Effect of Nano Urea, GA 3, Boron and Calcium on Growth, Yield, and Quality of Strawberry (Fragaria × ananassa Duch.) cv. Winter Dawn

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Abstract

Strawberry (*Fragaria × ananassa* Duch.) is a high-value fruit cultivated globally for its adaptability. Optimizing pre-harvest nutrition and growth regulators is critical for maximizing its growth, yield, and quality. A field experiment was conducted during 2024–25 to evaluate the effects of nano urea, GA_3, boron, and calcium on strawberry cv. 'Winter Dawn' under a naturally ventilated polyhouse at Prof. Rajendra Singh (Rajju Bhaiya) University, Prayagraj, Uttar Pradesh. The study followed a Randomized Block Design (RBD) with seven treatments and three replications.

Results revealed significant variations among treatments. Foliar application of T_7 [GA_3 150 ppm) + Boron (0.6%) + Calcium nitrate (1.0%)] at 25, 50, and 75 days after planting (DAP) recorded the maximum vegetative and yield attributes, including plant height (19.10 cm), plant spread (19.44 cm E–W, 22.16 cm N–S), leaf number (18.60), fruit weight (15.46 g), yield per plant (320.47 g), and the highest benefit–cost ratio (1:2.74). Conversely, treatment T_6 [Nano urea (0.2%) + Boron (0.6%) + Calcium nitrate (1.0%)] maximized fruit quality parameters, yielding the highest TSS (10.27°Brix), ascorbic acid (61.10 mg/100 g), and total sugar (7.20%).

Introduction

Strawberry (*Fragaria × ananassa* Duch.) is one of the most important temperate fruits belonging to the family *Rosaceae*. It is an aggregate fruit of high perishability and is classified as a “false fruit.” Globally valued for its flavour, aroma, and nutritional richness, strawberry has adapted to diverse climatic conditions—moderate, Mediterranean, subtropical, and even high-altitude tropical regions (Kumar et al., 2017).

Commercial strawberry (*F. × ananassa*) is a hybrid between two American dioecious octoploid species, *Fragaria chiloensis* and *Fragaria virginiana*, first developed in France in the seventeenth century. In India, it was introduced in the early 1960s by the NBPGR Regional Research Station, Shimla. There are about 20 recognized strawberry species grouped into five chromosome categories—ten tetraploids, one pentaploid, one hexaploid, and four octoploids. All cultivated varieties are octoploid (2n = 8x = 56) **(Verma et al., 2014).**

The strawberry plant is a low-growing, stoloniferous, perennial herb with fibrous roots and a compressed vertical stem (crown) that produces a rosette of compound trifoliate leaves (Finn & Strik, 2008). Flowers are generally white, perfect, and borne in cymose inflorescences, containing five sepals, five petals, and numerous stamens. Pollination results in an aggregate fruit (etaerio of achenes), propagated commercially through runners and tissue culture.

Globally, the USA, China, and Spain are leading producers, with total production in 2021 reaching 9.17 million MT. In India, production remains low compared to global levels, with 3,031 ha under cultivation producing 19,840 MT in 2020–21. Major production areas include Himachal Pradesh, Uttarakhand, Maharashtra, West Bengal, Nilgiri Hills, Punjab, Haryana, Delhi, and parts of Rajasthan. Notable clusters are Mahabaleshwar (Maharashtra), Nainital and Dehradun (Uttarakhand), Kashmir Valley, Bangalore, and Kalimpong (West Bengal).

Nutritionally, strawberries are a low-calorie, carbohydrate-rich fruit containing high levels of vitamin C (40–120 mg/100 g), vitamin E, beta-carotene, fiber, pectin (mainly calcium pectate), and minerals such as phosphorus, potassium, calcium, and iron **(Sharma et al., 2019).** They also contain ellagic acid, a bioactive compound with anti-carcinogenic properties (Seeram et al., 2006). With ~ 90% water content, strawberries are highly perishable, necessitating prompt post-harvest handling.

