Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Enhancing Wheat Yield and Grain Zinc Content through Foliar Application of Zinc Sulfate under Clay Soil Conditions

Mohamed Mostafa El-Fouly
National Research Centre
Samir Hosni Ahmed Shaaban
shashaaban@yahoo.com
National Research Centre

Research Article

Keywords: Wheat, Foliar zinc sulfate, Growth stages, Nutrient status, Yield

Posted Date: November 5th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11291450/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Abstract

Background: Since wheat is a primary staple food in Egypt, the bio-fortification of wheat grains with zinc serves as an effective strategy to increase dietary zinc intake and mitigate deficiency among the population.

The purpose of this study is to investigate the effects of foliar application of zinc sulfate ($ZnSO_4$) at different growth stages on nutrient concentrations, particularly zinc as well as on growth characteristics, and performance of wheat yield.

Materials and methods: Field experiments were conducted during the winter growth seasons 2019/2020 and 2020/2021 in the village of Kafr Al-Khadra, Al-Bagour District, Menoufia Governorate, Egypt. The location represents the typical Egyptian clay soil.

The experiment included, two bread wheat (Triticum aestivum L.) Giza 171 and Gemeiza 11, arranged in a randomized complete block design (RCBD) with three replications. Each experimental plot measured 10.5 m² (3.5 m × 3.0 m). Foliar treatments consist of Zn sulfate ($ZnSO_4.7H_2O$) applied at a rate of 5 g/l during the stem elongation and milk-ripening stages. Large-scale, farmer-managed validation experiments were conducted during the winter growth seasons 2021/2022 and 2022/2023.

Results: Foliar zinc application-particularly the double application significantly enhanced zinc Furthermore, the leaf foliar application of zinc sulfate ($ZnSO_4$) enhanced concentrations of potassium, calcium, magnesium, iron, and manganese in both grains and straw.

Applying of $ZnSO_4$ twice with a concentration of 5 g L^{-1} during the stem elongation and milk-ripening stages increased grain yield by 13–15% compared to untreated control. In addition, the biological yield and harvest index have been significantly improved, while the concentration of zinc in grains has increased to a nutritionally meaningful significant level of approximately 47-54 ppm.

Conclusion: The results confirmed a significant improvement in the concentration of zinc in grains and a markedly positive impact overall wheat yield.

Introduction

Zinc (Zn) is an essential micronutrient that plays a crucial role in the growth and development of plants, humans, and animals. Zinc deficiency is a widespread global nutritional problem, particularly in developing countries, where it poses significant risks to human health and agricultural productivity (WHO, 2020). In plant physiology, zinc serves as a vital cofactor for many enzymes that regulate auxin synthesis, membrane stability, photosynthesis, and carbohydrate metabolism. Thus, its deficiency leads to stunted leaf growth (little leaf), severe branching, and poor filling of grains. Since wheat is a primary staple food in Egypt, wheat grains with zinc biofortification serve as an effective strategy to increase dietary zinc intake and mitigate deficiency across the population.

Zinc deficiency in humans is associated with a wide range of serious health disorders, including impaired growth, weakened immune function, cognitive deficits, increased susceptibility to infectious diseases, DNA damage, and a high risk of cancer (Hotz and Brown, 2004; Gibson, 2006). In agriculture, zinc deficiency is particularly prevalent in alkaline soils with high phosphorus levels, where the availability of zinc to plants is markedly reduced. In Egypt, increasing evidence has documented widespread zinc deficiency in several wheat-growing sites (El-Metwally et al., 2012; El-Habasha et al., 2015; El-Dahshoury et al., 2017).

Shaaban et al. (2018) emphasized that the adoption of balanced fertilization strategies based on accurate soil and plant analyses is essential to maintain soil fertility, improve nutrient use efficiency and maximize the productivity of wheat crops. Also in Egypt, Ghanem et al. (2025) found that all zinc levels, especially 500 ppm, increased wheat production from grain by 65.3% to 66.95% and improved yield and chemical composition of grains (relative total protein content, wet and dry gluten, and N, P, K, and Zn levels in wheat grains) under both control and drought conditions. Thus, foliar application of zinc, specifically at a concentration of 500 ppm, can promote the growth of the wheat plant and increase the yield and nutrient content of grains under both control and water stress conditions.

Agronomic biofortification by foliar spraying during critical growth stages offers a precise method to increase nutrient density in cereals without inducing soil, side fixation and without the need for soil disturbance (Hussein et al., 2013; Das et al., 2020; Sánchez-Palacios et al., 2023). Leaves have the ability to absorb nutrients and transport them through the phloem or xylem directly to developing tissues and reproductive organs (Rengel et al., 1999 and Kamran et al. 2023). Previous studies show in Central Anatolia, Turkey, (Yilmaz et al., 1997), in India (Prasad et al., 2013, Paramesh et al., 2020), in Afghanistan (Hemmat et al. 2023), and in Pakistan (Ahmed et al. 2025), the results demonstrate that zinc fertilization increases wheat productivity and grain quality.

Foliar application of zinc during the grain-filling stage has been shown to substantially increase the concentration of zinc in grains, raising it from about 27.4 to 48.0 mg kg^{-1} (Zhang et al., 2012). Also, (Wang et al., 2020) mentioned that grain Zn content in wheat was 31.84 mg·kg^{-1} globally but varied across continents, for example, 25.10 mg·kg^{-1} in Europe, 29.00 mg·kg^{-1} in Africa, 33.63 mg·kg^{-1} in Asia, and 33.91 mg·kg^{-1} in North America. Grain Zn content in wheat improved from 28.96 to 36.61 mg·kg^{-1} after Zn fortification.

Also, Thapa et al. (2022) pointed out that extensive testing of zinc-enriched wheat strains in Nepal led to the release of five biofortified wheat varieties in 2020, and these varieties are characterized by high yields, improved disease resistance, and grain zinc content 30% to 40% higher than that of traditional varieties, and Ram et al., 2024 reported that the data showed the significant effect of foliar spraying with zinc sulfate ($ZnSO_4$) in increasing the zinc concentration of grains by 39.6%., they found that experiments conducted on large field plots, also showed a 40.3% in increase in the zinc concentration resulting from foliar application of zinc sulfate ($ZnSO_4$), highlighting the effectiveness technique and the possibility of its adoption in farmers' fields.

In addition to improving grain zinc enrichment for grains, foliar fertilization offers important environmental advantages by reducing the total amount of fertilizer required and minimizing the potential of soil accumulation and contamination in the long term. The enhanced bioavailability of zinc in biofortified wheat and its positive impact on human nutrition was well documented by Bhatt et al., 2020, and reported that the broadcasting of $ZnSO_4.7H_2O$ at 62.5 kg ha^{-1} and foliar application of Zn chelates such as Zn–HEDP at 2 g L^{-1}, Zn–HEDP at 3 g L^{-1}, or a 0.4–0.5% $ZnSO_4$ solution during grain development stage enhanced the growth, productivity, and micronutrients concentration in the edible portion of the plant which further improves the quality of wheat grains and ultimately improves human health.

Our department is working since years on the Zn biofortification in wheat on different scales and different locations, using general different varieties to conclude with a recommendation for farmers to improve yield and increase zinc in grains.

Materials and Methods

Experimental Design and Field Practices

Researcher - managed field Experiments were conducted during the winter seasons 2019/2020 and 2020/2021 at Kafr El-Khadra Village, El-Bagour District, Menoufia Governorate, Egypt. The location represents typical Egyptian clay soil.

Source of the Plant used in the study

Wheat (Triticum aestivum L.), was used in this study. Grains of two wheat cultivars, Giza 171 and Gemeiza 11, were obtained from the Central Administration for Seed Production, Ministry of Agriculture and Land Reclamation, Egypt.

