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EFFECT OF FOLIAR APPLICATION OF ZINC ON THE GROWTH AND YIELD OF SESAME *(Sesamum indicum L.) VARIETY*

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Abstract
Zinc (Zn) is one of the essential micronutrients needed by oilseed crops, although deficiency of this element is common in the calcareous soils of Sindh province of Pakistan. This experimental work was carried out on Student's Experimental Farm, Department of Agronomy, Sindh Agriculture University, Tandojam campus, Umerkot during Kharif season of year 2024. The current study was carried out to determine the effects of foliar spray of zinc sulphate ($ZnSO_4$) at different levels and different growth stages on the growth and yield attributes of sesame (Sesamum indicum L.). There were four treatments in a Randomized Complete Block Design (RCBD) having three replications; namely, T1=Control (without Zn), T2 = $ZnSO_4$ @ 1.5% at vegetative growth stage, T3 = $ZnSO_4$ @ 2.0% at flowering growth stage, and T4 = $ZnSO_4$ @ 2.0% at pod formation stage. It was found that treatment T4 gave the maximum plant height (124.8 cm), branches per plant (5.4), capsules per plant (58.7), seeds per capsule (61.3), weight of 1000 seeds (3.38 g), and seed yield (891 kg ha^{-1}), showing an increase of 58.5% over control treatment (562 kg ha^{-1}).

Keywords: *Zinc sulphate, $ZnSO_4$, micronutrient, foliar spray, oilseed, pod formation, seed yield, Sindh, Pakistan, RCBD*

1. Introduction

One of the ancient cultivated crops by humans is Sesamum indicum L. from the family Pedaliaceae (Ellis, 2024), where its history of domestication dates back to more than 4,000 years ago. Being known as the "Queen of Oilseeds" (Prasad, 2002), sesame acquires this name due to its rich oil composition, which may go up to 63%, higher than the oil of groundnut, sunflower, rapeseed, and soybean (Teklu et al., 2021; Production and Achievements of Sesamum indicum, 2024). Besides, being an oilseed, sesame also has numerous beneficial features, since its seeds contain 19% to 25% of quality protein, necessary minerals (Ca, P, Mg, Zn, Fe), vitamins B and E, as well as lignans (sesamin and sesamolin), which ensure excellent oil stability (Langyan et al., 2022; Wei et al., 2. Globally, the crop is cultivated in more than 90 countries within tropical and subtropical environments, with the two predominant sources of sesame production being Asia and Africa (FAOSTAT, 2024). The global production of the sesame crop has risen considerably in recent years because of increased demand for its use in the food, cosmetic, and medicinal sectors (FAOSTAT, 2024). In recent years, Pakistan has emerged as a dominant producer of sesame seeds worldwide, with 301,237 metric tonnes of production placing it at the 6th rank globally in 2023, alongside increased exports that reached $407 million, thus ranking it as the 5th largest producer of the crop (MNFSR, 2024; Tridge, 2024). The impressive performance achieved by the crop during the last five years can be attributed to the implementation of the National Oilseeds Enhancement Program, resulting in an increase in acreage from 139,400 ha to 399,493 ha with an average increase in yield of 69% (MNFSR, 2024).

Of the 17 essential nutrients needed by plants, zinc has the distinction of being the cofactor of more than 300 enzymes responsible for various biochemical activities in plants like photosynthesis, DNA synthesis, proteins synthesis, and hormone production like auxins and gibberellins required for cell division and elongation, branching and flower development (Dhaliwal et al., 2021; Verma et al., 2023). Zinc deficiency is the most common micronutrient deficiency throughout the world, especially in calcareous or alkaline soils which comprise the major portion of soil found in Pakistan provinces of Sindh, Punjab, and Balochistan (Hussain et al., 2023). It is an established fact that most soils in Pakistan suffer from zinc deficiency due to high pH, low organic matter, salts, and imbalanced fertilizer management (Ahmad et al., 2023). DTPA-extractable zinc in soils of the experimental site used in this experiment is very low at 0.38 mg kg^{-1}, which is far lower than the required levels of 0.50 – 2.0 mg kg^{-1} for most crops (Singh, 2020).