Strawberries are classified by bearing season into June-bearing, ever-bearing, and day-neutral types. Rising yields in recent decades have been driven by intensive culture systems, adoption of day-neutral cultivars, and optimized environmental management. Fruits are consumed fresh or processed into jams, preserves, juices, ice creams, and baked goods.

Protected cultivation, especially in plastic greenhouses, offers higher yields, off-season production, better fruit quality, and reduced chemical inputs. This system shields plants from adverse climatic conditions and pests (Dinar, 2003**).** However, micronutrient deficiencies, especially in soils, can lead to quality issues such as misshapen fruits.

Recent advances in nanotechnology offer potential for improved nutrient delivery. Nano-fertilizers increase nutrient use efficiency by enhancing foliar absorption, reducing leaching, and ensuring controlled nutrient release (Rameshaiah et al., 2015; **Suppan et al., 2013; Naderi et al., 2013).** Plant growth regulators (PGRs), such as gibberellic acid (GA_3), are widely used to stimulate vegetative growth, induce early flowering, and enhance runner production by influencing cell division and elongation (Adams et al., 1975**).** Boron plays a key role in cell wall synthesis, sugar transport, pollen germination, and fruit set (Marschner, 2012**).** Calcium contributes to root development, fruit firmness, and disease resistance, improving both yield and post-harvest quality **(Hernandez-Muñoz et al., 2006)**

Methods

The experiment was carried out in naturally ventilated polyhouse at Agriculture Research Field, Prof. Rajendra Singh (Rajju Bhaiya) University, Naini, Prayagraj, Uttar Pradesh. The soil of the experimental field was sandy loam in texture, with soil pH 7.8, low level of organic carbon (0.47%), available N (228 Kg/ha), P (22.9 kg/ha), K (236.1 kg/ha). The experiment was laid out in RBD with 7 treatments each replicated thrice. The treatment combinations are T_1 – Control, T_2 - Nano urea (0.2%) + Boron (0.6%), T_3 - Nano urea (0.2%) + Calcium Nitrate (1.0%), T_4 - GA_3 (150 ppm) + Boron (0.6%), T_5 - GA_3 (150 ppm) + Calcium Nitrate (1.0%), T_6 - Nano urea (0.2%) + Boron (0.6%) + Calcium Nitrate (1.0%), T_7 - GA_3 (150 ppm) + Boron (0.6%) + Calcium Nitrate (1.0%) as follows.

Vegetative Growth Parameters

Morphological observations were recorded at 30, 60, and 90 days after transplanting (DAT). Five plants per replication were randomly selected and tagged for consistent data collection.

Plant Height (cm)

Measured as the vertical distance from the ground level to the highest growing tip of the leaf using a standard meter scale.

Plant Spread (cm)

The maximum lateral expansion was recorded in both East-West (E-W) and North-South (N-S) directions using a meter scale.

Number of Leaves per Plant

The total number of fully expanded leaves was counted across the tagged plants, and the mean value was expressed as the average number of leaves per plant.

Reproductive and Yield Attributes

Days to First Flowering

The duration from the date of transplanting to the visual appearance of the first floral bud was recorded for each treatment.

Flower and Fruit Count

The total number of flowers and set fruits were counted manually per plant throughout the harvest period to determine the average count per plant.

Fruit Morphometry

Fruit length (from the calyx end to the floral apex) and maximum fruit diameter were measured using a digital Vernier caliper.

Fruit Weight and Total Yield

The average fruit weight (g) was determined by weighing ten representative fruits per treatment on an electronic precision balance. Harvesting was performed when three-fourths of the fruit skin turned red. Total yield (g/plant) was calculated by summing the mass of all fruit flushes per plant.

Physio-chemical Quality Analysis

Total Soluble Solids (TSS)

Measured using a digital hand refractometer and expressed in °Brix.

