

OPTIMIZING BORON APPLICATION FOR IMPROVED GROWTH,
FLOWERING, AND FLORAL QUALITY OF ORNAMENTAL SUNFLOWER
(*HELIANTHUS ANNUUS* L.)

Tasneem¹, Ghulam Khaliq², Muhammad Abuzar Jaffar³, Shahmir Ali Kalhoro⁴,
Aadil Hameed⁵, Nimra⁶, Afsa Bibi⁷

^{1, *2, 3, 5, 6, 7}Department of Horticulture, Faculty of Agriculture, Lasbela University of Agriculture, Water and Marine Science, Pakistan

⁴Department of Soil Science, Faculty of Agriculture, Lasbela University of Agriculture, Water and Marine Science, Pakistan

²ghulam-khan@live.com

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Corresponding Author: *

Ghulam Khaliq

Abstract

Boron is an important micronutrient involved in cell-wall development, reproductive growth, and flowering, but its application rate can strongly influence ornamental crop performance. The present study evaluated the effects of boron application on the germination, vegetative growth, flowering, and floral characteristics of ornamental sunflower (Red) under greenhouse conditions at Lasbela University of Agriculture, Water and Marine Sciences, Uthal, Balochistan, during the 2025 growing season. The experiment was arranged in a completely randomized design with three replications and four treatments: T0 (control), T1 (6 mL boron), T2 (12 mL boron), and T3 (18 mL boron). Data were recorded for germination percentage, leaves per plant, plant height, stem diameter, flowers per plant, days to flower initiation, flower diameter, fresh and dry flower weight, flower stalk length, and number of side branches. Boron application markedly improved most measured traits, with T2 generally producing the strongest overall response. Germination increased from 6.10% in the control to 12.17% under T2. T2 also produced the highest number of leaves (28.00 plant⁻¹), greatest plant height (131.30 cm), stem diameter (3.30 cm), flowers per plant (3.13), flower diameter (17.43 cm), fresh flower weight (152.87 g), and dry flower weight (65.13 g). T3 produced the longest flower stalks (48.37 cm), but also substantially delayed flower initiation (65.67 days). Overall, the results indicate that a moderate boron application of 12 mL was most effective for improving vegetative growth, flower development, and floral biomass of ornamental sunflower under the tested greenhouse conditions, whereas higher application did not consistently provide additional benefits.

1. INTRODUCTION

Terrestrial ecosystems and landscapes dominated by humans are being studied, and are increasingly experiencing threats from thermal stress due to

climate change and the growing frequency and intensity of extreme heat events. As the air and land-surface temperatures increase, the change can affect ecosystem productivity, can speed up soil

moisture depletion, can raise evaporative demand, and can decrease the ability of vegetation to sustain physiological function when stressed. The challenges have made people more interested in the vegetation establishment, ecological restoration and landscape greening as solutions that have multiple environmental benefits. The restoration of vegetation can help to regulate the local climate, as well as enhance the ecosystem function, biodiversity, soil condition, hydrological regulation, carbon storage, and ecological resilience (Ruijsch et al., 2024; Wu, 2025). However, it is not assumed that restoration will create uniform climatic benefits since performance is influenced by vegetation features, climate, water availability, landscape structure and stability of existing vegetation.

Vegetation is important factor in the land surface-atmosphere energy exchange. Incoming solar radiation is absorbed by a developing vegetation canopy, which decreases the amount of radiation reaching the soil and other bare surfaces. The vegetation also affects the surface roughness and aerodynamic conditions, which may affect turbulent heat exchange between the land surface and the atmosphere. Also, plants transpire and soil and other damp surfaces will evaporate water. These processes collectively account for evapotranspiration and provide a significant fraction of available energy to be used for latent heat as opposed to sensible heat. This means that the increase in vegetation will lead to lower energy available for surface heating and help to decrease land-surface temperatures (Li et al., 2022; Yu et al., 2024). But shading and evapotranspiration cannot be fixed and are influenced by canopy structure, climatic conditions, soil-water availability and atmospheric demand (Deng et al., 2024; Yu et al., 2024; Ma et al., 2025).

Therefore, the amount of vegetation is not the only factor affecting the thermal effect of vegetation; the structural and functional properties of vegetation also have an impact. The ability of vegetation to intercept radiation and alter near surface microclimatic conditions can be influenced by canopy height, leaf area index, crown density, vegetation cover, species

composition and spatial arrangement (Ma et al., 2025; Yang et al., 2025). It is possible that structurally more complex and dense vegetation has greater shading effects and surface roughness, while sparse vegetation has less effect on the surface energy balance. Likewise, species-specific attributes such as leaf morphology, rooting depth, stomatal control, and hydraulics can influence transpiration and consequently their ability to cool in various environments. This means that in addition to vegetation cover, vegetation structure and functional characteristics should be taken into account to determine the thermal performance of restored vegetation.

Availability of water is also an important factor controlling vegetation-mediated cooling. There should be a supply of water from the soil or from other water sources available for transpirational cooling. Plants may also decrease stomatal conductance and transpiration under water limited conditions thereby limiting their contribution to cooling. The combined effect of high vapour-pressure deficit in the atmosphere and water stress in plants further increases the demand for water from plants. Vegetation types with deeply or widely distributed roots can be capable of tapping deeper groundwater and sustaining transpiration when the air is very hot and dry. Some trees have shown evidence of being able to transpire large amounts during extreme heat due to their ability to tap into deeper water sources while other vegetation may see significant decreases in transpiration during water-limited conditions (Fang et al., 2025; Yu et al., 2026). Therefore, restoration planning should take into account not only the establishment of vegetation, but also the long-term availability of water for maintenance of vegetation mediated climate regulation.

