^{-1}) enhanced plant height and leaf-chlorophyll by 6 and 8%, respectively. Concerning the proline content, the soil addition of K-humate at the highest rate (KH 20 kg ha^{-1}) caused a significant decrease in the proline content by 10% as compared to the control. When compared to the control, the foliar spray of proline and nanoparticles of Si and Zn significantly increased plant height, leaf chlorophyll, and proline content in wheat by 10, 7, and 41%, respectively. Wheat plant height, leaf-chlorophyll content, and proline content were all significantly impacted by the interaction between soil applications of K-humate and proline and foliar spraying of Si and Zn nanoparticles. The maximum values of plant height and proline content were found in the soil-applied of 20 kg ha^{-1} K-humate combined with the foliar spray of proline and nanoparticles of Si and Zn. The soil-applied of 20 kg ha^{-1} K-humate along with a foliar spray of proline gave the maximum level of leaf-chlorophyll.

3.4. Yield and yield components of wheat plants

The soil addition of K-humate and the foliar spray of proline and nanoparticles of Si and Zn significantly affected the wheat yield (Table 4). As a result of applying K-humate to the soil, grain, straw, and biological yield all gradually and significantly increased. Grain, straw, and biological yield were increased by 26, 45, and 38%, respectively, from the control to the K-humate application at the highest rate (20 kg ha^{-1}). The foliar spray of proline and nanoparticles of Si and Zn significantly increased the grain, straw, and biological yield by 21, 26, and 24% in comparison with control. Wheat yield and yield components responded significantly to the interaction between the soil application of K humate and foliar spray of proline and nanoparticles of Si and Zn. Wheat biological yield ranged between 9.07 and 15.52 t ha^{-1} and the maximum value was found in the soil addition of 20 kg ha^{-1} K-humate along with the foliar spray of proline and nanoparticles of Si and Zn.