The experiment arranged in a randomized complete block design (RCBD) with three replications. Each experimental plot measured 10.5 m² (3.5 m × 3.0 m).

Before planting, the soil was prepared by chisel plowing followed by leveling using a wooden leveler. Farmyard manure was incorporated annually at a rate of 20 m^3 fed^{-1}. Wheat was sown during the first third of November with a seeding rate of 60 kg fed^{-1}. Phosphorus fertilizer was applied as a basal dose before sowing at a rate of 15.5 kg P_2O_5 fed^{-1} in the form of calcium superphosphate.

Nitrogen fertilizers have been applied at a total rate of 60 kg N fed^{-1}, and are supplied in the form of urea (46% N) and ammonium nitrate (33.5% N). The nitrogen was split into two equal applications and was broadcast during the first and second irrigations, respectively. The N, P fertilizers were broadcast on the soil surface.

All standard agronomic practices have been managed in alignment with local farming standards.

Foliar treatments consist of Zn sulfate ($ZnSO_4.7H_2O$) applied at a rate of 5 g/L, using a hand-held sprayer during the early morning hours to ensure uniform coverage and maximize nutrient absorption.

The initial experimental treatments included

1. 1. Control: (No zinc application)
2. 2. Zn applied at tillering/stem elongation stage (Stage 1)
3. 3. Zn applied at milk stage (Stage 2)
4. 4. Zn applied at both tillering and milk stages (Stage 1 + 2)

To validate the findings larger farmer – managed confirmatory trials were executed during 2021/2022 and 2022/2023 winter seasons, testing the control versus the stage 1 + 2 (Double Application).

Laboratory and Statistical Analysis

The physical and chemical properties of the experimental soil were determined before planting. Soil texture, pH, and electrical conductivity (EC), calcium carbonate ($CaCO_3$), organic matter (OM), available nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), sodium (Na), and available micronutrients, including zinc (Zn), iron (Fe), manganese (Mn), and copper (Cu) were determined following the procedures of Chapman and Pratt (1978), Lindsay and Norvell (1978) and Jackson (1986).

Plant samples were collected at the phase of tillering, stem extension (only the aerial part of the plant). Also, samples of mature grains and straw were collected.

Samples (flag leaves, grain, and straw) were analyzed for nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), iron (Fe), manganese (Mn), copper (Cu), and zinc (Zn). The total nitrogen concentration was determined using the micro-Kjeldahl method according to AOAC (1984), phosphorus by spectrophotometry, K, Ca and Na via flame photometry, Mg and micronutrients via atomic absorption spectrometry (Chapman and Pratt, 1978, Jackson, 1986).

Based on the previous experiments, the plot areas will be as large as possible and the trials were conducted as farmers managed the 2021/2022 and 2022/2023 trials to confirm the effect of foliar spraying with zinc sulphate found in the first experiment.

Treatments in this confirmatory trial were:

Control (no Zn)

Zn applied at Stage 1 and Stage 2

Zinc was applied in the form of zinc sulfate ($ZnSO_4.7H_2O$) at a rate of 5 g/L, with foliar spraying using a hand-held sprayer.

The analytical data of the soil were interpreted according to the classification criteria proposed by Ankerman and Large (1974), Lindsay and Norvell (1978), and Silvertooth (2001), while plant nutrient concentrations were evaluated based on the sufficiency ranges reported by Jones et al. (1991).

The harvest index (HI) at physiological maturity was calculated using the following equation:

HI (%) = (Grain yield / Biological yield) × 100

In addition, agronomic traits, including plant height, number of spikes m^{-2}, and weight of 1000-grain (g), were measured and recorded at harvest.

Yield Data: The harvest occurred during the first half of May. Grain and biological yields were measured from 1m2 of kilograms per plot and converted to tons/ha.

Experimental data were subjected to analysis of variance (ANOVA) using the CoStat statistical software package. Treatment means were compared using the Least Significant Difference (LSD) test at the 5% probability level ($P \leq 0.05$), following the procedures described by Snedecor and Cochran (1980) and Gomez and Gomez (1984).

Results and Discussion

Baseline Soil Characteristics and Zinc Availability:

Soil indicated a heavy clay texture with an alkaline reaction (pH = 8.6).

Also, Soil tests showed displayed moderate levels of calcium carbonate, organic matter, and electrical conductivity (2.3, 2.25, 0.30) respectively, alongside moderate zinc available. Potassium levels were high, sodium was low, phosphorus, magnesium, calcium, iron, and manganese were within medium ranges, while copper content was high (Table 1)..

Table 1
Physical and chemical properties of experimental soil (depth 0–30 cm) before sowing wheat.

Test	M ± SD	Test	M ± SD
Sand %	31 ± 2	mg/100g	
Silt %	28 ± 1	P	2.47 ± 0.13 **M**
Clay %	41 ± 1	K	33 ± 11**H**
Soil Texture	Clay	Ca	283 ± 30**M**
$CaCO_3$%	2.30 ± 0.12 **M**	Mg	114 ± 9 **M**
OM %	2.25 ± 0.14 **M**	Na	7.4 ± 1.05 **VL**
EC,dS/m	0.30 ± 0.04 **M**	mg/kg	
pH	8.6 ± 0.10 **H**	Fe	14 ± 2 **M**
		Mn	11 ± 1.0 **M**
		Zn	2.0 ± 0.3 **M**
		Cu	1.6 ± 0.3 **H**
VL= very low L = Low, M = Medium, H = High			

It is well known that the availability of most nutrients decreases under conditions of high soil pH. The high pH of the soil enhances the precipitation of zinc and adsorption on the soil particles, which reduces its mobility in the soil and its availability for plant absorption.

In addition, the availability of zinc is further diminished by its fixation on clay minerals, drought stress, high levels of phosphorus in the soil or excessive phosphorus use, and prolonged waterlogging. These factors reduce the availability of zinc from both soil and fertilizer to plant roots, exacerbating zinc deficiency. Collectively, these conditions limit the solubility, mobility, and absorption of zinc by plants (Lindsay and Norvell, 1978; Marschner, 1995; Alloway, 2008, 2009).

Therefore, foliar application of zinc sulfate is biologically justified because it bypasses soil-related constraints and delivers zinc directly to plant tissues, thus improving zinc nutrition.

1. Field Experiments

1.1. First Season (2019/2020)

1.1.1. The effect of the application of foliar zinc sulfate on nutrient concentrations in wheat flag leaves.

Based on the sufficiency ranges for nutrient concentrations in wheat flag leaves (Table 2), the data in (Table 3) show that concentrations of most nutrients were within the adequate range, although the

concentrations of some elements remained below the recommended sufficiency

Table 2
Sufficiency ranges of macro and micronutrient concentrations in wheat flag leaves (based on dry weight)

Macronutrient (%)	Sufficiency range	Micronutrient (mg kg^{-1})	Sufficiency range
N	3.50–4.50	Fe	50–250
P	0.30–0.50	Mn	35–475
K	2.00–3.00	Zn	15–70
Ca	0.20–0.50	Cu	5–25
Mg	0.20–0.60		
Source: Jones, et al. (1991)			

The results presented in Table 3 show that the foliar application of zinc sulfate significantly increased concentrations of nitrogen, phosphorus, potassium, calcium, magnesium, and zinc in the flag leaves of wheat varieties Giza 171 compared with the untreated control.

Table 3
The effect of foliar zinc sulfate at different physiological growth stages on the nutrient concentrations and nutritional status of flag leaves of wheat varieties Giza 171.

