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Effect of Organic Amendments and Synthetic Substances on Copper Availability, Absorption, and Wheat Productivity

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COPPER (Cu) plays a crucial role in various physiological processes in wheat plants and its presence is significant for the formation and structure of gluten in wheat grain. The effect of organic and synthetic substances on copper availability, absorption, and wheat productivity can vary depending on the specific substance and its interaction with the soil, plants, and environmental conditions. So, a research trial was conducted during seasons of 2021/2022 and 2022/2023 to assess the impacts of various soil amendments (T_1: Control; T_2: Compost; T_3: Zeolite; T_4: Compost + Zeolite) as main plot treatments, as well as the addition of copper sulphate (Cu_1: Control; Cu_2: 3.0 kg fed^{-1}; Cu_3: 6.0 kg fed^{-1}) as sub-main plot treatments. The study aimed to evaluate the effects of these treatments on plant performance and the availability of soil nutrients, with a particular focus on copper. The superior treatment for obtaining the highest values of N, P, K % of straw after 65 days from sowing was the combined treatment of zeolite and compost (T_4), while the check treatment (T_1) yielded the minimum values. Also, both studied rates of copper sulphate (3 and 6 kg fed^{-1}) significantly increased the values of straw N, P, K % compared to check treatment (Cu_1). The superior treatment for obtaining the highest values of grain and straw yield (Mg ha^{-1}) as well as grain chemical constituents [(N, P, K (%), Fe, Mn, Zn, Cu (mg kg^{-1})] and grain content of carbohydrate and protein was the combined treatment of zeolite and compost (T_4), followed by T_2 treatment (compost alone) then T_3 treatment (zeolite alone) and lately the check treatment (T_1). In terms of grain and straw yield (Mg ha^{-1}) and the chemical constituents of the grain (Fe, Mn, Zn, and Cu in mg kg^{-1}), the third rate of copper sulphate (6 kg fed^{-1}) outperformed the second rate (3 kg fed^{-1}) and the control treatment (without $CuSO_4$). Generally, the best performance in terms of yield and the most studied traits were achieved under the combined treatment of T_4 and Cu_3 (6 kg fed^{-1}). On the other hand, the addition of compost and zeolite (either alone or in combination) increased the availability of soil Cu. Simultaneously, the addition of copper sulphate contributed to raising nutrient availability as well. Finally, these improvements can positively impact the economic value of wheat crops, promote food security, and contribute to overall agricultural productivity.

Keywords: Compost, zeolite, $CuSO_4$, wheat.

1. Introduction

Copper is an essential micronutrients for the growth and development of plants, including wheat **(Kumar *et al.* 2009).** It plays a crucial role in various physiological processes, and its presence is particularly important for the formation and structure of gluten in wheat **(Azooz *et al.* 2012).** Additionally, copper plays a role in enzyme activity and redox reactions within the plant cells **(Liščáková *et al.* 2022).** Enzymes involved in gluten formation and modification require copper as a cofactor for their proper functioning **(Farooq *et al.* 2022).** Copper-dependent enzymes participate in the cross-linking of gluten proteins, helping to stabilize the gluten network and enhance its

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structural integrity **(Hosseinpour *et al.* 2022).** Adequate copper availability in the soil is necessary to ensure optimal gluten development in wheat **(Khan *et al.* 2022).** Copper deficiency can lead to poor gluten formation, resulting in weak dough that fails to rise properly and produces inferior bread quality. Insufficient copper levels may also impair overall plant growth and development, leading to reduced yields and increased susceptibility to diseases **(Ma *et al.* 2022).** Farmers and agricultural practices often address copper deficiency by supplementing the soil with appropriate copper fertilizers or amendments. This ensures that wheat plants have sufficient copper uptake, promoting healthy gluten development and enhancing the quality of wheat-based products **(Wieser *et al.* 2023).** In modern agriculture, maximizing plant performance and optimizing soil nutrient availability are essential goals for farmers and agricultural practitioners. One approach to achieve these goals is through the utilization of soil amendments, such as zeolite and compost (**Ghazi *et al.* 2023**). Zeolite is a naturally occurring mineral with a unique crystalline structure that can retain and release water and nutrients (**Khalifa *et al.* 2021; Rosalina *et al.* 2019**), while compost is an organic material rich in nutrients and beneficial microorganisms (**Elmahdy *et al.* 2022**). The application of zeolite and compost as soil amendments has gained increasing attention due to their potential to enhance plant growth, improve nutrient availability, and promote sustainable agricultural practices (**Soudejani *et al.* 2019**). The effect of zeolite on plant performance and soil nutrient availability can be attributed to its various properties **(Abdel-Hassan and Radi 2018).** Zeolite has a high cation exchange capacity, allowing it to hold onto essential plant nutrients such as potassium, calcium, and magnesium and release them slowly over time, making them more available for plant uptake **(Shahbaz *et al.* 2019).** Additionally, zeolite can improve soil structure by enhancing water retention and reducing nutrient leaching, thus creating a more favorable environment for root development and nutrient absorption by plants. The increased water-holding capacity of zeolite can also contribute to drought tolerance in plants **(Wang *et al*. 2021).** Compost, on the other hand, has multiple benefits for plant performance and soil nutrient availability **(Elsherpiny and Helmy 2022).** It enriches the soil with organic matter, improving soil structure, water-holding capacity, and nutrient retention. Compost acts as a slow-release fertilizer, gradually releasing essential nutrients for plant growth **(Elsherpiny 2023).** Furthermore, compost promotes the growth of beneficial soil microorganisms, which enhance nutrient cycling, suppress pathogenic organisms, and improve overall soil health **(Elsherpiny and Kany 2023).**

Therefore, the main objective of this research work is to assess the impacts of various soil amendments (compost and zeolite) as well as the addition of copper sulphate on wheat plant performance and the availability of soil nutrients, with a particular focus on copper.

