

FOLIAR NPK FERTILIZATION ENHANCES GROWTH, FLOWERING, AND ORNAMENTAL PERFORMANCE OF *ZINNIA ELEGANS* L. UNDER SEMI-ARID CONDITIONS

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Abstract

Zinnia elegans L. is one of the most economically important ornamental flowering species cultivated worldwide because of its attractive blooms, prolonged flowering period, and suitability for landscaping and cut-flower production. Balanced nutrient management, particularly through foliar fertilization, plays a pivotal role in improving vegetative growth and flower quality. The present study evaluated the effects of foliar application of nitrogen (N), phosphorus (P), and potassium (K) on the growth, flowering behavior, and ornamental performance of *Zinnia elegans* under the agro-climatic conditions of Lasbela, Pakistan. The experiment was conducted using a Completely Randomized Design (CRD) comprising four treatments, including an unfertilized control and three NPK concentrations (6, 12, and 18 g), each replicated three times. Growth and flowering parameters, including plant height, number of leaves, stem diameter, number of branches, flower diameter, flower stalk length, number of flowers per plant, fresh and dry flower weight, and days to flowering initiation, were recorded and statistically analyzed using analysis of variance (ANOVA). Foliar application of NPK significantly ($P < 0.05$) enhanced all measured vegetative and reproductive characteristics compared with the control treatment. Plants receiving 18 g NPK exhibited the greatest plant height, leaf production, stem diameter, flower diameter, flower weight, flower number, and branch development while producing earlier flowering than untreated plants. The findings demonstrate that balanced foliar nutrition effectively promotes plant vigor, accelerates flowering, and improves the ornamental quality of *Zinnia elegans*. Therefore, foliar application of 18 g NPK is recommended as an effective nutrient management strategy for maximizing the commercial production and aesthetic value of *Zinnia elegans* under the environmental conditions of Lasbela.

Introduction

Floriculture is one of the fastest-growing areas of horticulture and is a large industry that includes the growing of ornamentals, cut flowers, potted plants, bedding plants and various species used in landscaping. In addition to their beauty, ornamental plants offer significant ecological and environmental utilities such as contributing to increased urban biodiversity, higher environmental quality, ecosystem service provision, and human health. The floriculture industry has grown rapidly across the globe, due to the rise in urbanisation, the demand for ornamental plants and the development of landscape. With this, sustainable production systems that can enhance the quality of flowers while reducing environmental impacts have become a great concern in commercial ornamental horticulture (FAO, 2023; Bisht et al., 2022; Chandran et al., 2023).

Floriculture is gaining attention as an economically viable field of agriculture that has significant potential to diversify the income of farmers, create jobs and enhance the livelihoods of the rural people in Pakistan. But good management of water and plant nutrients is important to achieve good commercial production of ornamental crops. Adequate nutrient use in semi-arid regions is especially critical in areas where soil fertility and water availability, coupled with nutrient use efficiency, pose constraints to crop productivity. Thus, the development of effective fertilization strategies which can enable to maximize the growth and flowering of ornamental plants while minimizing the loss of fertilizer has been an important goal of modern ornamental crop production (Sharma et al., 2021; Kumar et al., 2022).

Zinnia elegans L. is one of the ornamental flowering plants. Its attractive flower colors, variety of flower shapes, extended flowering time, fast growth and tolerance of a wide variety of environmental conditions make it one of the most widely cultivated annual species (Asteraceae). *Zinnia* is native to Mexico and is widely cultivated in home gardens, urban areas, parks, road-side plantations and cut flower production. It is also

proposed as an excellent model plant for testing the effects of nutrient management due to its short growth period and quick response to agronomic management. Balanced mineral nutrition plays significant role in commercial value of *zinnia* as its influence on vegetative growth, branching, flower diameter, attractive color, extended flowering period and post-harvest quality (Riaz et al., 2021; Singh et al., 2023; Ahmad et al., 2024).

Plant nutrition is a key factor in the regulation of plant growth, metabolism and reproductive development. Proper availability of nutrients leads to improved photosynthesis, chlorophyll production, enzyme activation, protein synthesis, carbohydrate metabolism and hormonal control, which results in good vegetative growth and better floral development. On the other hand, nutrient deficiencies cause reduced accumulation of biomass, delayed flowering, poor flower quality and susceptibility to environmental stresses in plants. The mineral nutrients are essential for the growth and development of plants, with nitrogen (N), phosphorus (P) and potassium (K) being the most critical and limiting nutrients for plant productivity and ornamental quality (Marschner, 2019; Fageria, 2022).

Nitrogen is the major component of chlorophyll, amino acids, proteins and nucleic acids and is thus required for maximum vegetative growth and photosynthesis. Phosphorus is required for the synthesis of ATP and nucleic acids, which is used for energy transfer, root development, flowering, the production of pollen and reproductive growth. Potassium activates enzymes, regulates osmotic adjustment, carbohydrate translocation, stomatal function and water relations, strengthens stems, enhances flower quality, stress tolerance and vase life. These nutrients have complementary physiological roles and balanced NPK nutrition is required for synchronizing vegetative and reproductive growth, optimizing nutrient use efficiency, and maximizing the ornamental performance (Marschner, 2019; Wang et al., 2022; Fageria, 2022).

Application by conventional soil fertilization is the most widely used nutrient application technique in horticulture, but is often hampered by the lack

of efficiency due to nutrient fixation, leaching, volatilization, runoff and unfavourable soil conditions affecting the availability of nutrients. Such restrictions frequently lead to low fertilizer-use efficiency and high environmental pollution. As a consequence, much research has been focused on various supplementary fertilization practices that can enhance nutrient availability while minimizing nutrient losses (Fernández & Brown, 2018; Fernández et al., 2020).

