Enhancing Tuberose (*Polianthes Tuberosa* L.) Growth and Productivity Through Precision Zinc Fertilization

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ABSTRACT

Objective: Tuberose (*Polianthes tuberosa* L.), a bulbous flowering plant, is widely cultivated for bouquets, decorative purposes and essential oil extraction. Its growth, development and flowering are significantly influenced by climatic factors, soil conditions, water availability and nutrient deficiencies. The study's objective was to investigate the effects of precision zinc fertilization on tuberose growth and productivity, with a focus on determining the optimal zinc application rates for maximizing yields and flower quality.

Materials and Methods: The research was conducted at the Floriculture Research Area, Institute of Horticultural Sciences, University of Agriculture, Faisalabad. The experimental layout followed a Randomized Complete Block Design (RCBD). Five treatments were applied, including a control (T_0), with each treatment replicated five times. Zinc spray of different concentrations was prepared along with 0.1% Calcium carbonate ($CaCO_3$). The treatments consisted of T_0 (control), T_1 (0.25% $ZnSO_4$), T_2 (0.5% $ZnSO_4$), T_3 (0.75% $ZnSO_4$) and T_4 (1% $ZnSO_4$). Foliar application of Zn spray was done three times, starting one month after sowing, at 30-day intervals. The experiment was conducted using a randomized complete block design. The statistical analysis of the generated data was analyzed using the software Statistix 8.1. Fisher's analysis of variance (ANOVA) technique was used and treatment means were compared using Tukey's test at a 5 percent probability level.

Results: Data on different morphological attributes were collected which indicated that treatment T4 showed maximum plant height (93.03 cm), number of leaves per plant (36.33), leaf length (45.76 cm), leaf width (1.73 cm), leaf diameter (1.38 cm²), spike length (77.83 cm), number of florets per spike (44.33), floret length (7.0 cm), floret width (3.07 cm), floret diameter (3.96 cm²), petal length (2.85 cm), petal width (2.63 cm), petal diameter (2.80 cm²), vase life of flowers (10.67 days), leaf nutrients zinc analysis (0.24 mg/g), leaf nutrients calcium analysis (2.3 mg/g), flower quality (9.20) and total leaf chlorophyll contents (72.48). Results demonstrated that foliar application of $ZnSO_4$, particularly at 0.75 and 1.00% concentrations, significantly enhanced both vegetative and reproductive traits in tuberose. The improvements in morphological features, nutrient uptake, chlorophyll content and post-harvest life underscore zinc's crucial role in optimizing plant vigor and floral aesthetics.

Conclusion: The findings establish a strong dose-dependent response to zinc application, with 0.75% $ZnSO_4$ emerging as the optimal concentration. This study reinforces the significance of precision zinc fertilization in ornamental horticulture for enhancing productivity, quality and market value of cut flowers.

INTRODUCTION

Tuberose (*Polianthes tuberosa* L.), a captivating bulbous and scented flowering plant, belongs to the family *Asparagaceae* and is native to Mexico. Its sweet, exotic

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fragrance has secured its place as a staple in the luxury perfume industry. In addition to its role in perfumery, tuberose is widely cultivated as an ornamental flower, particularly prized for use in wedding decorations and floral arrangements. Its essential oil is highly valued in aromatherapy and the cosmetic sector for its calming and aromatic properties[1]. Tuberose adapts well to tropical and subtropical climates, with specific agronomic practices such as optimal spacing playing a crucial role in maximizing yield and quality. Countries such as Kenya, India and Mexico are leading exporters of tuberose, supplying markets in the USA, Europe and Japan[2]. In Pakistan, cities such as Karachi, Hyderabad, Lahore and Islamabad, along with surrounding rural areas, offer favorable conditions for floriculture. Pattoki, a city in Punjab, is particularly renowned as the "City of Flowers" due to its concentrated floriculture production. The region's ideal climate, fertile soil and proximity to markets make it a hub for growing a variety of flowers, including roses, gladiolus, gerbera and increasingly, tuberose[3,4].

Tuberose has emerged as a significant player in the global floriculture trade. Between March 2023 and February 2024, 3,143 tuberose shipments were recorded, with Mexico, Costa Rica and India accounting for all exports[5]. On the import side, India, Kazakhstan and the United States were the largest markets. The U.S. predominantly imported from Mexico, Costa Rica and India, indicating a strong global demand and robust trade network[6].

Tuberose cultivation requires sandy loam soil rich in organic matter, with a slightly acidic to neutral pH of 6.5-7.5[7]. Optimal growth occurs in temperatures between 20°C and 30°C. Growers typically use healthy bulbs measuring 2.0-2.5 cm in diameter, planted at depths of 5-7 cm with 20×25 cm spacing to ensure proper air circulation and growth. Irrigation is vital, particularly during the establishment and flowering stages, though overwatering must be avoided to prevent bulb rot[8]. Tuberose plants can reach up to 300 cm in height, with waxy, fragrant white flowers approximately 2.5 cm in length[9].

In the perfume industry, tuberose essential oil is used to create high-end fragrances, often combined with other floral and woody notes. Additionally, it is used in skincare, aromatherapy and cosmetic formulations, contributing to products such as facial mists, attars, soaps and scented candles[10,11]. Dried flowers and extracts are also used in decorative crafts and herbal sachets[12].

Despite its commercial potential, tuberose productivity is often constrained by micronutrient deficiencies, especially zinc (Zn) and calcium (Ca). Zinc is essential for chlorophyll production, protein synthesis and stress resistance, while calcium is critical for cell wall integrity and nutrient uptake[13,14]. Deficiencies in these nutrients lead to stunted growth, poor flowering and reduced plant health. Balanced fertilization, soil amendments and foliar applications are crucial to addressing these issues[15].

Foliar spraying of micronutrients has proven more effective than root applications, offering faster nutrient absorption and symptom relief[16]. Zinc, in particular, enhances physiological processes and extends vase life in floricultural crops. In studies on Gerbera and African marigold, foliar application of 0.6% $ZnSO_4$ significantly improved flower diameter, yield and vase life[17-19]. However, there remains a significant knowledge gap regarding optimal zinc application methods and doses specific to tuberose cultivation.

Thus, research focused on precision zinc fertilization in tuberose is essential to improving yield and flower quality. Determining the best zinc application rates and methods will help develop effective nutrient management strategies, enhance profitability for farmers and solidify tuberose's role in the global floriculture industry.