Nutrient	N	P	K	Ca	Mg	Fe	Mn	Zn	Cu
Treatment	%					ppm			
Without Zn	2.40 L	0.171L	1.30L	0.30M	0.35M	284H	97M	54M	5.7M
With Zn (stage 1)	2.80L	0.215L	1.75L	0.40M	0.52M	222M	110M	60M	1.0L
With Zn (stage 2)	2.47L	0.184L	1.53L	0.39M	0.44M	251M	94M	75H	2.7L
With Zn (stage 1 and 2)	2.70L	0.195L	1.43L	0.42M	0.54M	242M	80M	86H	1.7L
LSD. 5%	0.12	0.011	0.08	0.07	0.03	8.0	8	4	1.0
Stage (1) = Tillering stage, Stage (2) = Milk stage, Stage 1 and 2 = Tillering+ Milk stages									

1.1.2. Effect of foliar application of zinc sulfate on grain yield and yield components of wheat (cv. Giza 171)

As shown in Table 4, foliar application of zinc sulfate at a concentration of 5 g L^{-1} significantly improved grain yield and wheat components (cv. Giza 171) compared with the untreated control.

Among the treatments for applying zinc, two foliar sprays applied at the tillering and milky stages produced the greatest improvement in grain yield compared with the untreated control. In the 2020/2021 growing season, double-spray treatment achieved the highest grain yield (7.35 t ha^{-1}), compared with 6.52 t ha^{-1} for control, representing an increase of almost 13%.

Table 4
The effect of the application of foliar zinc sulfate at different physiological growth stages on grain yield and yield components of wheat (cv. Giza 171)

Yield **Treatment**	**Plant height** **(cm)**	**Grain yield** **ton/ha-^{1}**	**%**	**Straw yield** **ton/ha^{-1}**	**Biological yield** **ton/ha^{-1}**	**Harvest index** **%**
Without Zn	105	6.52	100	9.67	16.19	40.3
With Zn (stage 1)	104	6.84	105	8.04	14.88	46.0
With Zn (stage 2)	103	7.28	112	9.62	16.90	43.1
With Zn (stage 1 and 2)	102	7.35	113	8.81	16.16	45.5
LSD. 5%	3	0.76		0.99	1.61	
Stage (1) = Tillering stage, Stage (2) = Milk stage, Stage 1 and 2 = Tillering+ Milk stages						

1.1.3. The effect of the application of foliar zinc sulfate on nutrient concentrations in wheat grains (cv. Giza 171)

The data presented in Table 5 demonstrate that foliar application of zinc sulfate enhanced the concentrations of zinc (Zn), iron (Fe), and copper (Cu) in the grains of wheat (cv. Giza 171) compared with the untreated control.

Table 5
Effect of foliar application of zinc sulfate at different physiological growth stages on the concentrations of Zn, Fe, and Cu in wheat grains (cv. Giza 171).

Nutrient	**N**	**P**	**K**	**Ca**	**Mg**	**Na**	**Fe**	**Mn**	**Zn**	**Cu**
Treatment	**%**						**ppm**			
Control (without Zn)	2.80	0.130	0.267	0.200	0.133	0.543	088.0	52.7	42.0	6.3
With Zn (stage 1)	2.43	0.140	0.270	0.197	0.153	0.537	201.0	56.0	42.7	4.7
With Zn (stage 2)	2.77	0.137	0.273	0.210	0.127	0.570	094.0	51.0	44.7	8.7
With Zn (stage 1 and 2)	2.53	0.140	0.277	0.213	0.137	0.567	199.0	54.7	47.3	8.7
LSD. 5%	0.16	0.020	0.031	0.033	0.022	0.069	9.0	6.06	3.44	0.6
		N.S	N.S	N.S	N.S	N.S		N.S		

Stage (1) = Tillering stage, Stage (2) = Milk stage, Stage 1 and 2 = Tillering+ Milk stages

1.1.4. The effect of the application of foliar zinc sulfate on nutrient concentrations in wheat straw (cv. Giza 171)

The data presented in Table 6 demonstrate that foliar application of zinc sulfate enhanced the concentrations of magnesium (Mg), iron (Fe), zinc (Zn), and copper (Cu) in the straw of wheat (cv. Giza 171) compared with the untreated control.

Table 6
Effect of foliar application of zinc sulfate at different physiological growth stages on the concentrations of Mg, Fe, Zn, and Cu in wheat straw (cv. Giza 171).

Nutrient	**N**	**P**	**K**	**Ca**	**Mg**	**Na**	**Fe**	**Mn**	**Zn**	**Cu**
Treatment	**%**						**ppm**			
Control (without Zn)	1.97	0.120	1.267	1.500	0.190	0.250	181.0	37.3	20.0	3.7
With Zn (stage 1)	1.90	0.127	1.667	1.767	0.257	0.320	220.0	46.0	20.3	5.7
With Zn (stage 2)	2.17	0.117	1.300	1.567	0.217	0.250	173.0	36.7	23.0	4.0
With Zn (stage 1 and 2)	2.03	0.113	1.433	1.600	0.220	0.277	213.0	41.0	24.7	4.3
LSD. 5%	0.16	0.019	0.344	0.328	0.043	0.078	6.0	11.0	4.0	0.7
		N.S	N.S	N.S		N.S		N.S		

Stage (1) = Tillering stage, Stage (2) = Milk stage, Stage 1 and 2 = Tillering+ Milk stages

1.2. Second Season (2020/2021)

1.2.1. The effect of the application of foliar zinc sulfate on nutrient concentrations in wheat flag leaves (cv. Giza 171)

According to the nutrient sufficiency ranges presented in Table 2, the data in Table 7 indicate that the concentrations of nitrogen (N) and potassium (K) in the flag leaves of wheat (**cv. Giza 171**) were below the recommended sufficiency ranges. In contrast, the concentrations of phosphorus (P), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu) were within the adequate sufficiency ranges. Foliar application of zinc sulfate did not significantly affect the concentrations of most nutrients; however, significant increases were observed in calcium (Ca) and zinc (Zn).

Table 7
Effect of foliar application of zinc sulfate at different physiological growth stages on nutrient concentrations and nutritional status of wheat (cv. Giza 171) flag leaves.

Nutrient	**N**	**P**	**K**	**Ca**	**Mg**	**Fe**	**Mn**	**Zn**	**Cu**
Treatment	**%**					**ppm**			
Without Zn	2.84L	0.29S	0.91L	0.38S	0.33S	164S	45S	16.1S	5.0S
With Zn (stage 1)	2.77L	0.32S	0.86L	0.50S	0.34S	166S	43S	16.2S	5.8S
With Zn (stage 2)	2.70L	0.30S	1.05L	0.40S	0.36S	175S	45S	16.5S	7.2S
With Zn (stage 1 and 2)	2.60L	0.38S	1.03L	0.45S	0.34S	191S	45S	18.1S	6.3S
LSD. 5%	N.S	N.S	N.S	0.07	N.S	N.S	N.S	1.0	N.S
Stage (1) = Tillering stage, Stage (2) = Milk stage, Stage 1 and 2 = Tillering+ Milk stages									

1.2.2. The effect of the application of foliar zinc sulfate on grain yield and yield components of wheat (cv. Giza 171)

The data presented in Table 8 demonstrate that foliar application of zinc sulfate at a concentration of 5 g L^{-1} improved the grain yield and yield components of wheat (cv. Giza 171) compared with the untreated control. Among the different foliar application treatments, the highest grain yield was achieved when zinc sulfate was applied at the selected physiological growth stages. During the 2021/2022 growing season, grain yield reached 8.85 t ha^{-1}, compared with 7.70 t ha^{-1} in the untreated control, representing an increase of approximately 15%.

Table 8
Effect of foliar application of zinc sulfate at different physiological growth stages on grain yield and yield components of wheat (cv. Giza 171).

