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Enhancing the Quantitative and Qualitative Traits of Wheat Grown with Low Mineral Nitrogen Level through Zeolite, Sorbitol and Copper

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THIS FIELD experiment was conducted to investigate the effects of zeolite amendment and foliar applications of copper, both in normal and nano forms, combined with sorbitol spray on the growth, yield, and grain quality of wheat (*Triticum aestivum* L.) under varying mineral nitrogen doses. The scientific aim was to evaluate the potential of these treatments to improve wheat performance and nutrient use efficiency while reducing nitrogen fertilizer inputs (ammonium sulphate, 20.6 % N). The experiment followed a split-split plot design, with nitrogen fertilizer rates (100% and 80% of the recommended dose, equivalent to 75 and 60 kg N per feddan, respectively) as the main plots, zeolite application (applied at rate of 1.7 ton fed^{-1} or not), as the sub-plots, and foliar applications [control (without), copper sulphate ($CuSO_4.7H_2O$, 25 % Cu, 20 mg Cu L^{-1}), sorbitol (500 mM L^{-1}), copper oxide Nanoparticles (CuO NPs, 2.0 ng L^{-1}), sorbitol + mineral Cu as combined treatment, sorbitol+ nano Cu as combined treatment) as sub-sub plots. Results showed that higher nitrogen doses generally increased growth parameters, grain yield, and grain quality attributes, but zeolite incorporation significantly enhanced these parameters even at lower nitrogen levels. Additionally, foliar applications of copper, especially in nano form, combined with sorbitol, further improved wheat performance, emphasizing the importance of integrated nutrient management strategies. Notably, the presence of zeolite mitigated the negative effects of reduced nitrogen doses, highlighting its role in enhancing nutrient use efficiency and crop resilience. The most significant findings included increased grain yield, nitrogen content, protein content, and total sugar content in wheat grains with zeolite application and foliar treatments. The interaction effects demonstrated the synergistic benefits of zeolite with foliar applications, particularly in improving nitrogen and protein contents. Also, the obtained results confirmed that zeolite possessed a vital role in improving soil fertility via raising the soil content of NPK as well as water holding capacity (WHC). Overall, the study underscores the potential of zeolite and foliar applications as effective tools for optimizing wheat production while reducing environmental impacts associated with excessive nitrogen fertilization. It is recommended to further explore these treatments under diverse agro-climatic conditions and crop systems to validate their efficacy and scalability. Additionally, future research should focus on elucidating the mechanisms underlying the observed improvements in nutrient uptake, utilization efficiency, and crop performance to optimize their application strategies for sustainable agriculture.

Keywords: Zeolite, Sorbitol, Copper, Nanoparticles, Sustainable agriculture.

1. Introduction

Wheat holds immense importance for the Egyptian people, serving as a staple food crop that forms the basis of their diet and sustains millions of households across the nation. However, despite its significance, the agricultural sector faces challenges, particularly in reducing the overreliance on mineral nitrogen fertilizers (Farid *et al*. 2023). While essential for wheat growth and productivity, excessive nitrogen application poses environmental risks, including soil degradation and water pollution. Therefore, there is a pressing need to explore sustainable agricultural practices that mitigate these concerns while ensuring food security (Abd El-Aty *et al.* 2024; Gamal *et al.* 2024).

Zeolite emerges as a promising solution in this regard, renowned for its ability to hold nitrogen

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and water in the soil, thereby enhancing nutrient availability and improving soil properties (Szatanik-Kloc *et al.* 2021; El-Ghamry *et al.* 2024; Aslan and Arslan, 2024). Zeolites are a group of hydrated aluminosilicate minerals with a three-dimensional framework structure consisting of aluminum, silicon, and oxygen atoms (Chester and Derouane 2009; Mosa *et al.* 2020). These minerals have a porous crystal structure that allows them to trap and exchange ions, gases, and molecules, making them valuable in various industrial, agricultural, and environmental applications (Sedaghat *et al.* 2022; Elawady *et al*. 2024).

Additionally, copper plays a crucial role in wheat nutrition, aiding in various physiological processes crucial for growth and development (Sarhan and Bashandy 2021). The advent of nano-copper further amplifies its importance, offering increased efficiency and effectiveness in nutrient uptake and utilization (Kumar *et al.* 2021).

Moreover, sugar alcohols, particularly sorbitol, have garnered attention for their potential benefits in wheat cultivation, including improved stress tolerance and yield (El-Sherpiny and Faiyad 2023). Sorbitol, a hexose sugar alcohol with the chemical formula $C_6H_{14}O_6$, is synthesized directly during photosynthesis in mature plant leaves. Its production parallels that of sucrose. It facilitates the translocation of carbon skeletons and energy between source and sink organs within the plant (Elbatrawy *et al.* 2023; Li *et al.* 2023).

Against this backdrop, the main goal of this experiment is to evaluate the efficacy of zeolite amendment, foliar applications of copper in normal and nano forms, and sorbitol spray in enhancing wheat growth, yield, and grain quality while reducing the dependency on mineral nitrogen fertilizers. Through rigorous experimentation and analysis, this study aims to provide valuable insights into sustainable agricultural practices tailored to the unique needs and challenges of wheat cultivation in Egypt, ultimately contributing to the advancement of food security and environmental sustainability in the region.

2. Material and Methods

2.1 Experimental location

Throughout two consecutive seasons, from 2022 to 2024, an experimental study was conducted on a privately-owned farm situated in Met Antar village, within the Talkha district of El-Dakahlia Governorate, Egypt (coordinates: 31°4'54"N - 31°24'4"E).

2.2 Soil sampling

Table 1 displays the properties of the original soil, just before the experiment started, with analysis conducted using standardized methods derived from **Sparks *et al.* (2020) and Dane and Topp (2020),** as the soil samples were collected at a depth of 0-30 cm both initially and at the time of harvest.

Table 1. Characteristics of soil before sowing.

Characteristics	Values
C. sand,%	3.300
F. sand,%	17.10
Silt,%	30.15
Clay	49.45
Textural class	**Clay**
WHC ,%	36.25
EC, dS m^{-1}	3.370
pH	8.100
Organic matter, %	1.190
Nitrogen, mg kg^{-1}	40.92
Phosphorus, mg kg^{-1}	9.150
Potassium, mg kg^{-1}	210.9

2.3 Studied substances preparation

Zeolite was obtained from Alex Company located in Egypt. Table 2 illustrates the attributes of this zeolite. Copper sulphate was obtained from Shams Chemicals Company located in Egypt. Copper oxide nanoparticles were acquired from the National Research Center in Egypt. The size of these nanoparticles (12.9 – 29 nm) was analyzed using TEM imaging (Fig 1), while the X-ray diffraction (XRD) pattern of the copper oxide nanoparticles is depicted in Fig 2. Sorbitol was obtained from Techno Green Company located in Egypt.

Table 2. The characteristics of the studied zeolite.

Characteristics and units	Values
EC, dS m^{-1}	2.5
CEC, cmolc kg^{-1}	160
SiO_2,%	65
AlO_3,%	12

2.4 Experimental design and treatments

The experiment followed a split-split plot design, with nitrogen fertilizer rates (100% and 80% of the recommended dose, equivalent to 75 and 60 kg N per feddan, respectively) as the main plots, zeolite application (applied at rate of 1.7 ton fed^{-1} or not), as the sub-plots, and foliar applications [control (without), copper sulphate ($CuSO_4.7H_2O$, 25% Cu, 20 mg Cu L^{-1}), sorbitol (500 mM L^{-1}), copper oxide Nanoparticles (CuO NPs, 2.0 ng L^{-1}), sorbitol + mineral Cu as combined treatment, sorbitol+ nano Cu as combined treatment) as sub-sub plots. Fig 4 shows the flowchart of this research work.