2. Material and Methods

A research trial was conducted during seasons of 2021/2022 and 2022/2023 to assess the impacts of various soil amendments [T_1: Control; T_2: Compost alone (6 ton ha^{-1}); T_3: Zeolite alone (6 ton ha^{-1}); T_4: Compost combined with Zeolite (3 ton ha^{-1} of each one)] as main plot treatments, as well as the addition of copper sulphate at different rates (Cu_1: Control; Cu_2: 3.0 kg fed^{-1}; Cu_3: 6.0 kg fed^{-1}) as sub-main plot treatments on wheat plant performance, productivity and the availability of soil nutrients.

- Experimental location

This work research was executed in the Sakha Experimental Farm (31°5' 38.543" N latitude and 30°56' 49.65" E longitude), Kafr El-Sheikh Governorate, Egypt.

- Soil sampling

Before conducting the experiment, a soil sample was collected from a depth of 0-30 cm and subsequently analyzed using standard methods. The resulting characteristics of the soil sample are outlined in Table 1.

- Studied substances

The compost, zeolite, and copper sulfate used in the experiment were acquired from the Egyptian commercial market. The specific characteristics of these materials are provided in Table 2.

- **Wheat seeds**

The seeds used in the experiment were specifically "**Cv. Sakha 95**" and they were obtained from the Agricultural Research Center (ARC), Egypt. The sowing of these seeds was conducted on the 15th of November during both seasons.

- **Experimental set up**

Wheat seeds were planted at a rate of 145 kg ha^{-1} in plots with a sub-plot area of 10.24 m2 (3.2 m × 3.2 m) under a split plot experimental design with three replicates. One month prior to planting, the assigned compost and zeolite treatments were applied to the respective plots as previously mentioned. Copper sulfate was added at the specified rates along with the first nitrogen dose, which was administered 30 days after sowing. Ammonium sulfate (20.6% N) was applied in two equal portions during cultivation, specifically at 30 and 50 days after planting, with a total rate of 300 kg N ha^{-1}. Additionally, calcium superphosphate (6.6% P) was incorporated before plowing at a rate of 250 kg ha^{-1}, and potassium sulfate (48% K_2O) was applied together with calcium superphosphate at a rate of 120 kg ha^{-1}. All standard agricultural practices, including irrigation through six flood system applications, were followed. Harvesting took place on May 1st during both seasons.

- **Measurements**

a- At 65 days from sowing

- Straw nitrogen, phosphorus and potassium content,%

b- At harvest stage

- Grain and straw yield, Mg ha^{-1}
- Grain nitrogen, phosphorus and potassium content,%
- Grain iron, manganese, zinc and copper content, mgk g^{-1}
- Grain content of carbohydrate and protein,%
- Soil available nitrogen, phosphorus, potassium and copper, mgkg^{-1}
- Soil water holding capacity WHC,%
- Cation exchange capacity CEC, cmol kg^{-1}

Methods

To prepare the samples for analysis, 0.5 g of ground and dried plant materials were placed into 125 mL conical digestion flasks. A triacid mixture consisting of sulfuric acid, and perchloric acid in a ratio of 2:1 (v/v) was added to the flasks, totaling 12 mL. The plant materials were digested at room temperature for 3 hours, followed by an additional 2-3 hours of digestion on a hot plate until the resulting digest became clear or colorless. After cooling, the contents of the flasks were diluted to an appropriate volume for further analysis **(Sahrawat *et al*. 2002).**

The levels of nitrogen (N), phosphorus (P), and potassium (K) in the wheat straw and grain were assessed using specific methods. The Kjeldahl method was employed to measure nitrogen levels, the spectrophotometric method was used for phosphorus level analysis, and the flame photometer method was utilized to determine potassium levels. These methods were adopted based on **Ashworth *et al*. (1997).** While the levels of iron (Fe), manganese (Mn), zinc (Zn) and copper (Cu) in the wheat grain were assessed using Atomic Absorption Spectroscopy (AAS) **(Soil Science Research Institute of Sinica, 1983).** Furthermore, the total carbohydrate and protein content in the wheat grain samples were determined following the guidelines outlined by **AOAC (2000)** (Association of Official Agricultural Chemists), as the wheat grains were subjected to a milling process to remove the outer husk, and then they were ground into flour using a stainless steel grinder. The available soil nutrients were determined using various extraction methods following formal protocols. Specifically, the following extraction methods were used to assess the availability of different nutrients in the soil. Potassium sulfate (K_2SO_4) at a concentration of 1% was employed to extract available soil nitrogen (Kjeldahl method). The Olsen method was used to extract available soil phosphorus (spectrophotometric method). Ammonium acetate was used to extract available soil potassium (flame photometer method). DTPA (diethylene triamine pentaacetic acid) was utilized to extract available soil copper (BY AAS) **(Jackson 1967)**. pH was determined *via* 1:2.5 soil: water suspension, while EC was determined *via* soil paste extract. Soil water holding capacity was determined according to **Klute and Dirksen (1986).** Cation exchange capacity was determined according to **Black (1965)** using ammonium acetate at pH 7.0.

- Statistical analysis

The data analysis was performed using CoStat version 6.303 (1998-2004), following the statistical technique described in the methodology based on **Gomez and Gomez (1984).** The significance level for the least significant difference (LSD) test was set at 0.05.

Table 1. The mean values of some physical and chemical properties of the experimental soil before cultivation depending on Sparks *et al.* (2020) and Dane and Topp (2020).

