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Effects of Phosphate Fertilizer Type and Application Rate, Zinc Foliar Application, and Their Interactions on the Growth and Yield of Sweet Corn Grown in Gypsum Soil

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Abstract

A field trial was conducted at the Faculty of Agriculture, Tikrit University, during the 2025 growing season, to investigate the effects of phosphate fertilizer type and application rate, and zinc foliar application, on the growth and yield of sweet corn grown in gypsum soil. The experiment was conducted using a Randomized Complete Block Design (RCBD) with three replicates and three parameters: two phosphate fertilizer sources (di ammonium phosphate (DAP) and tri calcium superphosphate (TSP)), three phosphate application rates (0, 90, and 180 kg P ha^{-1}, denoted as P0, P1, and P2) respectively, and three foliar zinc application rates (0, 25, and 50 mg Zn L^{-1}, denoted as Zn0, Zn1, and Zn2) respectively. The results showed that increased phosphate application led to a significant increase in growth characteristics and yield. At the highest level (180 kg P ha^{-1}), the average above-ground dry weight (45.71 g $plant^{-1}$ and 93.90 g $plant^{-1}$ for the first and second harvests, respectively) and absolute growth rate (1.607) were at their highest. Average dry weight (g $plant^{-1}day^{-1}$), number of grains per panicle (545.94, 540.63 grains per panicle), 500-grain weight (156.85 g), grain yield (6779 kg ha^{-1}), and biological yield (13882kg ha^{-1}) were all significantly improved. DAP fertilizer showed significantly better results than TSP fertilizer in most of the traits investigated.

Foliar application of zinc significantly improved growth and yield characteristics. At a concentration of 50mg Zn L^{-1}, average dry weight (44.06g and 91.25g $plant^{-1}$), absolute growth rate (1.573 g $plant^{-1}$ day^{-1}), number of grains per panicle (540.63 grains) and 500-grain weight (155.39g), and grain yield (6442kg ha^{-1}) were all significantly improved. The highest values were observed for both ha^{-1} and biological yield (13536 kg ha^{-1}). The three-factor interaction also showed clear results. Significant effects were observed, with the (DAP × P_2 × Zn_2) treatment showing the highest values in all traits investigated: (Dry weight after two harvests: 51.52 g plant-1 and 105.14 g plant-1), (Absolute growth rate: 1.787 g plant^{-1} day^{-1}), (Number of panicles: 601.32 grain ear^{-1}), (162.66 g per 500 panicles), (Grain yield: 7957 kg ha^{-1}), and (Biological yield: 15505 kg ha^{-1}). In contrast, the control treatment (P_0Zn_0) showed the lowest values for all parameters with both fertilizer sources.

Keywords: Sweet corn, Phosphate fertilizer, Di ammonium phosphate (DAP), Tri calcium superphosphate (TSP), Foliar zinc application, Gypsum soil

1. Introduction

Gypsum soils are widely distributed in arid and semi-arid regions and are characterized by high concentrations of gypsum ($CaSO_4 \cdot 2H_2O$). This high concentration of gypsum negatively impacts the soil's physical, chemical, and biological properties. High gypsum leads to soil compaction, reduced aeration, decreased cation exchange capacity, and reduced availability of nutrients essential for plants. Furthermore, increased soluble calcium promotes the fixation of certain nutrients, particularly phosphorus and zinc, limiting their absorption and thus affecting plant growth and yield [1].

Phosphorus is a major nutrient essential for plant growth, playing a crucial role in nucleic acid formation, intracellular energy transport via ATP, root growth promotion, maturation promotion, and yield increase. However, in gypsum soils, phosphorus reacts with calcium to form sparingly soluble compounds such as $Ca_3(PO_4)_2$ and $Ca_{10}(PO_4)_6(OH)_2$, limiting its availability. This reduces phosphorus absorption by plants, negatively impacting growth and productivity [2]. Studies show that plants utilize only 15–20% of added phosphorus, with the majority being fixed in the soil complex or converted into organic forms [3].

Phosphate fertilizers play a crucial role in increasing phosphorus availability. DAP fertilizers are characterized by their high solubility and availability in the early stages of growth, while triple superphosphate (TSP) fertilizers provide a relatively sustained effect on plant nutrition. In gypsum soils, the use of DAP has been shown to significantly increase plant growth and sweet corn yield compared to TSP [4]. This is due to DAP's high solubility and low susceptibility to precipitation reactions.

Zinc is an essential micronutrient involved in enzyme formation and activation, chlorophyll synthesis, and the regulation of life-sustaining processes within plants. However, in gypsum soils, zinc tends to be deficient in available zinc due to its adsorption to the colloidal surface, competition with calcium, and high pH levels, leading to reduced plant growth and yield. [5] Zinc deficiency inhibits photosynthesis, suppresses root growth, and reduces grain formation.

Sweet corn (*Zea mays* L. saccharata) is an economically and nutritionally important crop due to its high nutritional value and adaptability to diverse environmental conditions, including semi-arid regions and gypsum soils, making it essential for achieving food security. [6] Therefore, improving the management of phosphorus and zinc fertilization is a crucial factor in increasing the growth efficiency and yield of sweet corn. This study aimed to determine the optimal sources and application rates of phosphorus and zinc to achieve maximum vegetative growth and highest yield in sweet corn grown in gypsum soil.

2. Materials and Methods

1.2 Experimental Fields and Soil Analysis

During the 2025 growing season, field experiments using factorial design were conducted at the Faculty of Agriculture, Tikrit University, to investigate the effects of phosphorus and zinc fertilizer sources and application rates on the growth and yield indicators of sweet corn in gypsum soil.

Soil samples were collected from 10 randomly selected locations at a depth of 0–30 cm using a soil drill. After drying and aeration, the collected soil was thoroughly mixed through a 2 mm sieve, and its physical and chemical properties were measured as shown in Table 1.

