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Effect of foliar spraying with zinc and copper nanofertilizers on the growth, yield, and protein content of two sorghum cultivars (Sorghum bicolor L.).

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I. Abstract

The research was carried out in the Al-Ghamij region, part of the Al-Qurna district, north of Basrah Governorate, situated at 30 ° 56′25′ ′ N, 47 ° 27′55′ E, on soil characterized by a loam clay texture in July 2023. The current field experiment aims to evaluate the effect of the application of zinc and copper nanofertilizers in the foliar application on the growth, yield and protein content of two different cultivars of sorghum (Sorghum bicolor L.). The factorial results indicated that the Al- Khair cultivar (S1) was superior in quantitative traits (plant height, leaf area, number of grains per head and total grain yield of (3.81 ton ha^{-1}), while the Inkath (S2) cultivar was superior in thousand grain weight and protein content in some treatments. Zinc was the most effective element in increasing the number, yield, and protein content of grains, while the combination of zinc and copper (F6 = 2Zn + 1Cu kg·ha^{-1}) gave the largest significant increase in grain yield of (4.215 ton ha^{-1}). Regarding the interaction treatment between the varieties and the concentration of nano fertilizers, the combination (F6 × S1) gave the highest grain yield (4.52 tons.ha^{-1}). The study recommends the use of Zn-NPs at moderate concentrations at a rate of (1-2 kg.h^{-1}) and the continuation of the evaluation of the effects of nano-Cu on the plant and the environment before expanding the application.

Keywords: Al- Khair and Inkath cultivar, Nanofertilizers, Protein content , and Yield

II. INTRODUCTION

Sorghum (Sorghum bicolor L.) is one of the most important cereal crops globally, widely grown in arid and semi-arid regions to replace other crops. According to FAOSTAT data, in 2023, the sorghum-growing area was approximately 42 million hectares and production was around 58–60 million tonnes (FAO, 2023). The grain typically contains protein in a range of 9 to 13% depending on the variety and crop growing conditions, with an approximate average used in nutritional reviews (Feedipedia, n.d.; Frankowski, Przybylska-Balcerek, & Stuper-Szablewska, 2022). In the United States, a significant portion of sorghum is used as animal feed and as a raw material for the production of ethanol, with the remainder used in industry or for food consumption (Sorghum Checkoff, n.d.; USDA ERS, n.d.), while the United States is the leading producer, with a production of 8.73 million metric tons in the 2024/2025 season (USDA FAS, 2024).

Sorghum production in Iraq remains relatively low, with the average harvested area and productivity for the last five-year period (2020–2025) indicating an area of 2,000 hectares and an average yield of 1.50 tha-1 (USDA FAS, 2025). This level is considered low compared to the genetic potential, showing the existence of factors that limit productivity, including soil fertility and the lack of micronutrients, particularly zinc and copper, or their poor access to plants. This is a significant factor in semiarid or unfertilized agricultural environments (Majeed et al., 2022; Sheik-Abdullah, 2019). The issue is even more complicated because Iraq has a lot of alkaline and calcium soils, which causes basic microelements to chemically fix. Chemical reactions happen in alkaline soils (pH > 7.5) and calcareous soils (which have calcium carbonate ($CaCO_3$) in them). These reactions change important microelements like zinc, copper, iron, manganese, and manganese (Mn) from soluble and absorbed forms to insoluble or fixed forms of soil. This makes it harder for plants to take them up (Wang et al., 2022). This prevents the development of all crops. Genetics must achieve its full potential, both in quantity and in quality, as represented by the percentage of proteins.

Previous studies have shown significant differences in the reactions of sorghum growers to fertilizers and stress conditions. Genetic variations between cultivars greatly affect growth characteristics such as plant height, leaf area, and flowering time, leading to differences in grain amount per head, grain weight, and yield (Kebede et al. 2020; Zegada-Lizarazu & Monti 2019). Local and global studies on sorghum have shown that some genetically predisposed cultivars are capable of increasing the number and yield of cereals due to nutrients, while others tend to improve the quality of cereals (Abdulrahman, 2021; El Naim, 2020).