Of these, foliar fertilization has proven to be a successful method to provide nutrients to foliage at times of peak nutrient need. The rapid absorption of nutrients applied as foliage sprays through the cuticle and through stomata and their rapid movement to the growing tissues means that nutrient deficiencies can be corrected more rapidly than when nutrients are applied to the soil alone. The application of fertilizers at the leaf surface also involves lower amounts of fertilizer, higher nutrient-use efficiency, lower losses to the environment and is also suitable if soil fertilization is not possible due to limited root uptake. These features have led to foliar nutrient application being an integral part of precision agriculture and sustainable production of ornamental crops (Fernández & Brown, 2018; Fernández et al., 2020; Dimkpa et al., 2022).

Many studies have shown that foliar fertilization with balanced NPK fertilizers has an improving effect on vegetative growth, chlorophyll content, biomass production, flowering attributes, nutrient uptake, and post harvest quality in ornamental crop species such as chrysanthemum, marigold, gladiolus, gerbera, petunia, carnation and rose. The effect of balanced nutrient management has been reported on *Zinnia elegans* with an increase in plant height, stem thickness, branching, flower diameter, flower number and biomass accumulation. However, there are many factors that affect plant responses, such as fertilizer application rate, timing, environmental conditions, cultivar and management practices. Thus, the nutrient recommendations formulated in one agro-climatic zone cannot be applied generally to other production areas, underscoring the importance of optimizing nutrient application

for each specific region (Ali et al., 2022; Kumar et al., 2022; Singh et al., 2023).

Although foliar fertilization has been gaining popularity, there is limited information available on the optimum foliar application rate of NPK to maximize the growth, flowering pattern and ornamental value of *Zinnia elegans* under the semi-arid agro-climatic conditions of Lasbela, Pakistan. In order to optimize nutrient-use efficiency, flower quality, minimize fertilizer inputs and to support environmentally friendly floriculture production, region-specific recommendations are important.

It was hypothesized that the vegetative growth, flowering period, quality of flowers, and biomass production of plants with balanced foliar application of N, P and K would be greater than for the untreated plants. Hence, the present study aimed to investigate the growth, flowering traits and quality of *Zinnia elegans* under the agro-climatic condition of Lasbela, Pakistan, when subjected to various levels of foliar applied NPK. The results would help to offer practical solutions to manage nutrients efficiently and would aid in sustainable commercial production of ornamental crops.

2. Materials and Methods

This experiment was carried out in the department of horticulture, Faculty of Agriculture, Lasbela University of Agriculture, Water and Marine Sciences (LUAWMS), Uthal, Balochistan, Pakistan in the agro-climatic condition of Lasbela. The climate is semi-arid with high summer temperatures, low annual rainfall and relatively low air humidity, which allows the evaluation of the reaction of plants of ornamental flowering plants to foliar application of nutrients.

Uniform seeds of *Zinnia elegans* L. were purchased from a commercial seed company and were planted in trays filled with a sterile growth medium in the nursery. The standard nursery management practice of irrigating regularly, controlling weeds and protecting plants was observed to assure a uniform seedling emergence and healthy growth. Once the seedlings had formed 4-5 leaves and a good root system, uniform

and healthy seedlings were carefully transplanted into experimental pots filled with a suitable potting medium.

The experiment was laid out in a Completely Randomized Design (CRD) of four treatment with three replications. Three concentrations of foliar applied NPK fertilizer (6g, 12g and 18g) and an untreated control (T_1) were used. The experimental conditions were the same for all plants throughout the experimental period with regard to both agronomic and environmental conditions. All the irrigation, weed management, and plant protection activities were carried out uniformly to reduce variations caused by non-treatment.

The foliar spray solutions were made up to the required concentrations of NPK fertilizer with water. The solutions were sprayed across the entire area with the same application rate, on both the top and bottom of the leaf, until it ran off with a hand-operated sprayer. Foliar applications were performed early in the morning to maximize the nutrient uptake and minimize losses due to evaporation. The plants of the control treatment were treated with water only for uniformity in the experimental procedure. The foliar applications were carried out at suitable vegetative growth stage to facilitate the uptake of nutrients and improve plant growth and flowering.

Growth, flowering and yield data was recorded at suitable growth stages, according to standard horticultural practice. Germination percentage was determined once the seeds have germinated and emerged completely, using the formula: $\text{Germination (\%)} = (\text{Number of germinated seeds} / \text{Total number of seeds sown}) \times 100$. The height of plants was determined from the soil surface to the top of the plants with a graduated measuring scale (cm). Total number of fully expanded leaves and primary side branches per plant were hand counted and stem diameter (cm) measured at the base of each plant using a digital Vernier caliper. Days to flowering initiation were measured as days

after transplanting from the first sign of the appearance of a flower bud. The number of flowers in full bloom on each plant was counted during the flowering period. Digital Vernier caliper was used to measure the diameter of flower (cm) and length of flower stalk (cm). The fresh flower weight (g) was measured after harvesting on a digital electronic balance and dry flower weight (g) was measured after oven-drying the flowers at 70°C until a constant weight was reached and weighing on an analytical balance. Mean values from representative plants of each experimental unit were used for statistical analyses later on.

Statistical Analysis: The recorded data were subjected to analysis of variance (ANOVA) using to determine the significance of treatment effects. The data was statistically analyzed using the Least Significant Difference (LSD) test at 5% probability level ($P \leq 0.05$). Pearson's correlation analysis was carried out to analyze the correlation between measured growth and flowering traits and linear regression analysis was conducted to determine which variables were positively correlated with growth and flowering performance of *Zinnia elegans*. The normality and homogeneity of variance were tested before statistical analysis, to guarantee the validity and reliability of the analysis's results.

Results

Effect of Foliar NPK Application on Flowering Characteristics of *Zinnia elegans*

All three *Zinnia elegans* flowering parameters were significantly ($P < 0.05$) enhanced by foliar fertilization in this study as compared to the untreated control (Figures 1 A-C). Balanced application of NPK fertilizer applied under foliar nutrition gradually improved flower size, fresh and dry biomass, suggesting reproductive growth response to balanced NPK fertilizer application.