2.2 Experimental Implementation

Field experiments were conducted to investigate the effects of phosphate fertilizer sources and application rates, as well as foliar application of zinc, on the growth and yield of sweet corn. The experimental factors were as follows:

- Phosphate fertilizers: Tricalcium superphosphate (TSP) and diammonium phosphate (DAP).
- Phosphate application rates: (0, 90, 180 kg P ha^{-1}), denoted as P0, P1, and P2, respectively.
- Foliar application of zinc: (0, 25, 50 mg Zn L^{-1}), zinc sulfate ($ZnSO_4 \cdot 7H_2O$), denoted as Zn0, Zn1, and Zn2, respectively.

Therefore, the number of treatments was (2 × 3 × 3) = 18, and each treatment was performed in 3 replicates, resulting in a total of 54 experimental plots. The soil was tilled using a disc plow, harrowed, and leveled. The field was divided into 3 sections at 2-meter intervals. Each section was further subdivided into 18 experimental plots, each measuring 3 meters × 2.8 meters (8.4 m^2), with a 1-meter spacing between plots.

Imported Spanish maize variety (CADZ 79 F1) was sown between the rows on July 20, 2025. The sowing rate was 2-3 seeds per hole, at a depth of 3-5 cm. The row spacing was 70 cm, the hole spacing was 25 cm, and there were 4 rows per plot. 12 plants were planted in each plot, and then thinning was performed to leave 1 plant per hole, followed by patching to ensure uniform plant density. Urea fertilizer (nitrogen content 46%) was used as the nitrogen source, and a fixed amount of 320 kg ha^{-1} of nitrogen was applied to all treatment plots in two installments. The first application was at sowing, and the second was 40 days after germination.

Phosphorus fertilizer was applied once at the beginning of the season according to the planting plan. Potassium fertilizer (potassium sulfate (41.5% K)) was applied at a rate of 200 kg ha^{-1} in three installments: at planting, 20 days after germination, and 40 days after germination. Irrigation was carried out using a plate irrigation method with well water, as shown in Table 2. Weeds were controlled manually, and the maize stem borer (*Semia gilica* L.) was controlled by spraying 10% granular diazinon at a rate of 6 kg ha^{-1} on the growing points 20 and 40 days after germination. Maintenance and irrigation continued until the end of the season on November 20, 2025, which was 123 days after planting.

Table 1. Some Physical and Chemical Properties of the Study Soil

Property	Unit	Value	Method of Analysis

Sand	$g\ kg^{-1}$	446	Determined by the pipette method [7]
Clay		321	
Silt		233	
Texture	Loamy	S.L	
CEC	$cmol\ kg^{-1}$	13.57	Using ammonium acetate solution [7]
pH (1:1)		7.47	Measured using pH meter [8]
EC (1:1)	$dS\ m^{-1}$	2.51	Measured using electrical conductivity meter [8]
$CaSO_2$	$g\ kg^{-1}$	52.11	Determined by dilution method [9]
$CaCO_2$		201	Determined by gravimetric method [8]
O.M (Organic Matter)		7.24	Determined by wet digestion method [7]
Available Nitrogen	$mg\ kg^{-1}$	16.87	Determined by Micro-Kjeldahl method [10]
Available Phosphorus		6.57	Extracted with 0.5M $NaHCO_3$ at pH 8.5 (Olsen method) [11]
Available Potassium		122.87	Extracted with ammonium acetate and measured using Flame Photometer [7]
Available Zinc		0.498	Extracted using DTPA and measured by Atomic Absorption Spectrophotometer [12]

Table 2. Some Chemical Properties of Irrigation Water

Property	Unit	Value	Property	Unit	Value
Sodium	$mmol\ L^{-1}$	1.19	EC	$dS\ m^{-1}$	3.01
Magnesium		5.59	Chloride	$mmol\ L^{-1}$	5.77
Calcium		10.02	Sulfate		12.10
Potassium		0.12	Bicarbonate		3.31
pH		7.77	Carbonate		Nil

3.2

Characteristics of the Subject

3.2.1 Dry Weight of Vegetative Body (g plant^{-1}) at Growth Stages 1 and 2

At each growth stage (Stage 1 at 45 days after germination, and Stage 2 at 75 days after germination), the dry weight of the vegetative body (stem and leaves) was measured. Samples were placed in perforated paper bags and dried in an electric oven at 70°C for 72 hours. Afterward, multiple measurements were taken using a high-precision balance until the weight stabilized.

3.2.2 Calculation of Absolute Growth Rate (AGR) (g plant^{-1} day^{-1})

The absolute growth rate was calculated using formula [13]. The results are as follows:

A.G.R (gm day^{-1} plant^{-1}) = (T2 - T1) ÷ (W2 - W1)

W1, W2 = Dry weight of vegetative organs at the first and second harvests, respectively... (1)

T1, T2 = Harvesting dates (days) at the first and second harvests, respectively... (2)

3.2.3 Number of grains per panicle (grains panicle^{-1}) :

Grains were removed from 5 panicles, washed, and the number of grains was manually averaged to calculate the number of grains.

3.2.4 Weight of 500 grains (g):

500 grains were manually weighed, and the weight was measured using a high-precision balance.

3.2.5 Grain yield (kg ha^{-1})

Yields from 10 plants were collected from each experimental plot and divided by the number of plants to calculate the yield per plant. Weights were adjusted based on a moisture content of 15.5% [14].

Grain Yield (**kg ha^{-1}**) = Yield per Plant × Planting Density

3.2.6 Biological Yield (kg ha^{-1}**)**

Five plants were randomly selected from the central row of each experimental plot, air-dried, and weighed using a precision balance. The average yield per plant was then calculated, and the biological yield was calculated using the following formula:

Biological Yield (**kg ha^{-1}**) = Yield per Plant × Planting Density

4.2 Statistical Analysis

Data obtained from the two experiments were statistically analyzed using analysis of variance (ANOVA) based on the RCBD design and factorial experiment. The difference between arithmetic means was tested at a 5% significance level using Duncan's test with SAS software [15].