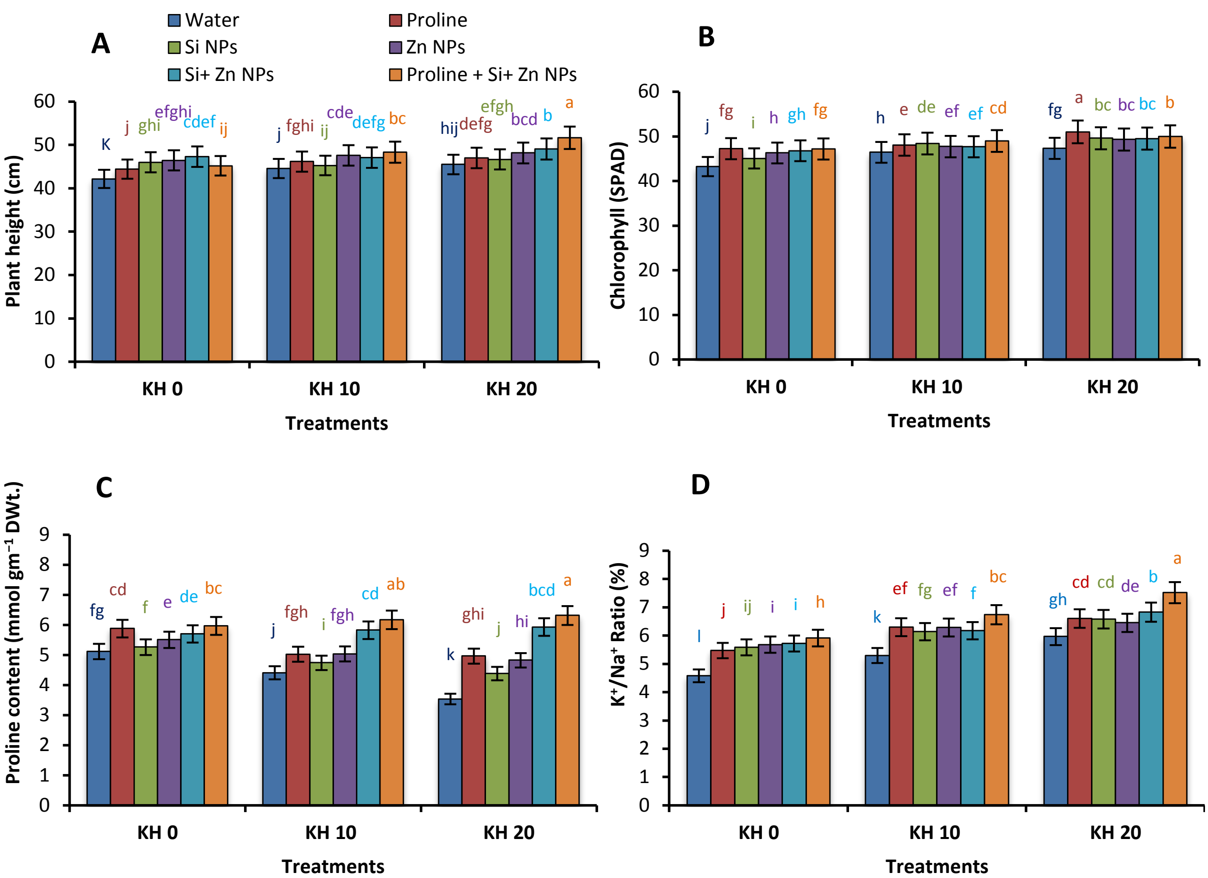


Fig. 5. Effects of K-humate soil application and foliar spray of proline and nanoparticles of Si and Zn on plant height (A), chlorophyll (B), proline (C), and K^+/Na^+ ratio (D) in wheat plant at booting stage. Means (± standard deviation, n=3) denoted by different letter are significantly different at P< 0.05.

TABLE 4. Biological, grain, and straw yields (t ha^{-1}) of wheat plant as affected by using soil application of K-humate and foliar spray of proline and nanoparticles of Si and Zn

Treatments		Biological yield (t ha^{-1})		Grain yield (t ha^{-1})		Straw yield (t ha^{-1})	
		Seasons		Seasons		Seasons	
Soil application of K humate (A)		**2019/20**	**2020/21**	**2019/20**	**2020/21**	**2019/20**	**2020/21**
KH 0 (control)		10.14 c	10.32 c	3.79 c	3.80 c	6.35 c	6.52 c
KH 10 kg ha^{-1}		12.47 b	11.68 b	4.19 b	4.31 b	8.29 b	7.37 b
KH 20 kg ha^{-1}		14.20 a	14.04 a	4.76 a	4.78 a	9.44 a	9.26 a
$LSD_{0.05}$		**0.22**	**0.25**	**0.12**	**0.06**	**0.22**	**0.28**
Foliar Spray of Proline and NPs (B)							
Water spraying		11.04 d	10.52 e	3.85 e	3.92 e	7.19 e	6.60 e
Proline spraying		12.31 c	12.04 c	4.15 d	4.34 b	8.16 bc	7.70 c
SiO_2 NPs spraying		12.17 c	11.60 d	4.27 c	4.23 cd	7.90 d	7.37 d
ZnO NPs spraying		12.19 c	11.92 c	4.22 cd	4.21 d	7.97 cd	7.70 c
SiO_2 + ZnO NPs spraying		12.61 b	12.58 b	4.40 b	4.30 bc	8.22 b	8.28 b
Proline + SiO_2 + ZnO NPs spraying		13.31 a	13.43 a	4.61 a	4.78 a	8.71 a	8.65 a
$LSD_{0.05}$		**0.18**	**0.20**	**0.09**	**0.07**	**0.20**	**0.20**
Interaction effects of (A × B)							
KH 0 (control)	Water	9.14 k	9.00 k	3.37 k	3.48 i	5.76 i	5.52 i
	Proline	10.28 ij	10.56 h	3.68 j	3.86 fg	6.61 g	6.70 fg
	SiO_2 NPs	10.25 ij	10.10 ij	3.82 hij	3.77 g	6.42 gh	6.33 h
	ZnO NPs	9.97 j	9.85 j	3.87 ghi	3.62 h	6.10 hi	6.22 h
	SiO_2 + ZnO NPs	10.43 i	10.97 g	3.94 fgh	3.91 f	6.48 g	7.05 ef
	Proline + SiO_2 + ZnO NPs	10.79 h	11.47 f	4.07 f	4.18 e	6.72 g	7.29 e
KH 10 kg ha^{-1}	Water	11.00 h	10.34 hi	3.73 ij	3.94 f	7.27 f	6.40 gh
	Proline	12.41 g	11.47 f	4.00 fg	4.42 d	8.41 de	7.05 ef
	SiO_2 NPs	12.35 g	10.92 g	4.24 e	4.19 e	8.12 e	6.73 fg
	ZnO NPs	12.46 g	12.17 e	4.27 de	4.42 d	8.19 de	7.75 d
	SiO_2 + ZnO NPs	12.91 f	11.96 e	4.41 cd	4.12 e	8.49 d	7.84 d
	Proline + SiO_2 + ZnO NPs	13.71 e	13.22 d	4.46 c	4.79 b	9.25 c	8.43 c
KH 10 kg ha^{-1}	Water	12.98 f	12.22 e	4.44 c	4.35 d	8.54 d	7.87 d
	Proline	14.25 bc	14.09 c	4.78 b	4.75 b	9.47 bc	9.34 b
	SiO_2 NPs	13.90 de	13.78 c	4.75 b	4.72 bc	9.15 c	9.06 b
	ZnO NPs	14.15 cd	13.73 c	4.52 c	4.60 c	9.63 b	9.13 b
	SiO_2 + ZnO NPs	14.50 b	14.80 b	4.83 b	4.85 b	9.68 b	9.95 a
	Proline + SiO_2 + ZnO NPs	15.44 a	15.60 a	5.28 a	5.38 a	10.16 a	10.22 a
$LSD_{0.05}$		**0.30**	**0.35**	**0.15**	**0.13**	**0.34**	**0.34**