MATERIALS AND METHODS

The research was conducted in April 2024 at the Floriculture Research Area, Institute of Horticultural Sciences, University of Agriculture, Faisalabad. A Randomized Complete Block Design (RCBD) was used to reduce field variability and ensure reliable results. The experiment included five treatments, including a control, each replicated three times. Each replication consisted of five plants, spaced 15 cm apart and 75 cm between rows, to support healthy growth and facilitate management. Treatments were selected based on prior studies. Uniform cultural practices were applied across all plots. Statistical analysis was conducted using Fisher's analysis of variance (ANOVA) and treatment means were compared at a 5% probability level to assess the significance of differences, ensuring accuracy in evaluating treatment effects.

Preparation of zinc spray: To ensure effective foliar application, zinc spray solutions of varying concentrations were freshly prepared by dissolving the required amount of zinc compound in distilled water, followed by the addition of 0.1% calcium carbonate ($CaCO_3$) to stabilize the solution and prevent phytotoxicity. The volume was adjusted to 100 mL, ensuring uniformity. Sprays were applied three times during the crop growth period first, one month after sowing and then at 30-day intervals. Applications were done using a fine mist sprayer during early morning or late afternoon to avoid evaporation losses, ensuring maximum absorption while avoiding windy or rainy conditions for optimal efficacy.

Details of treatments are as under:

- T_0 = Control (foliar spray with distilled water)
- T_1 = 0.25% $ZnSO_4$
- T_2 = 0.50% $ZnSO_4$
- T_3 = 0.75% $ZnSO_4$
- T_4 = 1% $ZnSO_4$

Data collection: Data collection followed standard procedures to ensure consistency and accuracy. Methods were chosen to match established scientific protocols. Calibrated instruments and validated techniques minimized errors. Each step was documented for transparency and reproducibility. Trained personnel handled equipment and followed guidelines. Details on data collection are provided below.

Plant height (cm): The height of the tuberose plants was determined by measuring from the base of the plant to the topmost floret using a measuring rod, with measurements taken at the time of flower harvest. To ensure accuracy, five plants were randomly selected from each replication and their heights were recorded. The average height was then calculated to obtain a representative value for each treatment (Fig. 1).

Number of leaves per plant: To count the number of leaves per plant for tuberose, numbers of leaves were counted at the time of flower harvest. Five plants from each replication were randomly selected and their leaves were carefully counted. The total number of leaves for each selected plant was recorded and the average number of leaves per plant was calculated (Fig. 2).

Leaf length (cm): To measure the leaf length of tuberose, a mature and healthy leaf was selected from the plant. The base of the leaf, where it met the stem and the tip of the leaf were identified. A measuring rod was placed along the leaf from the base to the tip and the length was recorded in centimeters (cm). For accuracy, multiple leaves were measured and the average length was calculated. The leaves were ensured to be flat and not curved or bent during measurement and the length was measured from the point where the leaf met the stem to the tip of the leaf (Fig. 3).

Leaf width (cm): To measure the leaf width of tuberose, a mature and healthy leaf was selected from the plant. The widest part of the leaf was identified and a measuring rod was placed across it, perpendicular to the midrib. The measurement was recorded in centimeters (cm). For accuracy, multiple leaves were measured and the average width was calculated (Fig. 4).

Leaf diameter (cm^2): Leaf area was measured using the method by Carleton and Foote[20]. Fully matured lower leaves from five plants per replication were selected. Length and maximum breadth were recorded and leaf area was calculated using the formula: Leaf area = Length×Max. Breadth×0.68, ensuring consistency and accuracy (Fig. 5).

Spike length (cm): At the flower harvesting stage, five plants were randomly selected from each replication and the spike length was measured using a measuring rod. The measurement was taken from the base of the spike to the tip and the average spike length was calculated for each replication. This random sampling approach ensured a representative measurement of spike length, minimizing any potential bias and providing reliable data for analysis and comparison across different treatments (Fig. 6).

Number of florets per spike: From each replication, five spikes were randomly selected. The flowers on each spike were counted carefully to ensure accuracy. After counting, the number of flowers recorded for all five spikes was added

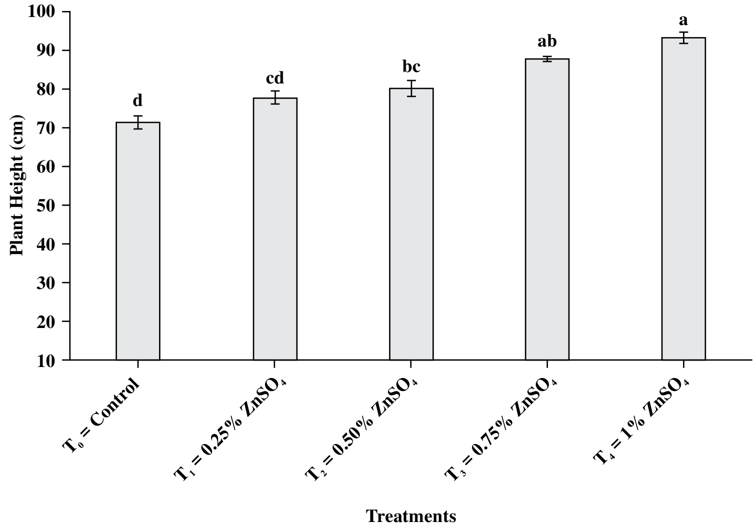

Fig. 1: Effect of foliar application of $ZnSO_4$ on height of tuberose plants
Vertical bars represent ±S.E. of means. Different letters indicate significant differences among treatments at $p \leq 0.05$, N = 3 replicates

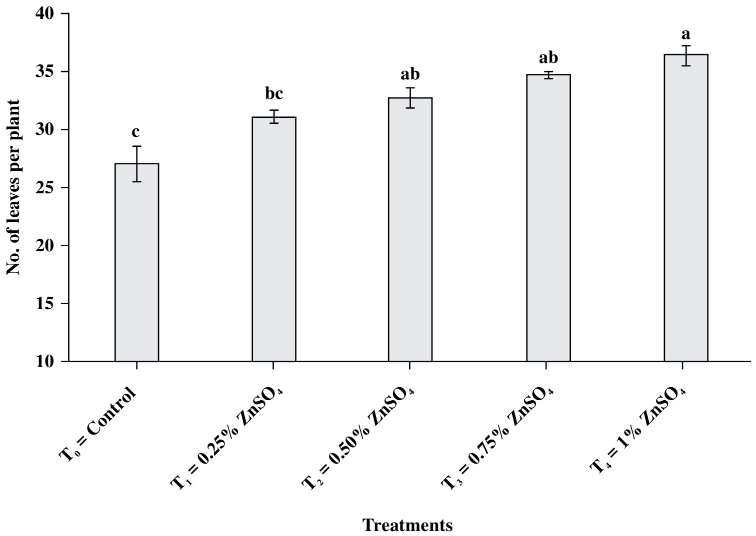

Fig. 2: Effect of foliar application of $ZnSO_4$ on number of leaves per plant of tuberose plants