3. Results and Discussion

1.3 Vegetative Dry Matter Yield (g plant^{-1}) at 45 Days Post-Germination

Table (3) shows significant differences in dry matter yield of 45-day-old maize plants across various treatments. These differences are due to the source of phosphate fertilizer, phosphorus levels, the effect of foliar application of zinc, and the interactions between these factors. The results show that dry matter yield significantly increases with increasing levels of added phosphorus. Treatment with 180 kg P ha^{-1} resulted in the highest average yield of 45.71 g plant^{-1}, compared to 42.12 g plant^{-1} and 34.79 g plant^{-1} for treatment with 90 kg P ha^{-1} and no phosphorus application, respectively. This is due to phosphorus playing a crucial physiological role in energy transport within plants via ATP, as well as contributing to the activation of numerous enzymes involved in photosynthesis, cell division, and plant tissue formation. This increases the plant's vegetative growth efficiency and dry matter accumulation. The availability of phosphorus also contributes to increased plant biomass by stimulating root growth and enhancing the ability to absorb water and other nutrients from the soil. These results are consistent with those obtained in [16 and 17]. The results also show that di ammonium phosphate (DAP) is superior to tri calcium superphosphate (TSP) in increasing dry matter yield, averaging 42.38 g plant^{-1} compared to 39.37 g plant^{-1} for the other sources. The superiority of DAP fertilizer may be due to its high water solubility and its ability to decompose into ammonium and HPO^{-4}, which are sources of nitrogen and phosphorus. The acids produced by this dissolution move downward and can be absorbed by plants as monophosphate or di phosphate. This has a positive effect on plant condition and, consequently, their dry matter weight. These results are consistent with those of researchers [18 and 19] who observed that growth and yield indicators significantly increased when multiple phosphate fertilizers were applied, and that the most soluble and acidic phosphate fertilizer performed better than the others.

[18] and [19] Regarding the effects of foliar application of zinc, the results showed that dry matter yield significantly increased with increasing zinc concentration. Average yield was highest with foliar application of 50 mg L^{-1}, followed by 25 mg L^{-1} at an average of 41.05 **g** $plant^{-1}$. Without foliar application (Zn0), the average yield was lowest at 37.51 g plant-1. This is due to the important role of zinc in plant physiological processes. Zinc is an essential micronutrient involved in the synthesis or activation of numerous enzymes related to photosynthesis and carbohydrate and protein metabolism. Zinc also functions as a cofactor for several enzymes, including carbonic anhydrase and alcohol dehydrogenase, and contributes to the production of the amino acid tryptophan, a precursor of auxin (IAA), a hormone responsible for cell elongation and division. Furthermore, zinc is involved in chlorophyll production, regulates photosynthesis, and promotes nutrient absorption within plants, leading to improved efficiency in vegetative growth, dry matter accumulation, and plant physiological functions [20, 21].

The results of the binary interaction show significant influences between different study factors. In the interaction between phosphate fertilizer type and phosphorus level (F×P), the D×P2 treatment performed best, with the highest average dry matter (48.22 g per plant) compared to the control treatment. The control treatment recorded the lowest value, while the D×P2 treatment had the highest average dry matter. This is due to the synergistic effect of the high concentration of phosphorus in the DAP fertilizer and the availability of nitrogen, which increases nutrient absorption efficiency and promotes plant physiological activity.

The interaction between phosphorus concentration and foliar application of zinc (P×Zn) also showed significant differences. The P2×Zn2 treatment group had the highest average yield (48.46 g $plant^{-1}$), while the control group (P0×Zn0 treatment) had the lowest average yield (31.24 g $plant^{-1}$). This is due to the complementary effect of phosphorus and zinc. Phosphorus promotes root growth and energy production, while zinc promotes vegetative growth and dry matter accumulation by contributing to enzyme activation and plant hormone regulation.

The interaction between the phosphate fertilizer source and the foliar application of zinc (F × Zn) showed the superiority of the D × Zn2 treatment, which had the highest average yield (45.93 g $plant^{-1}$) compared to other treatments. This can be explained by the synergistic effect of the availability of essential nutrients in the DAP fertilizer and the role of zinc in activating physiological processes within the plant, leading to increased photosynthesis and improved plant growth. Table (3) shows the significant impact of the triple interaction of phosphate fertilizer source, phosphorus levels, and zinc application on the dry matter yield of maize. The interaction treatment D × P2 × Zn2 yielded the highest average yield (51.52) g $plant^{-1}$ and was significantly superior to the other treatments, while the comparative treatment P0 × Zn0 with both sources yielded the lowest average yield (31.24) g $plant^{-1}$.

Table 3. Effect of phosphorus source and level, zinc foliar application, and their interaction on dry matter yield at 45 days stage of maize (g plant^{-1})

Phosphate Fertilizer Source F	Phosphorus Level P	Added Zinc Levels (mg L^{-1}) Zn			F × P
		Zn_0	Zn_1	Zn_2	
T	P_0	31.24 i	35.14 h	37.99 fg	34.79 d
	P_1	37.14 g	40.01 e	43.21 d	40.12 c
	P_2	41.00 e	43.22 d	45.39 c	43.20 b
D	P_0	31.24 i	35.14 h	37.99 fg	34.79 d
	P_1	39.41 ef	44.67 cd	48.28 b	44.12 b
	P_2	45.00 c	48.13 b	51.52 a	48.22 a
					P
P × Zn	P_0	31.24 f	35.14 e	37.99 d	34.79 C
	P_1	38.28 d	42.34 c	45.75 b	42.12 B
	P_2	43.00 c	45.68 b	48.46 a	45.71 A
					F
F × Zn	T	36.46 d	39.46 c	42.20 b	39.37 B
	D	38.55 c	42.65 b	45.93 a	42.38 A
Zinc Levels (Zn)		37.51 C	41.05 B	44.06 A	

T : Triple superphosphate D : Di ammonium	Zn_0 : No zinc foliar spray Zn_1 : Zinc foliar spray at 25 mg·L^{-1}	P_0 : No phosphorus added P_1 : 90 kg P ha^{-1}

Means sharing the same letters are not significantly different according to Duncan's test at 5% probability level

.2

3 Dry Matter Yield of Vegetative Organs (g plant^{-1}) at 75 Days Post-Germination

The results in Table (4) show that the dry matter yield of maize at 75 days post-germination is significantly affected by the type and application rate of phosphate fertilizer, zinc application, and their interactions. Increasing the phosphate application rate significantly increased the dry matter yield of the plants, reaching the highest value at the P2 level, with an average of 93.90 g plant-1. This is higher than the average values of 85.92 g plant^{-1} and 74.99 g plant^{-1} at the P1 and P0 levels, respectively. This is due to the important role of phosphorus in plant physiological processes. Phosphorus is an essential element for the formation of energy-rich compounds such as ATP and nucleic acids. Phosphorus also promotes root growth and improves the efficiency of water and nutrient absorption from the soil. This promotes increased leaf area, improved photosynthetic efficiency, and the accumulation of carbohydrates and proteins in plant tissues, resulting in an increase in the dry weight of the plant [22].