The spatial arrangement is also significant as the cooling effect can be more than just a single plant or restoration area. The movement of heat and moisture over the landscape can be affected by the connectivity, size, continuity and distribution of vegetated and non-vegetated surfaces. Urban or peri-urban areas, for instance, may experience modifications in the cooling effect provided by

vegetation due to the presence of surrounding impervious surfaces, background land-surface temperature, connectivity of vegetation, and canopy structure (Deng et al., 2024; Yang et al., 2025). Restored rural and degraded landscape can have similar spatial controls that influence how vegetation interacts with exposed soil, water bodies, agricultural areas and surrounding natural ecosystems. Outcomes of restoration projects, therefore, should be evaluated at a landscape level, rather than at the single plant or restoration site. Thermal conditions may also be affected indirectly by vegetation restoration as it affects soil and hydrology. More vegetation cover, more biomass can lead to better soil structure and more water holding and infiltration capacity in the soils and more moisture storage capacity. These changes can aid evapotranspiration and maintain vegetation during dry spells and establish feedbacks among vegetation establishment, soil-water availability, and surface temperature. On the other hand, the loss and degradation of vegetation can lower biomass, weaken soil structure, lower soil-water retention and raise the fraction of incoming energy which is converted to sensible heat. Some of these processes can be reversed through restoration by enhancing the vegetation cover and biomass and thus the soil-water dynamics (Yu et al., 2022; Liu et al., 2024). This is a way of illustrating that the thermal effects of restoration cannot be completely divorced from soil and hydrological function.

At larger spatial scales, restoration has been linked to alterations in land-surface temperature and ecosystem water fluxes, though this response is also very variable. For dryland systems, higher vegetation cover and leaf area can contribute to evapotranspiration, affect energy partitioning and the water demand of the system (Li et al., 2023). However, the more dense the vegetation, the more the water that is available will be limited, and this does not necessarily mean that the cooling will increase continuously. Restoration-induced vegetation structure and land-surface characteristics changes are linked to measurable changes in land-surface temperature at continental scale, but the magnitude and direction of these

changes vary across climatic and ecological regions (Ruijsch et al., 2024). The results highlight the significance of considering the restoration under the local climatic and hydrological conditions.

Importantly, the environmental benefits of restoration go beyond temperature regulation. Re-established vegetation may help to maintain carbon storage, provide habitat, conserve biodiversity, stabilize soils, regulate water, and contribute to the overall health of an ecosystem. These benefits, however, do not always go together and efforts to increase one ecosystem service can result in trade-offs between other services. The effects are variable, such as the additional shading and carbon storage benefits of increased vegetation density, which could also lead to increased water demand under water-limiting conditions. Likewise, the chances of a successful restoration can be reduced if the vegetation is not able to survive due to drought, inappropriate climatic conditions, poor soil quality or failure to manage the area over time appropriately. So its effectiveness should be measured in terms of short-term environmental responses and restored ecosystems' ability to sustain their function in the future climate.

Although more people are acknowledging vegetation as a nature-based solution for regulating the local climate, there are still significant gaps in the knowledge of how vegetation establishes, how it influences ecosystem processes and how it influences the thermal outcomes. Specifically, the relative influence of shading, evapotranspiration, soil-water dynamics, and vegetation structure and landscape configuration can be highly variable among ecosystems and climates. Greater understanding is needed to differentiate restoration approaches that do not provide long-term and/or integrated environmental benefits from those that do.

Thus, this study/review aims to focus on how vegetation restoration influences the surface thermal conditions and other ecosystem processes, while emphasizing the interactions between the vegetation structure, evapotranspiration, soil-water availability, surface energy balance, and landscape configuration. These processes serve to illustrate

the need to tailor restoration methods to local climate and ecological conditions and not assume that more vegetation equals more cooling. This holistic approach is needed to provide for the concurrent needs of thermal regulation, water conservation, carbon sequestration, biodiversity and long-term climate change resilience in restoration plans.

Material and Methods

3.1 Study Site and Experimental Procedure

The present study was carried out at Lasbela University of Agriculture, Water and Marine Sciences (LUAWMS), Uthal, Balochistan, Pakistan in the greenhouse of the Department of Horticulture, Lasbela University of Agriculture, Water and Marine Sciences (LUAWMS), Uthal, Balochistan, Pakistan in the growing season of 2025. The seeds of ornamental sunflower were bought from Sunny view store, Lahore. Nursery seedlings were grown in plastic trays with 128 cells. The growing medium used on the trays was peat moss and the seeds were planted in the greenhouse. All seedlings were kept under identical irrigation and nursery practices. Once they had reached an appropriate size and had good seedling growth they were gently transplanted into the same size pots. The experiment was designed in Completely Randomized Design (CRD) with three replications. Boron was chosen as the micronutrient treatment because it is crucial for plant growth, cell-wall formation and

reproduction (pollen germination and pollen-tube growth). Sunflower also shows a relatively high sensitivity to boron nutrition, which is greatly influenced by the level and availability of boron (Asad et al., 2002; Khalid et al., 2020). It was previously shown that the application of boron affected the growth and reproductive traits of sunflower plants, and that high levels of boron can cause phytotoxic effects (Khalid et al., 2020). Thus, various applications were tested in the present greenhouse trial.