Seasons	Particle size distribution				Bulk density, kg m^{-3}	Total porosity, %	Void ratio (Vr)	OM, %	$CaCO_3$, %	SAR
	Sand, %	Silt, %	Clay, %	Texture class						
1st	17.52	32.18	50.30	Clayey	1.30	50.55	1.12	1.21	2.42	5.48
2nd	17.63	32.10	50.27	Clayey	1.34	50.59	1.10	1.24	2.34	5.77

Seasons	pH	EC, dSm^{-1}	Soluble cations and anions, meq L^{-1}								Available nutrients, mg kg^{-1}			
			Ca^{++}	Mg^{++}	Na^{+}	K^{+}	CO_3^{--}	HCO_3^{-}	Cl^{-}	SO_4^{--}	N	P	K	Cu
1st	8.82	4.23	11.98	11.19	18.64	0.426	-	3.18	15.21	23.84	33.8	6.43	267	1.08
2nd	8.82	4.20	11.92	11.05	18.70	0.417	-	3.15	15.06	23.79	31.2	6.72	271	1.14

Table 2. Characteristics of compost, zeolite and copper sulphate used in this study depending on Tandon (2005).

Compost		Zeolite	
Characteristics	Values	Characteristics	Values
EC, dsm^{-1}	4.10	**EC, dsm^{-1}**	2.70
pH	6.45	**CEC, cmol$_c$ kg^{-1}**	145
C:N ratio	12.0	**K_2O,%**	6.30
CEC, cmol kg^{-1}	125.0	**P_2O_5,%**	1.00

Copper sulphate	
Characteristics	Values
Chemical Formula	$CuSO_4$
Molecular Weight	159.61 g/mol
Purity	98%
Density	3.60 g/cm³
Appearance	Blue crystalline solid
Solubility	Highly soluble in water
Toxicity	Toxic to aquatic life
Melting Point	110 °C
pH Level	Acidic (approximately 4)

3. Results

- Chemical constituents of straw at 65 days from sowing

Table 3 displays the impact of various techniques for adding compost and zeolite, along with different rates of copper sulphate, to soil on the chemical constituents (N, P, K %) of straw after 65 days from sowing, during the 2021/2022 and 2022/2023 seasons.

Effect of the studied substances (compost and zeolite): The data illustrate that the superior treatment for obtaining the highest values of N, P, K % was the combined treatment of zeolite and compost (T_4), while the check treatment (T_1) yielded the minimum values. Also, T_3 treatment (zeolite alone) came in the third order. The different between T_4 treatment and T_2 treatment was non-significant as for all aforementioned traits except the values of N% in the first season, as the T_2 ranked second.

Effect of copper sulphate: The data presented in Table3 show that the both studied rates of copper sulphate (3 and 6 kg fed^{-1}) significantly increased the values of straw N, P, K % compared to check treatment (**Cu_1**). Also, it worth mentioning that the different between **Cu_2** and **Cu_3** treatments was non-significant as for N% values in the first season and P % in both seasons. However, the Cu_3 treatment was superior in terms of N% values in the second season and K% in both seasons. Generally, the highest values of straw N, P, K % were achieved under the combined treatment of T_4 and Cu_3, while the lowest values were recorder under check treatment (T_1 x Cu_1).

Table 3. Impact of compost, zeolite, and copper sulphate on chemical constituents of wheat straw at 65 days from sowing in the seasons of 2021/2022 and 2022/2023.

Treatments		N		P		K	
		(%)					
		1st	2nd	1st	2nd	1st	2nd
Addition of soil amendments							
T_1		0.25d	0.23c	0.045c	0.045c	1.21c	1.20c
T_2		0.55b	0.54a	0.088a	0.086a	1.60a	1.58a
T_3		0.50c	0.47b	0.077b	0.073b	1.43b	1.40b
T_4		0.60a	0.57a	0.089a	0.088a	1.62a	1.59a
LSD at 5%		**0.05**	**0.05**	**0.008**	**0.006**	**0.06**	**0.04**
Soil addition of $CuSo_4$							
Cu_1		0.44b	0.42b	0.061b	0.058b	1.35c	1.33c
Cu_2		0.48a	0.46ab	0.080a	0.080a	1.48b	1.46b
Cu_3		0.51a	0.49a	0.083a	0.081a	1.57a	1.55a
LSD at 5%		**0.04**	**0.04**	**0.004**	**0.004**	**0.04**	**0.04**
Interaction							
T_1	**Cu_1**	0.21	0.19	0.032	0.030	1.13	1.08
	Cu_2	0.25	0.23	0.057	0.058	1.20	1.18
	Cu_3	0.29	0.26	0.045	0.048	1.31	1.35
T_2	**Cu_1**	0.50	0.51	0.082	0.080	1.49	1.50
	Cu_2	0.56	0.54	0.090	0.087	1.60	1.58
	Cu_3	0.59	0.57	0.092	0.092	1.70	1.67
T_3	**Cu_1**	0.47	0.43	0.056	0.052	1.36	1.34
	Cu_2	0.50	0.47	0.086	0.083	1.43	1.40
	Cu_3	0.54	0.50	0.088	0.084	1.50	1.46
T_4	**Cu_1**	0.56	0.53	0.074	0.071	1.43	1.40
	Cu_2	0.61	0.58	0.099	0.096	1.69	1.66
	Cu_3	0.63	0.61	0.095	0.097	1.75	1.70
LSD at 5%		**0.07**	**0.07**	**0.008**	**0.007**	**0.07**	**0.08**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

T_1: Control; **T_2:** Compost; **T_3:** Zeolite; **T_4:** Compost + Zeolite; **Cu_1:** Control; **Cu_2:** 3.0 kg fed^{-1}; Cu_3: 6.0 kg fed^{-1}

- Yield and grain chemical content and quality

Tables 4 and 5 indicate the effect of the soil addition of compost and zeolite as well as various rates of copper sulphate on yield (grain and straw, Mg ha^{-1}) and grain chemical constituents [(N, P, K (%), Fe, Mn, Zn, Cu (mg kg^{-1})] at harvest stage during seasons of 2021/2022 and 2022/2023. On the other hand, Fig 1 illustrates the individual effect of soil amendments (compost and zeolite) on grain content of carbohydrate and protein, while Fig 2 shows the individual effect of copper sulphate on grain content of carbohydrate and protein at harvest stage in the seasons of 2021/2022 and 2022/2023.