Furthermore, it was found that the type of phosphate fertilizer had a significant effect on dry matter yield. Di ammonium phosphate (DAP) outperformed tri calcium superphosphate (TSP), achieving an average dry matter yield of 86.44 g plant^{-1}. In contrast, the average yield for TSP was 83.43 g plant^{-1}. The difference in dry matter yield between the two fertilizers is thought to be due to differences in their chemical composition. DAP granules contain both nitrogen and phosphorus; the nitrogen is released slowly throughout the growing season and is easily absorbed by plants. TSP fertilizer contains phosphorus, and its nitrogen content is adjusted with urea fertilizer. The nitrogen in urea fertilizer leaches and volatilizes more readily than the nitrogen in DAP fertilizer granules, resulting in increased plant dry weight [23].

Furthermore, zinc application significantly increased dry matter yield. At a concentration of 50 mg L^{-1}, the average yield was highest at 91.25 g plant^{-1}, while at concentrations of 25 mg L^{-1} and 0 mg L^{-1}, the average yields were 85.06 g plant^{-1} and 78.50 g plant^{-1}, respectively. This is due to the fact that zinc plays a crucial role in activating many enzymes involved in photosynthesis and metabolic processes, and is also involved in auxin production, which promotes cell elongation and plant tissue growth. Zinc also contributes to chlorophyll production, improving nutrient absorption within the plant and promoting vegetative growth and dry matter accumulation [24].

Furthermore, the interaction between phosphate fertilizer type and phosphorus concentration (F×P) showed significant differences between treatments. The interaction with DP2 (high-phosphorus di ammonium phosphate fertilizer) resulted in the highest average dry matter content at 96.32 g plant^{-1}, while the interaction with TP0 resulted in the lowest average dry matter content at 74.99 g plant^{-1}. The interaction between phosphorus concentration and zinc foliar application (P×Zn) also showed significant differences between treatments. The interaction with P2Zn2 resulted in the highest average dry matter content at 101.07 g plant^{-1}, while the control group P0Zn0 resulted in the lowest average dry matter content at 68.27 g plant^{-1}.

Significant differences were also observed between treatments in the interaction between the type of phosphate fertilizer and zinc foliar application (F×Zn). The interaction with DZn2 was superior, showing the highest average dry matter content (93.54 g plant^{-1}) with the TZn0 treatment, compared to the lowest average (77.21 g plant^{-1}). Regarding the effects of the three interactions, the interaction between DAP fertilizer and high levels of phosphorus P2 and zinc Zn2 application showed the highest dry matter value (105.14) g plant^{-1}, while the control treatment P0Zn0 with two sources showed the lowest value (68.27) g plant^{-1}, indicating significant differences between treatments.

Table 4. Effect of phosphorus source and level, zinc foliar application, and their interaction on dry matter yield at 75 days stage of maize (g plant^{-1})

Phosphate Fertilizer Source F	Phosphorus Level P	Added Zinc Levels (mg L^{-1}) Zn			F × P
		Zn_0	Zn_1	Zn_2	
T	P_0	68.27 j	75.98 i	80.71 h	74.99 e
	P_1	77.23 i	85.00 g	89.19 ef	83.81 d
	P_2	86.14 fg	91.33 de	97.00 b	91.49 b
D	P_0	68.27 j	75.98 i	80.71 h	74.99 e
	P_1	80.98 h	88.34 ef	94.77 bc	88.03 c
	P_2	90.09 e	93.72 cd	105.14 a	96.32 a
					P
P × Zn	P_0	68.27 f	75.98 e	80.71 d	74.99 C
	P_1	79.11 d	86.67 c	91.98 b	85.92 B
	P_2	88.12 c	92.53 b	101.07 a	93.90
					F
F × Zn	T	77.21 f	84.10 d	88.97 b	83.43 B
	D	79.78 e	86.01 c	93.54 a	86.44 A
Zinc Levels (Zn)		78.5 C	85.06 B	91.25 A	

T : Triple superphosphate
D : Diammonium phosphate

Zn_0 : No zinc foliar spray
Zn_1 : Zinc foliar spray at 25 mg·L^{-1}
Zn_2 : Zinc foliar spray at 50

P_0 : No phosphorus added
P_1 : 90 kg P·ha^{-1} added
P_2 : 180 kg P·ha^{-1} added

Means sharing the same letters are not significantly different according to Duncan's test at 5% probability level

.3

3 Absolute Growth Rate (AGR) (g plant^{-1} day^{-1})

The results in Table (5) show that the absolute growth rate of maize is significantly influenced by the type and amount of phosphate fertilizer applied, zinc application, and their interactions. The mean absolute growth rate increased with increasing phosphate application, reaching 1.340, 1.460, and 1.607 g plant^{-1} day^{-1} for application amounts of 0, 90, and 180 kg P ha^{-1}, respectively. This is due to the important role of phosphorus in root growth and proliferation, and in improving the efficiency of nutrient absorption from the soil. This effect is particularly pronounced in soils with low available phosphorus. This promotes photosynthesis and dry matter formation, improving the absolute growth rate of the plant. These results are consistent with the results in [25].