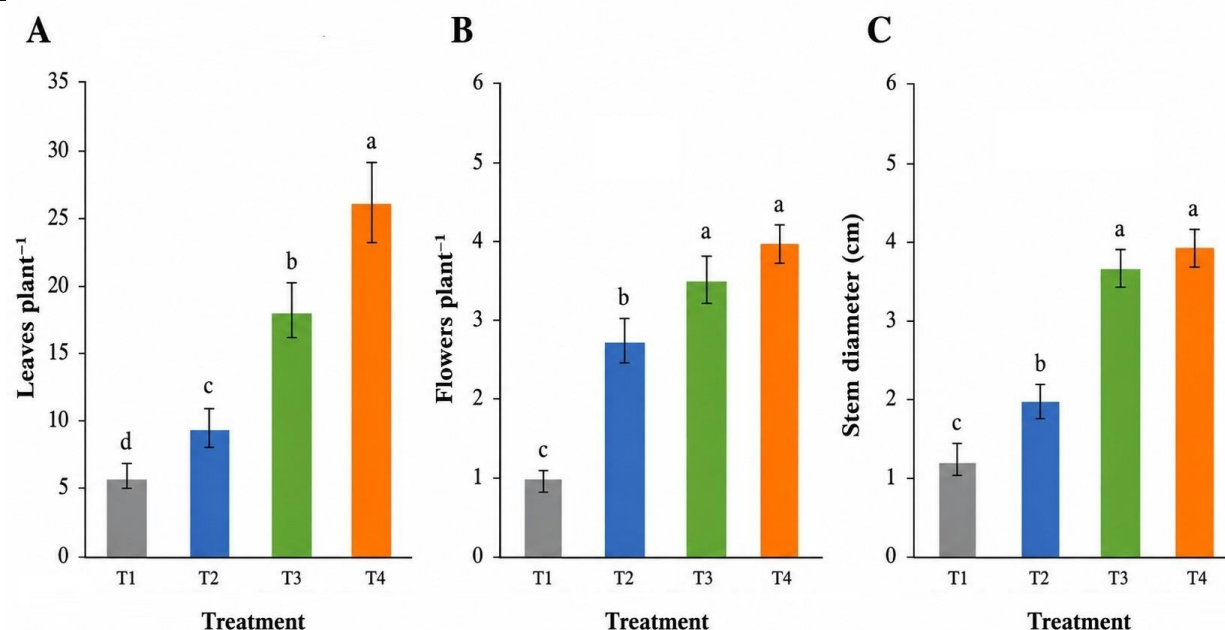


Figure 1. The effect of various levels of foliar fertilizer (NPK) on the number of leaves per plant (L plant⁻¹), number of flowers per plant (F plant⁻¹) and the stem diameter (SD, cm) of *Zinnia elegans*. Bars are mean $\pm$ standard error (SE). Significant differences among treatments are represented by different lowercase letters above the bars as determined by Tukey's Honestly Significant Difference (HSD) test at $P < 0.05$.

The flower diameter (FD) significantly increased with the increase of NPK concentration (Figure 2 A-B). The most concentrated of all the NPK treatments (T4; 18 g) resulted in the most flower size (19.35 ± 0.78 cm) that was significantly larger than the other treatments. Intermediate concentrations also enhanced flower diameter, where the T3 (12g) flower diameter was $10.70 \pm$

0.78 cm and in T2 (6g) was 8.83 ± 0.78 cm which were both significant but not different from each other as indicated by same significance letter (b). The control plants (T1) had the smallest flower diameter (1.86 ± 0.78 cm), showing the necessity of foliar nutrient supplement for flower development.