Effect of the studied substances (compost and zeolite): The data illustrate the studied treatments significantly affected all aforementioned traits. The superior treatment for obtaining the highest values of grain and straw yield (Mg ha^{-1}) as well as grain chemical constituents [(N, P, K (%), Fe, Mn, Zn, Cu (mg kg^{-1})] and grain content of carbohydrate and protein was the combined treatment of zeolite and compost (T_4), followed by T_2 treatment (compost alone) then T_3 treatment (zeolite alone) and lately the check treatment (T_1).

Effect of copper sulphate: In terms of grain and straw yield (Mg ha^{-1}) and the chemical constituents of the grain (Fe, Mn, Zn, and Cu in mgkg^{-1}) as well as the carbohydrate and protein content of the grain (%), the third rate of copper sulphate (6 kg fed^{-1}) outperformed the second rate (3 kg fed^{-1}) then the control treatment (without $CuSO_4$), which came in the last order. Generally, the best performance in terms of yield and the most studied traits were achieved under the combined treatment of T_4 and Cu_3 (6 kg fed^{-1}).

Table 4. Impact of compost, zeolite, and copper sulphate on yield and grain chemical constitutes (macronutrients) at harvest stage in the seasons of 2021/2022 and 2022/2023.

Treatments		Grain yield (Mg ha^{-1})		Straw yield (Mg ha^{-1})		N (%)		P (%)		K (%)	
		1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
Addition of soil amendments											
T_1		4.11d	4.08d	6.85d	6.70d	1.14d	1.13d	0.181d	0.176d	1.32c	1.32c
T_2		6.13b	6.13b	9.68b	9.40b	2.15b	2.16b	0.310b	0.306b	3.36a	3.35a
T_3		5.94c	5.71c	8.75c	8.63c	2.07c	2.02c	0.252c	0.244c	3.27b	3.23b
T_4		6.67a	6.24a	9.89a	9.66a	2.26a	2.22a	0.386a	0.378a	3.38a	3.34a
LSD at 5%		**0.06**	**0.04**	**0.06**	**0.05**	**0.03**	**0.04**	**0.003**	**0.003**	**0.06**	**0.06**
Soil addition of CuSo$_4$											
Cu_1		5.52c	5.40b	8.28c	8.25c	1.76c	1.75c	0.267b	0.266b	2.68c	2.64c
Cu_2		5.72b	5.41b	8.80b	8.47b	1.92b	1.87b	0.290a	0.28a	2.87b	2.86b
Cu_3		5.89a	5.81a	9.30a	9.08a	2.04a	2.03a	0.292a	0.28a	2.94a	2.93a
LSD at 5%		**0.04**	**0.04**	**0.06**	**0.05**	**0.05**	**0.04**	**0.005**	**0.005**	**0.04**	**0.04**
Interaction											
	Cu_1	4.05	4.06	6.63	6.49	1.07	1.08	0.167	0.171	1.19	1.21
T_1	**Cu_2**	4.10	4.07	6.87	6.74	1.12	1.10	0.188	0.183	1.33	1.30
	Cu_3	4.17	4.10	7.06	6.87	1.24	1.21	0.187	0.173	1.44	1.44
	Cu_1	5.94	5.95	9.86	9.19	1.96	2.00	0.287	0.289	3.22	3.19
T_2	**Cu_2**	6.07	6.08	9.10	9.14	2.19	2.18	0.322	0.317	3.42	3.41
	Cu_3	6.39	6.37	10.09	9.88	2.31	2.30	0.320	0.313	3.43	3.45
	Cu_1	5.82	5.58	7.94	8.08	1.78	1.72	0.246	0.241	3.20	3.17
T_3	**Cu_2**	5.94	5.68	8.50	8.38	2.15	2.10	0.256	0.248	3.28	3.25
	Cu_3	6.05	5.87	9.82	9.42	2.29	2.23	0.255	0.244	3.34	3.27
	Cu_1	6.22	5.77	9.45	9.28	2.21	2.18	0.368	0.364	3.12	2.98
T_4	**Cu_2**	6.83	6.03	9.97	9.58	2.23	2.11	0.392	0.382	3.46	3.47
	Cu_3	6.97	6.91	10.24	10.13	2.33	2.37	0.397	0.387	3.56	3.56
LSD at 5%		**0.08**	**0.08**	**0.11**	**0.09**	**0.09**	**0.08**	**0.011**	**0.010**	**0.07**	**0.07**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

T_1: Control; **T_2:** Compost; **T_3:** Zeolite; **T_4:** Compost + Zeolite; **Cu_1:** Control; **Cu_2:** 3.0 kg fed^{-1}; Cu_3: 6.0 kg fed^{-1}

Table 5. Impact of compost, zeolite, and copper sulphate on grain chemical constitutes (micronutrients) at harvest stage in the seasons of 2021/2022 and 2022/2023.