Vertical bars represent ±S.E. of means. Different letters indicate significant differences among treatments at $p \leq 0.05$, N = 3 replicates

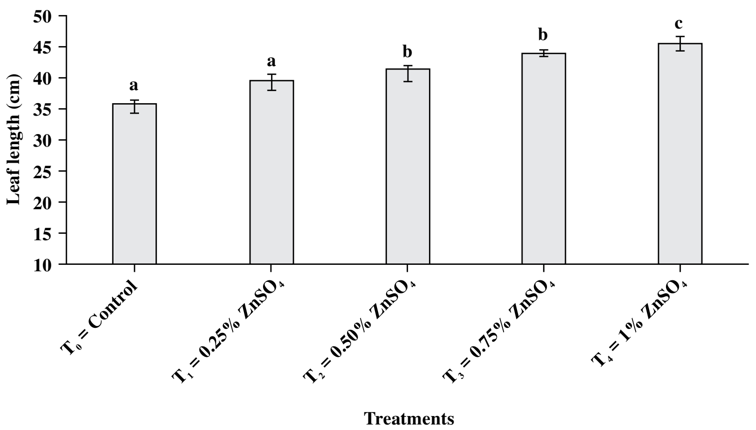

Fig. 3: Effect of foliar application of $ZnSO_4$ on leaf length of tuberose plants

Vertical bars represent±S.E. of means. Different letters indicate significant differences among treatments at $p \leq 0.05$. N = 3 replicates

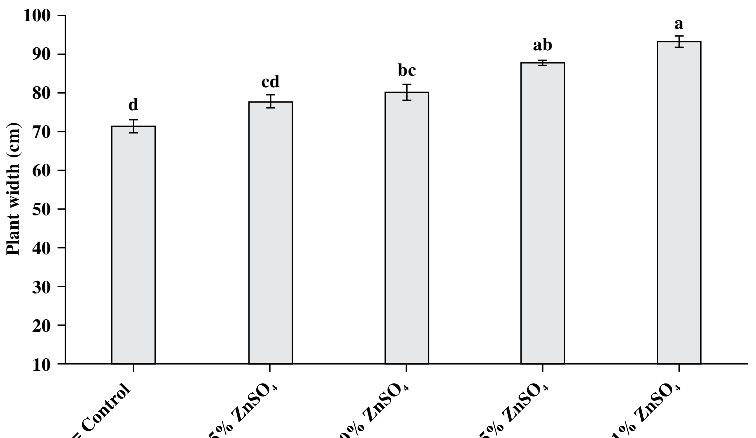

Fig. 4: Effect of foliar application of $ZnSO_4$ on leaf width (cm) of tuberose plants

Vertical bars represent ±S.E. of means. Different letters indicate significant differences among treatments at $p \leq 0.05$. N = 3 replicates

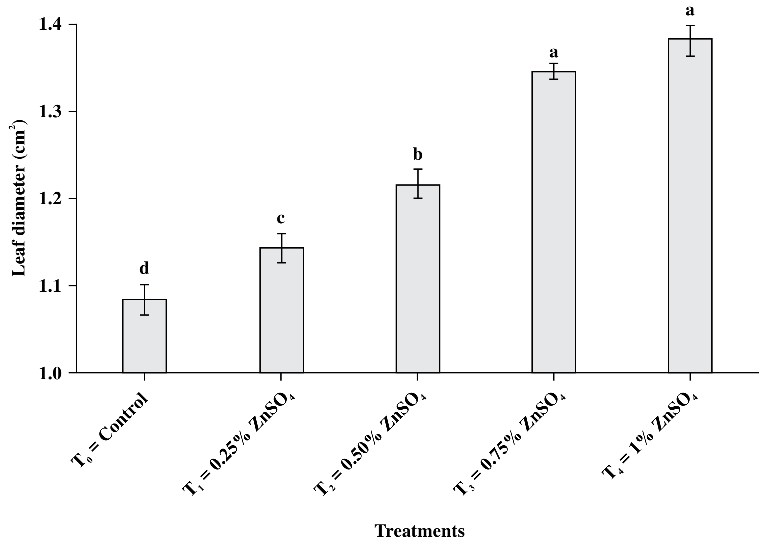

Fig. 5: Effect of foliar application of $ZnSO_4$ on leaf diameter of tuberose plants
Vertical bars represent±S.E. of means. Different letters indicate significant differences among treatments at p≤0.05. N = 3 replicates

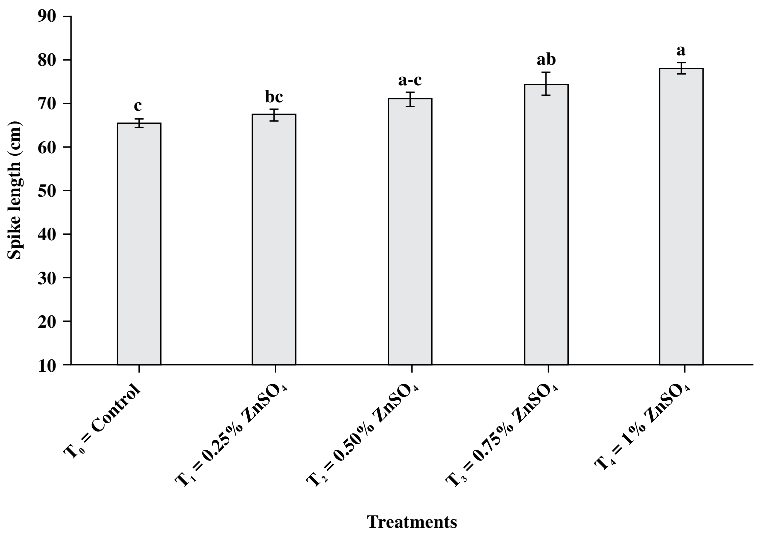

Fig. 6: Effect of foliar application of $ZnSO_4$ on leaf spike length of tuberose plants
Vertical bars represent±S.E. of means, Different letters indicate significant differences among treatments at p≤0.05. N = 3 replicates

together and divided by five to calculate the average number of flowers per spike. This average was used to represent the flowering performance for each replication (Fig. 7).