Titrable Acidity (TA)

Determined by titrating a known volume of juice against 0.1 N *NaOH* using phenolphthalein as an indicator, expressed as a percentage.

Ascorbic Acid (Vitamin C)

Quantified by the 2,6-dichlorophenol-indophenol dye titration method and expressed in mg $100gm^{-1}$ of fresh pulp.

Sugar Profile

Reducing and total sugars were estimated using the Lane and Eynon (1923) copper titration method. Non-reducing sugars were calculated by subtracting the reducing sugars from the total sugars and multiplying by a factor of 0.95.

Sugar-to-Acid Ratio

Calculated as the quotient of the total sugar content divided by the titrable acidity.

Economic Analysis

The economic feasibility was evaluated on a per-hectare basis. The total Cost of Cultivation was calculated based on current market rates for inputs and labour. Gross Returns were determined using the prevailing market price of the produce. Net Returns were calculated by subtracting the total expenditure from the gross returns. The Benefit-Cost (B:C) ratio was derived as:

$$\mathrm{B:C\,Ratio} = \frac{Gross\ Returns}{Total\ Cost\ of\ Cultivation}$$

Statistical Analysis

The experimental data were subjected to an Analysis of Variance (ANOVA) following the procedure for a Randomized Block Design (RBD), as described by Gomez and Gomez (1976). The significance of treatment effects was tested using the F-test, and the Critical Difference (CD) at a 5% level of significance was used to compare treatment means.

Results

Growth parameters

Plant height (cm)

The application of gibberellic acid, micro and macronutrients significantly influenced the vegetative architecture of the strawberry plants. At 90 days after transplanting (DAT), the maximum plant height was achieved in T_7 - GA_3 (150 ppm) + Boron (0.6%) + Calcium Nitrate (1.0%) at (19.1cm), Conversely, the lowest plant height was recorded in the T_1 Control at (9.18) cm, representing a reduction of over 50% compared to the leading treatment.

Plant spread E-W (cm)

The horizontal expansion of the canopy, measured as plant spread in the East-West (E-W) direction, exhibited significant variation among treatments at 90 DAT. The most extensive canopy development was recorded (19.44 cm) in the T_7 - GA_3 (150 ppm) + Boron (0.6%) + Calcium Nitrate (1.0%). However, the Control (T_1) recorded the minimum spread of (14.99 cm), representing a 29.7% increase in lateral growth for the T_7 treated plants.

Plant spread N-S (cm)

Significant differences were observed in the North-South (N-S) plant spread at 90 DAT, with T_7 -GA_3 (150 ppm) + Boron (0.6%) + Calcium Nitrate (1.0%) establishing the most expansive lateral growth at (22.16 cm). In comparison, the Control (T_1) produced the minimum N-S spread of (18.12 cm). The treatment T_7 resulted in a 22.3% improvement over the control, indicating a more vigorous expansion of the vegetative canopy.

Number of leaves per plant

The foliar density of strawberry plants significantly increased in response to the integrated application of gibberellic acid, micro and macronutrients. At 90 DAT, the maximum number of leaves per plant (18.60) was recorded in T_7 - GA_3 (150 ppm) + Boron (0.6%) +

Calcium Nitrate (1.0%), which was significantly higher than the Control (T_1), which produced the minimum count of (13.73). This represents a 35.5% increase in leaf production for the T_7 treatment.

Days taken to first flowering

The temporal transition from the vegetative to the reproductive phase was significantly accelerated by T_4 - GA_3 (150 ppm) + Boron (0.6%) recorded the earliest floral induction, requiring only (58.47 days) for the emergence of the first flower. In contrast, the (T_1) Control exhibited a prolonged juvenile phase, taking a maximum of (78.33 days) to initiate flowering a substantial delay of approximately 20 days.