Foliar spray of zinc sulphate ($ZnSO_4$) is a recognized technique for overcoming zinc deficiency due to its effectiveness, efficiency, speed, and economy (Cakmak, 2008; Irmes et al., 2023). Since Zn in foliar application does not interact with the fixation processes in soil, it reaches the mesophyll cells of leaves and helps restore enzymes and physiological functions almost instantly. As per the recent findings in a pioneering experiment conducted by Tavassoli et al. (2023), foliar spraying of $ZnSO_4$ caused a 6-9% increase in yield, 6% increase in oil content, and 10-30% increase in biomass in five cultivars of S. indicum, despite water deficit conditions. Similar results have been found in other studies as well; for instance, Patil et al. (2020) recorded an increased yield in sesame due to the application of soil-foliar Zn treatment.

In spite of the increasing amount of evidence available, there still is a huge dearth in information about the ideal concentration of foliar zinc along with the most productive phase of crop growth to apply the same in sesame plants, under the specific agricultural and climatic conditions in Sindh province, Pakistan. Several experiments in this regard have been conducted using different concentrations of zinc from 0.5% to 1%, but comparisons among the different growth stages of crop application have not been made in literature for this region (Manaf et al., 2019; Jha et al., 2023). Hence, the current experiment was undertaken to bridge this gap with the assumption

that foliar zinc sprayed during pod formation, which is the period with the highest nutrient requirement of the plant, will show the most beneficial effects.

Following are the objectives of the experiment: (i) to investigate the effect of foliar spraying of $ZnSO_4$ at different concentrations and crop growth stages on different growth characteristics of sesame; (ii) to study the impact on yield and its different components, especially yield per hectare; and (iii) to determine the most agronomically productive treatment for sesame cultivation in the area.

2. MATERIALS AND METHODS

2.1 Experimental Site and Soil Characterization

The field trial was carried out in the experimental farm, Agronomy department, Sindh Agriculture University, Tandojam Campus, Umerkot. Umerkot is located in the desertic tract of eastern Sindh (24.36°N, 69.73°E) with semi-arid type of climate, having maximum temperature up to 45°C in summer with scarce precipitation (<200 mm) annually. The conditions in this region are very similar to those in which sesame is grown commercially in southern parts of Pakistan.

Before seeding of sesame, a combined soil sample of 0-30 cm depth was taken in the experiment field and analyzed at the laboratory of SAU Tandojam for physicochemical attributes of the soil. The physicochemical characteristics of the experimental soil have been given in Table 1 below.

Table 1. Physico-chemical properties of the experimental soil (0–30 cm), Kharif 2024.

Soil Parameter	Value	Unit
Soil Texture	Sandy Clay Loam	–
pH (1:2.5 soil:water)	7.8	–
Ece	1.42	dS m^{-1}
Organic Matter	0.61	%
Available N	0.047	%
Available P	5.3	mg kg^{-1}
Available K	186	mg kg^{-1}
DTPA-extractable Zn	0.38	mg kg^{-1}

The soil had sandy clay loam soil texture with a pH value of 7.8. The pH value suggested the presence of a calcareous reaction in the soil (Singh, 2020). Zinc content (DTPA extractable) of 0.38 mg/kg was less than the critical value of 0.5 mg/kg, suggesting that zinc was not available in sufficient quantities (Singh, 2020). This result supports the wide prevalence of zinc deficiency in soils (>70%) found in Sindh province (Ahmad et al., 2023). Zinc deficiency was exacerbated by low soil organic matter content (0.61%).

2.2 Experimental Design and Treatments

The experimental design was RCBD with four treatments replicated thrice. The size of each plot was 5 m by 4 m (20 m^2). There were sufficient guard rows and channels between plots to avoid interference between the treatments. The treatment schedule is described in Table 2.

Table 2. Treatment details — foliar zinc application concentrations and timings.

Treatment	Zinc Concentration	Stage of Application
T1	Control (No Zinc)	–
T2	$ZnSO_4$ @ 1.5%	Vegetative Stage (30 DAS)
T3	$ZnSO_4$ @ 2.0%	Flowering Stage (45 DAS)
T4	$ZnSO_4$ @ 2.0%	Pod Formation Stage (60 DAS)

The source of zinc was zinc sulphate heptahydrate ($ZnSO_4 \cdot 7H_2O$; 21% Zn). All solutions were freshly made on the day of application. The foliar applications were done using a handheld knapsack sprayer in such a way that both the upper and lower sides of leaves were equally wetted. Application was done in the early morning hours (06:00–08:00 hrs) so that there would

be minimal evaporation and degradation of sprayed zinc through photodegradation as advised by Cakmak (2008), which has been reinforced by more recent studies on foliar fertilization (Irmes et al., 2023).