As shown in Table (5), the type of phosphate fertilizer has a significant impact on the absolute growth rate. Di ammonium phosphate (DAP) significantly outperformed tri calcium superphosphate (TSP), showing a high average growth rate of 1.488 g plant⁻¹day⁻¹. In contrast, the average growth rate for TSP was lower at 1.469 g plant⁻¹day⁻¹.

Table 5. Effects of phosphorus sources, phosphorus application rates, zinc spraying, and their interactions on absolute growth rate (g plant^{-1} day^{-1})

Phosphate Fertilizer Source F	Phosphorus Level p	Added Zinc Levels (mg L^{-1}) Zn			F × P
		Zn_0	Zn_1	Zn_2	
T	P_0	1.234 e	1.361 cd	1.424 bc	1.340 c
	P_1	1.336 de	1.500 b	1.533 ab	1.456 b
	P_2	1.505 bc	1.604 a	1.720 a	1.610 a
D	P_0	1.234 e	1.361 cd	1.424 bc	1.340 c
	P_1	1.386 d	1.456 bc	1.550 ab	1.464 b
	P_2	1.503 bc	1.520 ab	1.787 a	1.603 a
					P
P × Zn	P_0	1.234 e	1.361 d	1.424 cd	1.340 C
	P_1	1.361 d	1.478 bc	1.542 ab	1.460 B
	P_2	1.504 bc	1.562 ab	1.754 a	1.607 A
					F
F × Zn	T	1.358 de	1.488 bc	1.559 ab	1.469 A
	D	1.374 e	1.446 cd	1.587 a	1.469 A
Zinc Levels (Zn)		1.366 C	1.467 B	1.573 A	

T : Triple superphosphate D : Diammonium	Zn_0 : No zinc foliar spray Zn_1 : Zinc foliar spray at 25 mg·L⁻ ¹	P_0 : No phosphorus added P_1 : 90 kg P·ha⁻ ¹

Means sharing the same letters are not significantly different according to Duncan's test at 5% probability level

This is because DAP has high soil solubility and can supply both phosphorus and nitrogen to plants. This increases nutrient availability, promoting vegetative growth and consequently improving the absolute growth rate. These results are consistent with findings [26] showing that the use of DAP fertilizer results in higher absolute growth rates compared to other phosphorus sources.

Regarding zinc application, the absolute growth rate significantly increased with increasing application levels, with averages of 1.366, 1.467, and 1.573 g plant⁻¹day⁻¹ for zinc levels of 0, 25, and 50 mg L⁻¹, respectively. The highest absolute growth rate was observed at [unknown - likely "0"]. This is due to zinc's important physiological role in activating many plant enzymes, its involvement in protein and nucleic acid synthesis, and its role in regulating growth hormone synthesis, particularly auxin. This leads to increased cell elongation, improved photosynthetic efficiency, increased dry matter accumulation, and an increase in the absolute growth rate of plants. [27] has shown that the addition or spraying of zinc improves enzyme activity, increases the efficiency of life processes within plants, and has a positive effect on the growth of field plants. The results of the binary interaction (F×P) between the source and level of phosphate fertilizers show significant differences among several treatments. Treatments TP2 and DP2 recorded the highest mean values (1.610 and 1.603 g $plant^{-1}day^{-1}$, respectively), while control treatments TP0 and DP0 showed the lowest mean values (1.340 g $plant^{-1}day^{-1}$, respectively). Similarly, the interaction between phosphorus levels and zinc application (P×Zn) showed significant differences, with treatment P2Zn2 recording the highest mean (1.754 g $plant^{-1}day^{-1}$) and treatment P0Zn0 recording the lowest mean (1.234 g $plant^{-1}day^{-1}$). Finally, the results for the interaction between phosphorus source and zinc levels (F×Zn) showed limited differences between treatments, with treatment DZn2 recording the highest mean. Phosphorus yield was lowest in the DP3Zn3 treatment group (average 1.587 g $plant^{-1}$ day^{-1}) and in the TZn0 treatment group (average 1.358 g $plant^{-1}$ day^{-1}).

The interaction between the three factors—phosphorus source, phosphorus concentration, and zinc concentration—was significant in some treatment groups. The average value for the DP3Zn3 treatment group was 1.787 g $plant^{-1}$ day^{-1}, while the two control treatment groups (DP0Zn0 and TP0Zn0) had the lowest average value for this interaction, at 1.234 g $plant^{-1}$ day^{-1}.

4.3 Number of grains per ear (grain ear^{-1})

As shown in Table (6), the number of grains per panicle significantly increased with increasing phosphorus fertilizer application. The average number of grains in the unfertilized plot (P0) was approximately 414.66 grain ear^{-1}, but this increased to 487.51 grain ear^{-1} with fertilizer application P1 (90 kg P ha^{-1}), and further to 545.94 grain ear^{-1} with fertilizer application P2 (180 kg P ha^{-1}). Compared to the control plot, significant increases of 17.58% and 31.67% were observed in P1 and P2, respectively. The increase in grain number with increasing phosphorus fertilizer application is thought to be due to the importance of phosphorus in plant metabolism, its role in energy transfer, and its role in the formation of essential growth compounds. Furthermore, phosphorus promotes root growth and improves the efficiency of water and nutrient absorption from the soil, thereby positively influencing panicle formation and increasing the number of grains. Phosphorus also plays a crucial role in kernel formation and filling. These results are consistent with those of researchers who found that phosphorus supplementation significantly increases the yield components of maize, particularly the number of kernels per ear [28, 29].

Table (6) also shows that the type of phosphate fertilizer applied to the soil has a significant impact. Di ammonium phosphate (DAP) showed significantly better results than tri calcium superphosphate (TSP), with an average kernel count of 486.31 grain $ear^{-1}$when using DAP compared to 479.10 grain ear^{-1} when using TSP. This is thought to be because DAP fertilizer contains nitrogen in addition to phosphorus, which promotes vegetative growth. As a result, carbohydrate formation and translocation to the ear increase, leading to an increase in kernel count. Furthermore, the high solubility of DAP fertilizer enhances the availability of phosphorus at various stages of plant growth, positively impacting plant productivity.These results are consistent with the findings of studies [30 and 31] that di ammonium phosphate fertilizer is superior in promoting growth and increasing yield components of maize .