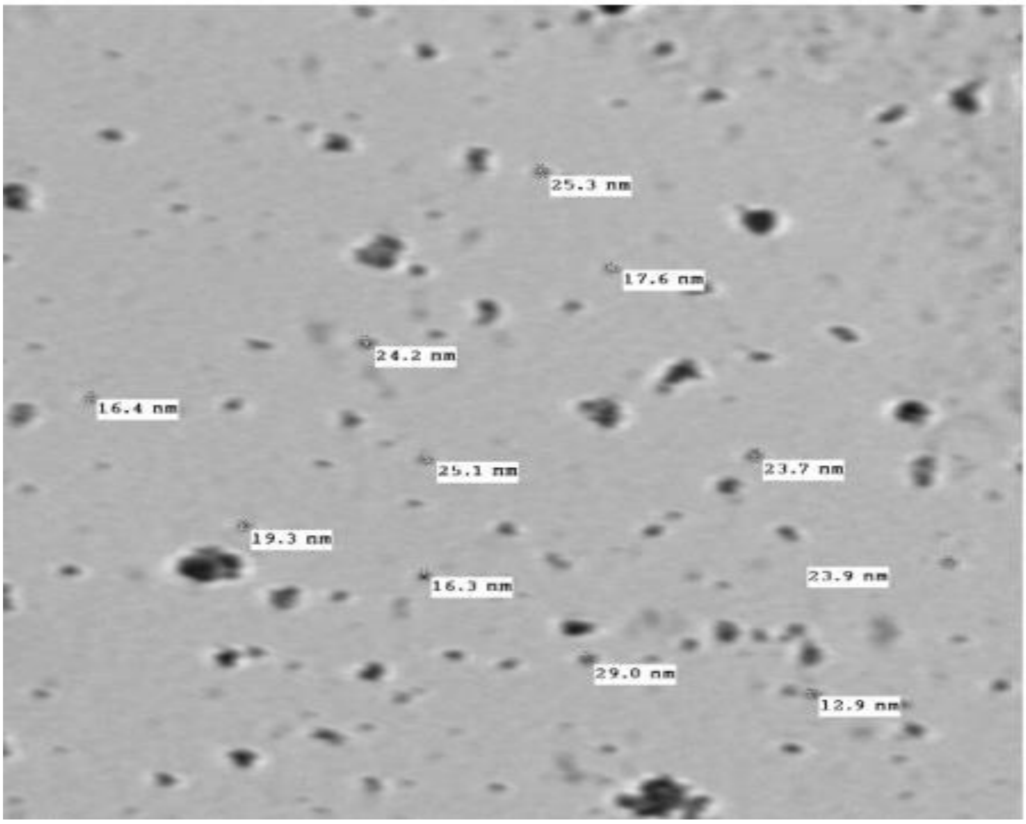

Fig. 1. TEM imaging of the prepared copper oxide Nanoparticles.

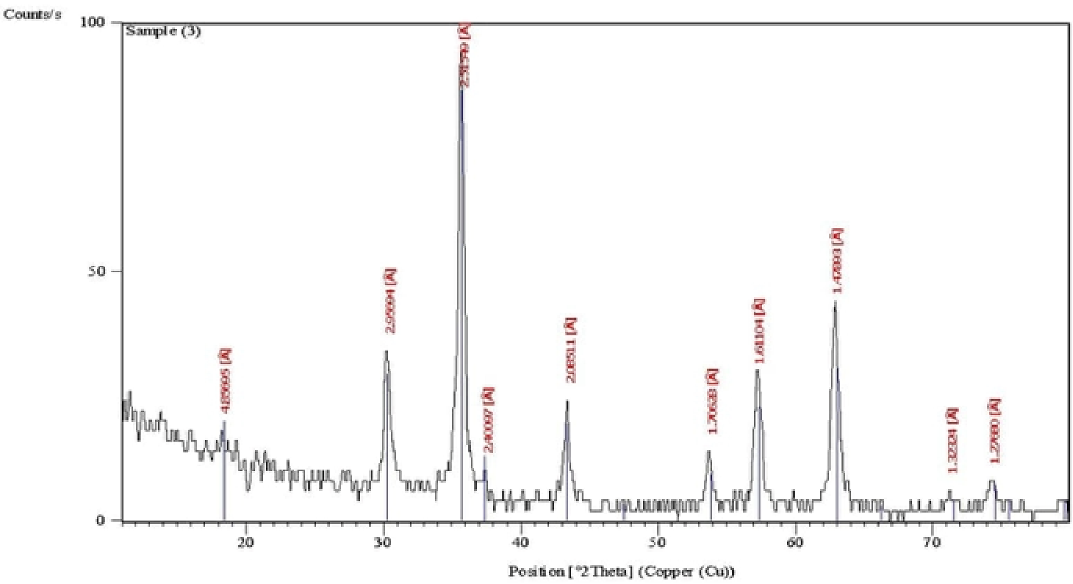

Fig. 2. X-ray diffraction (XRD) pattern of Copper oxide Nanoparticles.

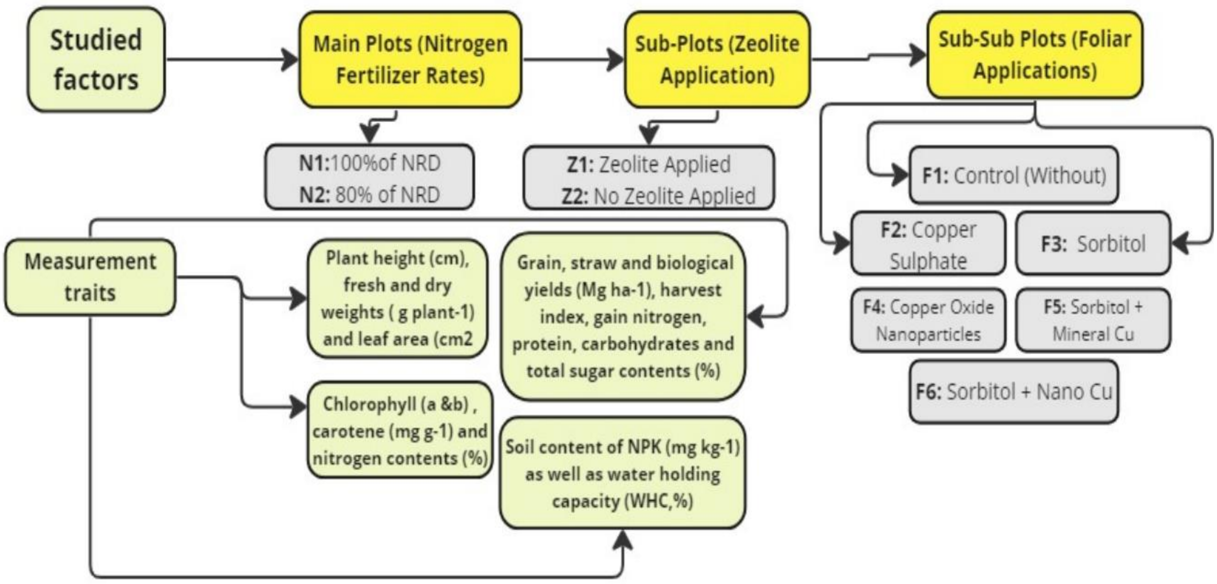

Fig. 3. Flowchart of this research work.