Note: Means denoted by the same letter indicate no significant difference according to Duncan's test at $p<0.05$.

4. Discussion

Potassium humate (K-humate) addition to the saline soil enhanced the availability and uptake of N, P, and K. In comparison to the control, the soil's available N, P, and K increased by 38, 67, and 21% at the maximum rate of K-humate (20 kg ha^{-1}), and the uptake of these nutrients increased by 6, 13, and 12%. The benefits of K-humate in raising the amount of N, P, and K that are available to plants come from increasing soil organic matter. K-humate raised the organic matter in the soil by 13% compared to the control. The positive effect of K-humate in increasing the availability of nutrients in the soil is through the formation of organic complexes that preserve them from fixation factors and reduce their leaching chances (Kenawy 2017; Dinçsoy and Sönmez 2019). These outcomes are a result of the organic matter concentration (65–70%) of humic compounds in K-humate. The addition of K-humate reduced the soil pH compared to the control. The action of humic substances on lowering soil pH may be due to the carboxyl and phenolic hydroxyl that produce H+ in soil solution. In addition, humic substances applied to the soil could promote biological activity and neutralize soil alkalinity (Khattak et al., 2013).

According to Wong et al. (2009) and Dinçsoy and Sönmez (2019), when the organic matter in humic substances decomposes, it increases the soil's CO_2 concentrations and releases H^+ ions, which lower the pH. The soil pH is one of the most significant factors controlling nutrients availability in alkaline sandy soils (Ding et al., 2021).

The current study's findings show that the foliar spraying of proline and nanoparticles of Si and Zn increased the nutrients N, P, K, Si, and Zn in wheat plants at the booting stage. When wheat was exposed to salt stress, proline applied topically improved the plant's ability to absorb nutrients (Mahboob et al., 2016; Asghar et al., 2021). Proline mitigates the harmful effects of salt stress and enhances nutrient uptake by shifting plant energy toward growth rather than consuming it in the face of stress (Eissa and Abeed, 2019). The positive effects of proline application in improving nutrient uptake were also reported in corn (Nessim et al. 2008) and faba bean (Abd El-Samad et al. 2011). Additionally, according to the findings of the current study, foliar spraying of Si and Zn nanoparticles and their combinations enhanced the nutrient levels, including N, P, K, Si, and Zn, at the booting stage as compared to the control (water spray). Foliar spray of Si and Zn nanoparticles mediates the synthesis of protein, amino acids, nutrient uptake, chlorophyll and stimulates antioxidant enzyme activity (Li et al., 2012; Ding et al., 2022). The nanoparticle size of Si and Zn allows to penetrate the leaf tissue, causing changes in the physicochemical reactions in the cell and activating the growth, hence reducing the adverse effects of irrigation by saline water (Behboudi et al., 2018; Manish et al., 2021).