3.2 Treatments and Boron Application

The effect of boron application on the growth and flowering performance of ornamental sunflower was evaluated by using four treatments. The levels of boron treatments included an untreated control and three boron application amounts: T0 (control), T1 (6 mL of boron), T2 (12 mL of boron), and T3 (18 mL of boron). All treatments were applied to the plants and all other cultural and environmental conditions were kept as uniform as possible between the treatments to reduce any variation due to conditions other than the boron treatments. Different levels of boron were applied to determine the sunflower plant's reaction under increasing levels of boron supply because under- and over-supply of boron can impact the plant performance (Shorrocks, 1997; Camacho-Cristóbal et al., 2008; Khalid et al., 2020).

Table 1. Experimental treatments and boron application levels

Treatment	Boron application level	Description
T0	0 mL	Control (No boron)
T1	6 mL	Boron application
T2	12 mL	Boron application
T3	18 mL	Boron application

Note: Boron Treatments

3.3 Parameters Recorded

The effects of the boron application on the growth, physiological and flowering performance of the ornamental sunflower, germination, vegetative growth and flowering characteristics were recorded at appropriate growth stages. The

selected parameters were germination percentage, number of leaves per plant, plant height, stem diameter, number of flowers per plant, days to flower initiation, flower diameter, fresh flower weight, dry flower weight, flower stalk length and number of side branches. The selected

measurements were made because vegetative growth and reproductive development can be influenced by the micronutrients available, specifically when the availability of B affects reproductive development and tissue growth (Asad et al., 2002; Camacho-Cristóbal et al., 2008). The percentage (%) germination was calculated based on the number of seeds that have germinated on the number of seeds sown by the following formula.

Germination (%) = (Germinated seeds / No. of seeds sown) × 100

All the fully expanded leaves of each plant selected were counted to determine the number of leaves/plant. The height of plants (cm) was measured from the base of the plant at soil level up to the top growing point using a measuring scale or tape and the average height was recorded. Stem diameter (cm) was determined at a constant point on the main stem with a digital Vernier caliper for accurate and consistent measurements. To assess flowering traits, all fully mature flowers were counted by hand from each of the plants selected. Days to flower initiation was observed by frequent visits to the plants from transplanting and days when the first visible flower bud was recorded. The diameter of flowers (cm) was determined by measuring across the widest part of the open flower through its center with a ruler or Vernier caliper from 1 edge to the opposite edge. The fresh weight of the flowers (g) was measured after harvesting fully-grown flowers and weighing them on a digital scale. Fully developed flowers were harvested, dried to constant weight and weighed for dry flower weight (g). The length of the flower stalk (cm) was measured from the bottom of the stalk to the stem, the measuring tool used is a ruler or measuring tape, the measurement of the flower stalk must be made straight on the stem. All lateral branches which were emerging from the main stem of each selected plant at the proper growth stage were counted by hand to determine the number of side branches. The mean observations of the selected plants in each experimental unit were used for further statistical analysis.

3.4 Statistical Analysis

The data obtained for all recorded agronomic and flowering traits were subjected to analysis of variance (ANOVA) using a Completely Randomized Design (CRD). Treatment means were compared using the Least Significant Difference (LSD) test at the 5% probability level ($P < 0.05$) to determine significant differences among treatments. Pearson's correlation analysis was also performed to evaluate the relationships among vegetative growth and flowering traits. Statistical analyses were conducted using standard statistical procedures.

4. Results

4.1 Agronomic and Phenotypic Responses

Boron application had a significant effect on agronomic and phenotypic characteristics of ornamental sunflower. Treatment effects for germination response, number of leaves, plant height, stem diameter and side branches were statistically significant; response was variable across treatments and traits. As a whole, the outcomes showed that B supplementation had a beneficial result on vegetative growth as compared to the untreated control (Figure 1).

There were significant differences in the number of leaves per plant among the treatments. Treatment T2 gave the maximum value of leaves/plant as 28.00 leaves/plant followed by T1 (22.57 leaves/plant), and T0 and T3 gave 21.40 and 21.37 leaves/plant, respectively. Treatment T2 performed significantly better than the other treatments, with T0, the T1 and the T3 treatments being grouped statistically together (Figure 1).

Boron application was also found to significantly influence plant height. The tallest plants were recorded under T2, with a mean height of 131.30 cm, followed by T3 (123.37 cm), T1 (115.97 cm), and the control T0 (92.10 cm). T2 and T3 were found to be statistically comparable while control plants produced significantly shorter plants (figure 1).

A significant effect was similarly observed for stem diameter. The heaviest stems were recorded in T2 (3.30 cm), followed by T3 (2.67 cm) and T1 (2.33 cm) and the lowest diameter in T0 (1.80 cm).

Application of Boron was found to be highly significant treatment effect ($F = 21.8$, $p < 0.01$) and hence it has improved the stem development in the experimental conditions (Figure 1).