In order to overcome the challenges of low efficiency of conventional fertilizers in chemically limited soils, nano fertilizers are a promising and sustainable solution. Conventional fertilizers tend to reduce the amount of nutrients available for plants due to chemical fixation, leakage, and volatilization, while nano fertilizers have small particles (usually less than 100 nm), increasing contact surface area, and improving absorption when applied as leaves sprays. Plant spraying with nanofertilizer reduces environmental pollution, improves plant nutrient absorption efficiency, and improves the growth and yield of many crops in harsh or poor soil conditions (Mahil & Kumar, 2019; Raaliya et al., 2018).

Zinc is an important component of plant biological processes. It is a cofactor for many important enzymes, including as carbon anhydrase and rubisco, which fix carbon dioxide during photosynthesis. It also helps govern how DNA makes proteins and how genes are turned on and off (Cardini et al., 2021; Dang, 2024). Recent research indicates that applying zinc oxide nanoparticles to foliar plants enhances the efficacy and absorption of photosynthetic compounds. The height of the plants, the size of the leaves, the number of grains per head, the weight of 1000 grains, the yield of grains, and the protein content all rely on the application rate, crop type, and environmental circumstances (Guo, 2024). Zinc sprays increase the weight, yield, and protein content of 1000 grains more than normal fertilizers do (Dimkpa et al. 2019; Khan et al. 2021). Copper (Cu) is a necessary element of many plant activities. It helps move electrons and make chlorophyll. Studies show that using foliar nanocopper increases the amount of grain produced per person and the weight of 1000 grains by making photosynthesis and carbohydrates more evenly distributed (Dimkpa et al., 2019). It also increases the quantity of protein in the grain and the amount of grain produced by speeding up protein synthesis (Raliya & Tarafdar, 2018). The safety range is restricted, especially with copper oxide nanoparticles, since high levels of these particles create reactive oxygen species and oxidative stress, which slow down root growth, lower chlorophyll levels, and lower output (Fitz 2023; Tretella 2024).

The study of varieties is an essential component in the process of improving the quality and productivity of sorghum, as well as adapting it to the circumstances in the local area. Consequently, the process of comparing different types involves an unbiased evaluation of the following factors: the height of the plants, the area of the leaves, the weight of the heads, the weight of a thousand grains, the amount of grain that is produced, and the amount of protein that is present. The results of local trials have indicated that the performance of these two varieties, Al-Khal and Inqaz, varies significantly from season to season and is also affected by the density of the planting. The variability influences farmers' decisions regarding crop varieties, fertilizer application, irrigation techniques, and overall management strategies (Wuhaib et al., 2017; Fadil, 2024). Inadequate management of nutritional fertilizers and the limited effectiveness of conventional fertilizers have led to suboptimal sorghum production levels and reduced grain protein content. This underscores the current research problem. Investigating the potential of nanofluorides as a more efficient substitute is essential to achieving this goal. This study aims to assess the sustainable enhancement of yield and quality in two types of white maize through the application of foliar sprays of nanofertilizers containing zinc and copper in different quantities and combinations.This research aims to identify the crop type most responsive to nanofertilizer treatment, establish optimal concentrations for combined foliar application regarding growth and yield, and enhance grain protein content. This research investigates the efficacy of microelement-containing nanofertilizers in improving crop yields in Iraq, considering the prevailing climatic and agro-environmental conditions.

III. MATERIAL AND METHODS

Study Site

The agricultural experiments in the study were carried out in the Al-Ghamij area, affiliated with the Al-Qurna district, north of Basrah Governorate, which is geographically located at 30 ° 56′25′N, 47 ° 27′55′E (Figure 1), in a soil with a clay texture.

Figure 1. Site of study field.