2.3 Agronomic Management

An indigenous variety of sesame seeds suitable for Sindh environment was selected. The seeds were soaked in fungicide (Thiram @ 3 g kg^{-1} seeds) prior to sowing. The seeds were planted on a well-prepared bed on 15 June 2024 with an intra- and inter-row distance of 10 cm and 45 cm, respectively, producing a total plant population of 22.2 plants m^{-2}. Thinning of plants was done after 3 weeks from sowing by maintaining two plants per hill. The suggested rate of nitrogen, phosphorus, and potassium (NPK: 60-30-30 kg ha^{-1}) was equally provided to all the plots, ensuring that any difference in yield is due to zinc application only and not due to macro-nutrients (Manaf et al., 2019). Furrow irrigation was provided at the interval of 10 days.

2.4 Observations Recorded

Population of Plants (m^{-2}): Population recorded following full germination by randomly placing a metallic square frame of 1 m^2 in three plots.

Height of Plant (cm): Recorded when the crops matured using a measuring tape from the ground surface to the apex of the meristem of 10 randomly tagged plants.

No. of branches $plant^{-1}$: Counting all the primary branches of 10 randomly sampled plants from each plot and taking an average.

No. of capsules $plant^{-1}$: Recording all the capsules of 10 randomly sampled plants and taking an average.

No. of Seeds $capsule^{-1}$: Opening 10 capsules chosen from various parts of tagged plants, counting seeds and computing the average.

Weight of 1000 seeds (g): 1000 seeds from each plot counted using seed counter and weighing on an electronic analytical balance with 0.001 g precision.

Seed Yield (kg ha^{-1}): Physiological maturity stage harvested for seed, sun dried for one week, thrashed and cleaned. Seed yield estimated as: Seed yield (kg ha^{-1}) = [Plot yield (kg) / Plot area (m^2)] x 10,000.

2.5 Statistical Analysis

All the data obtained were analyzed by Analysis of Variance (ANOVA) using the software package Statistix 8.1. The treatment means were further compared using the LSD test at the probability level of 0.05 (Steel et al., 1997). Pearson's coefficient of correlations was calculated to establish the relationship between yield contributing factors and seed yield.

3. RESULTS AND DISCUSSION

3.1 Plant Population (m^{-2})

The plant population after germination was similar in all treatments (Table 3), varying from 24.3 m^{-2} for the control (T1) to 25.6 m^{-2} for T3. This observation was anticipated because zinc applications were done after the emergence of plants and, therefore, should not affect germination and the establishment of seedlings. This outcome is also in agreement with those reported by Patil et al. (2020) where the application of zinc as a foliar spray after germination had no effect on the plant population. Similarity in plant population among the treatments was important in ensuring that yield differences were due only to zinc effects.

3.2 Plant Height (cm)

Zinc foliar spray greatly impacted mature plant height (Table 3; Figure 1). Treatment four (T4-$ZnSO_4$ @ 2.0% during pod formation) achieved the highest mature plant height (124.8 cm) compared to treatment one (control - T1 at 98.4 cm). Treatment three (T3-flowering period) and treatment two (T2-vegetative period) registered intermediate heights of 119.5 cm and 111.7 cm,

respectively. This is because zinc plays a vital role in auxin (indole acetic acid; IAA) synthesis. Zinc deficiency adversely affects tryptophan production, the building block of IAA; hence, affecting apical dominance and internodal extension. Zinc deficiency limits cell elongation in plants since apical dominance will be hindered; as a result, plants cannot reach their maximum growth potential (Dhaliwal et al., 2021). However, adequate zinc supply facilitates cell extension and internodal extension during pod formation since crops are undergoing vigorous vegetative-to-reproductive transformation.

The results above agree with those by Tavassoli et al. (2023), who observed that foliar spraying of $ZnSO_4$ increased plant height significantly in five varieties of S. indicum. Patil et al. (2022) further noted a maximum plant height of 125.73 cm with foliar spray of $ZnSO_4$ @ 0.75%. According to Yanthan and Singh (2021, 2022), zinc plays an important role in the growth of shoots and roots and is required to achieve proper cell elongation.