Floret length (cm): The floret length of tuberose was measured precisely from the base to the tip using a measuring rod. Five plants were randomly selected from each treatment and representative florets were chosen to avoid bias. Each floret was measured individually under uniform conditions, ensuring accuracy. Care was taken to avoid pressure that might alter natural length. Data from individual florets were recorded systematically and the average floret length was calculated for each treatment to obtain a reliable and consistent value for further analysis. This method ensured uniformity and precision in measuring floret length across all experimental units (Fig. 8).

Floret width (cm): The floret width of tuberose was measured to ensure accuracy and consistency. Floret width was determined at the widest part of the floret, perpendicular to its length, using a calibrated measuring rod. For this study, five plants were randomly selected from each treatment or plot. From each plant, a representative sample of florets was chosen randomly to avoid bias. Each selected floret was measured individually under uniform conditions to maintain consistency across all observations (Fig. 9).

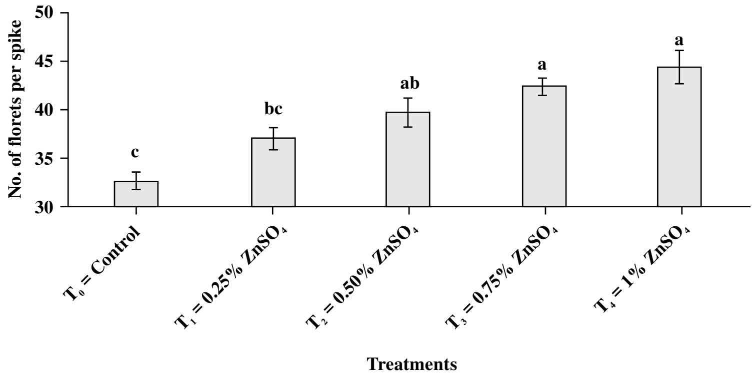

Fig. 7: Effect of foliar application of $ZnSO_4$ on no. of florets per spike of tuberose plants

Vertical bars represent ±S.E. of means. Different letters indicate significant differences among treatments at $p \leq 0.05$. N = 3 replicates

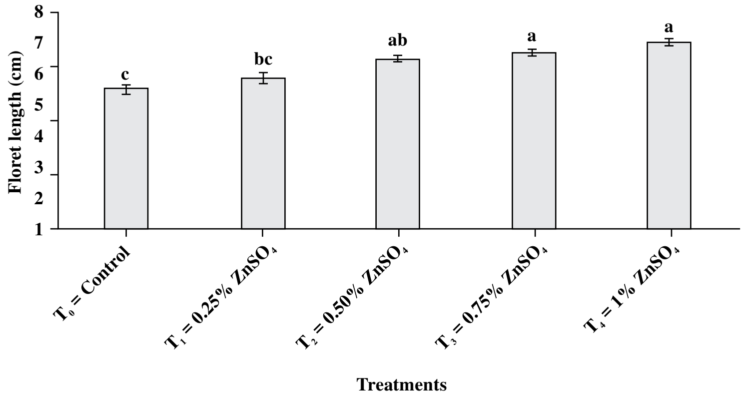

Fig. 8: Effect of foliar application of $ZnSO_4$ on floret length of tuberose plants

Vertical bars represent ±S.E. of means. Different letters indicate significant differences among treatments at $p \leq 0.05$. N = 3 replicates

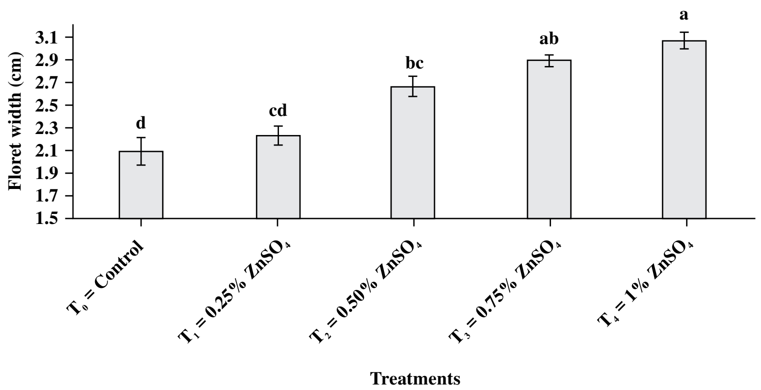

Fig. 9: Effect of foliar application of $ZnSO_4$ on floret width of tuberose plants

Vertical bars represent ±S.E. of means. Different letters indicate significant differences among treatments at $p \leq 0.05$. N = 3 replicates

Floret diameter (cm^2): The floret diameter of tuberose was measured using a measuring rod. Five plants were randomly selected from each treatment and a representative sample of florets was measured from each plant. The diameter was taken at the widest part of the floret and the average diameter was calculated for each sample (Fig. 10).

Petal length (cm): Petal length of tuberose was measured from the base to the tip of the petal using a precise measuring instrument, such as a digital caliper. To ensure accuracy, the measurements were taken carefully for each selected petal, avoiding any distortion or stretching. The average petal length was then calculated from the individual

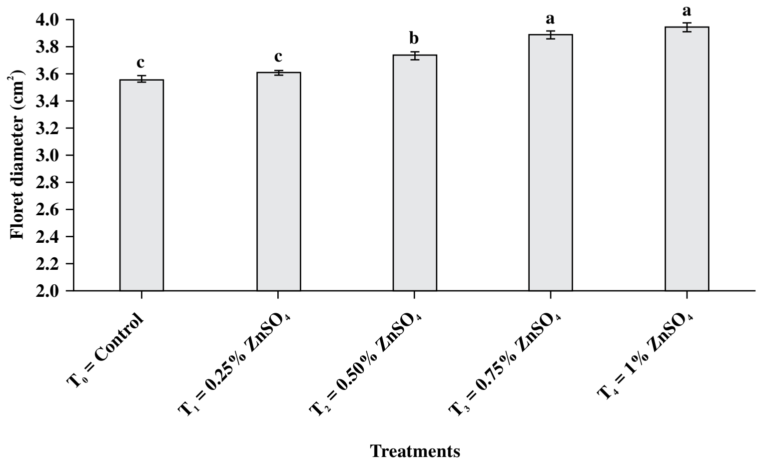

Fig. 10: Effect of foliar application of $ZnSO_4$ on floret diameter of tuberose plants

Vertical bars represent ± S.E. of means. Different letters indicate significant differences among treatments at $p \leq 0.05$. N = 3 replicates.