Experimental Factors:

The experiment included studying two factors:

- The first factor: Two varieties of white corn (Al-Khair =S1, Inqaz =S2).
- The second factor: Levels of zinc and copper nanofertilizers, including chelated zinc (20% Zn) at two levels (1 and 2 kg. h^{-1}) and chelated copper (15% Cu) at two levels (0.5 and 1 kg. h^{-1}). Each was added separately and both were mixed with 400 liters of water per hectare. The mixture was divided into two batches: the first 25 days after planting and the second 50 days after planting, at seven levels (1 kg). E-1 (F0=0Zn+0Cu,F1=1Zn+0Cu, F2=2Zn+0Cu, F3=0Zn+0.5Cu, F4=0Zn+1Cu, F5=1Zn+0.5Cu, F6=2Zn+1Cu)

Soil Properties

A random sample of field soil was taken at a depth of 0-30 cm from several places and mixed, air-dried, and sieved with a sieve with a diameter of 2 mm. Subsequently, a representative sample was taken and analyzed in the central laboratory of the College of Agriculture/University of Basrah to determine some physical and chemical properties, texture, salinity, and degree of reaction of the experimental soil, as shown in Table (1).

Table (1) Some chemical properties of the initial soil of the experimental field

Trait		Value	Value	References
pH		7.51		Richards,1954
ECe		6.4	dS m^{-1}	
Organic matter		1.8	g kg^{-1}	Walkley & Black,1934
Available nutrients	Nitrogen	15.63	g kg^{-1}	Bremner,1965
	Phosphorus	7.13		Olsen et al.,1954
	potassium	11.68		Landon,1984
	Zinc	0.30		Tandon,1999
	Copper	0.26		
Soil texture		Loam clay		

Field Operations

The soil was plowed twice perpendicularly with a moldboard plow. The field was then harrowed, leveled, and divided according to the design used into three sectors. Each sector contained 14 experimental units, each with an area of 3 x 3 m². The distance between each line was 75 cm and the distance between each plant was 25 cm. The experiment was then fertilized with NPK 20-10-10 at a rate of 460 kg ha^{-1}, divided into two batches: 50% at the time of planting and 50% 45 days later.

Traits studied

1- **Plant height (cm):** Estimated as the average of ten plants randomly selected from each experimental unit in the flowering stage from the median lines and measured from soil level to the highest plant apex.

2- **Leaf area (cm2):** Calculated from the average leaf area of ten plants randomly selected at 50% flowering, using the following equation: leaf length × maximum leaf width × 0.75, for all leaves in the plant, and according to the method of Liang et al. (1973).

4- Number of grains per head: The number of grains per head was calculated for each of the ten randomly selected plants and for all experimental units. 5- Weight of 1000 grains (g): 1000 grains were randomly taken from the yield of ten plants after their grains were separated and mixed. They were then weighed using a sensitive balance, and the weight was adjusted to the required moisture content (15%).

6- Grain yield (tons h^{-1}): The midribs were harvested and the harvested grains were weighed after adding the ten plants used to calculate the yield components. These weights were converted to tons h^{-1} at 15% moisture.

5- Protein in grains (%): The protein content was estimated using the semi-micro Kjeldal method (Sallee, 1969) by calculating the nitrogen content using a micro-Kjeldal device in the graduate laboratory of the Department of Field Crops/College of Agriculture. The protein content was estimated according to the following equation:

Percentage of protein = Percentage of nitrogen × 6.25

Statistical analysis

A factorial experiment was implemented using a randomized complete block design (RCBD) with three replicates. The main plots included the varieties, while the subplots included the nano-fertilizer concentrations. Therefore, the number of experimental units used in the experiment was (7 x 2 x 3) = 42 experimental units. Data were collected and statistically analyzed using analysis of variance (ANOVA) using the Genstat statistical program. The arithmetic means of the treatments were compared using the least significant difference (LSD) test at a probability of 0.05.