Figure 1. Plant Height (cm) Across Treatments

T1 (Control)	**98.4**
T2 (1.5% Veg.)	111.7
T3 (2.0% Flow.)	119.5
T4 (2.0% Pod)	124.8

Figure 1. *Effect of foliar $ZnSO_4$ application on plant height (cm) of sesame at maturity. Kharif 2024, SAU Tandojam, Umerkot.*

3.3 Number of Branches Plant^{-1}

The number of branches per plant showed significant differences depending on zinc treatments (Table 3; Figure 2). The maximum number of branches was recorded for T4 (5.4 branches per plant), then T3 (4.9 branches per plant), T2 (4.3 branches per plant), and finally T1 (3.1 branches per plant). The difference between the control and T4 is highly significant as the latter showed a 74% higher value than the former, which has agricultural significance because every branch is a producer of capsules and thus seeds. Zinc promotes branching via cytokinins and lateral shoot initiation from lateral meristems (Verma et al., 2023).

The observation of the superiority of pod stage over flowering stage or vegetative stage treatments shows that zinc transport from leaves to meristem sinks becomes more effective during the vegetative-reproductive transition stage where cytokinin-auxin signaling takes place intensely. According to Singh et al. (2022), similar results were observed on sesame plants where increased branching was associated with improved carbohydrate allocation due to the action of zinc-dependent enzymes on meristem sinks. Sybany (2023) further confirms that both growth hormones and micronutrient applications increase branching in Sesamum indicum during active growth stages.

Figure 2. Branches Per Plant Across Treatments

T1 (Control)	**3.1**
T2 (1.5% Veg.)	4.3
T3 (2.0% Flow.)	4.9
T4 (2.0% Pod)	5.4

Figure 2. *Effect of foliar $ZnSO_4$ application on number of branches per plant in sesame. Kharif 2024.*

3.4 Capsules Per Plant

Number of capsules per plant – another yield-influencing trait – responded very significantly to zinc sprays on leaves (Table 3; Figure 3). The treatment T4 had the maximum number of capsules (58.7 capsules plant^{-1}), whereas the lowest number of capsules was observed in treatment T1

(control) (32.6 capsules plant^{-1}). Such an improvement in capsule number is around 80% and correlates positively (r = 0.98**) with seed yield as seen from Table 5.

Increased capsule number is a direct effect of increased branching (r = 0.94**) because branches develop capsules at their nodes. Furthermore, the importance of zinc in pollen viability and ovule fertilization has been proven (Dhaliwal et al., 2021). The role of zinc in male gametophyte development and deficiency resulting in poor anther dehiscence and poor fertilization leading to low capsule set is well-documented. Therefore, the use of zinc fertilizer when pods are formed, which also involves fertilization and initial development of capsules, is directly addressing the physiological demand. Patil et al. (2022) obtained 54.60 capsules per plant in sesame by application of $ZnSO_4$ @ 0.75%, whereas Raj et al. (2022) observed that zinc deficiency results in the poor development of reproductive structures in sesame. From the Sulfur-Zinc combination study conducted by Kumar et al. (2023) at SHUATS, Prayagraj, which reported 28.25 capsules per plant after spraying Zn @ 0.5%, it can be deduced that higher concentrations of zinc, as in this study, result in higher capsule set.

Figure 3. Capsules Per Plant Across Treatments

T1 (Control)	**32.6**
T2 (1.5% Veg.)	44.8
T3 (2.0% Flow.)	51.3
T4 (2.0% Pod)	58.7

Figure 3. *Effect of foliar $ZnSO_4$ application on number of capsules per plant in sesame. Kharif 2024.*

3.5 Seeds Per Capsule

Similarly, the number of seeds per capsule also showed a pattern analogous to the number of capsules (Table 4; Figure 4). Treatment T4 accounted for the highest seeds per capsule (61.3), which was statistically greater than T1 (45.2). This was a 36% enhancement that demonstrated the necessity of zinc in embryo formation inside the capsule. The enzymatic activities of zinc in nucleic acid formation and cell division are necessary for proper seed set (Yanthan & Singh, 2021). Following fertilization, zinc uptake takes place within the developing seeds, ensuring that sufficient zinc foliar application occurs at pod formation to meet the demand of developing embryos and endosperm tissue.