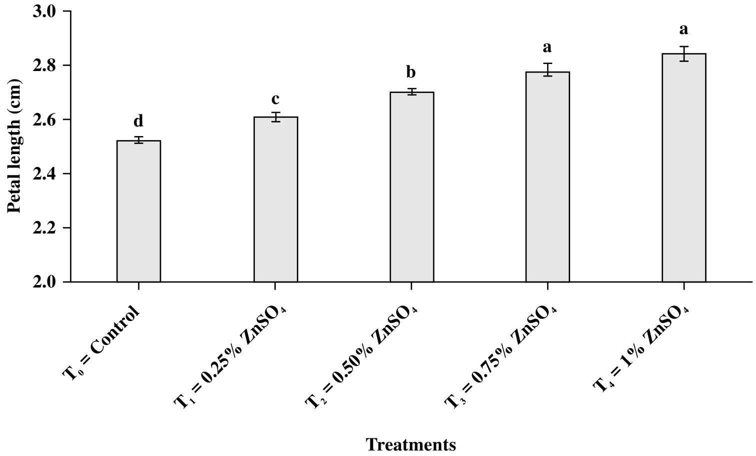

Fig. 11: Effect of foliar application of $ZnSO_4$ on petal length of tuberose plants

Vertical bars represent ±S.E. of means. Different letters indicate significant differences among treatments at $p \leq 0.05$. N = 3 replicates.1.12. Petal

measurements, providing a reliable estimate of petal size. This measurement was crucial for evaluating the floral characteristics and overall aesthetic appeal of the tuberose flowers (Fig. 11).

Petal width (cm): The petal width of tuberose flowers was measured at the widest point using a digital caliper to ensure accuracy. Each flower was carefully handled to avoid damage and multiple measurements were taken from different flowers to account for natural variations. The average petal width was calculated by adding all individual measurements and dividing by the total number of flowers measured (Fig. 12).

Petal diameter (cm^2): Petal diameter of tuberose was measured at the widest point using a digital caliper for precision. Measurements were recorded in centimeters and converted to square centimeters (cm^2) to calculate petal surface area. This enabled accurate comparison of flower size across treatments, aiding in the evaluation of growth and development (Fig. 13).

Vase life of flower spike (days): For vase life evaluation, five flower spikes were selected from each replication and harvested when the lower two florets showed color. Spikes were placed in distilled water, trimmed to 70 cm and defoliated to reduce moisture loss. Each was placed in a vase with 400 mL distilled water. Vase life ended when 50% of petals wilted, discolored, or the stem bent beyond 90°. The time taken to reach these conditions was recorded as vase life in days. This standardized method ensured accurate assessment of post-harvest quality and flower longevity across different treatments (Fig. 14).

Leaf nutrients analysis (Zinc) Zn: Leaf nutrient analysis for zinc (Zn) in tuberose was conducted to assess the plant's

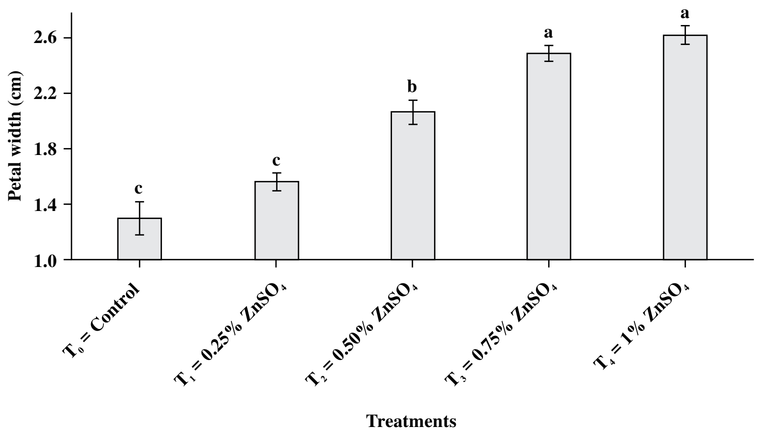

Fig. 12: Effect of foliar application of $ZnSO_4$ on petal width of tuberose plants

Vertical bars represent±S.E. of means. Different letters indicate significant differences among treatments at p≤0.05. N = 3 replicates

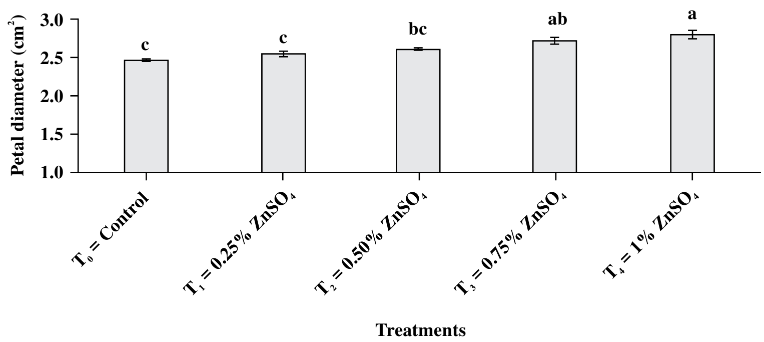

Fig. 13: Effect of foliar application of $ZnSO_4$ on petal diameter of tuberose plants

Vertical bars represent ±S.E. of means. Different letters indicate significant differences among treatments at p≤0.05. N = 3 replicates

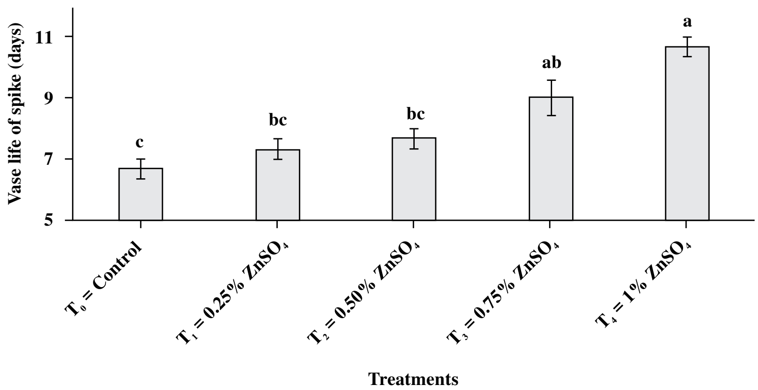

Fig. 14: Effect of foliar application of $ZnSO_4$ on vase life of flower spike of tuberose plants

Vertical bars represent ±S.E. of means. Different letters indicate significant differences among treatments at p≤0.05. N = 3 replicates

nutritional status for optimal growth and flower production. Leaf samples were collected from representative plants, washed to remove contaminants and oven-dried at a low temperature to preserve nutrient integrity. The dried leaves were then ground into a fine powder for uniformity. Zinc content was measured using Atomic Absorption Spectroscopy (AAS), which detects zinc concentration by measuring light absorption by zinc atoms. This method provided accurate and reliable data, helping to identify whether zinc levels in the tuberose plants were adequate, deficient, or excessive for proper plant development (Fig. 15).