Yield Treatment	Plant height (cm)	Spike No./m^2	Grain yield ton/ha-^{1}	Straw yield ton/ha^{-1}	Biological yield ton/ha^{-1}	Harvest index %
Without Zn	110	155	7.700	11.653	19.352	39.78
With Zn (stage 1)	113	163	8.647	11.643	20.290	42.62
With Zn (stage 2)	113	166	8.854	11.414	20.268	43.68
With Zn (stage 1 and 2)	113	157	8.758	11.893	20.651	42.41
LSD. 5%	0.75	N.S	0.756	N.S	N.S	2.35
Stage (1) = Tillering stage, Stage (2) = Milk stage, Stage 1 and 2 = Tillering+ Milk stages						

1.2.3. The effect of the application of foliar zinc sulfate on nutrient concentrations in wheat grains (cv. Giza 171)

The data presented in Table 9 demonstrate that foliar application of zinc sulfate significantly increased the concentration of zinc (Zn) in the grains of wheat (cv. Giza 171) compared with the untreated control.

Table 9
Effect of foliar application of zinc sulfate at different physiological growth stages on nutrient concentrations in wheat grains (cv. Giza 171).

Nutrient	N	P	K	Ca	Mg	Fe	Mn	Zn	Cu
Treatment	%						ppm		
Control (without Zn)	2.67	0.45	0.68	1.07	0.22	79.3	24.3	14.0	4.5
With Zn (stage 1)	3.00	0.33	0.89	1.12	0.22	89.4	26.3	14.9	5.5
With Zn (stage 2)	3.07	0.40	0.87	1.27	0.23	103.2	28.0	15.0	3.5
With Zn (stage 1 and 2)	2.83	0.43	0.71	1.11	0.23	103.5	19.0	15.3	3.7
LSD. 5%	0.07	0.04	0.06	0.10	0.02	3.0	1.8	1.0	0.3
Stage (1) = Tillering stage, Stage (2) = Milk stage, Stage 1 and 2 = Tillering+ Milk stages									

1.2.4. The effect of the application of foliar zinc sulfate on nutrient concentrations in wheat straw (cv. Giza 171)

The data presented in Table 10 demonstrate that foliar application of zinc sulfate significantly increased the concentration of zinc (Zn) in the straw of wheat (cv. Giza 171) compared with the untreated control.

Table 10
Effect of foliar application of zinc sulfate at different physiological growth stages on nutrient concentrations in wheat straw (cv. Giza 171).

Nutrient	**N**	**P**	**K**	**Ca**	**Mg**	**Fe**	**Mn**	**Zn**	**Cu**
Treatment	**%**					**ppm**			
Control (without Zn)	2.73	0.41	0.73	1.21	0.22	98.6	16.7	14.4	3.5
With Zn (stage 1)	2.53	0.46	0.88	1.09	0.23	93.7	24.3	15.1	4.0
With Zn (stage 2)	2.53	0.33	0.74	0.94	0.23	87.3	22.0	15.2	5.0
With Zn (stage 1 and 2)	2.73	0.40	0.74	1.28	0.23	88.4	36.3	16.9	4.7
LSD. 5%	0.17	0.01	0.07	0.10	0.01	6.8	5.0	1.9	0.6
Stage (1) = Tillering stage, Stage (2) = Milk stage, Stage 1 and 2 = Tillering+ Milk stages									
Impact on nutrient status and yield parameters									

Across the seasons, foliar application of zinc sulfate 5 g/l has positively changed the nutritional features of flag leaves, grains, and straw for both 'Giza 171' and ' Gemeiza 11' varieties. The double application (stage 1 + 2) emerged as the most efficient treatment, resulting in significant increases in the concentration of zinc within the flag leaf and grains. In addition, the application of zinc stimulated synergetic absorption pathways, enhancing the Ca, Mg, Fe and Mn profiles without creating nutritional imbalances.

The yield parameters responded positively to the application of zinc. The double application resulted in a statistically large increase in grain yields of 13% to 15% over the untreated controls.

The stable harvest index suggests that zinc delivery has improved both early vegetative activity and carbohydrate mobilization from the source to the aquarium later during grain filling.

This is consistent with those reported by Afshar et al. (2020), Ramadan et al. (2020) and Hafez et al., (2021).

2- Large-scale trials (farmer managed trials)

2.1. Season 2021/2022

2 – 1. 1. Soil tests

The data shown in Table 11 indicate that the soil in which the wheat varieties grew has a clay texture. The soil was characterized by a high pH, while electrical conductivity (EC), calcium carbonate ($CaCO_3$), and organic matter contents were within the medium range. Available concentrations of phosphorus (P), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), and zinc (Zn) were classified as moderate, while potassium (K) and copper (Cu) levels were high.

Table 11
Physical and chemical properties of experimental soil (depth 0–30 cm) before sowing wheat.

Test	**M ± SD**	**Test**	**M ± SD**
Sand %	27 ± 1	mg/100g	
Silt %	20 ± 0	P	2.2 ± 0.42**M**
Clay %	53 ± 1	K	33 ± 2**H**
Soil Texture	Clay	Ca	114 ± 7**M**
$CaCO_3$%	2.6 ± 0.2 **M**	Mg	118 ± 3 **M**
OM %	2.1 ± 0.2 **M**	Na	8 ± 1 **VL**
EC,dS/m	0.31 ± 0.11**M**	mg/kg	
pH	8.6 ± 0.1**H**	Fe	12 ± 1 **M**
		Mn	10.0 ± 1 **M**
		Zn	2.4 ± 0.13 **M**
		Cu	1.6 ± 0.24 **H**
VL= very low L = Low, M = Medium, H = High			

High soil pH is known to trigger zinc precipitation and adsorption onto clay minerals, severely limiting its root uptake and translocation (Lindsay & Norvell, 1978; Marschner, 1995; Alloway, 2008). Consequently, bypassing these soil constraints via foliar zinc sulfate application is highly justified.

2.1.2. Nutrient concentrations in wheat flag leave (cv. Gemeiza 11)

The data presented in Table 12 demonstrate that two foliar applications of zinc sulfate at a concentration of 5 g L^{-1}, applied at the tillering and milk growth stages, significantly increased the

concentrations of zinc (Zn), calcium (Ca), magnesium (Mg), and manganese (Mn) in the flag leaves of wheat (cv. Gemeiza 11) compared with the untreated control.

Table 12
Effect of foliar application of zinc sulfate at different physiological growth stages on nutrient concentrations and nutritional status of wheat (cv. Gemeiza 11) flag leaves.

Nutrient	**N**	**P**	**K**	**Ca**	**Mg**	**Fe**	**Mn**	**Zn**	**Cu**
Treatment	**%**					**ppm**			
Control (without Zn)	2.57L	0.164L	1.40L	0.40S	0.31S	227S	70S	48S	4.0L
With Zn (stage 1 and 2)	2.63L	0.185L	1.53L	0.45S	0.43S	197S	88S	63S	2.0L
LSD. 5%	N.S	N.S	N.S	0.04	0.08	14	5.2	2.5	1.4
Stage 1 and 2 = Tillering+ Milk stages									

2.1.3. The effect of the application of foliar zinc sulfate on grain yield and yield Components of wheat (cv. Gemeiza 11)

The data presented in Table 13 demonstrate that foliar application of zinc sulfate significantly enhanced the grain yield and yield components of wheat (cv. Gemeiza 11) compared with the untreated control. Significant improvements were observed in plant height, number of spikes m^{-2}, grain yield, straw yield, and biological yield following foliar application of zinc sulfate.

Table 13
Effect of foliar application of zinc sulfate at different physiological growth stages on grain yield and yield components of wheat (cv. Gemeiza 11).