2.5 Experimental setup and cultivation

Initially, the research area was prepared through a series of steps, including ploughing twice, compacting, dividing, and then subdividing into specific experimental units. Each sub-sub plot measured 1.5 x 1.5 meters, covering an area of 2.25 m^2. Cultivation took place on November 7th in both observed seasons, with a seeding rate of 75 kg per feddan (***Triticum aestivum* Cv. Giza 171**, from the Ministry of Agriculture and Soil Reclamation in Egypt MASR) utilizing the broadcasting "Afir method". Ammonium sulphate (20.6 % N) was used as the nitrogen fertilizer, applied according to the studied treatments, as the recommended is 75 kg of N per feddan. Potassium sulfate (39.84% K) served as the potassium fertilizer, applied at a rate of 50 kg K per feddan for all experimental units. Calcium superphosphate (6.75% P) was utilized as the phosphorus fertilizer, applied at a rate of 30 kg P per feddan during soil preparation for all experimental units. The first irrigation was conducted 30 days after sowing, followed by subsequent irrigations every 25 days until reaching the dough stage. These cultivation practices followed the standard agricultural guidelines for wheat cultivation set by the MASR, Egypt.

Before cultivation, zeolite amendment was incorporated into the soil surface layer according to the studied treatments outlined above. The application of sorbitol and copper (both normal and nano forms) occurred either individually or in combination at 30, 45, and 60 days after sowing. The sprayed solution was applied at a volume of 350 liters per feddan for each study treatment. Harvesting was done on April ١5th during both investigated seasons.

2.6 Measurement traits

After 70 days from sowing, plant samples randomly selected to measure plant height (cm), fresh and dry weights (g $plant^{-1}$) and leaf area (cm^2 $plant^{-1}$) as well as to determined chlorophyll (a &b) , carotene (mg g^{-1}) and nitrogen contents (%). Leaf area was estimated using the leaf disc method as described by **Watson (1952).** Photosynthetic pigments were determined in fresh weights (straw) using spectrophotometer apparatus *via* acetone (80%) method according to **Porra *et al.* (1989).** The nitrogen concentration in dry weights samples (straw) was determined using a micro-Kjeldahl apparatus following the method outlined by **Walinga *et al.* (2013).** Wheat tissue samples were dried and then digested with a mixture of

H_2SO_4 and $HClO_4$ (1:1), as described in the standard method by **Peterburgski (1968).**

At harvest stage, yield and its components, including grain, straw and biological yields (Mg ha^{-1}) and harvest index (%) were measured. biological yield is the total biomass of both grain and straw combined. Harvest index reflects the proportion of total biomass allocated to grain production. It was calculated as follows;

$$\% = \frac{\text{Economic yield (grain yield)}}{\text{Biological yield (grain + straw yields)}} \times 100$$

Also, at harvest stage, grain quality such as nitrogen, protein, carbohydrates and total sugar contents (%) were determined according to the **AOAC (2000).** Nitrogen content reflects the nitrogen concentration in the grains, influencing protein content and overall nutritional value. Protein content indicates the proportion of protein in the grains, essential for human and animal nutrition. Protein content was determined by first calculating the nitrogen percentage and then multiplying it by a factor of 5.78. Carbohydrates represents the carbohydrate content in the grains, serving as a major energy source. Carbohydrate levels were assessed using a spectrophotometer, employing hydrochloric acid and anthrone. Total sugar content reflects the total sugar concentration in the grains, contributing to taste and palatability. Total sugar content was determined following extraction with ethyl alcohol (80%). Also, a phenol solution (5%) was used. The nitrogen content was determined as formerly mentioned with the straw samples in the first stage (after 70 days from sowing). ALSO, soil content of NPK (mg kg^{-1}) as well as water holding capacity (WHC, %) were determined using the standard methods as described by **Sparks *et al.* (2020) and Dane and Topp (2020).**

2.7 Statistical analyses

Statistical analysis of the data was conducted using **CoStat version 6.303, copyrighted from 1998 to 20**04, following the methodology outlined by **Gomez and Gomez (1984).**

3. Results

3.1 Plant performance at period of 70 days from sowing

Data of Tables 3 and 4 show the effect of zeolite amendment and sorbitol spray, combined with copper in normal or nano form, on growth performance of wheat grown under different mineral nitrogen doses, including plant height (cm), fresh and dry weights (g $plant^{-1}$) and leaf area (cm^2 $plant^{-1}$) (Table3), chlorophyll (a &b) , carotene (mg g^{-1}) and nitrogen contents (%) (Table 4) after 70 days from sowing during two successive seasons (2022/2023-2023/2024). These tables compares the growth performance of wheat under two nitrogen fertilizer rates: 100% and 80% of the nitrogen recommended dose (NRD). It's evident that higher nitrogen levels generally resulted in increased plant height, fresh & dry weights and leaf area as well as chlorophyll, carotene and nitrogen contents compared to lower nitrogen levels, as indicated by the numerical values and significant differences denoted by asterisks. The inclusion of zeolite amendment in the soil significantly improved wheat growth parameters, photosynthetic pigments and nitrogen concentration across both seasons. Plants treated with zeolite exhibited notably higher plant height, fresh & dry weights and leaf area as well as higher chlorophyll, carotene and nitrogen contents compared to those without zeolite. The statistical analysis confirms the significance of these differences. These tables also explore the effects of different foliar application techniques, including mineral copper, sorbitol, and nano copper, either individually or in combination. Overall, foliar application of copper, especially in nano form, along with sorbitol, resulted in enhanced plant performance, including growth traits, photosynthetic pigments and nitrogen concentration compared to the control and other treatments. Regarding interaction effects or combined treatments, it can be noticed that the presence of zeolite significantly influenced the growth parameters, photosynthetic pigments and nitrogen concentration of wheat, especially when compared to all combined treatments without zeolite. Notably, in treatments with 80% of the nitrogen dose and zeolite application, the plants exhibited comparable or even superior growth performance to those receiving 100% of the nitrogen dose without zeolite. This suggests that the inclusion of zeolite enabled the plant to effectively utilize nitrogen resources, resulting in enhanced growth despite a 20% reduction in nitrogen application. The same trend was found under all studied foliar applications as combined treatments, as these treatments also contributed to variations in growth parameters, photosynthetic pigments and nitrogen concentration further emphasizing the importance of holistic management practices in optimizing crop performance. Finally, the data of both studied seasons were similar, as the consistency of the data across both studied seasons underscores the reliability and reproducibility of the experimental results.

3.2 Yield and its components

Tables 5 and 6 indicate the effect of the studied treatments on grain, straw and biological yields (Mg ha^{-1}) and harvest index (%) (Table5) as well as grain quality such as nitrogen, protein, carbohydrates and total sugar contents (%) (Table6) during two successive seasons (2022/2023-2023/2024) after harvest. Table 5 shows that higher nitrogen doses generally resulted in increased grain yield, straw yield, and biological yield, reflecting the essential role of nitrogen in plant growth and development. Also, the same table illustrates that the incorporation of zeolite into the soil enhanced grain yield, straw yield, and biological yield, indicating improved nutrient availability and utilization efficiency. Additionally, various foliar applications, including mineral copper and sorbitol, showed minor differences in yield parameters compared to the control, suggesting limited impact on yield under the conditions tested. Table 5 also shows that the combined treatments with zeolite demonstrated notable effects on yield parameters, especially when compared to treatments without zeolite. This highlights the synergistic benefits of zeolite in optimizing nutrient uptake and utilization efficiency, particularly in conjunction with reduced nitrogen doses. The consistent harvest index across treatments suggests that the proportion of biomass allocated to grain production remained relatively stable regardless of the experimental conditions. This indicates efficient resource allocation strategies by the wheat plants, contributing to stable grain yields.