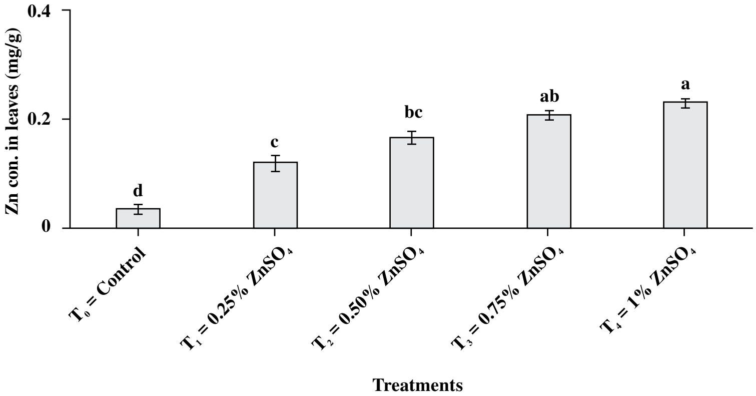

Fig. 15: Effect of foliar application of $ZnSO_4$ on zinc concentration in leaves of tuberose plants
Vertical bars represent ±S.E. of means. Different letters indicate significant differences among treatments at $p \leq 0.05$. N = 3

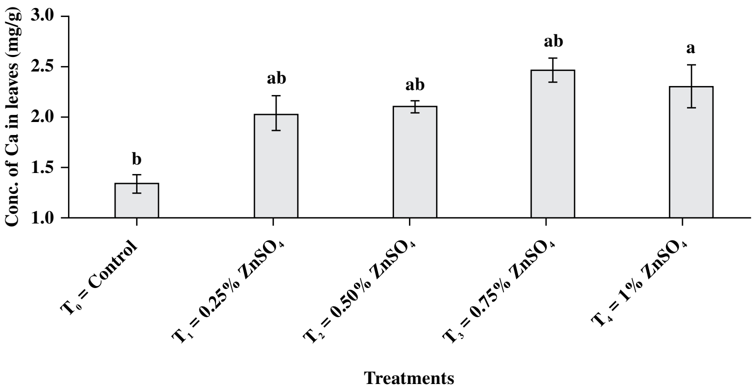

Fig. 16: Effect of foliar application of $ZnSO_4$ on calcium concentration in leaves of tuberose plants
Vertical bars represent ± S.E. of means. Different letters indicate significant differences among treatments at $p \leq 0.05$. N = 3

Leaf nutrients analysis (calcium) Ca: Calcium (Ca) analysis in tuberose leaves was performed by collecting, washing, drying and grinding samples into fine powder. Calcium concentration was measured using Atomic Absorption Spectroscopy (AAS). This analysis identified nutrient status, guiding fertilization strategies to ensure balanced calcium levels, promoting healthy growth and enhanced flower production (Fig. 16).

Flower quality: Flower quality was assessed based on characteristics like color, bud development, form, size and overall appearance. A 1-9 visual rating scale was used, where 1 indicated poor and 9 represented excellent quality. Three experienced judges independently evaluated the flowers following Cooper and Spokas[21] and the average score ensured objective, consistent and reliable assessment (Fig. 17).

Total leaf chlorophyll contents (μmolm^{-2}): Total leaf chlorophyll content in tuberose was measured using a chlorophyll meter. Five leaves from five plants per replication (25 leaves total) were selected, with readings taken from each leaf's center. Values were averaged per plant and replication, providing accurate, non-destructive insights into plant health, vigor and photosynthetic efficiency across treatments (Fig. 18).

Statistical analysis: The experiment will follow a Randomized Complete Block Design (RCBD) to reduce environmental variability and ensure reliable results. Treatments will be randomly assigned within homogeneous blocks. Data will be analyzed using Statistix 8.1 software. Fisher's ANOVA will determine significance and treatment means will be compared using Tukey's test at a 5% probability level[22].

RESULTS AND DISCUSSION

The present investigation clearly demonstrated that zinc sulphate application exerted a significant influence on the vegetative and reproductive performance of tuberose. Plant height showed a marked increase with rising $ZnSO_4$ concentrations, with the tallest plants observed in T_4

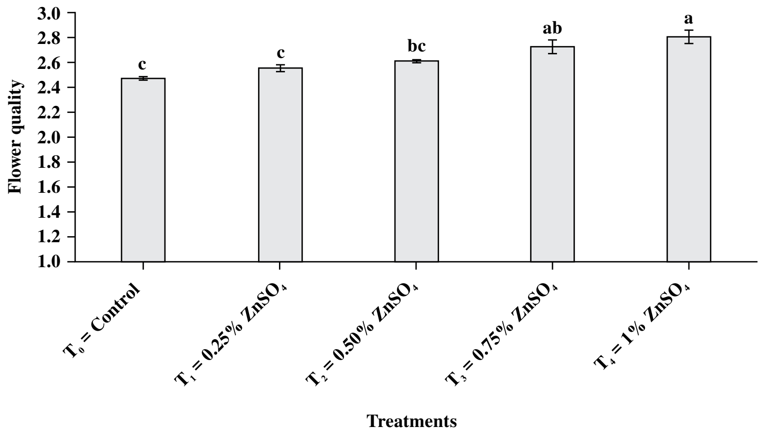

Fig. 17: Effect of foliar application of $ZnSO_4$ on flower quality of tuberose plants
Vertical bars represent ±S.E. of means. Different letters indicate significant differences among treatments at $p \leq 0.05$. N= 3 replicates

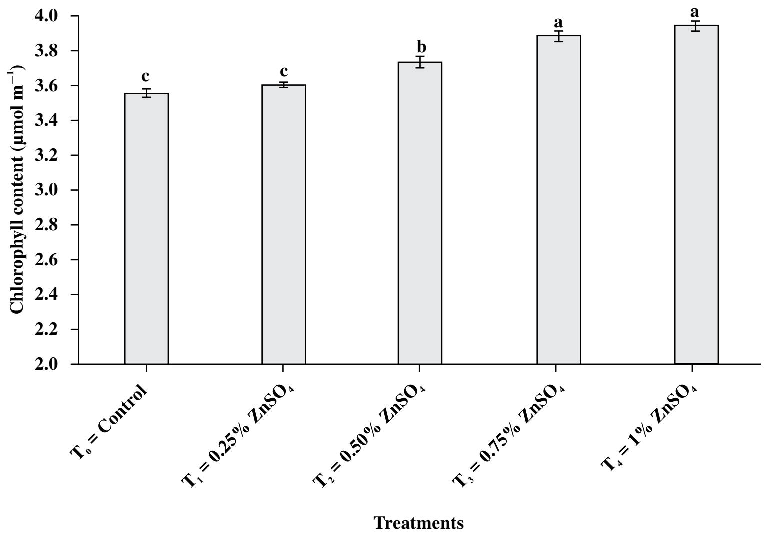

Fig. 18: Effect of foliar application of $ZnSO_4$ on total chlorophyll contents of tuberose plants
Vertical bars represent±S.E. of means. Different letters indicate significant differences among treatments at $p \leq 0.05$. N = 3 replicates