Boron treatment had a significant effect on the number of side branches. The greatest number of branches were found in T2 with 2.63 branches plant⁻¹, followed by T3 with 2.57 and T1 with 2.37 branches plant⁻¹, while T0 had 1.30 branches plant⁻¹. The ANOVA indicated that a highly significant treatment effect ($F = 10.1$, $p < 0.01$) was observed. The three T groups (T1, T2, and T3)

were grouped statistically and the control group was significantly lower (Figure 1).

For the germination analysis, a significant treatment effect was also observed ($F = 30.4$, $p < 0.01$). The recorded means of the treatments were the highest for T2 (12.17), followed by T3 (9.83), T1 (9.17) and T0 (6.10). These values must be compared to the original raw data before reporting as % germination, though, as 12.17 cannot be a percentage. The statistical table does show a treatment effect but needs to be verified in terms of the correct unit/scale (Figure 1).

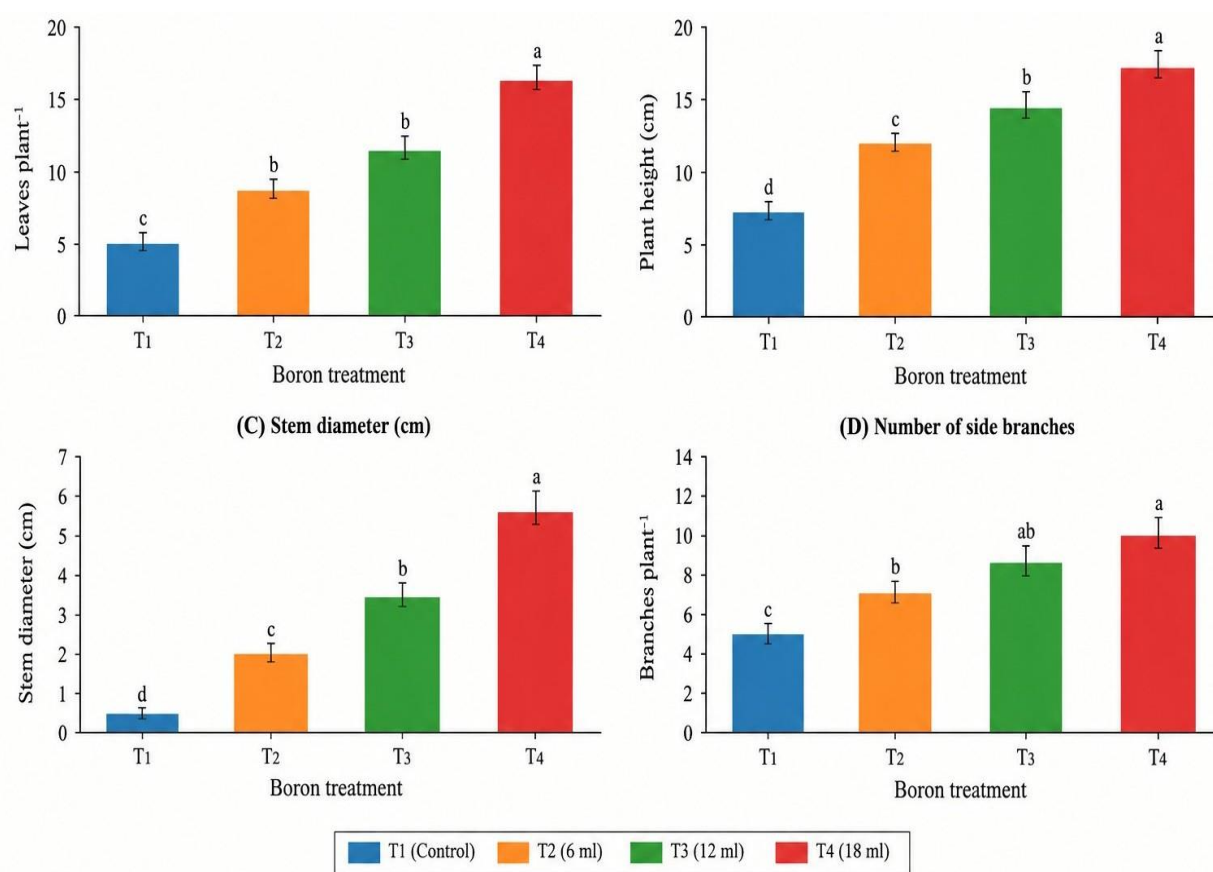


Figure 1. Agronomic and phenotypic responses of ornamental sunflower to boron application. Effects of boron treatments (T0 = control, T1 = 6 mL, T2 = 12 mL, and T3 = 18 mL) on germination, number of leaves per plant, plant height, stem diameter, and number of side branches. Bars represent treatment means, and different lowercase letters indicate significant differences

among treatments according to the LSD test at $P < 0.05$.

4.2 Flowering and Floral Characteristics

Ornamental sunflower flower and floral quality were greatly influenced by boron application. Days to flower initiation, number of flowers per plant, flower diameter, fresh flower weight, dry flower

weight and flower stalk length all had significant differences (Figure 2).