Similar findings were obtained by Patil et al. (2022), who showed 60.50 seeds capsule^{-1} with foliar application of $ZnSO_4$ at 0.75% in sesame. In another experiment, Kumar et al. (2023) reported 46.88 seeds capsule^{-1} using sulfur–zinc mixed application, implying that appropriate zinc nutrition is critical for obtaining increased seed set per capsule. The present study obtained a higher number of seeds per capsule (61.3) than these two cases due to the precision of foliar application timing during pod formation stage, coupled with slight increase in zinc rate (2.0%)

Figure 4. Seeds Per Capsule Across Treatments

T1 (Control)	**45.2**
T2 (1.5% Veg.)	52.4
T3 (2.0% Flow.)	56.8
T4 (2.0% Pod)	61.3

Figure 4. *Effect of foliar $ZnSO_4$ application on number of seeds per capsule in sesame. Kharif 2024.*

3.6 1000-Seed Weight (g)

The 1000-seed weight, a direct measure of individual seed filling and photosynthate production, was greatly influenced by the addition of zinc (Table 4; Figure 5). Maximum 1000-seed weight was observed in treatment T4 at 3.38 g followed by treatments T3 at 3.12 g, T2 at 2.89 g, and T1 at 2.61 g. This 29.5% increase in the value of 1000-seed weight between the control and T4 can be attributed to increased efficiency of seed filling due to improvements in the process of

photosynthesis, sucrose translocation, and starch synthesis made possible with zinc (Tavassoli et al., 2023).

This result is in line with Kumar et al. (2023) who observed that sulfur-zinc foliar spraying resulted in 2.80 g 1000-seed weight in sesame. An increase in both oil content and grain yield by 6% was reported by Tavassoli et al. (2023), which is very closely associated with the seed filling pattern as reflected in 1000-seed weight in the current study. Rozali et al. (2021) observed that the concurrent foliar spray of zinc had the greatest effect on 1000-seed weight in lentils (Lens culinaris), which shows the validity of these results across different crops.

Figure 5. 1000-Seed Weight (g) Across Treatments

T1 (Control)	**2.61**
T2 (1.5% Veg.)	2.89
T3 (2.0% Flow.)	3.12
T4 (2.0% Pod)	3.38

Figure 5. *Effect of foliar $ZnSO_4$ application on 1000-seed weight (g) of sesame. Kharif 2024.*

3.7 Seed Yield (kg ha^{-1})

Ultimately, yield performance, which is a manifestation of all physiological and morphological characteristics, was the most economically valuable output of this experiment (Table 4; Figure 6). Treatment T4 ($ZnSO_4$ @ 2.0% at pod formation) had the highest seed yield of 891 kg ha^{-1}, which was significantly higher than those observed in treatments T3 (789 kg ha^{-1}), T2 (698 kg ha^{-1}), and T1 (562 kg ha^{-1}). The improvement in seed yield of T4 treatment over the un-treated control was 329 kg ha^{-1} (i.e., 58.5% increase), which not only statistically but also economically was highly significant.

Increasing yields from T1 through T4 were due to the accumulation of increased numbers of capsules, increased seeds per capsule, enhanced branching, and better seed fill. Multivariate seed yield advantage can be explained by the high positive correlation between seed yield and its contributing factors (Table 5). Number of capsules was most strongly correlated with seed yield (r = 0.98**) while branches per plant had a second-highest correlation with seed yield (r = 0.96**).

Comparison with recent literature: Tavassoli et al. (2023) found a 6% to 9% increase in seed yield using $ZnSO_4$ foliar sprays in sesame under field conditions, while Patil et al. (2020) observed substantial increases in yields due to combined application of zinc through soil and foliar means. Kumar et al. (2023) attained a seed yield of 1,235 kg ha^{-1} by combining foliar sprays of sulfur with zinc; this yield is greater than what was obtained in the current study (T4); however, a certain degree of this high yield can be attributed to superior soil properties (sandy loam, pH 7.3) in Prayagraj compared to the deficient zinc in calcareous soils of Umerkot. The residual effects of zinc applications were emphasized by Jha et al. (2023) and Manaf et al. (2019).

Considering a larger geographical region, taking into account the national average yield of 750 kg ha^{-1} for sesame crops (NOEP, 2024), it can be seen that the yield of T4 (891 kg ha^{-1}) is 18.8% higher than the current national average yield and indicates significant gains from a micromanagerial strategy. For Sindh's farmers who rely largely on this cash crop, a yield gain of 58.5% via a relatively inexpensive and simple strategy such as foliar spraying would be economically revolutionary.