Table 6. Effects of phosphorus sources, fertilizer application rates, zinc application, and their interactions on the number of (grains ear^{-1})

Phosphate Fertilizer Source F	Phosphorus Level p	Added Zinc Levels (mg L^{-1}) Zn			F × P
		Zn_0	Zn_1	Zn_2	
T	P_0	333.31 l	421.14 k	489.54 hi	414.66 e
	P_1	428.35 j	488.13 i	530.14 e	482.21 d
	P_2	491.89 h	547.37 d	582.02 b	540.43 b
D	P_0	333.31 l	421.14 k	489.54 hi	414.66 e
	P_1	430 j	497.24 g	551.2 c	492.81 c
	P_2	502.04 f	550.98 c	601.32 a	551.45 a
					P
P × Zn	P_0	333.31 i	421.14 h	489.54 f	414.66
	P_1	429.18 g	492.69 e	540.67 c	487.51
	P_2	496.97 d	549.18 b	591.67 a	545.94
					F
F × Zn	T	417.85 f	485.55 d	533.90 b	479.10
	D	421.78 e	489.79 c	547.35 a	486.31
Zinc Levels (Zn)		419.82 C	487.67 B	540.63 A	
T : Triple superphosphate D : Diammonium		Zn_0 : No zinc foliar spray Zn_1 : Zinc foliar spray at 25 mg·L^{-1}		P_0 : No phosphorus added P_1 : 90 kg P·ha^{-1}	
Means sharing the same letters are not significantly different according to Duncan's test at 5% probability level					

4.3 Weight of 500 grains (g)

The results in Table (7) show that phosphorus fertilization significantly affects 500-grain weight. The highest average value was 156.85 g at a phosphorus fertilization of 180 kg P ha^{-1}, followed by 150.58 g at 90 kg P ha^{-1}, and 139.33 g at no phosphorus fertilization (P0). This is because phosphorus plays a crucial role in the production of energy compounds (ATP) and nucleic acids, and in activating cell division. Phosphorus promotes root and stem growth, increases leaf area and chlorophyll content, and consequently promotes photosynthesis and carbohydrate production. These substances are transported to the grain during the ripening stage. As a result, grain weight and plant dry weight increase. These results are consistent with the findings of the study [33] which showed that phosphorus fertilization increases grain weight in maize.

Table 7. Effects of phosphorus sources, phosphorus concentrations, zinc dispersion, and their interactions on the weight of 500 grains (g)

Phosphate Fertilizer Source F	Phosphorus Level p	Added Zinc Levels (mg L^{-1}) Zn			F × P
		Zn_0	Zn_1	Zn_2	
T	P_0	131.37 j	139.00 i	147.62 fg	139.33 e
	P_1	144.02 h	147.98 fg	154.38 d	148.79 d
	P_2	150.74 ef	155.16 d	161.29 ab	155.73 b
D	P_0	131.37 j	139.00 i	147.62 fg	139.33 e
	P_1	145.07 gh	153.30 de	158.74 bc	152.37 c
	P_2	155.00 d	156.24 cd	162.66 a	157.97 a
					P
P × Zn	P_0	131.37 g	139.00 f	147.62 d	139.33
	P_1	144.55 e	150.64 c	156.56 b	150.58
	P_2	152.87 c	155.70 b	161.98 a	156.85
					F
F × Zn	T	142.04 d	147.38 c	154.43 a	147.95
	D	143.81 d	149.51 b	156.34 a	149.89
Zinc Levels (Zn)		142.93 C	148.45 B	155.39 A	

T : Triple superphosphate D : Diammonium	Zn_0 : No zinc foliar spray Zn_1 : Zinc foliar spray at 25 mg·L^{-1}	P_0 : No phosphorus added P_1 : 90 kg P·ha^{-1}

Means sharing the same letters are not significantly different according to Duncan's test at 5% probability level

As a phosphorus source, di ammonium phosphate (DAP) was superior to tri calcium superphosphate (TAP), with an average grain weight of 149.89 g per 500 grains compared to 147.95 g with tri calcium superphosphate. This is because DAP contains readily absorbable nitrogen and phosphorus, which improves leaf area, plant dry weight, and photosynthetic efficiency, leading to carbohydrate translocation to the grain and consequently increasing grain weight. [34] Zinc (Zn) application also significantly increased grain weight with increasing application rate, averaging 142.93 g with Zn0, 148.45 g with 25 mg L^{-1}, and 155.39 g with 50 mg L^{-1}. This is because zinc activates enzymes involved in carbohydrate and protein metabolism, increasing chlorophyll and leaf area, thereby promoting dry matter accumulation and carbohydrate translocation to the grain, and consequently increasing grain weight. These results were consistent with those for maize [35] and wheat [36].

The results indicate that the interaction between fertilizer type and phosphorus levels significantly affected 500-grain weight. The D×P2 treatment resulted in the highest average weight (162.66g), while the T×P0 treatment resulted in the lowest average weight (131.37g).

This is because phosphorus plays a crucial role in the production of energy compounds (ATP) and the activation of cell division, promoting root and stem growth and increasing leaf area and chlorophyll content, thereby facilitating photosynthesis and carbohydrate translocation to the grain during the ripening stage.

The interaction between phosphorus and zinc levels also yielded significant differences. The P2×Zn2 treatment resulted in the highest average weight (161.98g), while the P0×Zn0 treatment resulted in the lowest (131.37g). This is thought to be due to the synergistic effect of phosphorus and zinc. Phosphorus promotes energy production and carbohydrate transport, while zinc contributes to enzyme activation and important metabolic processes, leading to increased grain weight.

Significant differences were observed in the interaction between fertilizer type and zinc application rate. The D×Zn2 treatment (156.34 g) yielded the highest average weight, while other treatments (142.04g) yielded the lowest.