IV. RESULTS AND DISCUSSION

1 - Plant height (cm)

The concentrations of nanofertilizers, the cultivars, and their interaction significantly influenced the height of the plants, according to statistical analysis. Table 2 indicates that cultivar S1 obtained a higher plant height of 136.71 cm than that of S2, which had the lowest plant height of 126.43 cm. This may be attributed to the genetic diversity between cultivars in the number and length of internodes, which has a substantial impact on the height of the plant. Disparities in growth are observed in certain cultivars due to their increased susceptibility to environmental factors (Kebede et al., 2020). This revealed that zinc has a greater effect than copper on plant height. However, it was observed that the treatment (F2 = 136 cm), significantly outperformed the treatment (F4 = 126 cm), and both significantly outperformed the control treatment (F0 = 104.5 cm). Therefore, the treatment that combined the two elements (F6) gave the highest significant increase in this trait, reaching 165.5 cm. This is because zinc is a cofactor for many enzymes responsible for cell division and chlorophyll formation, which stimulates plant growth at height (Dimkpa et al., 2019; Pandey, 2006). Copper may contribute to improving metabolic processes, but has a less significant effect on increasing plant height compared to zinc, and can become toxic at high concentrations (Raza et al., 2024).

Regarding the effect of interaction between varieties and nano fertilizer, Table (2) showed that the combination (F6 × S1) and (F6 × S2) gave the highest average plant height of (168 cm and 163) respectively, and significantly outperformed the combination (F0 × S2) which gave the lowest average plant height of (88 cm).

Table 2. Effects of Nanofoliar Sprays and sorghum cultivars and their interaction on plant height

Nano foliar	Sorghum cultivars		
F	**S1**	**S2**	**Mean (F)**
F0	121^{cde}	88^{f}	104.5^{d}
F1	132^{c}	119^{de}	125.5^{c}
F2	143^{bc}	129^{cd}	136^{b}
F3	126^{cd}	114^{e}	120^{c}
F4	126^{cd}	126^{cd}	126^{c}
F5	141^{bc}	146^{b}	143.5^{b}
F6	168^{a}	163^{a}	165.5^{a}
Mean (S)	136.71^{a}	126.43^{b}	

2- Leaf area (cm2)

The results of the statistical analysis showed a significant effect of the varieties and concentrations of nanofertilizer, as well as their interaction, on the leaf area trait of the plant. According to Table (3), the S1 variety produced a much higher average leaf area per plant (3768.857 cm2) than the S2 variety (average plant height: 3195.714 cm2), which in turn was a major improvement over the S2 variety. The genetic variety in white maize types is associated with their ability to make efficient use of light and water, which is why their genetic composition is different (Zegada-Lizarazu & Monti, 2019).

Based on the findings in Table (3), it seems that zinc has a stronger impact on plant leaf area than copper. The addition of nanofertilizers significantly increases the leaf area. The treatment group showed a considerable improvement in performance compared to the comparison group (F0 = 2787 cm²), and both groups were far more effective than the control group (F4 = 2996 cm2). Consequently, the treatment that included both components (F6) resulted in the most notable improvement in this attribute, reaching a value of (4448.5 cm2). The reason for this is that zinc plays a crucial role in improving chlorophyll creation and cell division. As a result, leaves expand and photosynthesis efficiency is increased (Semida et al., 2021; Upadhyay et al., 2023). Conversely, copper has less influence on this characteristic, and its effects often work in tandem with those of stress tolerance enhancers rather than leading to an increase in the plant's leaf area per se.

The effect of the interaction between the varieties and the concentration of nano fertilizer, as shown in Table (2), has a significant effect on the leaf area. The combination (F6 × S1), which gave the highest average leaf area per plant, reaching (5062 cm2), was significantly superior to the combination (F0 × S2) and (F0 × S1), which gave the lowest average leaf area per plant, reaching (2785 cm2) and (2789 cm2), respectively.