(1.00% $ZnSO_4$). This confirms zinc's role in promoting vertical growth by enhancing cell elongation, division and auxin synthesis. Similar trends have been documented in *Gladiolus* and *Tagetes erecta*, where zinc application led to substantial improvements in plant height and overall vigor[23,24].

Leaf attributes also responded positively to zinc fertilization. The number of leaves increased significantly, with the highest counts in T_4, though T_2 (0.50%), T_3 (0.75%) and were statistically similar, suggesting a threshold effect. Wider and thicker leaves are expected to support greater photosynthetic activity, translating into higher assimilate production and improved vigor. Comparable results have been reported in *Polianthes tuberosa* cv. Prajwal, where zinc and boron sprays significantly enhanced leaf area and biomass[25] and in *Iris*, where foliar zinc application improved pigment content and leaf growth[26].

Reproductive traits also exhibited significant improvements. Spike length increased steadily with higher zinc levels, with the longest spikes recorded at T_4 (1.00% $ZnSO_4$) and T_3 (0.75%). This indicates that zinc is not only essential for vegetative elongation but also for reproductive growth, possibly through its involvement in meristematic activity and hormonal regulation. Similar positive responses were reported in *Gladiolus*, where zinc foliar sprays significantly increased spike length, floret number and quality[23]. In the present study, floret production increased by 35.8% in T_4 over control, demonstrating zinc's role in floral initiation and differentiation. Comparable enhancements were observed in *Chrysanthemum* and *Marigold*, where zinc sprays increased flower number, size and overall floral yield[24].

Floret dimensions, including length, width and diameter, were also maximized under higher $ZnSO_4$ treatments, with floret width increasing by 46% at T_4

compared to control. This substantial improvement may be linked to zinc's role in auxin metabolism and protein synthesis, facilitating cell enlargement and organ development. Petal size followed a similar pattern, with significant increases in length, width and diameter at T_4 and T_3. These findings are consistent with studies on *Rosa hybrida*, where zinc sprays improved petal expansion, color intensity and overall floral quality[27].

Postharvest longevity is an important commercial trait in cut flowers and vase life in the present study was significantly enhanced by $ZnSO_4$ application. The longest vase life (10.67 days) was observed at T_4, representing a 60% increase over control. Such improvements may be attributed to zinc's role in delaying senescence by enhancing antioxidant enzyme activity and maintaining membrane stability. Similar results were reported in *Gladiolus* and *Chrysanthemum*, where zinc application extended vase life by improving water balance and reducing oxidative damage[23].

Nutrient content analysis further supported zinc's positive influence. Leaf zinc concentration increased in a dose-dependent manner, with the highest accumulation at T_4 (0.237 mg/g). Interestingly, calcium content also improved significantly, suggesting that zinc not only enhances its own uptake but may also facilitate the absorption and metabolism of other minerals, thereby strengthening cell wall structure and signaling pathways. These results align with findings of Alamer et al.[24] and Rahimi et al.[26] in *Marigold* and *Iris*, where zinc fertilization improved mineral content and nutrient balance in plant tissues.

Flower quality scores were likewise highest under T_4, reflecting the integrated effect of zinc on vegetative vigor, floral initiation, organ development and longevity. However, intermediate treatments (T_2 and T_3) also produced significant enhancements, suggesting a plateau effect beyond moderate zinc levels. Total leaf chlorophyll content increased substantially with $ZnSO_4$ application, with the highest concentration (72.48 units) observed in T_4 compared to 64.46 units in control. This increase underscores zinc's well-established role in chlorophyll biosynthesis and photosynthetic activity, which is consistent with previous reports in *Gladiolus*, *Tuberose* and *Iris*[25,26].

Overall, the results demonstrate that zinc sulphate application markedly improved plant growth, leaf morphology, spike length, floret number, floral dimensions, vase life, nutrient content and chlorophyll concentration in tuberose. These findings are in strong agreement with previous studies on other floricultural crops, highlighting zinc as a key micronutrient for optimizing both vegetative and reproductive traits. The improvements observed up to 0.75-1.00% $ZnSO_4$ also suggest that while zinc is essential, its application should be carefully managed to avoid diminishing returns at higher concentrations.

CONCLUSION

The comprehensive evaluation of $ZnSO_4$ foliar treatments establishes zinc as a critical micronutrient for optimizing both vegetative and reproductive growth in ornamental plants such as Tuberose. Higher zinc concentrations (0.75 and 1.00%) consistently promoted significant improvements across numerous morphological and physiological parameters, including plant height, leaf number, leaf size (length, width, diameter), spike length, floret number and dimensions, petal size and flower quality. Moreover, zinc application substantially extended vase life, enhancing the commercial value of cut flowers by prolonging freshness and delaying senescence. Enhanced leaf zinc and calcium content confirmed improved nutrient uptake facilitated by zinc fertilization, which also supported increased total leaf chlorophyll content and likely contributed to better photosynthetic efficiency and enzymatic activity. The results demonstrate a clear dose-dependent relationship, with the most optimal effects generally achieved at $ZnSO_4$ concentrations of 0.75% and above. These findings underscore the practical importance of precision zinc fertilization strategies in ornamental horticulture, offering valuable guidelines to maximize floral development, improve ornamental quality and promote robust plant growth.