Treatments		Fe		Mn		Zn		Cu	
		(mg kg^{-1})							
		1st	2nd	1st	2nd	1st	2nd	1st	2nd
Addition of soil amendments									
T_1		26.47d	27.00d	4.78d	4.78d	7.89d	7.66d	6.49d	6.38d
T_2		140.97b	140.90b	10.85b	10.68b	12.60b	13.09b	9.99b	10.27b
T_3		132.30c	131.67c	9.94c	9.91c	10.61c	11.31c	9.80c	9.33c
T_4		144.50a	144.07a	11.45a	11.75a	19.87a	19.07a	12.79a	12.40a
LSD $_{at\ 5\%}$		**0.34**	**0.41**	**0.15**	**0.14**	**0.08**	**0.09**	**0.08**	**0.03**
Soil addition of $CuSo_4$									
Cu_1		98.70c	97.18c	7.32c	7.30c	9.69c	9.36c	5.26c	5.17c
Cu_2		110.75b	109.70b	9.01b	9.17b	11.64b	10.88b	9.94b	9.35b
Cu_3		123.73a	125.85a	11.44a	11.37a	16.90a	18.11a	14.10a	14.26a
LSD $_{at\ 5\%}$		**0.15**	**0.33**	**0.09**	**0.10**	**0.09**	**0.10**	**0.05**	**0.06**
Interaction									
T_1	Cu_1	15.20	11.30	3.70	3.61	6.54	6.83	3.31	3.12
	Cu_2	22.00	20.20	4.93	5.12	7.94	7.01	6.63	6.28
	Cu_3	42.20	49.50	5.71	5.62	9.20	9.13	9.53	9.73
T_2	Cu_1	131.20	131.30	9.10	8.95	8.89	8.76	5.11	5.21
	Cu_2	140.40	141.20	10.12	10.11	10.20	10.50	10.65	10.85
	Cu_3	151.30	150.20	13.32	12.98	18.70	20.00	14.22	14.74
T_3	Cu_1	115.20	113.70	8.23	8.02	8.13	8.24	6.21	6.23
	Cu_2	135.40	133.20	9.21	9.27	9.20	9.49	9.86	8.76
	Cu_3	146.30	148.10	12.38	12.43	14.50	16.20	13.32	13.00
T_4	Cu_1	133.20	132.40	8.23	8.63	15.20	13.60	6.40	6.12
	Cu_2	145.20	144.20	11.77	12.19	19.20	16.50	12.62	11.52
	Cu_3	155.10	155.60	14.35	14.44	25.20	27.10	19.34	19.56
LSD $_{at\ 5\%}$		**0.30**	**0.65**	**0.17**	**0.20**	**0.19**	**0.20**	**0.09**	**0.12**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level
T_1: Control; **T_2:** Compost; **T_3:** Zeolite; **T_4:** Compost + Zeolite; **Cu_1:** Control; **Cu_2:** 3.0 kg fed^{-1}; Cu_3: 6.0 kg fed^{-1}

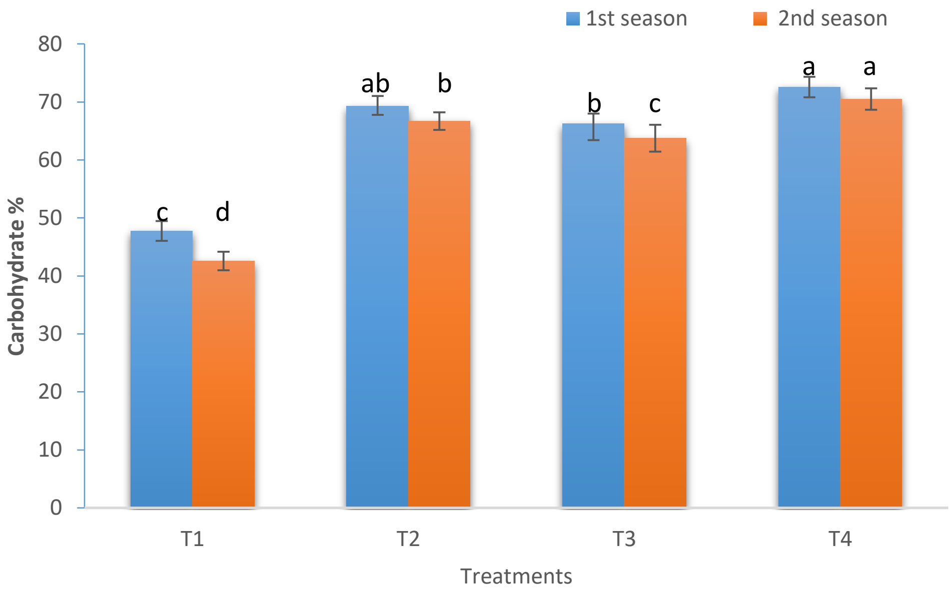
- Soil fertility at harvest stage (availability of nutrients, CEC and WHC)

1. **Availability of nutrients**

Table 6 presents the impact of various soil amendments and copper sulphate additions on the availability of soil nutrients (N, P, K, and Cu, mg kg^{-1}) after wheat harvest in the seasons of 2021/2022 and 2022/2023.

Effect of the studied substances (compost and zeolite): The data illustrate that the soil addition of compost alone resulted in the highest values of available N, P, and K in both seasons. However, it increased Cu availability only in the first season, while the effect of other studied soil addition treatments was different with each soil nutrient. The addition of zeolite alone increased the availability of cu in the second season compared to other treatments. Also, it can be noticed that the addition of zeolite either alone or in combination with compost led to raise the nutrients availability. **Effect of copper sulphate:** The addition of copper sulphate did not have a significant effect on soil N availability in the first season or soil K availability in both seasons, but copper sulphate additions were significant in increasing the availability of N in the second season and other soil nutrients (P, Cu) in both seasons. Generally, the addition of copper sulphate at 3 and 6 kg fed^{-1} led to increase the soil nutrient availability compared to control treatment. Also, it can be noticed that the availability with the first rate of copper sulphate (3 kg fed^{-1}) was more than that with the second rate (6 kg fed^{-1}).

Finally, the results indicate that the addition of compost and zeolite (either alone or in combination) increased the availability of most soil nutrients. Simultaneously, the addition of copper sulphate contributed to raising nutrient availability as well.