Table 3. Effects of Nanofoliar Sprays and sorghum cultivars and their interaction on leaf area

Nano foliar	Sorghum cultivars		
F	**S1**	**S2**	**Mean (F)**
F0	2789^{j}	2785^{j}	2787^{g}
F1	3852^{d}	3035^{g}	3443.5^{d}
F2	4426^{b}	3670^{e}	4048^{b}
F3	2854^{i}	2830^{ij}	2842^{f}
F4	3081^{g}	2912^{h}	2996.5^{e}
F5	4318^{c}	3303^{f}	3810.5^{c}
F6	5062^{a}	3835^{d}	4448.5^{a}
Mean (S)	3768.86^{a}	3195.71^{b}	

3- Number of grains per head

The statistical analysis revealed that the characteristic number of grains per head was significantly affected by the cultivars, the concentrations of nanofertilizer, and the relationship between the two. The findings in Table (4) indicated that cultivar S1 performed much better than cultivar S2, with an average of 1837.43 grains per head, compared to cultivar S2, which produced the lowest average number of grains per head (1411.29).This characteristic may result from the genetic predisposition of each cultivar to generate a specific number of grains per head. The variation in cultivated grain yield per head is influenced by factors such as flowering time, pollination effectiveness, and carbohydrate translocation efficiency (Hacisalihoglu, 2020). Moreover, cultivars possessing stress-resistant genes or robust root systems are more capable of supplying the energy required to generate a greater quantity of kernels for the flower (Rakgotho and colleagues 2022). The results presented in Table 4 indicate that the incorporation of nanofencing markedly enhanced the number of grains in the head. Among the elements studied, zinc appeared to exert a greater influence on this characteristic than copper. Consequently, the treatment (F2=1702) was significantly more effective than the control (F0=1351.5), with the treatment (F4=1613.5) also demonstrating a substantial improvement. Therefore, the treatment that combined the two elements (F6) gave the largest significant increase in this trait, amounting to (1888.5), and this is due in part to the effect of the zinc element, which plays a crucial role in the formation of flowers, their pollination, and the ripening of grains by improving the functions of pollen grains and transporting carbohydrates to reproductive tissues (Pandey, 2006; Dimkpa et al., 2019; Rakgotho et al., 2022). Copper helps activate oxidative enzymes and improve photosynthesis, but high concentrations may reduce the number due to oxidative stress (Liu et al., 2018; Raza et al., 2024).

The interaction effect between the varieties and the concentration of nano fertilizer had a significant effect on the number of grains per head. Table (4) showed that the combination (F6 × S1), which gave the highest average number of grains per head, reaching (2093), significantly outperformed the combination (F0 × S2), which gave the lowest average number of grains per head, reaching (1104).

Table 4. Effects of Nano foliar sprays and sorghum cultivars and their interaction on number of grains per head

Nano foliar	Sorghum cultivars		
F	**S1**	**S2**	**Mean (F)**
F0	1599^{f}	1104^{j}	1351.5^{g}
F1	1761^{d}	1339^{i}	1550^{e}
F2	1929^{b}	1475^{g}	1702^{c}
F3	1695^{e}	1315^{i}	1505^{f}
F4	1826^{c}	1401^{h}	1613.5^{d}
F5	1959^{b}	1561^{f}	1760^{b}
F6	2093^{a}	1684^{e}	1888.5^{a}
Mean (S)	1837.43^{a}	1411.29^{b}	

4 - 1000 grain weight (g)

The results of the statistical analysis indicated a significant effect of the cultivars, the concentration of the nanofertilizer, and their interaction on the weight trait. The results in Table (5) showed that cultivar S2 significantly outperformed cultivar S1, which produced the highest average weight (31.35gm), yielding the lowest average for this trait (27.81gm). Variation between cultivars in this trait is related to differences in carbohydrate absorption rates and their transfer to the grains during the grain filling stage (Abdulrahman et al., 2021).