Number of flowers per plant

Total number of flowers produced per plant, was significantly enhanced by T_4 - GA_3 (150 ppm) + Boron (0.6%) emerged as the most effective intervention, yielding the maximum number of flowers (27.93). While, the Control (T_1) produced the minimum floral count of (19.20), representing a 45.5% increase in flower production for the T_4.

Fruit and Yield parameters

Number of fruits per plant

Among the evaluated treatments, T_4 - GA_3 (150 ppm) + Boron (0.6%) was identified as the most effective intervention for maximizing fruit count, yielding (21.60) fruits per plant. Conversely, the Control (T_1) produced the minimum fruit count of (16.67), indicating a 29.5% increase in fruit set for the T_4.

Fruit length (cm)

The longitudinal growth of 'Winter Dawn' strawberry fruits was significantly enhanced by the synergistic application of GA_3, Boron, and Calcium Nitrate. Among the evaluated treatments, T_7 -GA_3 (150 ppm) + Boron (0.6%) + Calcium Nitrate (1.0%) emerged as the most effective intervention, yielding a maximum fruit length of (4.91 cm). In stark contrast, the Control (T_1) produced the minimum fruit length of (2.86 cm), representing a substantial 71.7% increase in fruit size for the T_7.

Fruit diameter (cm)

The transverse expansion of 'Winter Dawn' strawberry fruits was significantly enhanced by the integrated application of GA_3, Boron, and Calcium Nitrate. Among the evaluated treatments, T_7 -GA_3 (150 ppm) + Boron (0.6%) + Calcium Nitrate (1.0%) emerged as the most effective intervention, yielding a maximum fruit diameter of (3.45 cm). While, the Control (T_1) recorded the minimum diameter of (1.97 cm), representing a substantial 75.1% increase in fruit girth for the T_7.

Fruit weight (gm)

The individual fruit mass of 'Winter Dawn' strawberry was profoundly influenced by the integrated application of GA_3, Boron, and Calcium Nitrate. Among the evaluated treatments, T_7 - GA_3 (150 ppm) + Boron (0.6%) + Calcium Nitrate (1.0%) emerged as the most effective intervention, yielding a maximum fruit weight of (15.46 g). In stark contrast, the Control (T_1) produced the minimum fruit weight of (12.97 g).

Fruit yield per plant (gm)

The total reproductive productivity of strawberry cv. Winter Dawn, expressed as fruit yield per plant, was significantly enhanced by the integrated foliar application of GA_3, Boron, and Calcium Nitrate. Among the evaluated treatments, T_7 - GA_3 (150 ppm) + Boron (0.6%) + Calcium Nitrate (1.0%) emerged as the most effective intervention, achieving a maximum yield of (320.47 g) per plant. In contrast, the Control (T_1) produced the minimum yield of (208.91 g).

Quality parameters

Total Soluble Solids (°Brix)

On the basis of observations, it can be inferred that in general all the treatments were responsive towards increasing the TSS content as compared to control. However, T_6 Nano urea (0.2%) + Boron (0.6%) + Calcium Nitrate (1.0%) was most effective treatment in increasing the TSS content of the fruit with 10.27° Brix, while minimum TSS (7.57° Brix) recorded in T_1 Control.

Titrable Acidity (%)

The organic acid profile of 'Winter Dawn' strawberry fruits, measured as titrable acidity (TA), was significantly modulated by the application of Nano urea, boron and calcium. Analysis of the data reveals that all treatments elicited a positive response in TA compared to the untreated control. T_6 - Nano urea (0.2%) + Boron (0.6%) + Calcium Nitrate (1.0%) emerged as the most effective intervention, achieving the highest TA value of (0.86%). While, the Control (T_1) recorded the minimum TA of (0.66%).