There was a significant effect of the treatments on days to flower initiation ($F = 21.9$, $p < 0.01$). T1 flowered first at 46.00 days, followed by T2 at 47.67 days and the control (T0) at 52.00 days. T3 took the longest period of time to flower (65.67 days) So the boron treatment was not strictly linear; in between the treatments T1 and T3, the intermediate treatment produced earlier flowering than the intermediate treatments (Figure 2). Treatment had a significant effect on the number of flowers per plant ($F = 12.2$, $p < 0.01$). The highest number of flowers (3.13 flowers plant⁻¹) was recorded for T2 while T1 (2.73) and T3 (2.53) recorded the next highest number of flowers and T0 (2.20) recorded the lowest number of flowers. T2 was significantly better than the other treatments and gave the best flower response (Figure 2).

The application of boron resulted in a very high significant response with regard to flower diameter ($F = 88.0$, $p < 0.01$). The largest flowers were recorded under T2 (17.43 cm), followed by T3 (13.40 cm), T1 (9.83 cm), and T0 (7.53 cm). The treatments were randomized in separate statistical groups and it was observed that the effect of boron

treatment on floral size was very significant (Figure 2).

The treatment response was greatest for fresh flower weight of the measured flower traits. There was highly significant effect ($F = 337$, $p < 0.01$) on ANOVA. T2 produced the highest fresh flower weight (152.87 g), followed by T3 (121.17 g), T1 (72.60 g), and T0 (51.17 g). The reported mean grouping (Figure 2) revealed that all four treatments were different from each other. The application of boron also significantly affected the dry flower weight ($F = 11.5$, $p < 0.01$). T2 yielded the maximum dry weight of the flowers (65.13 g) followed by T3 (64.77 g), while the dry weight of flowers obtained from T1 and T0 were significantly lower at 27.57 and 18.70 g, respectively. There were no significant difference between T2 and T3, which indicated that both were similar, but T2 and T3 were significantly different than T1 and T0 (Figure 2). The length of the flower stalk was significantly different between treatments ($F = 87.1$, $p < 0.01$). T3 produced the longest stalks (48.37 cm), followed by T2 (36.77 cm), T1 (30.83 cm), and T0 (26.23 cm). The treatment resulted in distinct statistical groups, which were observed in floral stalk elongation and showed that the application of boron significantly affected this attribute (Figure 2).

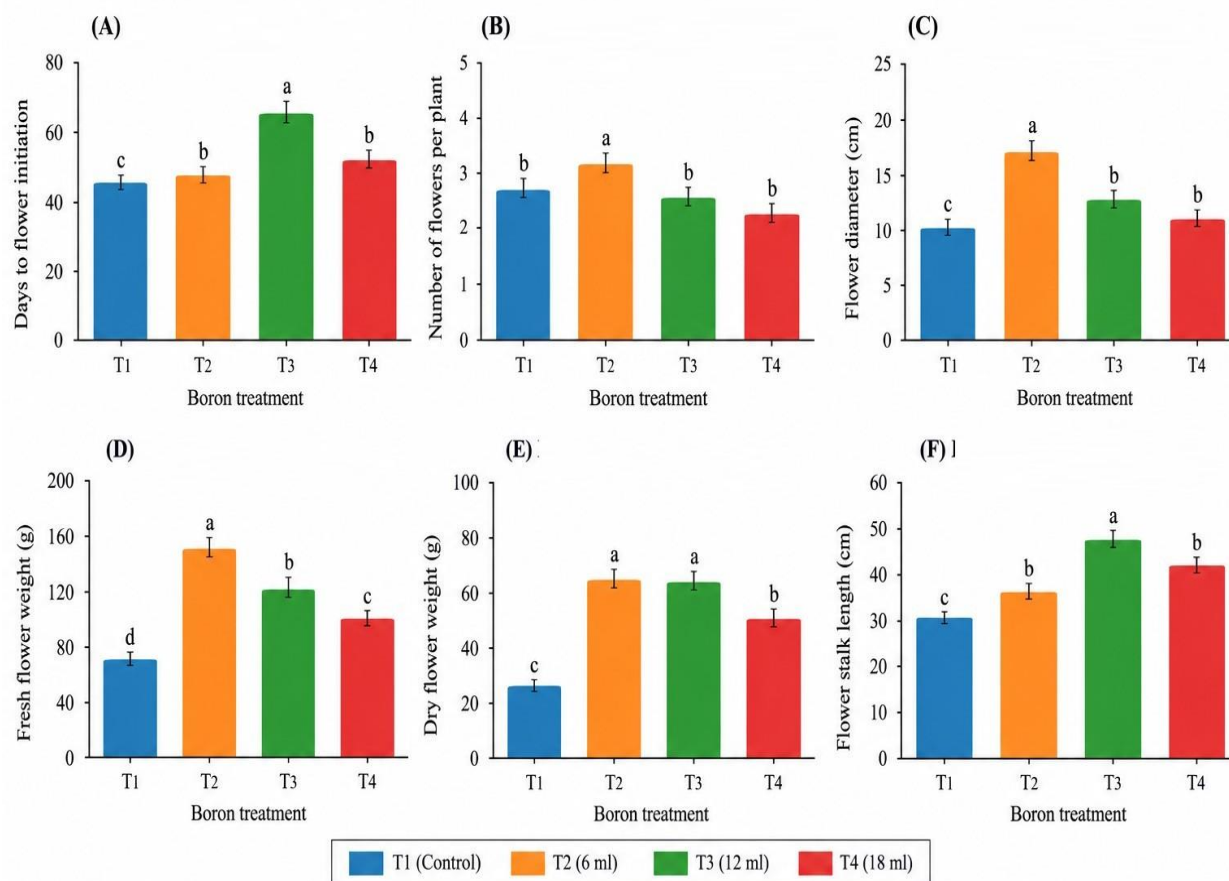


Figure 2. Flowering and floral characteristics of ornamental sunflower under different boron treatments. Effects of boron application (T0 = control, T1 = 6 mL, T2 = 12 mL, and T3 = 18 mL) on days to flower initiation, number of flowers per plant, flower diameter, fresh flower weight, dry flower weight, and flower stalk length. Bars represent treatment means, and different lowercase letters indicate significant differences among treatments according to the LSD test at $P < 0.05$.