On the other hand, Table 6 shows that higher nitrogen doses generally led to increased nitrogen and protein contents in the grains, indicating enhanced protein synthesis and nitrogen assimilation as well as carbohydrates and total sugar contents. Additionally, the Incorporation of zeolite into the soil resulted in higher nitrogen, protein, carbohydrates and total sugar contents in the grains, suggesting improved nutrient availability and uptake efficiency. Also, the same Table indicates that foliar applications showed minor effects on grain quality parameters compared to the control, indicating limited impact on nitrogen assimilation and carbohydrate metabolism. Regarding the interaction effects, it can be noticed that the combined treatments with zeolite exhibited notable effects on grain quality parameters, particularly nitrogen and protein contents. This underscores the importance of integrated nutrient management strategies in optimizing grain quality and nutritional value.

3.3 Soil properties at harvest

Table 7 provides data on the effect of the studied treatments on some soil properties across two consecutive seasons at harvest. Soil properties such as nitrogen (N, mg kg^{-1}), phosphorus (P, mg kg^{-1}), potassium (K, mg kg-1) concentrations, and water holding capacity (WHC, %) were evaluated under various combinations of nitrogen fertilizer rates, zeolite soil addition and foliar application of sorbitol and copper in normal or nano form.

The data reveals significant variations in soil properties among treatments. Firstly, regarding nitrogen fertilizer rates, it's evident that higher doses of nitrogen generally led to higher soil nitrogen concentrations, reflecting the direct influence of nitrogen application on soil nutrient content. Similarly, phosphorus and potassium concentrations tended to increase with higher nitrogen doses, indicating potential interactions between these nutrients due to fertilization practices.

Secondly, the incorporation of zeolite into the soil resulted in elevated levels of nitrogen, phosphorus, and potassium, highlighting the role of zeolite in enhancing nutrient retention and availability in the soil. Zeolite's ability to adsorb and release nutrients gradually likely contributed to these observed improvements in soil fertility. Moreover, the data of the same table show that the addition of zeolite led to a significant increase in WHC (%) of soil at the harvest stage (Figs. 5,6,7 and 8).

Thirdly, the foliar application of sorbitol and copper, whether in mineral or nano form, showed slight effects on soil properties compared to control treatments.

Moreover, the interaction effects between nitrogen fertilizer rates and zeolite application or foliar application of copper further influenced soil properties. For instance, treatments combining zeolite with higher nitrogen doses exhibited the highest soil nutrient concentrations, indicating synergistic effects between nitrogen fertilization and zeolite application in improving soil fertility.

Table 3. Effect of zeolite amendment and sorbitol spray, combined with copper in normal or nano form, on growth performance of wheat grown under different mineral nitrogen doses after 70 days from sowing during two successive seasons (2022/2023-2023/2024).

Treatments			Plant height, cm		Fresh weight, g plant^{-1}		Dry weight, g plant^{-1}		Leaf area, cm^2 plant^{-1}	
			1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor: Nitrogen fertilizer rates										
100 % of NRD			72.21a	81.17a	48.91a	54.49a	17.14a	18.28a	38.09a	40.25a
80 % of NRD			62.18b	68.08b	33.59b	39.96b	11.75b	12.58b	33.84b	35.98b
F test			**	**	**	**	**	**	**	**
Sub main factor : Zeolite application										
Without zeolite			55.72b	59.99b	26.24b	32.62b	8.97b	10.04b	30.71b	32.84b
With zeolite			81.67a	89.27a	56.26a	61.83a	19.92a	20.82a	41.22a	43.38a
F test			**	**	**	**	**	**	**	**
Sub-sub main factor : Foliar application										
Control			62.36f	69.68f	35.37f	40.92f	12.34f	13.44f	33.41f	35.57f
Mineral Cu			65.70e	71.67e	37.53e	43.13e	13.17e	14.03e	34.41e	36.57e
Sorbitol			67.91d	73.09d	39.60d	45.51d	13.99d	14.78d	35.32d	37.40d
Nano Cu			70.38c	74.72c	42.42c	48.07c	14.88c	15.94c	36.79c	38.95c
Sorbitol+ Mineral Cu			72.28b	78.27b	45.07b	51.87b	15.78b	16.84b	37.57b	39.73b
Sorbitol+ Nano Cu			73.54a	80.33a	47.52a	53.85a	16.52a	17.53a	38.10a	40.47a
F test			**	**	**	**	**	**	**	**
Interaction										
100 % of NRD	**Without zeolite**	**Control**	57.18	60.22	28.18	33.22	9.58	11.28	31.62	33.78
		Mineral Cu	58.90	63.14	29.32	35.44	9.97	11.78	31.92	34.08
		Sorbitol	60.54	64.62	31.68	37.90	10.75	12.72	32.20	34.31
		Nano Cu	63.33	68.23	34.74	41.48	11.79	13.93	33.43	35.59
		Sorbitol+ Mineral Cu	65.80	70.80	37.50	44.50	13.00	14.62	33.70	35.86
		Sorbitol+ Nano Cu	68.67	74.52	39.32	45.84	13.47	14.87	34.91	37.07
	With Zeolite	**Control**	82.36	90.35	58.22	61.36	20.60	21.12	41.25	43.41
		Mineral Cu	84.12	93.47	60.42	62.98	21.36	21.58	41.58	43.75
		Sorbitol	87.66	94.15	63.66	67.84	22.66	22.89	41.91	44.07
		Nano Cu	88.43	94.87	65.12	70.45	23.10	23.77	43.80	45.96
		Sorbitol+ Mineral Cu	92.26	99.30	68.33	75.33	24.32	25.03	45.00	47.16
		Sorbitol+ Nano Cu	93.33	100.46	70.46	77.62	25.12	25.79	45.84	48.00
80 % of NRD	**Without Zeolite**	**Control**	45.96	50.36	13.92	20.80	4.58	5.05	23.94	26.10
		Mineral Cu	46.62	50.83	15.69	22.99	5.52	5.58	25.72	27.88
		Sorbitol	48.97	51.16	16.48	23.61	6.05	5.73	28.35	30.17
		Nano Cu	50.42	52.34	20.46	25.82	7.30	7.37	30.52	32.68
		Sorbitol+ Mineral Cu	50.93	55.46	22.33	29.43	7.50	8.41	30.80	32.96
		Sorbitol+ Nano Cu	51.35	58.20	25.30	30.52	8.16	9.15	31.49	33.65
	With Zeolite	**Control**	63.95	77.80	41.16	48.31	14.63	16.32	36.84	39.00
		Mineral Cu	73.18	79.26	44.72	51.14	15.85	17.21	38.43	40.59
		Sorbitol	74.48	82.44	46.58	52.72	16.51	17.81	38.85	41.01
		Nano Cu	79.36	83.47	49.36	54.56	17.34	18.72	39.44	41.60
		Sorbitol+ Mineral Cu	80.16	87.55	52.15	58.23	18.30	19.33	40.80	42.96
		Sorbitol+ Nano Cu	80.83	88.16	55.00	61.42	19.36	20.32	41.00	43.16
F test			*	**	**	**	**	**	**	**

Table 4. Effect of zeolite amendment and sorbitol spray, combined with copper in normal or nano form, on photosynthetic pigments and nitrogen concentration of wheat grown under different mineral nitrogen doses after 70 days from sowing during two successive seasons (2022/2023-2023/2024).