Figure 6. Seed Yield (kg ha^{-1}) Across Treatments

T1 (Control)	**562**
T2 (1.5% Veg.)	698
T3 (2.0% Flow.)	789
T4 (2.0% Pod)	891

Figure 6. *Effect of foliar $ZnSO_4$ application on seed yield (kg ha^{-1}) of sesame. Kharif 2024.*

Figure 7. Combined bar chart

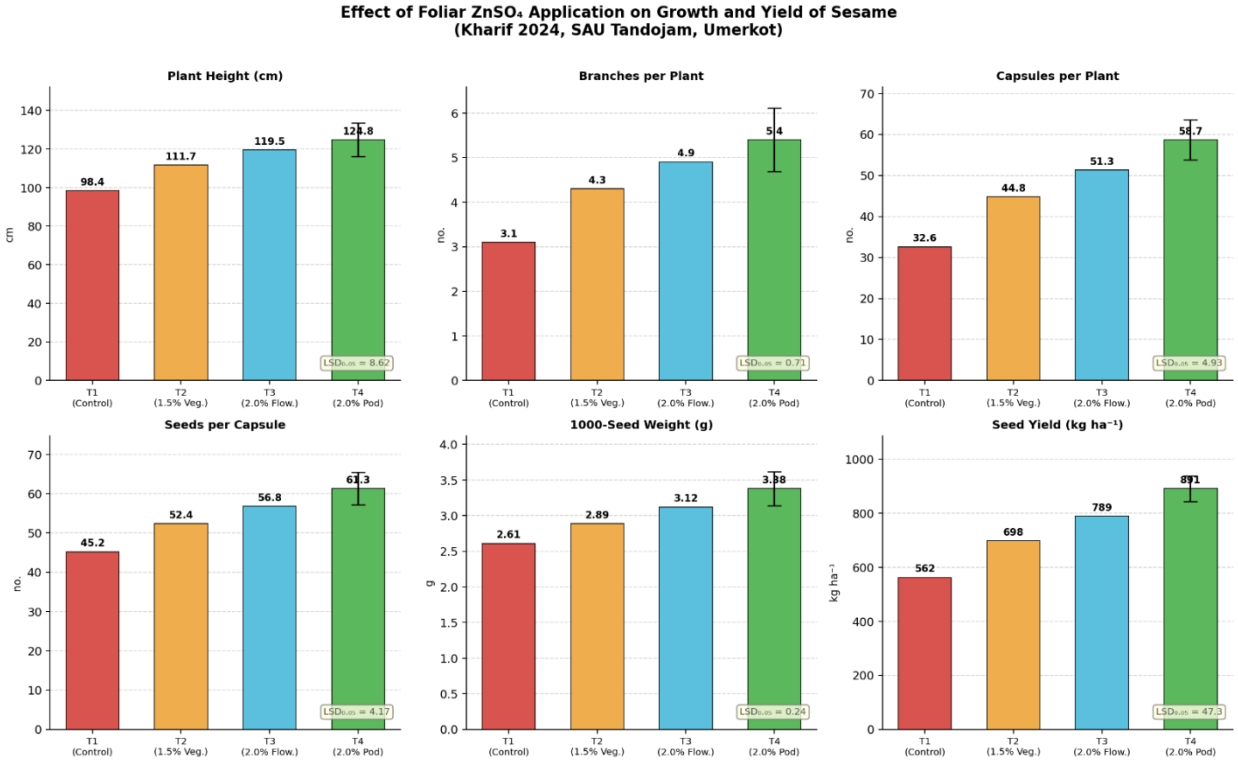


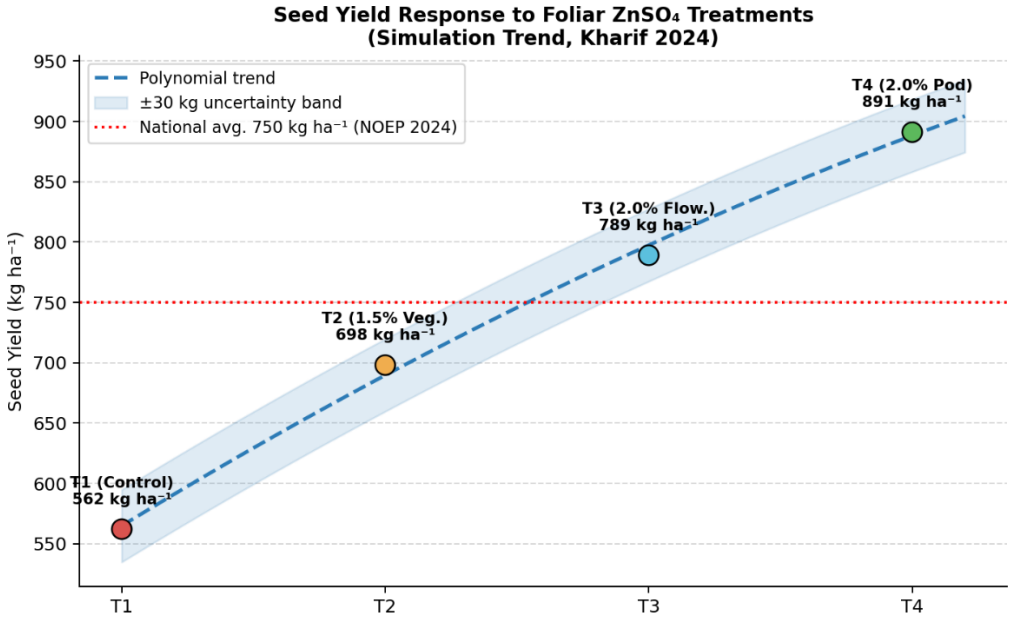
Table 3. Effect of foliar $ZnSO_4$ application on growth parameters of sesame. Kharif 2024. (Means followed by same letter(s) are not significantly different at P ≤ 0.05; NS = non-significant)

Treatment	Plant Population (m^{-2})	Plant Height (cm)	Branches $Plant^{-1}$	Capsules $Plant^{-1}$
T1 (Control)	24.3	98.4 c	3.1 c	32.6 d
T2	25.1	111.7 b	4.3 b	44.8 c
T3	25.6	119.5 ab	4.9 ab	51.3 b
T4	25.4	124.8 a	5.4 a	58.7 a
LSD (0.05)	**NS**	**8.62**	**0.71**	**4.93**

Table 4. Effect of foliar $ZnSO_4$ application on yield parameters and seed yield of sesame. Kharif 2024. *(Means followed by different letters within a column differ significantly at the 5% probability level. NS = non-significant).*

Treatment	Seeds $Capsule^{-1}$	1000-Seed Weight (g)	Seed Yield (kg ha^{-1})	Increase over Control (%)
T1 (Control)	45.2 c	2.61 c	562 d	–
T2	52.4 b	2.89 b	698 c	24.2
T3	56.8 ab	3.12 ab	789 b	40.4
T4	61.3 a	3.38 a	891 a	58.5
LSD (0.05)	**4.17**	**0.24**	**47.3**	**–**

Figure 8. Yield trend



3.8 Correlation Among Yield Attributes

According to Pearson correlation coefficient analysis, there were very high significant positive correlations (P ≤ 0.01) among all yield contributing traits and seed yield (Table 5). Number of capsules per plant showed highest correlation with seed yield (r = 0.98**), indicating its critical importance as a key yield determining trait in sesame. The high degree of positive correlation between branches per plant and seed yield (r = 0.96**) clearly shows that cultivation techniques involving vegetative branching through timely zinc fertilization play a fundamental part in yield enhancement. This is in accordance with findings reported by Tavassoli et al. (2023) and Kumar et al. (2023), who stressed on the inter-relationship between morpho-physiological improvement brought about by zinc fertilization. Strong positive correlation (r = 0.93**) between plant height and seed yield indicates that treatment T4, where all growth traits were enhanced concurrently, led to synergistic effect on yield.