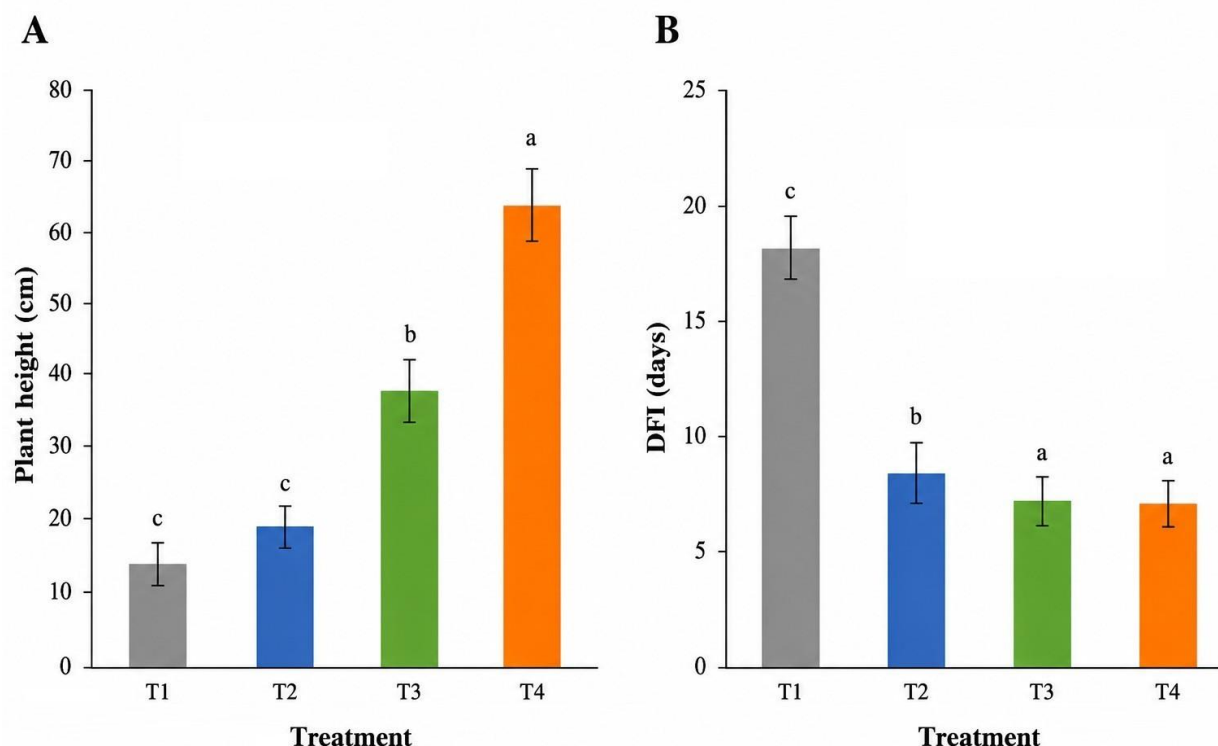


Figure 2. Effects of different concentrations of foliar-applied NPK fertilizer on (A) plant height (PH, cm) and (B) days to flowering initiation (DFI) of *Zinnia elegans*. Bars represent mean $\pm$ standard error (SE). Different lowercase letters above the bars indicate statistically significant differences among treatments according to Tukey's HSD test ($P < 0.05$).

Similar trends were found for the fresh weight of the flowers (FW) (Figure 2B). The concentration of fertilizer applied to the soil was seen to correspond with an increase in fresh biomass from 2.26 ± 0.15 g in the control to 6.12 ± 0.15 g applied at T4. The weight of fresh flowers was found to be significantly different among the various treatments and the weight of fresh flowers increased with an increase in NPK application (T4

> T3 > T2 > T1). More specifically, flower fresh weight of the T4 treatment was about 171% greater than that of the untreated control, suggesting better water accumulation, growth, and partitioning of assimilates into developing flowers. Application of foliar NPK also had a positive effect on flower dry weight (DW), an important indicator of biomass accumulation and structural development, (Figure 3C).

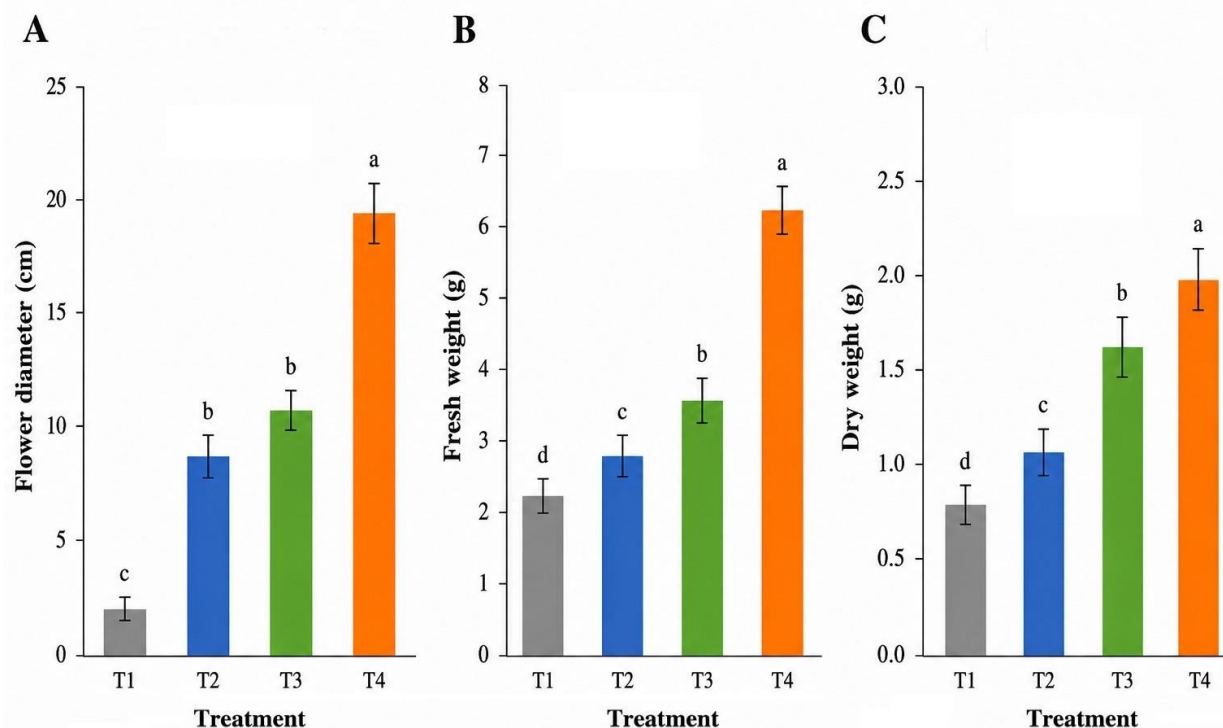


Figure 3. Effects of different concentrations of foliar-applied NPK fertilizer on (A) flower diameter (FD, cm), (B) flower fresh weight (FW, g), and (C) flower dry weight (DW, g) of *Zinnia elegans*. Bars represent mean $\pm$ standard error (SE). Different lowercase letters above the bars indicate significant differences among treatments based on Tukey's HSD multiple comparison test at $P < 0.05$.

The dry weight of the control plants was 0.79 ± 0.06 g while that of 18 g NPK was 1.98 ± 0.06 g. All treatments were significantly different from each other ($T4 > T3 > T2 > T1$) showing a regular increase in the production of dry matter as fertilizer concentration increases. T4 showed a higher rate of flower dry weight (about 152% higher) than the control, indicating higher photosynthetic efficiency and higher levels of structural carbohydrates accumulation.

In summary, the results showed that foliar application of NPK fertilization significantly affected the floral morphology and biomass production of *Zinnia elegans*. Of all the treatments, the flower diameter, fresh and dry weight of the plants treated with 18 g NPK (T4)

were always the greatest while the untreated plants resulted in the poorest flowering performance. The gradual increase in progressiveness across the treatments suggests that there was an appreciable positive dose-dependent response when it came to the floral growth in response to the balanced foliar nutrient supply.