From the data presented in Table (5), there was a significant increase in the number of grains per head with the addition of nanofertilizers. It appears that zinc has a greater effect than copper on this trait. This is observed in treatment (F2 = 32.400 g), which significantly outperformed treatment (F4 = 27.345 gm), and both significantly outperformed the control treatment (F0 = 1351.5). Therefore, the treatment that combined the two elements (F6) gave the largest significant increase in this trait, reaching 25.395 gm. This is because zinc enhances photosynthesis and sugar production and supports enzymes that fill grains with starch and protein structures. Therefore, zinc

tends to increase average grain weight by improving grain filling (Dimkpa et al., 2019). Copper acts as an active component in electron transfer and oxidative reactions, supports energy production, and activates enzymes responsible for building stored compounds. This can have a beneficial effect on grain weight; however, it can also have the opposite effect, as high concentrations reduce grain filling (Raza et al., 2024; Liu et al., 2018).
The effect of the interaction between varieties and the concentration of nano fertilizer. Table (5) showed that the combination (F6 × S2) gave the highest average weight of 1000 grains, which was 35.12 gm, which did not differ significantly from the combination (F5 × S2), which gave 34.79 gm. Treatments (F6 × S2 and F5 × S2) were significantly superior to treatment (F0 × S1), which gave the lowest average weight of 1000 grains, reaching 23.45 g.

Table 5. Effects of Nanofoliar Sprays and sorghum cultivars and their interaction on 1000-grain weight

Nano foliar	Sorghum cultivars		
F	**S1**	**S2**	**Mean (F)**
F0	23.45^{h}	27.34^{f}	25.395^{e}
F1	27.57^{f}	30.55^{cd}	29.060^{c}
F2	31.04^{cd}	33.76^{ab}	32.400^{b}
F3	24.95^{gh}	28.51^{ef}	26.730^{d}
F4	25.31^{g}	29.38^{de}	27.345^{d}
F5	30.29^{cd}	34.79^{a}	32.540^{b}
F6	32.05^{bc}	35.12^{a}	33.585^{a}
Mean (S)	27.81^{b}	31.35^{a}	

5 - Grain yield (tons h^{-1})

The results of the statistical analysis indicated a significant effect of cultivars on grain yield. The results in Table (6) showed that cultivar S1 significantly outperformed cultivar S2, producing the highest average grain yield (3.81 tons h^{-1}), compared to cultivar S2, which produced the lowest average for this trait (3.35 tons h^{-1}). The reason for the variation in the grain yield is attributed to their variability, since the cultivar S1 outperformed cultivar S1 in leaf area (Table 2) and number of grains per head (Table 3), while the cultivar S2 outperformed in weight (Table 4), which is directly reflected in the yield.
The results in Table (6) show a significant increase in grain yield with the addition of nano fertilizers, as it appears that the zinc element has the greatest effect than the copper element in this trait, and this is what we observed in the treatment (F2 = 3.835 tons - 1), which significantly outperformed the treatment (F4 = 3.520 tons - 1), and both significantly outperformed the comparison treatment (F0 = 2.895 ton.h^{-1}), and thus the treatment that combined the two elements (F6) gave the largest significant increase in this trait, amounting to (4.215 ton.h^{-1}), and this is due to the zinc element, which appeared more effective in increasing the leaf area, the number of grains, and the average weight of 1000 grains, and thus increasing the grain yield.

The effect of interaction between varieties and concentration of nano fertilizer. Table (6) showed that the combination (F6 × S1) gave the highest grain yield of (4.52 ton.h^{-1}), which did not differ significantly from the combination (F5 × S1), which gave (4.18 ton.h^{-1}), and both were significantly superior to the combination (F0 × S2), which gave a grain yield of (2.81 ton.h^{-1}).