4.3 Relationships among Growth and Flowering Traits

The correlation analysis showed mostly positive correlation between the vegetative and flowering properties (Figure 3). The diameter of the flower

was highly correlated with the weight of fresh and dry flower, and plant height, leaf number, stem diameter and branching were positively correlated with the flower development in general. The correlations suggest that the vegetative growth tended to be more closely related to floral performance.

The other correlation structure also revealed that, in addition to the plants which are closely related to each other, some of the growth characteristics were closely correlated with flower production and quality such as plant height, number of leaves, flower diameter, flower weight, and flower stalk length (Figure 3). The positive correlation among these characters indicates that better vegetative growth with proper B nutrition can be correlated with better reproductive and ornamental traits.

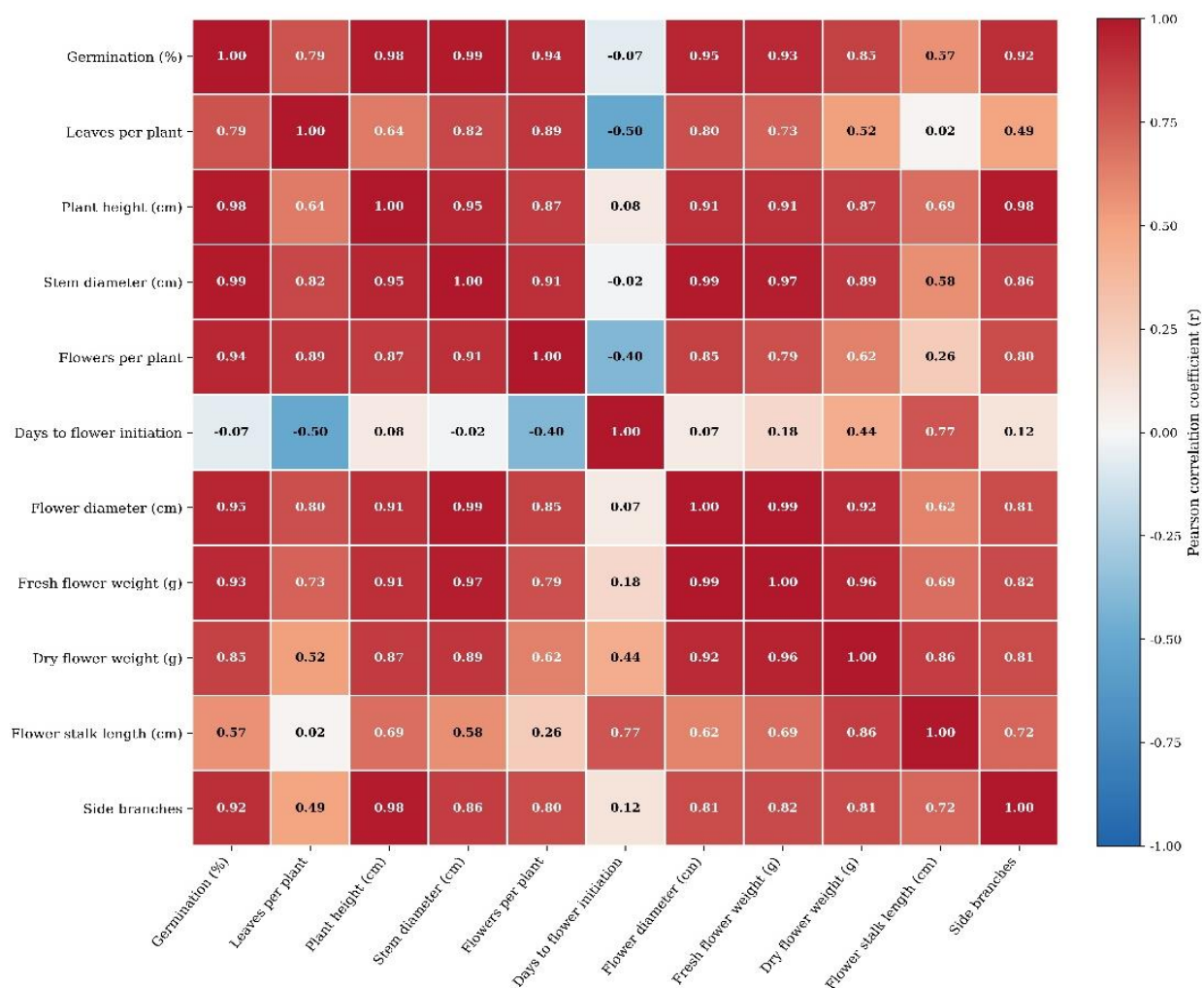


Figure 3. Correlation heat-map showing relationships among agronomic, vegetative, and flowering traits of ornamental sunflower. Pearson correlation coefficients illustrating the strength and direction of relationships among germination, leaves per plant, plant height, stem diameter, flowers per plant, days to flower initiation, flower diameter, fresh flower weight, dry flower weight, flower stalk length, and number of side branches. Positive correlations are represented by increasing intensity of one color, whereas negative correlations are represented by the contrasting color; the correlation coefficient (r) is shown within each cell.