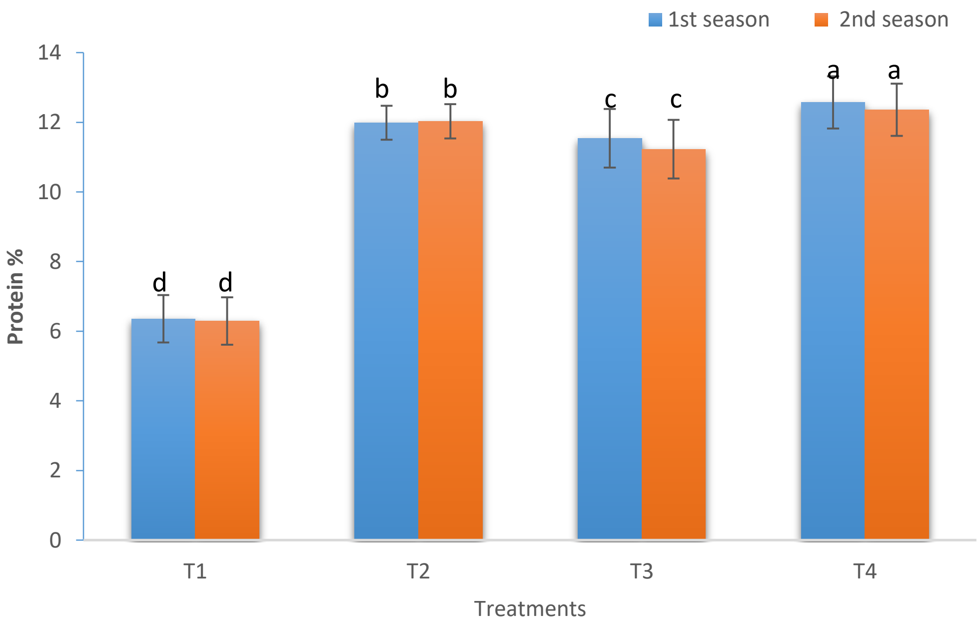
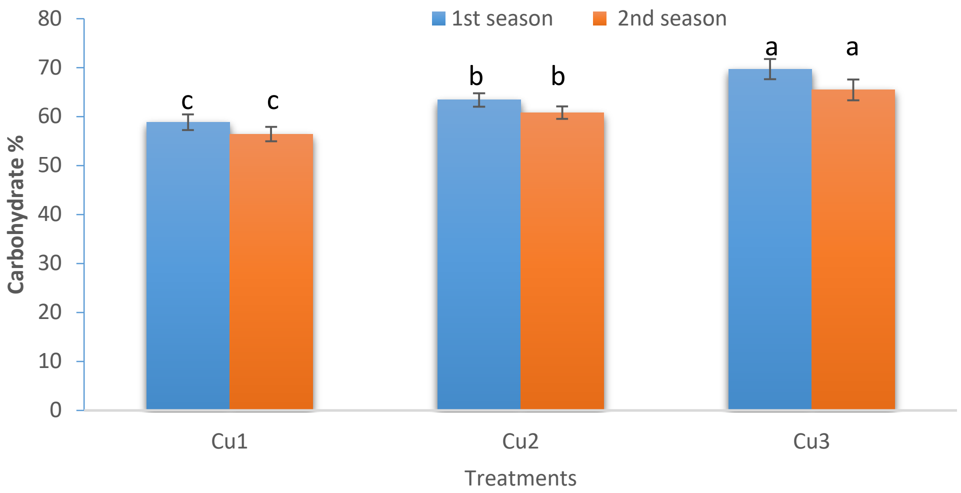


Fig. 1. Individual effect of soil amendments (compost and zeolite) on grain content of carbohydrate and protein at harvest stage in the seasons of 2021/2022 and 2022/2023.

T$_1$: Control; **T$_2$:** Compost; **T$_3$:** Zeolite; **T$_4$:** Compost + Zeolite



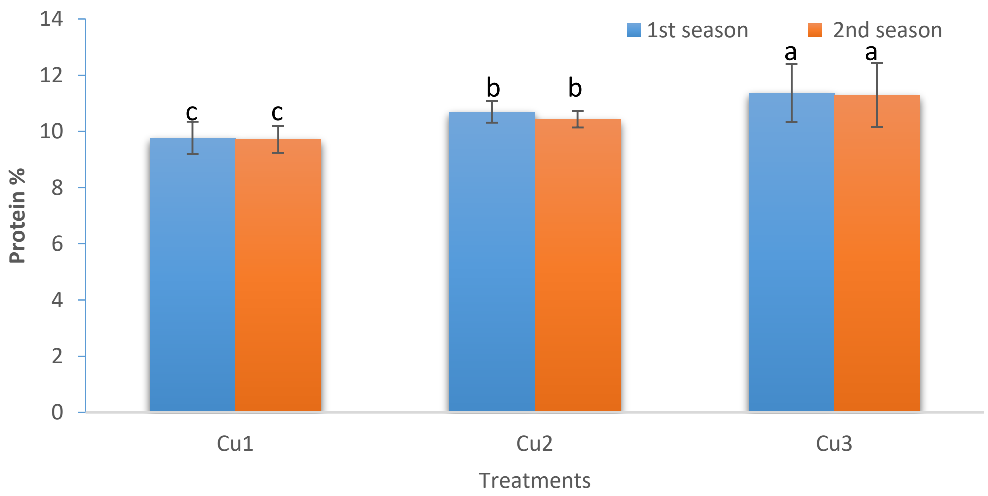


Fig. 2. Individual effect of copper sulphate on grain content of carbohydrate and protein at harvest stage in the seasons of 2021/2022 and 2022/2023.