These results clearly demonstrate that the interaction of three factors—fertilizer type, phosphorus application rate, and zinc foliar application—significantly affects the 500-grain weight. The D×P2×Zn2 treatment, combining diammonium phosphate with the highest level of phosphorus (180 kg ha^{-1}) and the maximum amount of zinc foliar application (50 mg L^{-1}), yielded the highest average yield at 162.66 g. Following this, the T×P2×Zn2 treatment, using tricalcium phosphate fertilizer with the same levels of phosphorus and zinc, yielded an average yield of 161.29 g, demonstrating the superiority of diammonium phosphate in improving plant nutrient utilization efficiency. On the other hand, the least effective treatment was the P0 × Zn0 treatment, which did not apply either phosphorus or zinc, with an average yield of 131.37 g. This indicates that phosphorus and zinc are important for grain formation and weight increase.

6.3 Grain Yield (kg ha^{-1})

The results in Table (8) clearly show that grain yield increases with increasing phosphorus fertilization. Increasing phosphorus fertilization from 0 to 90 kg P ha^{-1} and 180 kg P ha^{-1} increased yields from 4955 kg ha^{-1} to 5727 kg ha^{-1} and 6779 kg ha^{-1}, respectively. This increase is attributed to phosphorus's crucial role in promoting photosynthesis and cellular respiration, and in storing energy in the form of ATP. This positively impacts plant growth and the development of various organs, particularly the root system, and enhances the plant's ability to explore the soil and absorb other nutrients such as nitrogen and potassium. Phosphorus also promotes grain formation and the accumulation of carbohydrates and proteins. Furthermore, this increase in grain yield is also attributable to phosphorus's role in increasing grain number (as shown in Table 6) and grain weight (as shown in Table 7), ultimately leading to an increase in total grain yield. These results are consistent with those of [37] and [38].

Table 8. Effects of phosphorus sources, fertilizer application rates, zinc application, and their interactions on grain yield (kg ha^{-1})

Phosphate Fertilizer Source F	Phosphorus Level p	Added Zinc Levels (mg L^{-1}) Zn			F × P
		Zn_0	Zn_1	Zn_2	
T	P_0	4321 l	5033 j	5510 h	4955 e
	P_1	4788 k	5698 g	6100 f	5529 d
	P_2	5698 g	6318 e	7101 c	6372 b
D	P_0	4321 l	5033 j	5510 h	4955 e
	P_1	5300 i	6003 f	6471 d	5925 c
	P_2	6287 e	7311 b	7957 a	7185 a
					P
P × Zn	P_0	4321 h	5033 g	5510 f	4955 C
	P_1	5044 g	5851 e	6286 c	5727 B
	P_2	5993 d	6815 b	7529 a	6779 A
					F
F × Zn	T	4936 f	5683 d	6237 b	5619 B
	D	5303 e	6116 c	6646 a	6021 A
Zinc Levels (Zn)		5119 C	5899 B	6442 A	

T : Triple superphosphate D : Diammonium	Zn_0 : No zinc foliar spray Zn_1 : Zinc foliar spray at 25 mg·L^{-1}	P_0 : No phosphorus added P_1 : 90 kg P·ha^{-1}

Means sharing the same letters are not significantly different according to Duncan's test at 5% probability level

Regarding the effect of phosphate fertilizer type, DAP fertilizer was found to be superior to TSP fertilizer. Average yield was 6021 kg ha^{-1} for DAP compared to 5619 kg ha^{-1} for TSP. This is attributable to the nitrogen content in DAP granules. This nitrogen is thought to be released more slowly compared to urea, which was added in large quantities to TSP fertilizer to adjust the nitrogen content of both fertilizers. Because the nitrogen in DAP granules is released more slowly than urea, which is more leached and volatile, it is more readily available to plants. This is also reflected in the yield characteristics (Tables 17 and 18), which increased the total yield of maize. These results are consistent with those of the study in [39], in which DAP fertilizer showed superior efficacy to superphosphate and maximized maize yield. Furthermore, zinc application had a clear positive effect on yield, with average yields increasing from 5119 kg ha^{-1} to

5899 kg ha^{-1} and 6442 kg ha^{-1} as the application rate increased from 0 to 25 and 50 mg L^{-1}, respectively.

This increase in yield is thought to be due to zinc's role in activating several enzymes that control plant growth and starch and protein storage, as well as its effect on improving the efficiency of phosphorus and nitrogen uptake. Zinc also enhances the plant's resistance to environmental stress and reduces root rot, leading to healthier and more productive plant growth. In addition, phosphorus is involved in enzyme activation and promoting the translocation of photosynthetic products within the plant, which is reflected in the number and weight of grains (Tables 17 and 18). These results are consistent with [40 and 41]. Regarding the interaction between phosphorus and zinc, the treatment combining the highest phosphorus and zinc concentrations (P2Zn2) resulted in the highest yield (7529 kg ha^{-1}) compared to the treatment without added phosphorus or zinc (minimum yield 4321 kg ha^{-1}). This interaction reflects the synergistic effect of these essential nutrients promoting plant growth and increasing the efficiency of metabolic processes. Phosphorus promotes zinc absorption, and zinc improves the bioavailability of phosphorus, resulting in larger, plumper grains.

Furthermore, when examining the interaction between phosphorus concentration and fertilizer source, combining DAP with the highest phosphorus concentration resulted in the highest yield (7185 kg ha^{-1}) compared to the T×P0 treatment (yield 4955 kg ha^{-1}). This indicates the importance of selecting an effective phosphorus source during fertilizer application to ensure efficient nutrient delivery to plants. Similarly, when the interaction between zinc and fertilizer sources was investigated, the D×Zn2 treatment (yield 6646 kg ha^{-1}) yielded the highest yield compared to the T×Zn0 treatment (yield 4936 kg ha^{-1}).Finally, when the three-factor interaction of phosphorus, zinc, and fertilizer sources was investigated, the highest yield (7957 kg ha^{-1}) was obtained when the highest concentrations of phosphorus and zinc were combined with DAP, while the lowest yield (4321 kg ha^{-1}) was obtained with the P0×Zn0 treatment (regardless of the fertilizer source).