5. Discussion

5.1 Agronomic and Phenotypic Responses to Boron Application

Based on the present study, it could be concluded that boron application had significant effects on agronomic and phenotypic development of ornamental sunflower. The intermediate treatment (T2) was generally most favorable overall response with greater leaf number, plant height, stem diameter and some flowering attributes than the untreated control. Results confirmed the importance of B as an essential micronutrient in plant growth, development, cell-wall formation and physiological regulation (Matthes et al., 2020; Pereira et al., 2021; Vera-Maldonado et al., 2024). Boron deficiency causes developmental abnormalities, while B excess also has an effect on physiological processes, suggesting a relatively

narrow range between deficiency and toxicity (Chen et al., 2023; Wang et al., 2022).

The higher leaves number for the different level of B application suggests that there was adequate boron availability for vegetative growth. Boron is involved in cell-wall structure, membrane function, carbohydrate metabolism and maintenance of actively growing tissues that may lead to increased leaf production and expansion (Pereira et al., 2021; Vera-Maldonado et al., 2024). B application effects have been observed in sunflower also in which B application resulted in improved growth and other agronomic parameters when applied to foliar or soil (Tahir et al., 2014; Shaker, 2011; Ravikumar et al., 2021).

The height of the plants and stem diameter also showed significant growth after B application. The tallest plants and the highest diameter of the stems were found in T2 while the lowest values were found in control. The findings are in line with the previously reported findings of other sunflower studies that proper B nutrition can enhance plant growth and stem development (Tahir et al., 2014; Amin et al., 2023). Samreen et al. (2022) also showed that B uptake was higher and growth and productivity of sunflower improved when B was improved, especially when B was the limiting nutrient.

The agronomic significance of B application is also its ability to stimulate the production of side branches, which are directly related to ornamentals flower production and quality. The numerical branching response was the highest in T2 but some treatments were statistically similar, suggesting that branching is less sensitive to B concentration than some other traits such as flower diameter and flower biomass. These variations among traits align with B's multifunctional role in plants and the potential for genotype, tissue, developmental stage, and environmental conditions to affect B requirements, reflecting the complexity of B's nutritional importance in plants (Vera-Maldonado et al., 2024; Chen et al., 2023).

The overall better performance of T2 than of the highest treatment also indicates that the higher the B concentration, the better the performance is not

always. Although the optimal concentration range for boron is relatively narrow, the excess boron may be detrimental to the physiological processes of the plants (Wang et al., 2022; Chen et al., 2023). Thus, the present results suggest that not only the maximum rate of application, but also the optimal B concentration, is the critical factor to optimize the growth of ornamental sunflower.

5.2 Flowering and Floral Development

Differences caused by boron application were highly significant on flowering and floral quality. Days to flower initiation, flower number per plant, flower diameter, fresh flower weight, dry flower weight and flower stalk length were significantly affected by the treatments. These responses are biologically plausible due to the high requirement of B in reproductive tissues during floral development, pollen formation, pollen germination and reproductive tissue growth, as mentioned by Verma & Pandey (2021) and Chen et al. (2023).

The days to flower initiation indicated that moderate B application resulted in earlier flowering while the highest treatment delayed flower initiation. The non-linear response highlights the significance of B concentration in reproductive performance. Sunflower was found to be affected by both B deficiency and excess by previous studies, which involved reproductive growth (development of inflorescences) and pollen-related processes (Verma & Pandey, 2021). This suggests that T1 and T2 treatments created a more suitable nutritional status for the transition to reproductive growth, as the plants flowered earlier under these treatments.

One of the most significant results of the study is the marked increase in flower diameter. Appropriate B nutrition resulted in increased flower head size for T2 as compared to the control. Boron is involved in the development and expansion of rapidly growing floral tissues, and can therefore be involved in the formation of cell walls and structural development (Matthes et al., 2020; Pereira et al., 2021). Research on sunflower has also recorded that proper use of B also led to

better head diameter (Tahir et al., 2014; Shaker, 2011).

B application also resulted in higher number of flowers/plant (T2 had the highest number). Under optimal B nutrition, meristem development, carbohydrate transport and reproductive tissue formation might be linked to increased flower production (Vera-Maldonado et al., 2024; Verma & Pandey, 2021). There is also evidence from ornamentals indicating a positive relationship between adequate levels of B and flowering. The results of Lipinayak et al. (2024) also showed that B application had significant effects on growth and flowering data of African marigold, indicating that the effects of B are beyond the conventional field crops and could be significant in ornamental horticulture.

The flower weight of fresh and dry flowers was especially sensitive to the effects of B. The floral biomass harvest was highest for T2 and lowest for the control. An increase in dry weight showed that this was due not only to the difference in tissue water content but also to the accumulation of structural and organic biomass. Improved B nutrition has also brought about similar enhancements in sunflower productivity as reported by Tahir et al. (2014), Samreen et al. (2022), and Amin et al. (2023).