Treatments			Chlorophyll a, mg g^{-1}		Chlorophyll b, mg g^{-1}		Carotene, mg g^{-1}		Nitrogen, %	
			1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor: Nitrogen fertilizer rates										
100 % of NRD			1.007a	1.064a	0.677a	0.709a	0.376a	0.379a	3.21a	3.30a
80 % of NRD			0.946b	0.996b	0.613b	0.645b	0.338b	0.342b	2.92b	3.03b
F test			**	**	**	**	**	**	**	**
Sub main factor : Zeolite application										
Without zeolite			0.905b	0.952b	0.583b	0.615b	0.325b	0.328b	2.76b	3.03b
With zeolite			1.048a	1.108a	0.708a	0.740a	0.389a	0.393a	3.37a	3.30a
F test			**	**	**	**	**	**	**	**
Sub-sub main factor : Foliar application										
Control			0.953f	0.989f	0.617f	0.649f	0.340f	0.342f	2.94f	2.99f
Mineral Cu			0.964e	1.025e	0.628e	0.660e	0.346e	0.351e	2.99e	3.09e
Sorbitol			0.972d	1.027d	0.640d	0.672d	0.355d	0.360d	3.03d	3.15d
Nano Cu			0.980c	1.030c	0.653c	0.685c	0.361c	0.365c	3.09c	3.21c
Sorbitol+ Mineral Cu			0.990b	1.052b	0.662b	0.694b	0.367b	0.371b	3.14b	3.25b
Sorbitol+ Nano Cu			1.001a	1.058a	0.671a	0.703a	0.374a	0.375a	3.20a	3.30a
F test			**	**	**	**	**	**	**	**
Interaction										
100 % of NRD	**Without zeolite**	**Control**	0.905	0.937	0.583	0.615	0.327	0.331	2.76	2.87
		Mineral Cu	0.912	0.970	0.602	0.634	0.334	0.338	2.80	3.00
		Sorbitol	0.916	0.973	0.613	0.645	0.340	0.344	2.86	3.05
		Nano Cu	0.929	0.962	0.624	0.656	0.348	0.352	2.94	3.12
		Sorbitol+ Mineral Cu	0.940	1.00	0.633	0.665	0.355	0.359	3.00	3.15
		Sorbitol+ Nano Cu	0.954	1.016	0.645	0.677	0.368	0.362	3.07	3.20
	With Zeolite	**Control**	1.059	1.096	0.707	0.739	0.386	0.386	3.40	3.31
		Mineral Cu	1.074	1.147	0.715	0.747	0.390	0.394	3.46	3.47
		Sorbitol	1.085	1.155	0.732	0.764	0.408	0.412	3.50	3.56
		Nano Cu	1.094	1.163	0.750	0.782	0.411	0.415	3.54	3.60
		Sorbitol+ Mineral Cu	1.104	1.169	0.758	0.790	0.420	0.424	3.57	3.63
		Sorbitol+ Nano Cu	1.112	1.185	0.766	0.798	0.426	0.430	3.60	3.68
80 % of NRD	**Without Zeolite**	**Control**	0.872	0.911	0.518	0.550	0.287	0.291	2.50	2.55
		Mineral Cu	0.880	0.932	0.535	0.567	0.295	0.299	2.53	2.60
		Sorbitol	0.883	0.910	0.544	0.576	0.302	0.306	2.56	2.67
		Nano Cu	0.885	0.942	0.556	0.588	0.309	0.313	2.61	2.74
		Sorbitol+ Mineral Cu	0.890	0.948	0.568	0.600	0.315	0.319	2.70	2.80
		Sorbitol+ Nano Cu	0.900	0.926	0.575	0.607	0.320	0.324	2.74	2.85
	With Zeolite	**Control**	0.976	1.012	0.660	0.692	0.361	0.365	3.10	3.25
		Mineral Cu	0.992	1.053	0.663	0.695	0.367	0.370	3.15	3.30
		Sorbitol	1.005	1.069	0.672	0.704	0.370	0.374	3.20	3.35
		Nano Cu	1.014	1.054	0.682	0.714	0.376	0.380	3.26	3.40
		Sorbitol+ Mineral Cu	1.028	1.092	0.691	0.723	0.380	0.382	3.30	3.42
		Sorbitol+ Nano Cu	1.04	1.105	0.700	0.733	0.384	0.384	3.37	3.45
F test			**	**	*	*	**	**	**	**

Table 5. Effect of zeolite amendment and sorbitol spray, combined with copper in normal or nano form, on yield of wheat grown under different mineral nitrogen doses at harvest stage during two successive seasons (2022/2023-2023/2024).

Treatments			Grain yield, Mg ha^{-1}		Straw yield, Mg ha^{-1}		Biological yield, Mg ha^{-1}		Harvest index,%	
			1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor: Nitrogen fertilizer rates										
100 % of NRD			6.22a	6.36a	7.88a	8.11a	14.10a	14.47a	44.17a	44.02a
80 % of NRD			5.82b	5.93b	7.23b	7.47b	13.06b	13.41b	44.62a	44.25a
F test			**	**	**	**	**	**	*NS	*NS
Sub main factor : Zeolite application										
Without zeolite			5.60b	5.72b	6.92b	7.14b	12.53b	12.86b	44.72a	44.47a
With zeolite			6.45a	6.58	8.19a	8.44a	14.64a	15.02a	44.08b	43.80b
F test			**	**	**	**	**	**	*NS	*NS
Sub-sub main factor : Foliar application										
Control			5.86f	5.97f	7.31f	7.54f	13.17f	13.52f	44.47a	44.22a
Mineral Cu			5.92e	6.03e	7.40e	7.62e	13.32e	13.66e	44.45a	44.20a
Sorbitol			6.00d	6.12d	7.50d	7.74d	13.50d	13.85d	44.48a	44.16a
Nano Cu			6.06c	6.18c	7.58c	7.81c	13.64c	13.99c	44.44a	44.19a
Sorbitol+ Mineral Cu			6.13b	6.27b	7.72b	7.96b	13.86b	14.24b	44.29a	44.09a
Sorbitol+ Nano Cu			6.19a	6.32a	7.81a	8.07a	14.00a	14.39a	44.24a	43.94a
F test			**	**	**	**	**	**	*NS	*NS
Interaction										
100 % of NRD	**Without zeolite**	**Control**	5.60	5.72	6.95	7.17	12.53	12.89	44.52	44.37
		Mineral Cu	5.67	5.80	7.08	7.24	12.75	13.04	44.46	44.47
		Sorbitol	5.85	5.96	7.17	7.40	13.02	13.36	44.92	44.61
		Nano Cu	5.92	6.04	7.25	7.46	13.17	13.50	44.95	44.70
		Sorbitol+ Mineral Cu	5.96	6.13	7.35	7.56	13.31	13.69	44.77	44.77
		Sorbitol+ Nano Cu	6.08	6.17	7.43	7.67	13.51	13.84	45.00	44.58
	With Zeolite	**Control**	6.50	6.65	8.32	8.57	14.82	15.22	43.85	43.69
		Mineral Cu	6.53	6.70	8.40	8.64	14.93	15.34	43.73	43.67
		Sorbitol	6.59	6.74	8.52	8.77	15.11	15.51	43.61	43.45
		Nano Cu	6.62	6.77	8.64	8.87	15.26	15.64	43.37	43.28
		Sorbitol+ Mineral Cu	6.68	6.84	8.70	8.99	15.38	15.83	43.42	43.20
		Sorbitol+ Nano Cu	6.74	6.89	8.77	9.00	15.51	15.89	43.45	43.36
80 % of NRD	**Without Zeolite**	**Control**	5.23	5.34	6.49	6.68	11.72	12.02	44.62	44.42
		Mineral Cu	5.30	5.38	6.52	6.75	11.82	12.13	44.83	44.35
		Sorbitol	5.32	5.41	6.60	6.82	11.92	12.23	44.62	44.23
		Nano Cu	5.38	5.49	6.64	6.85	12.02	12.34	44.75	44.48
		Sorbitol+ Mineral Cu	5.47	5.58	6.77	6.98	12.24	12.56	44.68	44.42
		Sorbitol+ Nano Cu	5.50	5.62	6.85	7.11	12.35	12.73	44.52	44.14
	With	**Control**	6.11	6.20	7.50	7.76	13.61	13.96	44.89	44.41
		Mineral Cu	6.18	6.27	7.62	7.88	13.80	14.15	44.78	44.31
		Sorbitol	6.25	6.35	7.71	7.97	13.96	14.32	44.76	44.34
		Nano Cu	6.32	6.42	7.82	8.08	14.14	14.50	44.69	44.27
		Sorbitol+ Mineral Cu	6.43	6.54	8.08	8.34	14.51	14.88	44.30	43.95
		Sorbitol+ Nano Cu	6.45	6.60	8.20	8.51	14.65	15.11	44.02	43.67
F test			**	**	**	**	**	**	*NS	*NS

***NS = Non-significant**

Table 6. Effect of zeolite amendment and sorbitol spray, combined with copper in normal or nano form, on grain quality of wheat grown under different mineral nitrogen doses at harvest stage during two successive seasons (2022/2023-2023/2024).