Cu_1: Control**; Cu_2:** 3.0 kg fed^{-1}**; Cu_3:** 6.0 kg fed^{-1}

- **Soil CEC and WHC**

Since copper sulphate did not have any clear effect on both the cation exchange capacity (CEC, cmol kg^{-1}) and water holding cabacity (WHC,%). Therefore, the clear impact of compost and zeolite on the values of CEC and WHC (as averages as shown in Table 7) will be presented. It can be noticed that the addition of compost or zeolite either in single treatment or in combination pronouncedly increased the values of soil CEC (cmol kg^{-1}) and WHC (%) compared to control treatment as well as th initial soil which had the lowest values. Regarding CEC (cmol kg^{-1}), the maximum value was recorded with T3 treatment, while the highest values of soil WHC (%) was realized with T4 treatment.

Table 6. Impact of compost, zeolite, and copper sulphate on soil nutrient availability following wheat plant harvesting in the seasons of 2021/2022 and 2022/2023.

Treatments		Available N		Available P		Available K		Available Cu	
		(mg kg^{-1})							
		1st	2nd	1st	2nd	1st	2nd	1st	2nd
Addition of soil amendments									
T_1		26.06c	34.87b	5.39c	11.46b	238.41c	387.47a	1.02c	1.79b
T_2		40.03a	39.65a	15.79a	13.35a	427.50a	373.20a	2.02a	1.43c
T_3		24.28d	33.17c	5.28c	6.86c	226.19c	333.41a	0.91d	2.10a
T_4		34.79b	23.48d	11.92b	5.85d	372.69b	214.03b	1.70b	0.83d
LSD $_{at\ 5\%}$		**0.33**	**0.54**	**0.23**	**0.22**	**20.86**	**72.45**	**0.04**	**0.05**
Soil addition of $CuSo_4$									
Cu_1		31.43a	32.75b	9.16c	9.27b	315.75a	337.03a	1.34c	1.40c
Cu_2		31.31a	33.23a	9.69b	9.52a	314.78a	339.09a	1.39b	1.50b
Cu_3		31.13a	32.40b	9.94a	9.34b	318.07a	304.97a	1.51a	1.64a
LSD $_{at\ 5\%}$		**N.S**	**0.35**	**0.16**	**0.10**	**N.S**	**N.S**	**0.03**	**0.03**
Interaction									
	Cu_1	27.63	36.63	5.40	12.03	246.90	398.73	0.82	1.62
T_1	**Cu_2**	26.40	35.70	5.33	11.80	235.83	388.03	0.94	1.83
	Cu_3	24.13	32.28	5.43	10.54	232.50	375.63	1.29	1.91
	Cu_1	38.33	38.72	15.29	13.12	418.13	401.47	1.87	1.28
T_2	**Cu_2**	40.07	39.93	15.61	13.31	428.47	421.80	1.92	1.47
	Cu_3	41.70	40.30	16.47	13.61	435.90	296.34	2.26	1.53
	Cu_1	26.40	34.28	5.33	6.94	235.83	341.33	0.61	2.00
T_3	**Cu_2**	24.13	33.77	5.43	6.86	232.50	334.03	0.82	2.11
	Cu_3	22.30	31.47	5.07	6.78	210.23	324.87	1.29	2.00
	Cu_1	33.37	21.37	10.59	5.00	362.13	206.57	1.34	0.58
T_4	**Cu_2**	34.63	23.51	12.38	6.12	362.30	212.50	1.73	0.75
	Cu_3	36.37	25.57	12.80	6.43	393.63	223.03	2.04	1.15
LSD $_{at\ 5\%}$		**1.49**	**0.72**	**0.31**	**0.21**	**31.30**	**109.15**	**0.06**	**0.06**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

T_1: Control; **T_2:** Compost; **T_3:** Zeolite; **T_4:** Compost + Zeolite; **Cu_1:** Control; **Cu_2:** 3.0 kg fed^{-1}; Cu_3: 6.0 kg fed^{-1}

Table 7. Impact of compost and zeolite on CEC (cmol kg^{-1}) and WHC (%) following wheat plant harvesting in the seasons of 2021/2022 and 2022/2023 (as averages)

Treatments	CEC, cmol kg^{-1}		WHC,%	
	1st season	2nd season	1st season	2nd season
T_0	48.60	48.90	38.00	38.00
T_1	49.20	49.40	38.20	38.10
T_2	52.28	51.90	39.30	39.00
T_3	50.38	50.05	40.02	40.00
T_4	51.92	51.72	40.19	40.25

T_0: Initial soil; **T_1:** Control; **T_2:** Compost; **T_3:** Zeolite;**T_4:** Compost + Zeolite

4. Discussion

The results of the study indicate that the addition of compost and zeolite, either alone or in combination, had a significant positive effect on plant performance, grain yield, and nutrient availability in the soil. The combined treatment of zeolite and compost (T_4) consistently outperformed the other treatments in terms of straw and grain chemical constituents, grain and straw yield, and grain quality. Also, both compost and zeolite possessed the pivotal role in increasing soil cation exchange capacity and water holding capacity at harvest stage.

The superior performance of the combined treatment can be attributed to several scientific reasons. Firstly, zeolite has a unique porous structure that can retain water and nutrients, making them available to plants over a longer period. It acts as a reservoir for essential elements and enhances their availability to plants, thereby promoting their growth and development. Zeolite can also improve soil structure, increasing the water-holding capacity and reducing nutrient leaching, ultimately leading to improved plant performance. Compost, on the other hand, is a rich source of organic matter and nutrients. It enhances soil fertility, improves soil structure, and promotes microbial activity. The organic matter in compost releases nutrients gradually, providing a steady supply to plants throughout their growth stages. Compost also enhances nutrient retention capacity, reducing nutrient loss through leaching. These factors contribute to improved plant performance, grain yield, and nutrient content. Overall, the combination of zeolite and compost offers multiple benefits for plant growth, soil health, and agricultural sustainability. It improves nutrient availability, cation exchange capacity, water-holding capacity, soil structure, and microbial activity, leading to increased crop productivity and reduced environmental impact.