Yield **Treatment**	**Plant height (cm)**	**Spike No./m^2**	**Grain yield ton/ha^{-1}**	**%**	**Straw yield ton/ha^{-1}**	**Biological yield ton/ha^{-1}**	**Harvest index %**
Control (without Zn)	100	189	5.851	100	8.09	13.941	41.9
With Zn (stage 1 and 2)	103	196	6.843	117	10.00	16.843	40.63
LSD. 5%	1.4	N.S	0.633		1.02	1.48	N.S
Stage 1 and 2 = Tillering+ Milk stages							

2.1. 4. The effect of the application of foliar zinc sulfate on nutrient concentrations in wheat grains (cv. Gemeiza 11)

The data presented in Table 14 demonstrate that foliar application of zinc sulfate significantly increased the concentrations of iron (Fe) and zinc (Zn) in the grains of wheat (cv. Gemeiza 11) compared with the untreated control.

Table 14
Effect of foliar application of zinc sulfate at different physiological growth stages on nutrient concentrations in wheat grains (cv. Gemeiza 11).

Nutrient	**N**	**P**	**K**	**Ca**	**Mg**	**Na**	**Fe**	**Mn**	**Zn**	**Cu**
Treatment	**%**						**ppm**			
Control (without Zn)	3.07	0.140	0.257	0.203	0.127	0.563	81	54.3	37.7	5.0
With Zn (stage 1 and 2)	2.83	0.127	0.280	0.197	0.140	0.543	130	49.3	46.7	6.3
LSD. 5%	0.76	0.014	0.100	0.014	0.038	0.043	15	8.6	6.6	3.8
	N.S	N.S	N.S	N.S	N.S	N.S		N.S		N.S
Stage 1 and 2 = Tillering+ Milk stages										

2.1. 5. The effect of the application of foliar zinc sulfate on nutrient concentrations in wheat straw (cv. Gemeiza 11)

The data presented in Table 15 indicate that foliar application of zinc sulfate had no significant effect on most nutrient concentrations in wheat straw; however, it significantly increased the concentration of zinc (Zn) compared with the untreated control.

Table 15
Effect of foliar application of zinc sulfate at different physiological growth stages on nutrient concentrations in wheat straw (cv. Gemeiza 11).

Nutrient	N	P	K	Ca	Mg	Na	Fe	Mn	Zn	Cu
Treatment	**%**						**ppm**			
Control (without Zn)	2.00	0.127	1.43	1.67	0.213	0.293	226	42	18.7	4.0
With Zn (stage 1 and 2)	2.20	0.117	1.57	1.77	0.240	0.287	210	35	26.3	3.7
LSD. 5%	0.86	0.025	0.38	0.25	0.029	0.080	20	13	7.6	1.4
	N.S	N.S	N.S	N.S	N.S	N.S	N.S	N.S		N.S
Stage 1 and 2 = Tillering+ Milk stages										

2.2. Season 2022/2023

2.2.1. Wheat (cv. Giza 171)

2.2.1.1. The effect of the application of foliar zinc sulfate on nutrient concentrations in fag leave of wheat Giza 171

The data presented in Table 16 demonstrate that foliar application of zinc sulfate did not significantly affect the concentrations of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), iron (Fe), manganese (Mn), or copper (Cu) in the flag leaves of wheat (cv. Giza 171). However, the concentration of zinc (Zn) was significantly increased following foliar application of zinc sulfate at a rate of 5 g l^{-1}, with the greatest increase observed when the treatment was applied at the stem elongation and milk growth stages.

Table 16
Nutrient concentrations and nutritional status of Giza 171 wheat flag leaves as affected by foliar application of zinc sulfate

Nutrient	N	P	K	Ca	Mg	Fe	Mn	Zn	Cu
Treatment	**%**					**ppm**			
Control (without Zn)	2.47L	0.36S	1.03L	0.39S	0.33S	128S	41S	20S	7.0S
With Zn (stage 1 and 2)	2.55L	0.32S	0.94L	0.37S	0.34S	141S	40S	23S	5.0S
LSD. 5%	N.S	N.S	N.S	N.S	N.S	N.S	N.S	2.0	N.S
Stage 1 and 2 = Tillering+ Milk stages									

2.2.1.2. The effect of the application of foliar zinc sulfate on yield and yield components of Giza 171 Wheat

The data presented in Table 17 demonstrate that foliar application of zinc sulfate at a rate of 5 g L^{-1} improved the grain yield, straw yield, and biological yield of wheat (cv. Giza 171) compared with the untreated control, indicating the beneficial effect of foliar zinc application on wheat productivity.

Table 17
Yield and yield components of wheat (**cv. Giza 171**) as affected by foliar application of zinc sulfate.

Yield **Treatment**	**Plant height** **(cm)**	**Spike** **No./m^2**	**1000 grain weight (g)**	**Grain yield** **ton/ha**	**%**	**Straw yield** **ton/ha**	**Biological yield** **ton/ha-1**	**Harvest index** **%**
Control	111	164	618	8.203a	100	10.24a	18.443	44.48
With Zn (stage 1 and 2)	113	169	625	8.518	104	11.29b	19.808	43.00
LSD. 5%	N.S	N.S	N.S	0.182b		0.204	0.458	N.S
Stage 1 and 2 = Tillering+ Milk stages								

2.2.1.3. The effect of the application of foliar zinc sulfate on nutrient concentrations of Giza 171 wheat grains

The data presented in Table 18 demonstrate that foliar application of zinc sulfate significantly increased the concentrations of nitrogen (N), phosphorus (P), and zinc (Zn) in the grains of wheat (cv. Giza 171) compared with the untreated control.

Table 18
Nutrient concentrations of wheat (cv. Giza 171) grains as affected by foliar application of zinc sulfate.

Nutrient	**N**	**P**	**K**	**Ca**	**Mg**	**Fe**	**Mn**	**Zn**	**Cu**
Treatment	**%**					**ppm**			
Control (without Zn)	2.22	0.28	0.90	0.33	0.39	86	46	28	5.2
With Zn (stage 1 and 2)	2.73	0.31	0.79	0.33	0.40	91	43	34	5.4
LSD. 5%	0.20	0.02	0.10	N.S	N.S	N.S	N.S	4	N.S
Stage 1 and 2 = Tillering+ Milk stages									

2.2. 1.4. The effect of the application of foliar zinc sulfate on nutrient concentrations of Giza 171 wheat Straw

The data presented in Table 19 demonstrate that foliar application of zinc sulfate significantly increased the concentrations of iron (Fe), manganese (Mn) and zinc (Zn) in the straw of wheat (cv. Giza 171) compared with the untreated control. The greatest increase was observed for zinc (Zn), indicating the effectiveness of foliar zinc application in enhancing zinc accumulation in wheat straw

Table 19
Nutrient concentrations of wheat **(**cv. Giza 171**)** straw as affected by foliar application of zinc sulfate.

Nutrient	**N**	**P**	**K**	**Ca**	**Mg**	**Fe**	**Mn**	**Zn**	**Cu**
Treatment	**%**					**ppm**			
Control (without Zn)	2.97	0.42	0.80	1.47	0.23	96	44	14.0	6.7
With Zn (stage 1 and 2)	2.70	0.43	0.57	1.16	0.24	131	59	16.0	5.2
LSD. 5%	N.S	N.S	0.16	N.S	N.S	6	10	1.0	N.S
Stage 1 and 2 = Tillering+ Milk stages									

2.2.2. Wheat (cv. Gemeiza 11)

2.2.2.1. The effect of zinc sulfate spraying on the nutrient concentrations of Gemeiza 11 wheat flag leaves

The data presented in Table 20 demonstrate that foliar application of zinc sulfate did not significantly affect the concentrations of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), iron (Fe), manganese (Mn) and copper (Cu) in the flag leaves of wheat (cv. Gemeiza 11). However, foliar application of zinc sulfate at a rate of 5 g L^{-1} significantly increased the concentration of zinc (Zn), compared with the untreated control, when applied at the stem elongation and milk growth stages.