REFERENCES

1. Tehreema I, Majeed H, Waheed M, Zahra SS, Niaz M, Bilal B, Riaz M. Tuberose. In: Zia-Ul-Haq M, AL-Huqail AA, Riaz M, Gohar UF, editors. *Essentials of Medicinal and Aromatic Crops*. Cham: Springer; 2023. p. 373-397. doi:10.1007/978-3-031-35403-8_15
2. Kumar M, Sirohi U, Malik S, Kumar S, Ahirwar GK, Chaudhary V et al. Methods and factors influencing *in vitro* propagation efficiency of ornamental tuberose (Polianthes species): A systematic review of recent developments and future prospects. *Horticulturae*. [Internet]. 2022;8. Available from: https://doi.org/10.3390/horticulturae8110998
3. Mudassir S, Ahmad R, Anjum MA. Foliar application of micronutrients enhances growth, flowering, minerals absorption and postharvest life of tuberose (Polianthes tuberosa L.) in calcareous soil. *J Hortic Sci Technol*. 2021;4(2):41-47.
4. Hashmi M, Komba BP, Chattha MWA, Fatima A, Hyder MF. Emerging business: Cut-rose and gladiolus production by small-scale florists in Pakistan. *Sarhad J Agriculture*. 2024;40(2):570-577.
5. Sinha D, Sharma R. Global competitiveness, comparative advantage and intensity of Indian floriculture trade: Scenario after national horticulture mission. *Int J Trade Global Mark*. 2024;20:61-80.
6. Hinsley A, Hughes AC, Valkenburg JV, Stark T, Delft JV, Sutherland W et al. Understanding the environmental and social risks from the international trade in ornamental plants. *Bioscience*. 2025;75(3):222-239.

7. Sayyad-Amin P, Bayanati M, Kahramanoglu I, Edrisi B, Javan M, Samavat S et al. The effects of commonly used compounds on the post-harvest storage of gerbera, gladiolus, tuberose and rose: A review. *J Plant Growth Regul.* 2024;44:3139-3150.
8. Zaman R, Ahmmed ANF, Ferdous R. Investigating the incidence and severity of field diseases impacting tuberose (Polianthes tuberosa L.) cultivation: A case study in the Jashore district, Bangladesh. *Heliyon.* [Internet]. 2024;10. Available from: https://doi.org/10.1016/j.heliyon.2024.e39876
9. Biswas D, Sarkar R. The advent of tuberose floriculture: Agricultural growth and its impact on farmers' socio-economic well-being. In: Rai A, Karmakar S, Chatterjee S, Pandey JK, editors. *Contemporary social physics.* Cham: Springer Nature Switzerland; 2024. p. 275-306. doi:10.1007/978-3-031-77596-3_13.
10. Rashidy RI, Abdel-Rahman SS, Soliman WS, Gahory AM. Effect of vermicompost as a growth media on tuberose (Polianthes tuberosa L.) plant. *Aswan Univ J Environ Stud.* 2024;5(4):483-494.
11. Saravani M, Boogar AR, Aran M, Ramezan D, Zargar M, Diakite S. Optimizing tuberose (Polianthes tuberosa L.) production using mycorrhiza and biostimulants to enhance water-deficit tolerance. *Horticulturae.* [Internet]. 2025;11(1). Available from: https://doi.org/10.3390/horticulturae11010034
12. Ghosh PK, Tamili D, Das A, Datta S, Das S, Saha S et al. Valorization of tuberose flower waste through development of therapeutic products using supercritical carbon dioxide extraction and microencapsulation technologies. *World J MicroBiol BioTechnol.* [Internet]. 2023;39. Available from: https://doi.org/10.1007/s11274-023-03761-7
13. Zamin M, Khan A, Jan I, Rabbi F, Shah S, Ali R et al. Effect of nitrogen and potash on the yield and quality of gladiolus (Gladiolus grandiflorus L) flower. *Sarhad J Agriculture.* 2020;36(2):333-374.
14. Singh NK, Sachan K, Ranjitha G, Chandana S, Manoj BP, Panotra N et al. Building soil health and fertility through organic amendments and practices: A review. *Asian J Soil Sci Plant Nutr.* 2024;10(1):175-197.
15. Abdalghani S. Influence of nitrogen, potassium and phosphorus fertilizers with foliar application of micronutrient of iron, zinc and manganese on bulb characteristics of single flower tuberose plants (Polianthes tuberosa, L.). *Alqalam J Med Appl Sci.* 2024;7(3):656-663.
16. Lilay GH, Thiébaut N, Mee DD, Assunção AGL, Schjoerring JK, Husted S et al. Linking the key physiological functions of essential micronutrients to their deficiency symptoms in plants. *New Phytol.* 2024;242(3):881-902.
17. Wilson A, Singh D, Wesley CJ. Effect of micronutrients foliar application on growth and flowering of gerbera (Gerbera jamesonii) in naturally ventilated polyhouse under Prayagraj agro climatic conditions. *Int J Environ Clim Change.* 2023;13(10):651-658.
18. Sahu M, Tirkey T, Sharma G, Tiwari A, Kushram T. Effect of foliar application of micronutrients on growth and flower production of gerbera under protected condition. *J Pure Appl Microbiol.* 2016;10:3099-3103.
19. Hussain A. Effect of zinc and iron on growth, flowering and shelf life of marigold under the agro-climatic conditions of Sawabi. *Pure Appl Biol.* 2020;9(1):180-192.
20. Carleton AE, Foote WH. A comparison of methods for estimating total leaf area of barley plants. *Crop Sci.* 1965;5(6):602-603.
21. Cooper R, Spokas L. Growth, quality and foliar iron concentration of kentucky bluegrass treated with chelated iron sources. *J Am Soc Hortic Sci.* 1991;116(5):798-801.
22. Steel RGD, Torrie JH, Dickey DA. *Principles and Procedures of Statistics: A Biometrical Approach.* 3rd ed. Blacklick, Ohio, U.S.A.: McGraw-Hill; 1997.
23. Singh AK, Asmita A, Sisodia A, Hembrom R. Effect of foliar application of zinc and copper on leaf nutrient content, growth and flowering in gladiolus (Gladiolus spp) cv. pink friendship. *The Indian J Agric Sci.* 2015;85:955-959.
24. Alamer K, Ali E, Al-Thubait M, Moaz, Al-Ghamdi. Zinc nutrition and its activated roles on growth, inflorescences attributes and some physiological parameters of Tagetes erecta L. plants. *Pak J Biol Sci.* 2019;23(1):35-44.
25. Karuppaiah P. Effect of zinc and boron on growth, yield and quality of tuberose (Polianthes tuberosa L.) cv. prajwal. *Hortic Int J.* 2019;3(1):7-11.
26. Rahimi M, Asadi-Gharneh H. Effect of foliar application of zinc sulfate and seaweed on qualitative and quantitative characteristics of local Kermanshah cantaloupe (kalak). *J Crop Prod Process.* 2019;8(4):17-28.
27. Souri MK, Hatamian M. Aminochelates in plant nutrition: A review. *J Plant Nutr.* 2018;42(1):67-78.