By improving the K/Na ratio in wheat leaves, the addition of K-humate to wheat grown under salt stress conditions had a beneficial impact on enhancing the plant's resistance to salinity. K-humate improved the K/Na ratio by reducing Na^+ uptake. This decrease in Na^+ content as a result of soil application of K-humate is due to its ability to overcome osmotic stress through minimizing the adsorption of Na^+ and enhancing Na^+ leaching losses (Rady et al., 2019). Si and Zn NPs mitigate the toxicity of Na^+ ions by enhancing the defense mechanisms of plants (Sabaghnia and Janmohammad, 2015). Additionally, Si and Zn nanoparticle-treated wheat plants exhibited significant levels of proline accumulation, which may have contributed to ROS scavenging to reduce oxidative stress (Zulfiqar and Ashraf, 2021; Ding et al., 2022). Proline foliar spray affects photosynthetic efficiency, hazardous ion content, organic solute content, and osmotic adjustment (Aqsa et al., 2013). Applications of exogenous proline effectively modify osmotic potential and are essential for maintaining plant growth in the presence of osmotic stress (Ashraf and Foolad, 2007; Aqsa et al., 2013).

The addition of K-humate to wheat cultivated under saline stress gave the maximum growth and yield. This can be explained by the possibility that humic chemicals exhibit anti-stress properties under salt stress circumstances. As a result, humic substances might promote nutrient absorption and decrease the absorption of some toxic elements, which would improve the growth of wheat plants (Kulikova et al., 2005). The growth of wheat plants is positively impacted by potassium humate, an efficient fertilizer (Osman et al., 2017; Kandil et al., 2016). Plant growth is influenced by humic compounds both directly and indirectly. The direct benefits of humic acid are attributed to its metabolic activity in plant growth and therefore its usefulness in generating larger yields, while the indirect effects are linked to its improvement of the physical, chemical, and biological state of soil (Osman et al., 2017; Kenawy 2017). Due to its involvement in promoting microbial development, CEC, and enzyme activity, K-humate has a positive impact on crop yield in salt-affected soils (Ding et al., 2021).

This increase in the chlorophyll due to the application of K humate to the soil may be attributable to the function of humic compounds as growth regulators, which stimulate plant development processes (Salem et al., 2017). The addition of humate led to an increase in the chlorophyll content of the leaves as a result of protecting the chlorophyll molecules from the influence of toxic ions such as sodium. This might be explained by the possibility that humic compounds have anti-stress properties when exposed to salt stress (Salem et al., 2017). According to Cimrin et al. (2010), plants under salt stress exhibited the greatest increase in chlorophyll content when humic acid was applied externally. As the results obtained, foliar spraying of proline and nanoparticles of Si and Zn had positive and significant effects on chlorophyll compared to the unsprayed plants. Proline applied externally to wheat plants considerably increases their chlorophyll levels, either by promoting chlorophyll production or by preventing chlorophyll breakdown (Abd El-Samad et al. 2011). Additionally, the results revealed that the foliar spraying of Si NPs, Zn NPs, and their combinations increased the chlorophyll in wheat plants. This may be due to Si and Zn NPs' ability to enhance photosynthesis and improve the water status (Ding et al., 2022). Additionally, they can modulate the activity of antioxidant enzymes under salt stress and inhibit chlorophyll degradation in plants grown under stress. (Ding et al., 2022).

5. Conclusion

Saline soils are spread in arid and semi-arid areas, and they are difficult to exploit in agricultural production due to the toxicity of some ions, such as sodium. Foliar application of wheat plants under salt stress with silicon and zinc nanoparticles is a good tool in reducing the hazards of salinity. The soils in arid conditions have low amounts of organic matter and are characterized by high pH values. The application of potassium humate to the saline sandy soils increases the soil organic matter and nutrient availability. The addition of potassium humate had a direct positive effect on increasing wheat resistance to salinity by increasing the potassium to sodium ratio in the leaf tissues. The combined application of potassium humate and foliar spray of proline as well as Si and Zn nanoparticles can be employed as a suitable strategy for increasing wheat yield under saline conditions and enhancing salt resistance.

6. Conflicts of interest

The authors have no conflicts of interest.

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