Treatments			Nitrogen,%		Protein,%		Carbohydrates,%		Total sugar,%	
			1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor: Nitrogen fertilizer rates										
100 % of NRD			2.21a	2.27a	12.70a	13.06a	66.58a	67.62a	2.72a	2.79a
80 % of NRD			1.96b	2.00b	11.32b	11.53b	64.28b	65.57b	2.47b	2.52b
F test			**	**	**	**	**	**	**	**
Sub main factor : Zeolite application										
Without zeolite			1.80b	1.88b	10.39b	10.83b	62.89b	64.06b	2.35b	2.39b
With zeolite			2.37a	2.39a	13.63a	13.76a	67.97a	69.13a	2.84a	2.92a
F test			**	**	**	**	**	**	**	**
Sub-sub main factor : Foliar application										
Control			1.95f	2.00f	11.25f	11.52f	64.28f	65.49f	2.46f	2.51f
Mineral Cu			2.00e	2.07e	11.54e	11.91e	64.91e	66.03e	2.52e	2.57e
Sorbitol			2.05d	2.12d	11.81d	12.21d	65.47d	66.37d	2.58d	2.61d
Nano Cu			2.11c	2.17c	12.17c	12.50c	65.64c	66.68c	2.62c	2.70c
Sorbitol+ Mineral Cu			2.18b	2.21b	12.55b	12.69b	65.97b	67.27b	2.67b	2.75b
Sorbitol+ Nano Cu			2.21a	2.25a	12.75a	12.94a	66.33a	67.73a	2.72a	2.79a
F test			**	**	**	**	**	**	**	**
Interaction										
100 % of NRD	**Without zeolite**	**Control**	1.79	1.88	10.29	10.81	62.58	63.13	2.40	2.43
		Mineral Cu	1.83	1.97	10.52	11.32	63.49	64.22	2.44	2.47
		Sorbitol	1.88	2.03	10.81	11.67	64.04	64.57	2.50	2.50
		Nano Cu	1.95	2.09	11.21	12.02	64.31	65.21	2.56	2.58
		Sorbitol+ Mineral Cu	2.09	2.13	12.01	12.25	64.84	66.24	2.58	2.60
		Sorbitol+ Nano Cu	2.13	2.17	12.24	12.47	65.20	67.00	2.64	2.66
	With Zeolite	**Control**	2.38	2.40	13.68	13.80	68.36	69.52	2.84	2.90
		Mineral Cu	2.40	2.43	13.80	13.97	68.71	69.86	2.86	2.94
		Sorbitol	2.43	2.47	13.97	14.20	69.33	70.00	2.90	2.97
		Nano Cu	2.50	2.53	14.37	14.54	69.15	70.13	2.93	3.10
		Sorbitol+ Mineral Cu	2.55	2.56	14.66	14.72	69.45	70.62	3.00	3.18
		Sorbitol+ Nano Cu	2.59	2.62	14.89	15.06	69.60	70.96	3.07	3.22
80 % of NRD	**Without Zeolite**	**Control**	1.51	1.56	8.68	8.97	60.73	62.19	1.95	2.02
		Mineral Cu	1.59	1.67	9.14	9.60	61.24	62.66	2.09	2.15
		Sorbitol	1.65	1.72	9.48	9.89	61.78	63.07	2.18	2.24
		Nano Cu	1.72	1.76	9.89	10.12	62.00	63.24	2.24	2.30
		Sorbitol+ Mineral Cu	1.76	1.80	10.12	10.35	62.15	63.52	2.31	2.36
		Sorbitol+ Nano Cu	1.79	1.84	10.29	10.58	62.40	63.76	2.38	2.40
	With Zeolite	**Control**	2.15	2.18	12.36	12.53	65.48	67.13	2.67	2.70
		Mineral Cu	2.21	2.22	12.70	12.76	66.22	67.41	2.70	2.74
		Sorbitol	2.26	2.28	12.99	13.11	66.73	67.87	2.74	2.76
		Nano Cu	2.30	2.32	13.22	13.34	67.10	68.15	2.78	2.83
		Sorbitol+ Mineral Cu	2.33	2.34	13.39	13.45	67.46	68.72	2.80	2.87
		Sorbitol+ Nano Cu	2.36	2.38	13.57	13.68	68.12	69.22	2.82	2.90
F test			**	**	**	**	**	**	**	**

Table7. Effect of the studied treatments on soil properties at harvest stage during two successive seasons (2022/2023-2023/2024).

Treatments			N, mg kg^{-1}		P, $mgkg^{-1}$		K, $mgkg^{-1}$		*WHC,%	
			1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor: Nitrogen fertilizer rates										
100 % of NRD			44.09a	45.18a	10.10a	10.32a	222.67a	225.88a	39.13a	39.43a
80 % of NRD			42.31b	43.40b	9.38b	9.56b	213.81b	216.65b	40.42a	40.35a
F test			**	**	**	**	**	**	*NS	*NS
Sub main factor : Zeolite application										
Without zeolite			41.52b	42.52b	9.02b	9.19b	207.11b	209.49b	37.13b	38.27b
With zeolite			44.89a	46.05a	10.46a	10.70a	229.37a	233.04a	40.42a	41.51a
F test			**	**	**	**	**	**	**	**
Sub-sub main factor : Foliar application										
Control			43.91a	45.01a	10.03a	10.26a	221.77a	224.82a	38.52b	39.32bc
Mineral Cu			43.63a	44.8ab	9.94a	10.18a	220.36a	223.19a	39.11a	39.71b
Sorbitol			43.46a	44.50b	9.81a	10.06a	219.27a	221.89a	39.18a	40.15b
Nano Cu			43.07a	44.20b	9.70a	9.86a	217.69b	220.60a	38.81ab	41.01a
Sorbitol+ Mineral Cu			42.76b	43.81b	9.57a	9.71ab	215.98b	219.08b	38.50b	40.84b
Sorbitol+ Nano Cu			42.39b	43.46c	9.38ab	9.57b	214.38b	218.02b	38.53b	39.33bc
F test			*	*	*	*	*	*	*	*
Interaction										
100 % of NRD	**Without zeolite**	**Control**	43.14	44.22	9.74	9.90	213.70	216.34	36.57	37.49
		Mineral Cu	43.00	44.07	9.66	9.82	213.37	215.20	36.63	37.66
		Sorbitol	42.86	43.7	9.52	9.74	211.75	214.41	36.76	37.60
		Nano Cu	42.30	43.12	9.40	9.52	210.45	212.77	36.81	37.60
		Sorbitol+ Mineral Cu	41.94	42.90	9.27	9.36	208.23	211.15	36.48	37.58
		Sorbitol+ Nano Cu	41.65	42.76	9.00	9.20	206.71	209.37	36.59	37.49
	With Zeolite	**Control**	46.66	47.80	11.00	11.34	238.22	241.57	41.05	37.64
		Mineral Cu	46.30	47.56	10.96	11.26	237.35	240.44	41.18	42.32
		Sorbitol	45.96	47.04	10.80	11.17	235.44	238.96	40.96	42.12
		Nano Cu	45.33	46.85	10.73	11.00	234.12	238.09	40.76	41.84
		Sorbitol+ Mineral Cu	45.09	46.16	10.65	10.82	232.50	237.14	41.11	41.78
		Sorbitol+ Nano Cu	44.90	46.00	10.50	10.76	230.24	235.17	41.09	42.15
80 % of NRD	**Without Zeolite**	**Control**	41.24	42.30	8.93	9.13	205.45	208.72	37.29	42.00
		Mineral Cu	41.02	42.00	8.80	9.10	203.98	206.96	38.37	37.80
		Sorbitol	40.87	41.96	8.71	8.94	203.60	205.73	38.40	39.23
		Nano Cu	40.66	41.68	8.59	8.70	202.95	204.91	37.09	39.14
		Sorbitol+ Mineral Cu	40.15	41.22	8.43	8.52	202.76	204.30	37.22	37.92
		Sorbitol+ Nano Cu	39.43	40.42	8.22	8.35	202.37	204.12	37.37	37.82
	With Zeolite	**Control**	44.62	45.73	10.45	10.70	229.71	232.66	39.18	40.17
		Mineral Cu	44.23	45.42	10.36	10.56	226.74	230.18	40.27	41.09
		Sorbitol	44.16	45.30	10.22	10.39	226.32	228.49	40.62	41.65
		Nano Cu	44.00	45.16	10.11	10.24	223.26	226.66	40.58	41.46
		Sorbitol+ Mineral Cu	43.86	44.97	9.96	10.16	220.45	223.73	39.19	46.08
		Sorbitol+ Nano Cu	43.58	44.66	9.80	10.00	218.20	223.44	39.07	39.88
F test			**	**	*	*	**	**	**	**