Table 20
Nutrient concentrations and nutritional status of wheat (cv. Gemeiza 11) flag leaves as affected by foliar application of zinc sulfate.

Nutrient	**N**	**P**	**K**	**Ca**	**Mg**	**Fe**	**Mn**	**Zn**	**Cu**
Treatment	**%**					**ppm**			
Control (without Zn)	2.65L	0.24L	1.06L	0.40S	0.27S	137S	43S	17S	4.8L
With Zn (stage 1 and 2)	2.50L	0.34S	1.07L	0.41S	0.25S	158S	39S	21S	5.0S
LSD. 5%	N.S	N.S	N.S	N.S	N.S	N.S	N.S	3	N.S
Stage 1 and 2 = Tillering+ Milk stages									

2.2.2. 2. Effect of the application of foliar zinc sulfate on the yield and yield components of Gemeiza 11 wheat

The data presented in Table 21 demonstrate that foliar application of zinc sulfate at a rate of 5 g L^{-1} improved the grain yield and biological yield of wheat (cv. Gemeiza 11) compared with the untreated control, when zinc sulfate was applied twice, at the tillering and milk growth stages.

Table 21
Yield and yield components of wheat (cv. Gemeiza 11) as affected by foliar application of zinc sulfate.

Yield **Treatment**	**Plant length** **(cm)**	**Spike** **No./m^2**	**1000 grain weight (g)**	**Grain yield** **ton/ha^{-1}**	**%**	**Straw yield** **ton/ha^{-1}**	**Biological yield** **ton/ha^{-1}**	**Harvest index** **%**
Control (without Zn)	110	168	544	8.469a	100	11.436	19.905	42.55
With Zn (stage 1 and 2)	113	171	606	8.895b	105	11.997	20.892	45.58
LSD. 5%	N.S	N.S	N.S	0.285		N.S	0.86	N.S
Stage 1 and 2 = Tillering+ Milk stages								

2.2.2.3. Effect of zinc sulfate spraying on the nutrient concentrations of Gemeiza 11 wheat grains

The data presented in Table 22 demonstrate that foliar application of zinc sulfate significantly increased the concentration of zinc (Zn) in the grains of wheat (cv. Gemeiza 11) compared with the untreated

control.

Table 22
Nutrient concentrations of wheat (cv. Gemeiza 11) grains as affected by foliar application of zinc sulfate.

Nutrient	N	P	K	Ca	Mg	Fe	Mn	Zn	Cu
Treatment	%					ppm			
Control (without Zn)	2.38	0.26	0.88	0.32	0.38	70	34	33	4.7
With Zn (stage 1 and 2)	2.35	0.25	0.86	0.33	0.36	81	41	39	4.5
LSD. 5%	N.S	N.S	N.S	N.S	N.S	N.S	N.S	4	N.S
Stage 1 and 2 = Tillering+ Milk stages									

2.2.2. 4. Effect of zinc sulfate spraying on the nutrient concentrations of Gemeiza 11 wheat straw

The data presented in Table 23 demonstrate that foliar application of zinc sulfate significantly increased the concentrations of nitrogen (N), iron (Fe), zinc (Zn) and copper (Cu) in the straw of wheat (cv. Gemeiza 11) compared with the untreated control.

Table 23
Nutrient concentrations of wheat (cv. Gemeiza 11) straw as affected by foliar application of zinc sulfate

Nutrient	N	P	K	Ca	Mg	Fe	Mn	Zn	Cu
Treatment	%					ppm			
Control (without Zn)	2.40	0.45	0.69	1.54	0.23	87	25	13.8	3.5
With Zn (stage 1 and 2)	2.97	0.49	0.67	1.28	0.23	101	22	14.9	5.0
LSD. 5%	0.14	N.S	N.S	N.S	N.S	13	N.S	1.0	1.2
Stage 1 and 2 = Tillering+ Milk stages									

Discussion

The prevalence of heavy and highly alkaline soils with low organic matter content in many wheat-growing areas restricts the availability of zinc (Zn) because the zinc applied to the soil is easily immobilized

through fixation and exhibits limited mobility. Under these conditions, the foliar application of zinc sulfate provides an efficient, practical and cost-effective approach to improving zinc nutrition and enhancing wheat productivity.

By bypassing soil-related constraints, the application of foliar zinc provides nutrients directly to the foliage, thus enhancing the absorption of zinc, facilitating its transfer to the growing tissues actively, and promoting grain filling. These results are consistent with the results of Ramadan et al. (2020), who reported that the application of foliar zinc was more effective than applying soil in improving zinc nutrition for wheat under conditions of limited availability of zinc in soil.

Also, Abbas et al. (2025) reported that the use of zinc in the soil did not lead to significant increases in the concentration of zinc in grains. However, increases of 45% and 47% were recorded using the application of foliar zinc compared to the unfertilized control treatment

The results of this study under the conditions of surface-irrigated clay soils, which constitute a significant part of agriculture in the Nile Delta, show that the foliar application of zinc (Zn) significantly increased zinc concentrations in both grains and straw, enhanced nutrient absorption, and improved grain yield in wheat, Giza 171 and Gemeiza 11.

The zinc grain concentration increased from about 42.7 ppm in untreated control to approximately 47–54 ppm after the application of foliar zinc.

A corresponding increase, although less pronounced, was also observed in the concentration of zinc in wheat straw. The results of the current study indicate that two foliar applications of zinc sulfate have produced the greatest improvements in wheat performance.

The application in the two stages of tillering and milk ripening resulted in the higher grain and straw yields, greater accumulation of zinc, and enhanced components of wheat in Giza 171 and Gemeiza 11. Grain yield increased by up to 15%, which is a statistically significant and agriculturally significant improvement.

Ram et al., 2024 reported that the data showed the significant effect of foliar spraying with zinc sulfate ($ZnSO_4$) in increasing the concentration of zinc for grains by 39.6%. Experiments conducted on large field also showed 40.3% in increased zinc concentration in grains resulting from the foliar application of zinc sulfate (ZnSO4), highlighting the effectiveness of the technique and the possibility of its adoption in farmers' fields

The superior effectiveness of foliar zinc fertilization is attributed to its ability to circumvent soil-related restrictions, promote the rapid absorption of zinc through the foliage, and facilitate the efficient transport of nutrients to the development of grains during the reproductive phase, thus improving both Zn grain enrichment and crop productivity

In this regard, Khalili et al., (2023), found that utilizing the TRB-72-311 genotype with 0.5% foliar Zn application and ZSB enhances wheat's Zn content, uptake, grain quality.

The current study showed an improvement in the absorption of certain nutrients, such as calcium, magnesium, iron, and manganese.

Similarly, the absence of any adverse effects on concentrations of other nutrients or on crop performance indicates that foliar application of zinc sulphate has improved Zn nutrition effectively without causing nutrient imbalances.

Likewise, the results of the present study demonstrated that the foliar application of zinc sulfate at the tillering and milky maturity stages was the most effective treatment to enhance the concentration of zinc for grains, nutrient absorption and yield performance.

Current results are also supported by the results of Yang et al. (2011), Hussein et al. (2012, 2013), Rahman et al. (2020), and Ahmed et al. (2025), all of whom reported that the application of foliar zinc significantly increased the concentration of zinc grains and wheat productivity, especially when applied during critical growth stages such as tillage and grain filling.

The observed increase in grain production can be attributed to the basic physiological functions of zinc in plants. Zinc plays a key role in many enzymatic reactions, protein synthesis, photosynthesis, hormone regulation, and carbohydrate metabolism, all of which contribute to improved plant growth, biomass accumulation and grain development. In addition, improved zinc nutrition enhances the absorption, use and transport of other essential nutrients, thereby promoting overall plant growth and productivity.