Effect of Foliar NPK Application on Flowering Stem Length and Secondary Branch Formation

The flowering stem length (FSL) and the number of secondary branches (NSB) in *Zinnia elegans* were significantly affected by foliar application of NPK fertilizer ($P < 0.05$) and both parameters increased with the increasing level of NPK fertilizer (Figure 4 A).

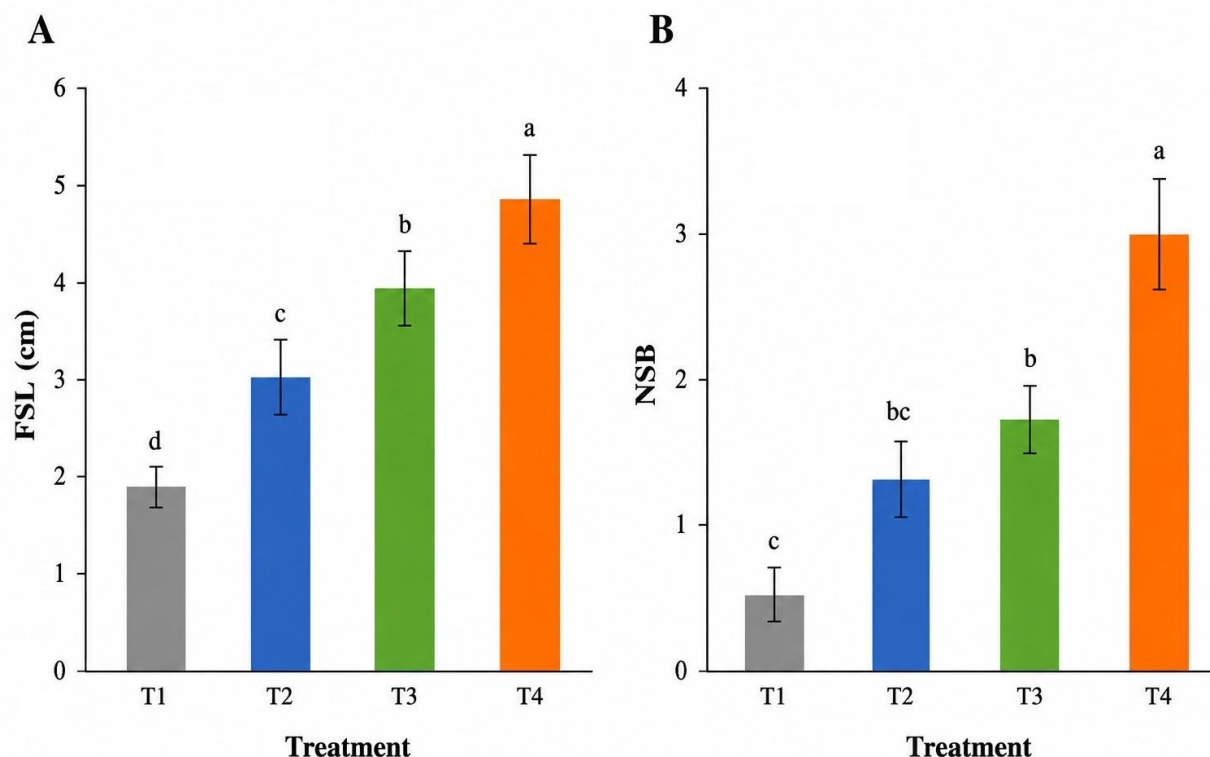


Figure 4. The effects of various levels of the foliar fertilizer NPK application on (A) flowering stem length (FSL, cm) and (B) number of secondary branches (NSB) of *Zinnia elegans*. Means $\pm$ SE are given. Letters on top of the bars represent statistically significant differences between treatments at $P < 0.05$ as determined by Tukey's HSD test.

The length of the flowering stem also increased significantly with the highest NPK concentration (T4) compared to the untreated ones (T1) (Figure 4A-B). The treatments were clearly separated statistically ($T4 > T3 > T2 > T1$), which suggested that stem elongation was increased in a dose-dependent manner. In addition, 12 g NPK also resulted in significantly longer flowering stems (3.92 ± 0.23 cm) compared to 6 g NPK (3.01 ± 0.23 cm). T4 also flowered stem length by about 155% compared with control showing the significant stimulatory effect of foliar application of NPK on vegetative structural growth and flower.

The same increasing pattern occurred with the number of secondary branches (Figure A-B). The number of secondary branches was 0.50 ± 0.31 in control plants but 3.00 ± 0.31 in T4. Intermediate treatments generated 1.25 ± 0.31 and 1.75 ± 0.31 branches found for T2 and T3, respectively. The

analysis of data revealed that T4 was significantly better than all other treatments and T3 was also significantly better than the control in terms of the number of branches produced. T2 was in the middle and was not statistically differentiated from either T1 or T3, and shared the same statistical grouping. The NPK rate of 2,400 ppm resulted in an almost six-fold greater amount of secondary branches when compared to the untreated plants. In general, foliar application of NPK showed important effect on the flowering architecture in terms of stem elongation and branching. Balanced foliar nutrient application resulted in a greater potential for flower production and better ornamental quality of *Zinnia elegans* as plants receiving 18 g NPK performed better than the other varieties. Based on the results, it may be concluded that higher level of NPK application results in better flowering stem development,

particularly under the highest NPK fertilizer application.

Correlation among the fertilizer application and growth parameters

The vegetative growth, flowering and yield related traits were significantly positively correlated with all others (Figure 5) suggesting high dependency among vegetative growth parameters. Days to first

inflorescence (DFI) showed strong positive correlations with dry weight (DW), flowers per day (FD), flower stalk length (FSL), fresh weight (FW), number of leaves per plant (NLP) and plant height (PH) whereas relatively weaker but still positive correlations were observed with number of fruits per plant (NFP), number of secondary branches (NSB) and stem diameter (SD).