***WHC= Water holding capacity**

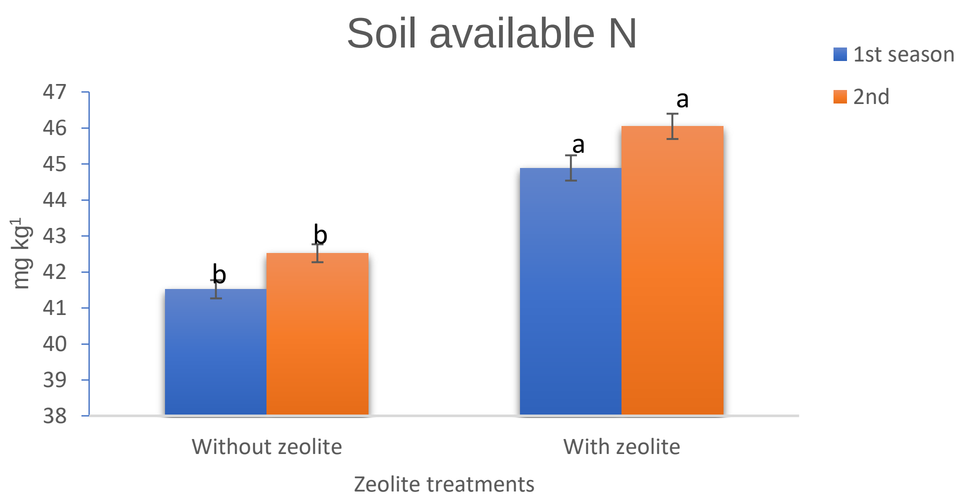

Fig. 4. Effect of zeolite treatments on soil available nitrogen.

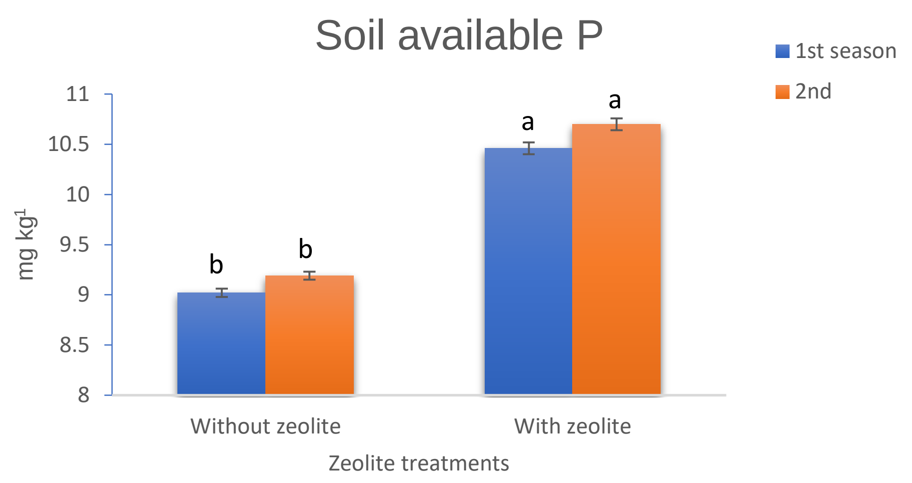

Fig. 5. Effect of zeolite treatments on soil available phosphorus.

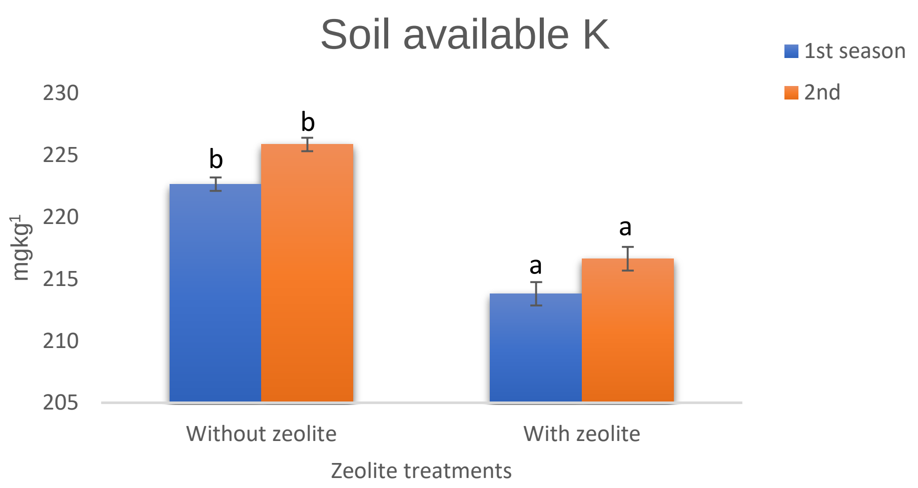

Fig. 6. Effect of zeolite treatments on soil available potassium.

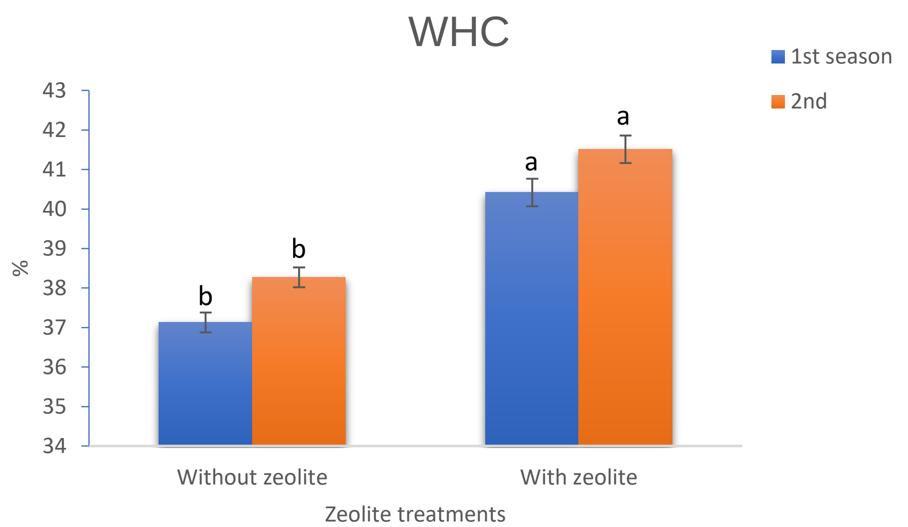

Fig. 7. Effect of zeolite treatments on soil water holding capacity.