The findings of this study are consistent with previous research conducted on the benefits of using a combination of zeolite and compost in agricultural practices. Several studies have reported similar outcomes, supporting the positive effects of combining these two materials on plant growth, soil nutrient availability, and overall agricultural productivity. For instance, research studies by **Ghazi *et al.* (2023)** have demonstrated that the use of zeolite in combination with compost enhances nutrient availability and uptake by rice plants. These studies have shown that zeolite acts as a reservoir, holding nutrients in the root zone and preventing their leaching, while compost provides a slow-release source of nutrients. The combined application of zeolite and compost results in improved nutrient retention, leading to increased rice plant growth and yield. Additionally, studies by **Rosalina *et al.* (2019)** have highlighted the positive impact of the zeolite-compost combination on soil structure and water-holding capacity. Zeolite's ability to absorb and retain water, combined with the organic matter content of compost, improves soil aggregation, aeration, and water infiltration **(Elmahdy *et al.* 2022).** This promotes root development, enhances water availability to plants, and mitigates the effects of drought stress. Moreover, research conducted by **Soudejani *et al.* (2019)** has shown that the use of zeolite and compost together enhances microbial activity in the soil. Zeolite provides a favorable environment for beneficial soil microorganisms, while compost supplies organic matter as a food source for microbial populations. This stimulation of microbial activity leads to improved nutrient cycling, decomposition of organic matter, and overall soil health. The consistency of our results with previous research reinforces the notion that the combination of zeolite and compost is an effective strategy for optimizing plant performance, enhancing soil nutrient availability, and improving agricultural productivity. These findings provide further scientific evidence supporting the practical application of this approach in sustainable agricultural systems.

The addition of copper sulphate had varying effects depending on the specific traits evaluated. The third rate of copper sulphate (6 kg fed^{-1}) generally outperformed the second rate (3 kg fed^{-1}) and the control treatment. Copper is an essential micronutrient for plant growth and plays a vital role in various physiological processes. At appropriate concentrations, copper promotes enzyme activity and enhances nutrient uptake, leading to improved plant performance. However, excessive copper can become toxic to plants, inhibiting their growth and causing adverse effects on grain quality. The results are in harmony with those of **Kumar *et al*. (2009).** The superiority of copper, especially at the higher studied rate, can be attributed to its vital role in various physiological processes within wheat plants. Copper is particularly crucial for the formation and structure of gluten in wheat, as highlighted by previous study of **Azooz *et al.* (2012).** Moreover, copper is known to participate in enzyme activity and redox reactions within plant cells, as documented by **Liščáková *et al.* (2022).** These essential functions of copper contribute to improved plant growth, nutrient uptake, and overall productivity, explaining its superior performance in enhancing wheat yield and grain quality in the research trial.

The availability of soil nutrients was significantly influenced by the addition of compost, zeolite, and copper sulphate. Compost increased the availability of N, P, and K in the soil, while zeolite contributed to increased Cu availability, particularly in the second season. Copper sulphate additions further enhanced nutrient availability. These findings suggest that the studied treatments positively influenced nutrient cycling and availability in the soil, ensuring an adequate nutrient supply for plant uptake and utilization. The results are in agreement with those of **Elsherpiny *et al.* (2023) and Ghazi *et al.* (2023)**.

5. Conclusion

The research trial provided valuable insights into the effects of various soil amendments and copper sulphate treatments on plant performance, soil nutrient availability, and wheat productivity. The combined treatment of zeolite and compost (T_4) showed superior results in terms of straw and grain yield, as well as grain chemical constituents, compared to the other treatments. Additionally, the addition of copper sulphate, particularly at the rate of 6 kg fed^{-1} (Cu_3), positively influenced grain yield and nutrient content. Furthermore, the study highlighted the importance of copper for wheat growth and the formation of carbohydrates and protein. Copper's role in physiological processes and its impact on grain quality were demonstrated, emphasizing the significance of maintaining adequate copper availability in the soil.

Based on the findings, the following recommendations can be made:

1. Farmers and agricultural practitioners should consider adopting the combined treatment of zeolite and compost (T_4) along with the application of copper sulphate at the third rate (Cu_3, 6 kg fed^{-1}) to maximize wheat yield and improve grain quality.

2. The use of compost and zeolite, either individually or in combination, can be beneficial for enhancing soil cation exchange capacity (CEC) and water holding capacity (WHC). Thus, farmers should explore incorporating these soil amendments to improve soil structure and water retention.

3. Further research should be conducted to understand the long-term effects of these treatments on soil health, nutrient cycling, and crop sustainability to support more sustainable agricultural practices.

4. Given the significance of copper in wheat grain formation and structure, continued research on the interactions between copper and other soil nutrients and elements is essential to optimize copper availability and its effects on plant physiology.

5. It is advisable to conduct field trials in different agro-climatic regions to validate the results and assess the generalizability of the findings under various environmental conditions.

6. Farmers should follow recommended application rates of copper sulphate and other soil amendments to avoid excessive application that could lead to negative environmental impacts.

Finally, the practical application of these research findings can significantly improve wheat productivity and grain quality. Farmers can adopt recommended treatments like combining zeolite and compost, along with an appropriate copper sulphate rate, to enhance crop yields and optimize nutrient content. Implementing these practices can lead to higher grain and straw yields, improved nutrient content in grains, and potentially enhanced gluten formation. These improvements can positively impact the economic value of wheat crops, promote food security, and contribute to overall agricultural productivity.

Conflicts of interest

Authors have declared that no competing interests exist.

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