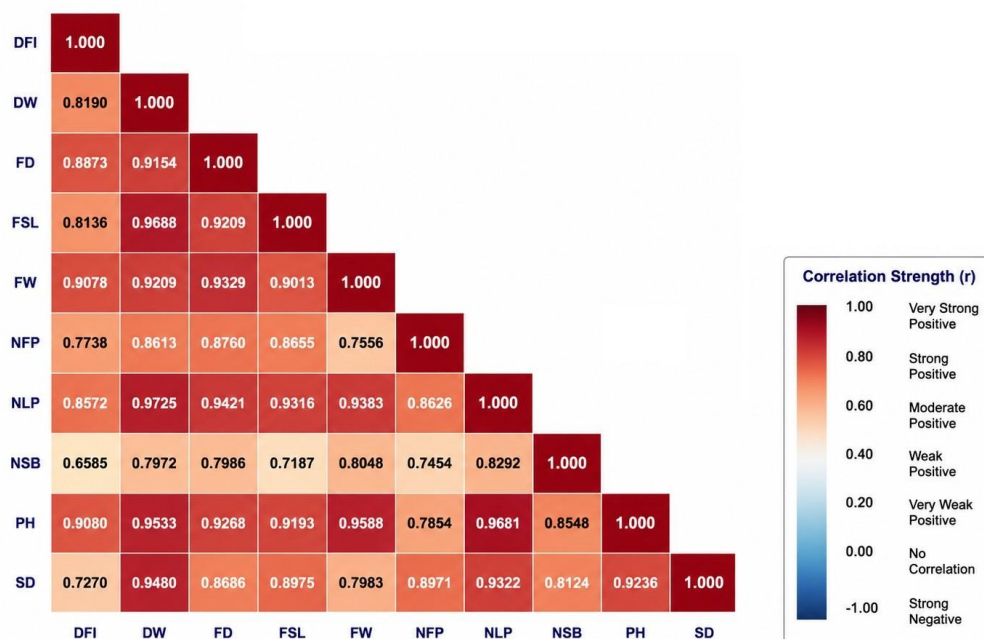


Figure 5. Relationships among vegetative growth, flowering, biomass, and yield-related traits of *Zinnia elegans* were determined by a Pearson correlation matrix. The general trend of the correlation pattern is the positive relationship between vegetative growth, biomass gain, flowering traits and yield-related traits, suggesting a coordinated development of vegetative and reproductive growth traits. Abbreviations: SD = stem diameter, PH = plant height, DFI = days to flowering initiation, FD = flower diameter, FW = flower fresh weight, DW = flower dry weight, FSL = flowering stem length, NSB = number of secondary branches, SD = standard error, HSD = honestly significant difference.

Dry weight had very high positive correlations with flower stalk length ($r = 0.969$), number of leaves per plant ($r = 0.973$), plant height ($r = 0.953$), stem diameter ($r = 0.948$), flowers per day ($r = 0.915$) and fresh weight ($r = 0.921$) indicating that biomass accumulation was tightly linked to increased vegetative growth and reproductive performance. In the same way, fresh weight was highly correlated with number of flowers per day ($r = 0.933$), number of leaves per plant ($r = 0.938$),

plant height ($r = 0.959$), and flower stalk length ($r = 0.901$), meaning that plants that produced more biomass also showed better morphology.

The close association between canopy development and plant vigor was best illustrated by the strong relationships found between plant height and leaf, fresh weight, dry weight, flower per day, flower stalk length and stem diameter ($r = 0.968, 0.959, 0.953, 0.927, 0.919$, and 0.924 , respectively). Similarly, the dry weight ($r = 0.948$),

number of leaves per plant ($r = 0.932$), plant height ($r = 0.924$), flowers per day ($r = 0.869$), flower stalk length ($r = 0.898$), and number of fruits per plant ($r = 0.897$) had positive correlation with stem diameter.

The fruits per plant showed positive correlation with all the measured traits, especially flowers per day ($r = 0.876$), length of flower stalk ($r = 0.866$), number of leaves per plant ($r = 0.863$) and stem diameter ($r = 0.897$); it is inferred that increased vegetative growth played a significant role in increased fruit production. Generally, all the positive correlations were fairly consistent showing that the vegetative characteristics improved proportionately with the reproductive growth and yield related characteristics.

4. Discussion

The present study presented a definite and concentration-dependent reaction of *Zinnia elegans* to foliar NPK nutrition and the following progressive improvement in flower diameter, fresh flower weight, dry flower weight, flowering stem length and secondary branching with increasing concentration of NPK. The plants supplied with 18 g NPK (T4) always performed better than others, showing that foliar balanced nutrition promoted better vegetative capacity along with reproductive development under agro-climatic conditions of Lasbela, Pakistan. This is in line with recent reports that foliar nutrient application can quickly meet the physiological needs of plants during times of high nutrient demand, and enhance growth, flowering, flower quality, and biomass production of ornamental plants (Jeeva et al., 2025). Importantly, a recent 2-year study that compared *Z. elegans* exposed to foliar Nano-NPK application with untreated plants showed a significant increase in the numbers of leaves and branches, stem diameter, flower-head size and flower fresh weight, indicating the nutrient-mediated response observed in the present experiment.

Flower size is a critical factor for both ornamental and market acceptance, especially from a diameter perspective. In the present study, flower diameter

increased as the foliar concentration of NPK increased and flower diameter was the greatest at the highest level of NPK (T4). Better development of flower can be correlated with increased nutrient availability and growth of cells under adequate nutrient supply. The nitrogen is used in the production of chlorophyll and photosynthetic activity, phosphorus is part of energy transfer and metabolic control and potassium helps to regulate enzyme activity, osmosis and assimilate transport. These nutrients are therefore available in a coordinated manner to reinforce the source-sink relationship during the reproductive development. In recent studies on *Z. elegans*, foliar Nano-NPK application led to an increase in the size of flower heads along with the accumulation of chlorophyll and carbohydrates, which indicates the better nutritional status was correlated with better photosynthetic and carbon-assimilation capacity (Badawy et al., 2025).