The significant differences in flower stalk length are also a reflection of the role of B on the quality of the flowers. T3 produced the longest stalks but T2 gave a well balanced response over most of the measured traits. In the case of ornamental sunflower, this is a significant distinction since marketable quality is determined by size of the flower, characteristics of the stalk, plant architecture, flowering time, and flower biomass, rather than any single factor.

The results also support the notion of optimizing B application depending on the target trait and production goal. Dhaliwal and Sardana (2023) proved that the growth and yield response of sunflower could vary with B application under various crop-management conditions and Samreen et al. (2022) reported that B availability and uptake can significantly be altered by altering the soil environment. Thus, the variations in soil

properties, genotype, application method, and the developmental stage may be responsible for the discrepancies in optimal B responses from study to study.

5.3 Interrelationships among Vegetative Growth and Flowering Traits

Correlation analysis shows that the vegetative and flowering characteristics of the plants are mostly positively correlated. Specifically, there were high positive correlations for flower diameter with flower weight, leaf number, plant height, branching and other attributes of the flower. The relationships between vegetative growth and floral performance were generally positive, with increased vegetative growth being correlated with improved floral performance.

A positive correlation between vegetative growth and floral biomass could be explained by the use of leaves as a source of photosynthates which are required for reproductive development. The sufficient B nutrition can help in carbohydrate metabolism and transport, which can benefit assimilate movement towards actively growing reproductive organs (Pereira et al., 2021; Vera-Maldonado et al., 2024). Thus, the plants with more vegetative growth could have more potential to flower development and biomass production.

From an ornamental point of view, the relationship between flower diameter and flower weight is very significant. Larger flowers are indicative of the floral biomass and visual appeal. In sunflower, studies have reported similar growth-reproductive relationship that improved nutritional status resulted in enhanced vegetative growth and reproduction (Tahir et al., 2014; Amin et al., 2023).

The correlation also confirms the conclusions of the treatment, showing that the improvement seen was not just for one particular characteristic. Rather, B application altered a suite of plant architecture and floral development traits. However, correlation does not imply causation, and any relationships seen here should be viewed as within the range of the experimental population.

5.4 Overall Implications for Boron Application

Overall, the results suggest that an optimized B application has the potential to significantly enhance the agronomic and ornamental characteristics of *H. annuus*. The best overall response was seen under T2 especially in leaf production, plant height, stem development, flower number, flower diameter and flower biomass. This indicates a relatively good nutritional status of plants during the T2 stage for a balance between vegetative and reproductive growth.

These results corroborate with earlier studies which have shown that B application can boost the growth and productivity of sunflower (Shaker, 2011; Tahir et al., 2014; Ravikumar et al., 2021; Samreen et al., 2022; Amin et al., 2023). Concurrently, the non-linear response seen for some traits dovetails into current knowledge that B has beneficial and potentially toxic effects that depend on its concentration and availability (Matthes et al., 2020; Wang et al., 2022; Chen et al., 2023).

The results are especially pertinent from an ornamental horticulture point of view since the aim of the plant is not only to produce seeds but to produce attractive, structurally sound and marketable flowers. These improvements in flower diameter, flower weight, stalk length, branching and plant architecture are thus of direct practical importance. The same applies to other ornamentals such as African marigold where B nutrition can affect growth and flowering performance (Lipinayak et al., 2024).

6. Conclusion

The findings in the present study showed that the use of boron resulted in a definite and positive response on growth and flowering of ornamental sunflower (*Helianthus annuus* L., cv. 'Sunflower'). Generally, with increasing boron application, the number of leaves per plant, plant height, stem diameter, and number of side branches were improved when compared with the untreated control. Boron application also had beneficial effects on flowering characteristics, such as the early onset of flowering, larger diameter of

the flowers, longer flower stalks, increased fresh and dry flower weight, and increased number of flowers per plant.

The treatment T4, which had 18 ml of boron, gave the best results in most growth and floral traits while the control treatment generally yielded the lowest results. An increased boron level was accompanied by a progressive improvement, suggesting that a sufficient supply of boron can improve vegetative development and reproductive growth of ornamental sunflower in the greenhouse. The positive correlation seen between several vegetative characters and flowering characters further supports that better plant growth was closely related with better flowering development.

The results revealed that under the condition of the present experiment 18 mL boron was the best treatment to improve the ornamental value and growth of sunflower and could be regarded as a promising treatment. Further experiments under other soil types, environmental conditions, cultivars and different boron concentrations are recommended to establish the best application rate and to confirm the results under commercial production conditions.

Author Contributions: Tasneem contributed to the conceptualization of the study, data collection, and literature review; Ghulam Khaliq conceptualized and supervised the study, contributed to data interpretation, and critically revised the manuscript; Muhammad Abuzar Jaffar contributed to the research methodology, data analysis, and manuscript revision; Shahmir Ali Kalhoro performed statistical analysis, organized and interpreted the data, prepared the figures, and contributed to manuscript preparation; Aadil Hameed assisted with fieldwork, data collection, and laboratory analyses; Nimra contributed to data collection, laboratory experimentation, and literature review; and Afza Bibi contributed to data collection, data organization, and manuscript preparation. All authors reviewed and approved the final manuscript and agreed to be accountable for all aspects of the work.

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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