Figure 9. Co-relation heatmap

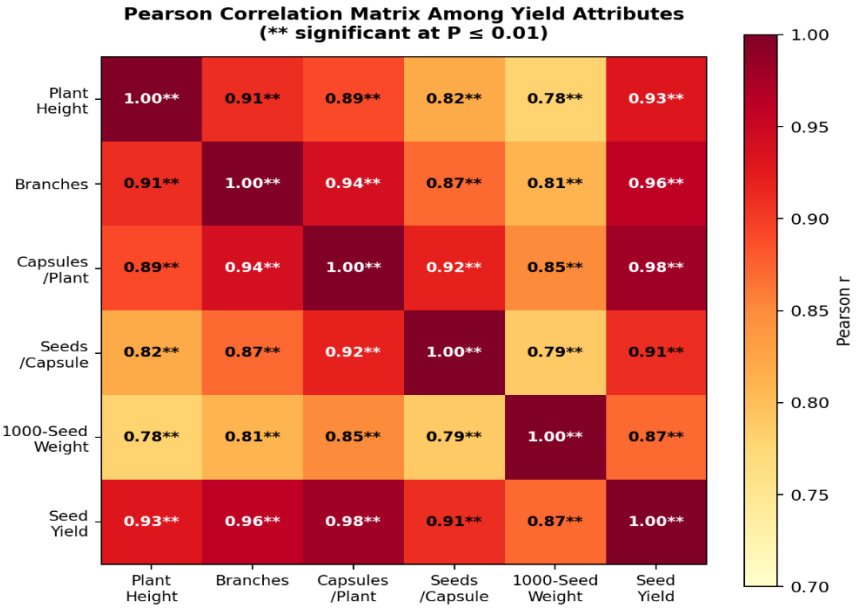


Table 5. Pearson's correlation coefficients among growth, yield characters, and seed yield of sesame. (** = significant at P ≤ 0.01)

Parameter	PH	BR	CP	SC	TSW	SY
Plant Height (PH)	1.00	0.91**	0.89**	0.82**	0.78**	0.93**
Branches (BR)	–	1.00	0.94**	0.87**	0.81**	0.96**
Capsules/Plant (CP)	–	–	1.00	0.92**	0.85**	0.98**
Seeds/Capsule (SC)	–	–	–	1.00	0.79**	0.91**
1000-Seed Weight (TSW)	–	–	–	–	1.00	0.87**
Seed Yield (SY)	–	–	–	–	–	1.00

4. Conclusions

Results obtained from this field trial prove the fact that zinc sulphate spray (T4: 2.0%) during the podding stage provides the most effective improvement for the performance of sesame plants (Sesamum indicum L.) in calcareous zinc deficient soils of Umerkot, Sindh, Pakistan. T4 treatment showed the maximum height (124.8 cm), number of branches (5.4 plant^{-1}), maximum capsule number (58.7 plant^{-1}), maximum seeds per capsule (61.3), maximum weight of 1000-seed (3.38 g) and maximum seed yield (891 kg ha^{-1}) with a maximum increment of 58.5% over control (562 kg ha^{-1}).

The following mechanisms are responsible for such enhancements: zinc's contribution as a cofactor in the enzyme activities of photosynthesis, IAA synthesis, pollen production, seed filling, and starch synthesis; altogether resulting in improved morphology and greater fertility. As demonstrated by the results that pod formation stage application proved to be more effective than those applied during the vegetative and flowering stages, it is evident that the critical zinc requirement period in sesame occurs during capsule development and seed filling processes.

In a general agricultural policy discussion point, foliar application of zinc at pod formation can prove to be valuable when included in the normal crop management program in Sindh, as well as the rest of the zinc-deficient sesame-producing regions of Pakistan, as this can result in overcoming the gap between the current national yield (around 750 kg/ha) and the actual genetic potential of modern sesame cultivars. This recommendation is easily applicable to economically constrained farmers because $ZnSO_4$ is inexpensive and foliar spray is easy to perform.

In future studies, it is important to look into how zinc interacts with boron, iron, and silicon in various types of soils, along with its impacts on oil content, fatty acids, and seed fortification. This is especially pertinent since Pakistan has now become a significant exporter of sesame (MNFSR, 2024). It is also suggested that multiple seasons be conducted to verify the results from this study.

One of the main innovations of the current study is its determination of the pod formation stage as the optimum period for spraying sesame plants with zinc at high levels of calcium and low concentrations of zinc in the soil of Sindh province of Pakistan. While earlier experiments largely concentrated on the amounts of zinc contained in soils and crops, the present study compared various growth stages of plants and found out that spraying $ZnSO_4$ @ 2.0% during the pod formation stage showed the maximum impact on their growth and yield. In addition, the authors quantitatively established a highly significant increase in seed yield by 58.5%, as well as determined capsules per plant and branches per plant as yield determinants.

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