The promotion of plant growth after the application of zinc is reflected in the increase in the biological yield, grain productivity and associated yield components. Moreover, the harvest index was not significantly affected, indicating that the grain absorption division was maintained while both vegetative growth and grain filling were promoted.

The present results are in agreement with previous studies conducted under diverse and a range of environmental conditions., including those of Karim et al. (2012), El-Metwally et al. (2012), Afshar et al. (2020), El-Fouly et al. (2023), Akça and Taban (2024) and Ahmed et al. (2025), all of which, reported significant improvements in zinc grain concentration and wheat productivity after the application of foliar Zn application.

In general, the results of this study confirm that the foliar application of zinc sulfate is an effective agricultural strategy to improve wheat productivity and enhance the biofortification of Zn grains under clay and alkaline soil conditions.

Based on these results, the foliar application of zinc sulfate at a concentration of 5 g L^{-1}, which is applied twice during the growing season in the ripening and milk stages, is recommended as an ideal management practice to maximize nutrient absorption, Zn grain concentration and wheat productivity.

Conclusions

Foliar application of zinc sulfate successfully overcomes the chemical constraints of alkaline clay soils in Egypt, delivering zinc directly to the plant canopy. This agronomic strategy significantly enriches flag leaves and the density of zinc for grains without triggering yield penalties. Instead, it concurrently stimulates the absorption of macro and micronutrient for Ca, Mg, Fe, Mn, maintaining an optimal nutritional balance while providing an effective tool for addressing human micronutrient malnutrition.

Recommendations

Application Standard: Farmers should adopt a two-fold foliar spraying regimen using zinc sulfate with a concentration of 5 g/l of water - once during the tillering stage and a second time during the milk-ripening stage. Economic Viability: With an average yield improvement of 13% to 15\% achieved via minimal input costs, this practice offers an economically robust and sustainable option for wheat cultivation in alkaline clay regions.

Declarations

Materials and methods

Field experiments were conducted during the winter growth seasons 2019/2020 and 2020/2021 in the village of Kafr Al-Khadra, Al-Bagour District, Menoufia Governorate, Egypt. The location represents the typical Egyptian clay soil.

Results

Foliar zinc application-particularly the double application significantly enhanced zinc Furthermore, the leaf foliar application of zinc sulfate ($ZnSO_4$) enhanced concentrations of potassium, calcium, magnesium, iron, and manganese in both grains and straw.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Consent to publish

declaration

Ethics and consent to publish declarations

Not applicable.

Permissions to collect the plant parts

No permission was needed to collect samples.

Ethics and Consent to Participate

The plant materials used in this study, including wheat leaves, grains, and straw from the cultivars Giza 171 and Gemeiza 11 (Triticum aestivum L.), were obtained from cultivated plants. Their collection and use complied with applicable local and national guidelines and regulations. No wild plants were collected for this study.

Author details

Mohamed Mostafa El-Fouly

Department of Fertilization Technology, National Research Centre, Egypt

Samir Hosni Ahmed Shaaban

Department of Fertilization Technology, National Research Centre, Egypt

Funding

No external funding was received for this study.

Author Contribution

Mohamed Mostafa El-Fouly, Samir Hosni Ahmed Shaaban wrote the main manuscript text and reviewed the manuscript

Acknowledgment

This work was conducted as a part of the activities of the Egypto-German Project “Micronutrients and Plant Nutrition Problems in Egypt” conducted by the National Research Centre, Cairo and the Institute for

Plant Nutrition, Technical University, Munich. It was supported by the German Agency for Technical Co-operation (GTZ) and the Egyptian Academy for Scientific Research and Technology (ASRT).

The Atomic Absorption spectrophotometer used in this study in measure micro elements has donated to M.M El-Fouly by Alexander von Humboldt Foundation, Germany.

We extend our thanks to Mr. Mohamed Abdel Fattah, an agriculture specialist in the Fertilization Technology Department, for his efforts during the implementation of the experiments in farmers' fields.

Data Availability

All data generated or analyzed during the current study are included in the published research.

References

1. Abbas M, Depar N, Ullah S, Irfan M, Shah JA, Afzal J. (2025). Comparative efficacy of soil and foliar zinc application for agronomic biofortification of wheat with zinc. Discover Soil (2025) 2:121. https://doi.org/10.1007/s44378-025-00153-1
2. Afshar RK, Chen C, Zhou S, Etemadi F, He H, Li Z. Agronomic and economic response of bread wheat to foliar zinc application. J Agron. 2020;112(5):4045–56. https://doi.org/10.1002/agj2.20247.
3. Ahmed Z, Ayesha, Afzal A, Ali M, Khan MH, Rehman R. Comparison of zinc fertilizer application response in biofortified and non-biofortified wheat (Triticum aestivum L.) varieties and advanced lines. J Agric Food. 2025;6(2):74–87. https://doi.org/10.52587/JAF060205.
4. Akça H, Taban S. Optimizing Grain Zinc Biofortification in Bread Wheat: Innovative Fertilization Strategies for Field Conditions. J Soil Sci Plant Nutr. 2024;24:4714–26. https://doi.org/10.1007/s42729-024-01865-z.
5. AOAC. (1984). Official Methods of Analysis of the Association of Official Analytical Chemists, 14th ed.; AOAC: Arlington, VA, Sec. 33.056.
6. Alloway BJ. (2008). Zinc in Soils and Crop Nutrition, Second edition, published by IZA and IFA Brussels, Belgium and Paris, France.
7. Alloway BJ. (2009). Soil factors associated with zinc deficiency in crops and humans.
8. Environmental. Geochem Health, 31(5), 537–48.
9. Ankerman D, Large L. Soil and Plant Analysis, AandL Agric. New York, USA: Lab. Inc; 1974.
10. Bhatt R, Hossain A, Sharma P. Zinc biofortification as an innovative technology to alleviate the zinc deficiency in human health: A review. Open Agric. 2020;5:176–87. https://doi.org/10.1515/opag-2020-0018.
11. Chapman HD, Pratt PF. (1978). Methods of Analysis for Soils, Plant and Water. 50, Univ. Calif., Dept. Agric. Sci., Priced Publication, 4034, USA. p. 309.