Table 6. Effects of Nanofoliar Sprays and sorghum cultivars and their interaction on grain yield

Nano foliar	Sorghum cultivars		
F	**S1**	**S2**	**Mean (F)**
F0	2.98^{fh}	2.81^{h}	2.895^{d}
F1	3.69^{bcde}	3.34^{def}	3.515^{c}
F2	4.11^{ab}	3.56^{cde}	3.835^{b}
F3	3.41^{def}	3.06^{fh}	3.235^{c}
F4	3.78^{bcd}	3.26^{ef}	3.520^{c}
F5	4.18^{ab}	3.52^{cde}	3.850^{b}
F6	4.52^{a}	3.91^{bc}	4.215^{a}
Mean (S)	3.81^{a}	3.35^{b}	

6- Protein percentage in grains (%)

The results of the statistical analysis indicated that the cultivars had no significant effect, while the concentration of nanofertilizer, the interaction between cultivars, and the concentration of nanofertilizer had a significant effect on the percentage of protein percentage trait in grains.

The results in Table (6) show that copper had no significant effect. No significant difference was observed between the F4 treatment (11.355%) and the control treatment (F0 = 10.960%). Therefore, the increase in protein percentage was due to the influence of zinc, with the F6 treatment outperforming it, producing the largest significant increase in this trait (12.730%), which did not differ significantly from the F2 treatment (12.385%). This is due to the role of zinc in improving the activity of nitrogen-reducing enzymes and improving nitrogen absorption and fixation in grains, leading to an increase in the protein percentage provided sufficient nitrogen is available (Dimkpa et al., 2019; Donia, 2023).

The percentage in grains was affected in interaction between varieties and the nano fertilizer, Table (7) showed that the combination (F6 x S2) gave the highest average protein percentage, which reached (13.15%), which was significantly superior to the combination (F0 x S1), which gave the lowest average protein percentage, which reached (10.83%).

Table 7. Effects of Nano foliar sprays and sorghum cultivars and their interaction on grain yield

Nano foliar	Sorghum cultivars		
F	**S1**	**S2**	**Mean (F)**
F0	10.83^{f}	11.09^{ef}	10.960^{c}
F1	11.54^{def}	12.38^{bc}	11.960^{b}
F2	11.82^{de}	12.95^{ab}	12.385^{ab}
F3	11.14^{ef}	11.27^{def}	11.205^{c}
F4	11.32^{def}	11.39^{def}	11.355^{c}
F5	11.89^{cd}	12.51^{abc}	12.200^{b}
F6	12.31^{bc}	13.15^{a}	12.730^{a}
Mean (S)	11.55^{a}	12.11^{a}	

CONCULUSION

The results of this study indicate that the Khair variety significantly outperformed Inkath in most of the studied parameters. These parameters included plant height, leaf area, and number of grains per head. Furthermore, the Khair variety achieved the highest average grain yield, reaching 3.81 t ha^{-1}. The superiority of Khair can be attributed to differences in the genetic makeup of each variety. Additionally, the use of nano-fertilizers improved all the studied parameters compared to the control treatment. Zinc nano-fertilizer showed a highly significant effect, with the F6 treatment achieving the highest average grain yield of 4.22 t ha^{-1}. This indicates a potential synergistic interaction between zinc and copper at optimal concentrations for all examined parameters. The interactions between the variety and the nano-fertilizer were statistically significant. Among the tested formulations, the (F6 x S1) combination achieved the highest grain yield, reaching 4.52 t ha^{-1}. These results provide evidence of the effectiveness of using nano-fertilizers in improving the physiological and productive performance of the crop. The results of the current study demonstrate the effectiveness of using nano-fertilizers in improving the physiological and productive performance of yellow corn. The study also highlights the importance of genetic and environmental interactions in enhancing the uptake of micronutrients such as zinc and copper. According to these results, the application of nano-fertilizers in two different formulations significantly improves both yield and grain quality. It is recommended that future research investigate the response of different yellow corn varieties, evaluate the accumulation of nanoparticles in the soil and grain, assess their environmental impact, and examine the interaction between nano-fertilizers and nitrogen levels to achieve an optimal balance between growth and yield.

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