The weight of fresh flowers was also increased, which indicated a further improvement in the development of the reproductive tissues. The observed response was likely due to the interplay and interaction of the three factors: increased assimilate production, nutrient assimilation, and water relations of the cells. Potassium is essential for osmotic regulation and maintenance of cell turgor, and nitrogen for protein synthesis, growth of leaves and formation of photo synthetically active tissues. Phosphorus helps in ATP-dependent processes involved in metabolic activities and assimilative utilization. Other recent research with ornamental crops has shown that foliar nutrient supplementation can have an effect on flower biomass and quality. For instance, foliar application of potassium nitrate and soluble fertilizers enhanced the vegetative and flower quality traits in hybrid tea rose and foliar micronutrient application enhanced stalk length, flower production and vase life in gerbera (Atal et al., 2023; Mounika & Fatmi, 2023).

The gain in dry flower weight is useful to consider since it suggests that the weight gain was not due to increased hydration of tissues alone, but was also related to increased structural biomass accumulation. Dry matter accumulation occurs

when the total amount of carbon and mineral nutrients derived by photosynthesis remains in plant tissues. So the higher DW under T4 indicates that adequate foliar NPK supply was responsible for better carbon assimilation and the allocation of the same towards photoassimilate sinks, floral structures. This interpretation is supported by the recent results obtained by foliar application of Nano-NPK in *Z. elegans* which showed that both growth and flowering traits improved in parallel with the increase of both carotenoid and chlorophyll contents and both carotenoid and carbohydrate contents (Badawy et al., 2025). In gladiolus, foliar fertilization also led to growth and flowering improvements in all cultivars (Kentelky & Szekely-Varga, 2021).

The flowering stem length also increased in response to increasing the concentration of NPK. This is one of the horticulturally significant characteristics as longer and sturdier stems add to the overall appearance of the flower and are especially desirable in cut-flower production. Stem elongation is a result of cell division and expansion, which requires sufficient supply of carbohydrates and mineral nutrition. Nitrogen encourages vegetative growth, phosphorus is involved in energy metabolism, and potassium is involved in water relations and transport of assimilates of the cells. This increase in stem length in the present study could be due to better nutritional condition to provide for sustained growth throughout vegetative and reproductive stages. This interpretation is supported by recent research in ornamental crops: The effects of foliar nutrient treatments were shown to improve the structural characteristics and floral performance in gerbera and tuberose, highlighting the significance of foliar nutrient supply on structural development and floral quality (Mounika & Fatmi, 2023; Mudassir et al., 2021).

The same concentration dependent response was observed for secondary branching, with the highest numbers of branches occurring in T4. Ornamental plant architecture is important due to branch development, as this will affect the number of potential sites for leaf and flower production. Nitrogen availability may lead to increased

vegetative growth and axillary bud development, whereas phosphorus and potassium may promote energy metabolism and tissue formation, and transport of assimilates. The increased branching, therefore, could have been responsible for the increased reproductive potential of the individual plants as flower initiation sites were added. This interpretation is well supported by the recently published study of Badawy et al., (2025) in which foliar Nano-NPK treatments were found to stimulate branch formation in addition to increment in plant height, stem thickness, leaf growth and flowering in *Z. elegans*.

The present findings also highlight the need for balanced (not single nutrient) nutrition. The positive response of flower size, flower biomass, stem growth and branching to fertilization indicates that reproductive function required the co-ordinated action of N, P, and K and not the action of any one nutrient. More recent studies on ornamental crops show that integrated nutrient management can yield greater responses than individual nutrient applications. In the case of marigold, foliar application of micronutrients and biostimulants significantly enhanced physiological and biochemical properties whereas integrated management of both Zn and Fe significantly boosted plant growth, flower quality and flower yield (Jena et al., 2022; Devdhara & Polara, 2024). The results support the idea that nutrient balance can affect plant architecture, plant physiology and reproductive fitness.

The efficacy of foliar treatment is also dependent on the method and time of nutrient delivery. Foliar fertilization may be used to supply nutrients directly to the above-ground parts of the plants and may help alleviate some nutrient limitations associated with soil conditions. The recent synthesis of foliar fertilization research in flower crops have shown that foliar nutrients can be utilized for providing relatively rapid nutrition support and enhancing growth, quality of flowers and productivity, but the efficiency of foliar fertilization depends on nutrient formulation, concentration, application timing, plant developmental stage and environmental factors (Jeevaa et al., 2025). The high nutrient demand

during active vegetative and reproductive growth may be a reason for the strong reaction seen in the present study, as this may indicate that the nutrients available in the leaves are in synergy with the high nutrient demand.

Progressively higher rates of NPK should not be assumed to always lead to a higher response in terms of flowering as seen here. Concentrations have a strong effect on the foliar nutrient effectiveness as the nutrient levels become too high, salt injury or imbalance can result. The optimization of nutrient concentration, application frequency, formulation and environmental conditions are highlighted in recent literature, aiming to maximize the uptake of nutrients from the foliage with minimal phytotoxicity (Jeeva et al., 2025). Thus, the better performance of T4 indicates an optimum, not universal optimum, in the concentration range studied in the present experiment, but rather an optimum within the range of this experiment.

Further evidence of this is provided by the correlation analysis showing that vegetative growth and reproductive performance were closely coupled. The highly significant correlation between dry weight and leaf number ($r = 0.973$), dry weight and flower stalk length ($r = 0.969$), and plant height and leaf number ($r = 0.968$) suggest close relationships between increased canopy development and biomass accumulation and better reproductive performance. The enhanced light interception and photosynthetic carbon fixation in a well-developed canopy can boost assimilate availability for stem growth and reproductive sinks. Relationships between vegetative vigor, nutrient status, and flowering performance have been documented in ornamentals which confirm the conclusions above that high flower productivity is related to high canopy development, which in turn, is related to the vigor or nutrient status.