12. Das S, Jahiruddin M, Islam MR, Mahmud AA, Hossain A, Laing AM. (2020). Zinc biofortification in the grains of two wheat (Triticum aestivum L.) varieties through fertilization. Acta Agrobotanica, 73 (2).
13. El-Dahshouri MF, El-Fouly MM, Khalifa RKM, Abd El-Ghany HM. Effect of zinc foliar application at different physiological growth stages on yield and quality of wheat under sandy soil conditions. Agricultural Eng International: CIGR J. 2017;19(3):193–200.
14. El-Fouly MM, Gehan A, Noureldein, ElZanaty AA, Abou El-Nour, Abdel-Wahab A, Abdel-Maguid. Effect of Spraying Zinc on Yield and Grain Zn Content in Two Wheat Cultivars. Egypt J Agron. 2023;45(3):249–58.
15. El-Habbasha ES, Badr EA, Latef EA. (2015). Effect of zinc foliar application on growth.
16. characteristics. and Grain Yield of some wheat varieties under Zn deficient sandy soil condition. Int J Chemtech Res, 8(6): 452–8.
17. Gibson RS. Zinc: the missing link in combating micro- nutrient malnutrition in developing countries. Proc Nutr Soc. 2006;65:51–60.
18. Gomez KA, Gomez AA. (1984). Statistical Procedures for Agricultural Research. 2nd Edn., Jhon Wiley and Sons Inc., New York, pp: 95–109.
19. Ghanem H, Hamza D, El-Abdeen A, Elbatrawy W, El-Habashy H. Influence of zinc foliar spray on growth, some important physiological processes, yield and yield attributes of bread wheat under water stress. Sci Rep |. 2025;15:14943. https://doi.org/10.1038/s41598-025-94728-1.
20. Hafeez MB, Ramzan Y, Khan S, Ibrar D, Bashir S, Zahra N, Rashid N, Nadeem M, Rahman S, Shair H, Ahmad J, Hussain M, Irshad S, Al-Hashimi A, Alfagham A, Diao Z-H. Application of Zinc and Iron-Based Fertilizers Improves the Growth Attributes, Productivity, and Grain Quality of Two Wheat (Triticum aestivum) Cultivars. Front Nutr. 2021;8:779595. 10.3389/fnut.2021.779595.
21. Hemmat N, Khaleeq KU, Nasrat NA, Meena SL, Shivay YS, Kumar D, Varghese C. Productivity of wheat (Triticum aestivum) as influenced by zinc fertilization under semi-arid conditions of Kandahar, Afghanistan. Ind J Agron. 2023;68(2):215–8.
22. Hotz C, Brown KH. Assessment of the risk of zinc deficiency in populations and options for its control. FoodNutr Bull. 2004;2:194–204.
23. Hussain S, Maqsoodab MA, Rengel Z, Aziz T. Biofortification and estimated human bioavailability of zinc in wheat grains as influenced by methods of zinc application. Plant Soil. 2012;361:279–90.
24. Hussain S, Maqsoodab MA, Azizac T, Basrad SMA. Zinc bioavailability response curvature in wheat grains under incremental zinc applications. Arch Agron Soil Sci. 2013;59:1001–16.
25. Kamran A, Ghazanfar M, Khan JS, Pervaiz S, Siddiqui MH, Alamri S. (2023).Zinc Absorption through Leaves and Subsequent Translocation to the Grains of Bread Wheat after.
26. Foliar Spray. Agriculture, 13, 1775. https://doi.org/10.3390/agriculture13091775
27. Karim MR, Zhang YQ, Zhao RR, Chen XP, Zhang FS, Zou CQ. Alleviation of drought stress in winter wheat by late foliar application of zinc, boron, and manganese. J Plant Nutr Soil Sci. 2012;175:142–

51.

28. Khalili A, Qayyum A, Khan SU, Ullah I, Khalofah A. (2023). Role of Temporal Zn Fertilization along with Zn Solubilizing Bacteria in Enhancing Zinc Content, Uptake, and Zinc Use Efficiency in Wheat Genotypes and Its Implications for Agronomic Biofortification. Agronomy 2023, 13, 2677. https://doi.org/10.3390/agronomy13112677
29. Jackson ML. Soil Chemical Analysis. Indian Private Limited, New Delhi, India: Printice Hall; 1986. pp. 251–80.
30. Jones J Jr., Benton B, Wolf HA, Mills. Plant Analysis Handbook. Macro Publishing, Inc.; 1991. p. 187. 183 Paradise Blvd, Suite 108, Athens, Georgia 30607 USA.
31. Lindsay WL, Norvell WA. Development of a DTPA soil test for zinc, iron, manganese, and copper. Soil Sci Soc Am J. 1978;42(3):421–8.
32. https://doi.org/10.2136/sssaj1978.03615995004200030009x
33. Marschner H. (1995). Mineral nutrition of higher plants, second edition. 889pp. London: Academic Press.
34. Paramesh V, Dhar S, Dass A, Kumar B, Kumar A, Diaa O, El-Ansary, Hosam O, Elansary. Role of Integrated Nutrient Management and Agronomic Fortification of Zinc on Yield, Nutrient Uptake and Quality of Wheat. Sustainability. 2020;12:3513.
35. Prasad R, Shivay YS, Kumar D. Zinc fertilization of cereals for increased production and alleviation of Zn malnutrition in India. Agric Res. 2013;2(2):111–8.
36. Ram S, Malik VK, Gupta V, Narwal S, Sirohi M, Ankush, Pandey V, Gupta OP, Misra AK, Singh G. Impact of foliar application of iron and zinc. fertilizers on grain iron, zinc; 2024.
37. and protein contents in bread wheat (Triticum aestivum L.). Front. Nutr. 11:1378937. 10.3389/fnut.2024.137893
38. Ramadan Y, Hafeez MB, Khan S, Nadeem M, Rahman S, Batool S, Ahmad J. Biofortification with zinc and iron improves the grain quality and yield of wheat. Crop Int J Plant Prod. 2020;14(3):501–10.
39. Rehman A, Farooq M, Ullah A, Nadeem F, Im SY, Park SK, Lee. D-J (2020). Agronomic.
40. Biofortification of Zinc in Pakistan. Status, Benefits, and Constraints. Front Sustain Food Syst 4:591722. 10.3389/fsufs.2020.591722
41. Rengel Z, Batten GD, Crowley DE. Agronomic approaches for improving the micronutrient density in edible portions of field crops. Field Crop Res. 1999;60:27–40.
42. https://doi.org/10.1016/S0378-4290(98)00131-2
43. Sanchez-Palacios JT, Henry D, Penrose B, Bell R. Formulation of zinc foliar sprays for wheat grain biofortification: a review of current applications and future perspectives. Front Plant Sci. 2023;14:1247600. 10.3389/fpls.2023.1247600.
44. Sendecor GW, Cochran WG. Statistical Methods. Ames, Iowa: Iowa State Univ.; 1980. pp. 149–51.
45. Shaaban SHA, Abou El-Nour EAA, El-Fouly MM. Impact of balanced fertilization based on soil testing on yield, nutrients uptake and net return on irrigated wheat in Delta, Egypt. Indian J Sci Technol.

2018;11(5):1–13.

46. Silvertooth JC. Soil Fertility and Soil Testing Guidelines for Arizona Cotton. USA: University of Arizona.; 2001.
47. Thapa DB, Subedi M, Yadav RP, Joshi BP, Adhikari BN, Shrestha KP, Magar PB, Pant KR, Gurung SB, Ghimire S, Gautam NR, Acharya NR, Sapkota M, Mishra VK, Joshi AK, Singh RP, Govindan V. Variation in Grain Zinc and Iron Concentrations, Grain Yield and Associated Traits of Biofortified Bread Wheat Genotypes in Nepal. Front. Plant Sci. 2022;13:881965. 10.3389/fpls.2022.881965.
48. Wang M, Kong F, Liu R, Fan Q, Zhang X. Zinc in Wheat Grain, Processing, and Food. Front Nutr. 2020;7:124. 10.3389/fnut.2020.00124.
49. White PJ, Broadley MR. Physiological limits to zinc biofortification of edible crops. Ann Botany. 2011;107(1):1–11.
50. World Health Organization, (WHO). (2020). Zinc deficiency and human health.
51. Yang XW, Tian XH, Lu XC, Gale WJ, Cao YX. Foliar zinc fertilization improves the zinc nutritional value of wheat (Triticum aestivum L.) grain. Afr J Biotechnol. 2011;10:14778–85.
52. Yilmaz A, Ekiz H, Torun B, Gultekin I, Karanlik S, Bagci SA, Cakmak I. Effect of different zinc application methods on grain yield and zinc concentration in wheat grown on zinc-deficient calcareous soils in Central Anatolia. J Plant Nutr. 1997;20:461–71.
53. Zhang YQ, Sun YX, Ye YL, Karim MR, Xue YF, Yan P, Meng QF, Cui ZL, Cakmak I, Zhang FS, Zou CQ. Zinc biofortification of wheat through fertilizer applications in different locations of China. Field Crops Res. 2012;125:1–7.