4. Discussion

4.1 Plant performance at period of 70 days from sowing

The obtained results can be attributed to several scientific factors. Higher nitrogen levels generally led to increased plant growth parameters and physiological characteristics due to the essential role of nitrogen in various metabolic processes, including protein synthesis, chlorophyll production, and enzyme activities. The availability of nitrogen directly influences plant growth and development, and thus, higher nitrogen doses typically result in superior plant performance (**Mălinaş *et al.* 2022)**.

Zeolite's high cation exchange capacity (CEC) allows it to effectively adsorb and retain ammonium ions (NH_4^+) released from nitrogen fertilizers. By immobilizing nitrogen within its porous structure, zeolite minimizes nutrient leaching and loss, thereby extending the period of nitrogen availability to plants. This enhanced nitrogen retention contributes to improved plant growth and nutrient utilization efficiency. The results are in harmony with those of **Mosa *et al.* (2020), Szatanik-Kloc *et al.* (2021) and El-Ghamry *et al.* (2024)**.

The superiority of the combined treatment of sorbitol + Nano Cu may be attributed to the following reasons. Sorbitol (sugar alcohol) serves as a biostimulant that may have enhanced the wheat plant's resilience and stress tolerance. It may have promoted nutrient uptake and translocation within the wheat plant, leading to increased nutrient use efficiency. Additionally, sorbitol could improve water uptake and retention, contributing to improved plant hydration and nutrient absorption **(El-Sherpiny and Faiyad 2023).** On the other hand, copper is an essential micronutrient that acts as a cofactor for numerous enzymes involved in metabolic processes, including photosynthesis, respiration, and lignin synthesis. Adequate copper availability is critical for optimal plant growth and development. Nano-sized copper particles offer enhanced bioavailability and efficacy due to their smaller particle size and increased surface area, allowing for better nutrient uptake and utilization by plants (**Kumar *et al.* 2021; Sarhan and Bashandy 2021)**.

The synergistic interactions between nitrogen, zeolite, sorbitol, and copper likely contributed to the observed results. Zeolite's ability to enhance nitrogen retention may have potentiated the effects of sorbitol and copper by providing a stable nutrient reservoir for plants. Similarly, the biostimulant effects of sorbitol and the metabolic benefits of copper may have synergized with the improved nutrient availability facilitated by zeolite, leading to enhanced plant growth and performance.

4.2 Yield and its components

The observed results in Tables 5 and 6 provide valuable insights into the complex interplay between agronomic practices, nutrient management, and crop physiology, influencing yield and grain quality parameters in wheat cultivation. Firstly, the significant impact of nitrogen fertilization on grain, straw, and biological yields, as evidenced by Table 5, underscores the pivotal role of nitrogen in plant growth and development. Nitrogen is a crucial component of chlorophyll, amino acids, and proteins, essential for photosynthesis, enzyme function, and structural integrity. Higher nitrogen doses generally promote increased biomass accumulation, translating into higher grain and straw yields. Additionally, the stability of the harvest index across treatments suggests efficient resource allocation towards grain production, contributing to stable grain yields (**Mălinaş *et al.* 2022)**.

Moreover, the incorporation of zeolite into the soil appears to enhance nutrient availability and utilization efficiency, as indicated by the improved grain, straw, and biological yields in Table 5. Zeolites possess ion-exchange properties, allowing them to retain and slowly release nutrients, including nitrogen, potassium, and calcium, thereby promoting sustained nutrient availability throughout the crop growth period. This, in turn, contributes to enhanced crop productivity and resilience to nutrient stress. The findings are in accordance with those of **Sedaghat *et al.* (2022) and Elawady *et al.* (2024).**

In terms of grain quality parameters depicted in Table 6, higher nitrogen doses result in increased nitrogen and protein contents in the grains, reflecting enhanced nitrogen assimilation and protein synthesis. Similarly, the incorporation of zeolite into the soil leads to higher nitrogen, protein, carbohydrates, and total sugar contents, indicating improved nutrient uptake efficiency and subsequent metabolic processes in the plant.

Furthermore, while foliar applications, including Nano copper and sorbitol, showed minor effects on yield and grain quality parameters compared to the control, the combined treatments with zeolite exhibited notable effects. This emphasizes the synergistic benefits of integrated nutrient management strategies, particularly when zeolite is utilized, in optimizing both yield and grain quality aspects of wheat cultivation (**Kumar *et al.* 2021; Elbatrawy *et al.* 2023; Li *et al.* 2023)**.

4.3 Soil properties at harvest

The zeolite amendment may have been the only factor, which positively affected the soil properties at harvest. The observed effects of zeolite on soil properties, particularly its role in holding water and nutrients, can be attributed to its unique properties and interactions with the soil environment. Zeolites are microporous, aluminosilicate minerals with a highly regular structure of pores and chambers. Zeolites possess a high CEC, which allows them to attract and retain positively charged ions, including essential plant nutrients like ammonium (NH_4^+), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}). This property enables zeolites to serve as reservoirs for nutrients, preventing their leaching and making them available for plant uptake over an extended period. The porous structure of zeolites enables them to adsorb and retain water molecules within their cavities through capillary action. This characteristic helps to increase soil water holding capacity (WHC) by reducing water loss through drainage and evaporation. Consequently, plants have improved access to water, especially during dry periods, leading to enhanced growth and productivity. Zeolites release nutrients gradually over time as they come into contact with soil moisture. This slow-release mechanism ensures a continuous supply of nutrients to plant roots, promoting sustained growth and development throughout the growing season. By holding onto nutrients, zeolites prevent nutrient runoff and leaching, thereby maximizing nutrient use efficiency. Incorporating zeolite into the soil may have improved soil structure and tilth by enhancing aggregation and reducing compaction. The results align with the discoveries made by **Elawady *et al.* (2024) and El-Ghamry *et al.* (2024)**.

5. Conclusion

The findings of this field experiment highlight the significant potential of zeolite amendment and foliar applications of copper, both in normal and nano forms, combined with sorbitol spray, to enhance the growth, yield, and grain quality of wheat under varying nitrogen fertilizer rates. Higher nitrogen doses generally led to improved growth parameters and grain yield, but the inclusion of zeolite in the soil substantially enhanced these effects even at reduced nitrogen levels. The synergistic benefits observed with foliar applications, particularly in nano form, further emphasize the importance of integrated nutrient management strategies in optimizing wheat production while minimizing environmental impacts. Zeolite played a crucial role in improving nutrient use efficiency, water retention, and crop resilience, particularly under conditions of nitrogen limitation. The results underscore the importance of holistic approaches to nutrient management, integrating soil amendments and foliar applications to maximize crop performance and sustainability. Overall, the findings contribute valuable insights into sustainable agricultural practices, providing practical recommendations for optimizing wheat production and minimizing nitrogen fertilizer inputs. Further research is warranted to explore the underlying mechanisms and validate the efficacy of these treatments across diverse agro-climatic conditions and crop systems, paving the way for more sustainable and resilient agriculture in the future.

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