Other strong and positive correlations were found to be between fresh weight and plant height, flowers per day, flower stalk length and leaf number. The plant reproductive capacity was found to be associated with vegetative biomass and tissue development as suggested by these

relationships. Importantly, there is a correlation between stem diameter and fruit number, a further suggestion that structural development may relate to reproductive productivity. These relationships should be viewed with some caution, however, as correlation does not necessarily indicate causation. The observed correlations are thus valid evidence for co-ordinated plant development, but are not sufficient on their own to prove that one of the traits was a direct cause of the other trait increasing.

The positive correlation of fruit number with flowers per day ($r = 0.876$), flower stalk length ($r = 0.866$), leaf number ($r = 0.863$) and stem diameter ($r = 0.897$) also illustrates the interrelatedness of vegetative and reproductive growth. Mature leaves provide more photosynthetic source capacity and more branching and stem development provide more structural support for reproductive organs. This suggests that a positive developmental cascade may have occurred; with improved vegetative growth, greater vegetative production and move, leading to greater reproductive production. The positive correlations among the measured traits are better explained when the traits are considered as a whole, as in source-sink coordination, than when considered separately.

The relatively low correlation with secondary branching does not mean that it is not as significant. Instead, branching can affect reproductive performance indirectly by affecting canopy structure and the number of potential locations for flower production. Therefore, branching appears to be closely coupled with leaf production, light interception, assimilate availability and floral initiation than it is just a single factor affecting productivity.

Overall, the fertilizer-response and correlation analysis revealed that the foliar NPK nutrition improved the performance of *Z. elegans* by improving plant vigor, biomass accumulation, canopy development and reproductive growth in a coordinated manner. The uniformity of the responses of all flower parameters – diameter, fresh and dry flower mass, flowering stem length, and branching – indicates that balanced foliar nutrition may be able to affect several aspects of

ornamental quality at the same time. These results are especially significant given the recent results in the ornamental crop *Z. elegans* of positive response to foliar application of macro- and micronutrients (Badawy et al., 2025; Jeevaa et al., 2025; Aral et al., 2023; Kentelky & Szekely-Varga, 2021).

In practical terms the performance of T4 clearly shows its superiority over other concentrations and it is considered as the best treatment under the conditions of Lasbela, Pakistan. Before general recommendations are given, however, the best concentration needs to be tested over different cultivars, seasons, intervals and environments. Further research could also incorporate the foliar nutrient uptake, leaf nutrient concentration, chlorophyll fluorescence, photosynthetic rate, nutrient-use efficiency and postharvest flower quality to understand the physiological mechanism for the observed response. This approach would go beyond evaluation of morphological traits and would give better evidence to create precision foliar nutrition strategies for sustainable ornamental production.

5. Conclusion

The results of the present study showed that foliar balanced NPK fertilizer application significantly enhanced the plant growth and flowering of *Zinnia elegans* in the agro-climatic conditions of Lasbela, Pakistan and enhanced the ornamental quality of this plant. The effects of the different NPK concentrations on all the measured flowering and growth parameters were positive, which clearly demonstrated the importance of balanced mineral nutrition on the improvement of reproductive development. The number of leaves and flowers per plant, stem diameter, plant height, flowering stem length, flower diameter, flower fresh weight, flower dry weight and the number of secondary branches were significantly higher in the foliar NPK than in the untreated plants. The improvements suggest that foliar application of nutrients has resulted in an increase in photosynthetic efficiency, vegetative vigor, effective partitioning of assimilates and better use of nutrients.

18 g NPK (T4) foliar application gave the highest value for all the parameters tested and proved to be the most effective with respect to plant growth and floral performance. The enhanced improvement is believed to result from the complimentary physiological role of N, P and K in regulation of synthesis of chlorophyll, energy metabolism, enzyme activation, carbohydrate translocation, cell expansion and water relations. The steady increase in response with treatments also shows that balanced nutrient supply to the foliage is an effective means of promoting vegetative growth as well as reproductive development which leads to better quality flowers and higher ornamental value.

The results also point out the practical benefits of foliar fertilization as an efficient nutrient management tool in producing ornamentals. Foliar treatment provides nutrient delivery directly to metabolically active tissues, reducing nutrient losses due to fixation, leaching, and volatilization of nutrients from the soil and increasing the efficiency of nutrient use. This is especially beneficial in semi-arid environments where soil fertility limitations and water resource limitations can limit the impact of traditional soil fertilization. So overall, the findings indicated that foliar application of 18 g NPK is the most promising approach for optimum growth and flowering of *Zinnia elegans* under the environmental condition of Lasbela, Pakistan. The use of this nutrient management strategy can contribute to sustainable production of flowers and could lead to better flower quality and greater commercial productivity and efficient use of fertilizer.

Some of the future research needs are to determine the long-term impact of foliar NPK fertilization under various agro-climatic conditions, the interaction between NPK and micronutrient and plant growth regulators and the economics and environmental impact of foliar NPK fertilization in commercial production systems. These investigations will help develop integrated nutrient management strategies for sustainable ornamental horticulture and increased flower production.

Author Contributions: Nimra contributed to field sampling, data collection, and laboratory analyses; Shahmir Ali Kalhoro performed statistical analysis, organized the data, prepared the figures, and contributed to manuscript preparation; Muhammad Abuzar Jaffar, conceptualized and supervised the study and contributed to manuscript revision; Aadil Hameed coordinated the research activities, contributed to laboratory experimentation and data collection, Afsa Bibi contributed to the literature review and manuscript editing; Tasneem contributed to data collection and manuscript preparation; and Muhammad Ikram contributed to data interpretation, literature review, and critical revision of the manuscript. All authors reviewed and approved the final version of the manuscript.

Data and material availability

This article contains all the soil and plant analysis data generated during the course of this research study. The analysis and the resulting data presented herein may be obtained at the reasonable request of the corresponding author.

Conflicts of interest

Authors declare no potential conflicts of interests

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