7.3 Biological Yield (kg ha^{-1})

The results in Table (9) show that the type of phosphate fertilizer, the amount of phosphate fertilizer applied, the application of zinc foliar spray, and the interactions of these two and three factors significantly affect biological yield. Mean values were statistically significant using Duncan's test at a 5% significance level.

The results showed a significant increase in biological yield with increasing phosphate fertilizer application. The highest average yield was 13,882 kg ha^{-1} at a phosphate fertilizer application of 180 kg P ha^{-1}, followed by 12,648 kg ha^{-1} at a phosphate fertilizer application of 90 kg P ha^{-1}, and the lowest average yield was 10,351 kg ha^{-1} in the control group P0. This increase can be explained by the important role of phosphorus in activating many physiological processes within the plant, particularly its involvement in the production of energy compounds such as ATP, which are essential for photosynthesis and growth. Phosphorus also positively impacts plant dry weight by promoting root system growth and increasing the efficiency of water and other nutrient absorption (Tables 5 , 6). This improves yield characteristics such as grain number (Table 6), grain weight (Table 7), and total grain yield (Table 8), ultimately leading to an increase in biological yield (Table 20). These results are consistent with [42 , 43].

Table 9. Effects of phosphorus sources, phosphorus application rates, zinc spraying, and their interactions on biological yield (kg ha^{-1})

Phosphate Fertilizer Source F	Phosphorus Level p	Added Zinc Levels (mg L^{-1}) Zn			F × P
		Zn_0	Zn_1	Zn_2	
T	P_0	9317 n	10489 m	11247 k	10351 e
	P_1	10522 m	12388 i	14011 e	12307 d
	P_2	11098 l	13756 f	14821 b	13225 b
D	P_0	9317 n	10489 m	11247 k	10351 e
	P_1	11577 j	13000 h	14387 d	12988 c
	P_2	13611 g	14498 c	15505 a	14538 a
					P
P × Zn	P_0	9317 i	10489 h	11247 f	10351 C
	P_1	11050 g	12694 d	14199 b	12648 B
	P_2	12355 e	14127 c	15163 a	13882 A
					F
F × Zn	T	10312 f	12211 d	13360 b	11961 B
	D	11502 e	12662 c	13713 a	12626 A
Zinc Levels (Zn)		10907 C	12437 B	13536 A	

T : Triple superphosphate
D : Diammonium

Zn_0 : No zinc foliar spray
Zn_1 : Zinc foliar spray at 25 mg·L^{-1}

P_0 : No phosphorus added
P_1 : 90 kg P·ha^{-1}

Means sharing the same letters are not significantly different according to Duncan's test at 5% probability level

Regarding the effect of different types of phosphate fertilizers, diammonium phosphate (DAP) was significantly effective, with an average biological yield of 12,626 kg ha^{-1}. This is a remarkable difference compared to 11,961 kg ha^{-1} for superphosphate (TSP). This advantage is attributed to DAP fertilizer supplying plants with both phosphorus and nitrogen. Nitrogen promotes vegetative growth and dry matter formation, resulting in increased dry matter weight of two cuttings and improved photosynthetic efficiency. This increases dry matter formation, which is essential for the development of crop characteristics and biological yield.

Regarding the effects of zinc application, it was shown that biological yield significantly increased with increasing zinc concentration. The 50 mg L^{-1} treatment group had the highest average yield at 13,536 kg ha^{-1}, followed by the 25 mg L^{-1} treatment group at 12,437 kg ha^{-1}. The untreated group had the lowest average yield at 10,907 kg ha^{-1}. This is attributed to the important physiological role of zinc in activating many enzymes involved in photosynthesis, protein synthesis, and the regulation of plant hormones such as auxin. This increased vegetative growth efficiency and dry matter accumulation, leading to increased dry matter weight of cuttings, as well as improved yield characteristics such as grain number and grain weight, resulting in increased biological yield. These results are consistent with [44].

The interaction between phosphorus sources and their application rate (F×P) had a significant impact on biological yield. The D×P2 interaction resulted in the highest average yield of 14,538 kg ha^{-1}, while the T×P0 and D×P0 treatments yielded the lowest average yield of 10,351 kg ha^{-1}. The interaction of phosphorus and zinc fertilizer application (P×Zn) also had a clear and significant impact. The P2×Zn2 interaction resulted in the highest biological yield of 15,163 kg ha^{-1}, while the P0×Zn0 interaction resulted in the lowest yield of 9,317 kg ha^{-1}.

Regarding the interaction of phosphorus and zinc sources (F×Zn), the D×Zn2 treatment demonstrated superiority, recording the highest biological yield (13,713 kg ha^{-1}) compared to the T×Zn0 treatment (lowest value: 10,312 kg ha^{-1}).

Finally, in the results of the interaction of the three nutrients (F × P × Zn), the D × P2 × Zn2 treatment showed the highest biological yield (15,505 kg ha^{-1}), while the P0 × Zn0 treatment resulted in the lowest value for both sources (9,317 kg ha^{-1}). This reflects the synergistic effect between the different nutrients. Combining the application of high concentrations of phosphorus and zinc from appropriate sources promoted vegetative growth, increased dry matter accumulation in the plant body and cuttings, improved yield characteristics, and ultimately led to the highest biological yield.

4. Conclusions and Recommendations

1.4 Conclusions

1. Increasing phosphorus fertilization to 180 kg P ha^{-1} significantly increased growth and yield.
2. DAP fertilizer showed superior effects compared to TSP in most traits investigated.
3. Application of zinc (50 mg L^{-1}) significantly improved growth and yield components.
4. The best results were obtained with a triple fertilization combination of DAP fertilizer (180 kg P ha^{-1}) and zinc (50 mg Zn L^{-1}).

2.4 Recommendations

1. In gypsum soils, prioritize DAP fertilizer as a phosphorus source.
2. Apply phosphorus at a level of 180 kg P ha^{-1}.
3. Apply zinc at a concentration of 50 mg L^{-1}.
4. To improve productivity, implement a combined fertilization of phosphorus and zinc.

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