Ascorbic acid (mg per 100 gm)

The antioxidant potential of strawberry fruits, quantified by their ascorbic acid (Vitamin C) content, was significantly enhanced by the integrated application of Nano urea, boron and calcium. Analysis of the experimental data indicates a positive response across all treatments compared to the untreated control. T_6 - Nano urea (0.2%) + Boron (0.6%) + Calcium Nitrate (1.0%) emerged as the most effective intervention, achieving a maximum ascorbic acid concentration of (61.10 mg $100g^{-1}$). In contrast, the Control (T_1) recorded the minimum value of (53.60 mg $100g^{-1}$)

Reducing Sugar (%)

Experimental observations indicate that all treatments elicited a positive response in reducing sugar accumulation compared to the untreated control. T_6 Nano urea (0.2%) + Boron (0.6%) + Calcium Nitrate (1.0%) emerged as the most effective intervention, achieving a maximum reducing sugar content of (4.87%). In contrast, the Control (T_1) recorded the minimum value of (3.17%),

Non-Reducing Sugar (%)

Experimental observations indicate that all treatments were responsive, exhibiting a marked increase in non-reducing sugar content compared to the untreated control. T_6 - Nano urea (0.2%) + Boron (0.6%) + Calcium Nitrate (1.0%) emerged as the most effective intervention, achieving a maximum value of (2.33%). In contrast, the Control (T_1) recorded the minimum content of (1.67%).

Total sugar (%)

On the basis of observations, it can be inferred that in general all the treatments were responsive towards increasing the total sugar content as compared to control. However, T_6 Nano urea (0.2%) + Boron (0.6%) + Calcium Nitrate (1.0%) was most effective treatment in increasing the total sugar content of the fruit with (7.2), while minimum total sugar (4.83%) recorded in T_1 Control.

Sugar to acid ratio

The sugar-to-acid ratio, a critical determinant of the flavour profile and overall palatability of strawberry cv. 'Winter Dawn', was significantly influenced by the integrated application of GA_3 Boron and calcium. Analysis of the data reveals that all treatments elicited a positive response in this ratio compared to the untreated control. T_7-GA_3 (150 ppm) + Boron (0.6%) + Calcium Nitrate (1.0%) emerged as the most effective intervention, achieving a maximum sugar-to-acid ratio of (9.08). In contrast, the Control (T_1) recorded the minimum ratio of (7.37).

Economics

The data clearly indicated that T_7 GA_3 (150 ppm) + Boron (0.6%) + Calcium Nitrate (1.0%) proved to be the best treatment in respect of fetching maximum net profit of ₹ 1566721 per ha^{-1}. The minimum net profit of ₹ 869469 ha^{-1} was obtained in T_1Control. Similarly, the highest benefit: cost ratio 2.74 was found in T_7 GA_3 (150 ppm) + Boron (0.6%) + Calcium Nitrate (1.0%).

Discussion

Vegetative Growth attributes

The exogenous application of gibberellic acid GA_3, boron (B), and calcium exerted a highly significant positive influence on the vegetative architecture of strawberry plants, as evidenced by enhanced plant height, radial plant spread (E-W and N-S), and leaf proliferation.

The pronounced elongation of stems can be primarily attributed to the classic physiological role of GA_3 in inducing intercalary meristem activity, accelerating both cellular division and longitudinal cell expansion by upregulating xyloglucan endotransglycosylase/hydrolase (XTH) activity.

This vegetative vigor was further synergized by the structural contributions of boron and calcium. Boron is indispensable for intact cross-linking of rhamnogalacturonan II (RG-II) in cell walls, which maintains wall elasticity and facilitates rapid meristematic development at the shoot apex. Concurrently, calcium acts as a vital secondary messenger in growth-hormone signaling pathways and provides structural rigidity as calcium pectate in the middle lamella. This dual fortification allowed for a more robust skeletal framework, leading to a significantly expanded canopy (canopy spread) and a denser leaf area index via augmented leaf primordia differentiation. These findings are strongly supported by the observations of Verma et al. (2022), who reported matching trends in morpho-structural parameters under balanced phytohormone and micronutrient regimes.

Flowering, fruiting and Yield attributes

The transition from vegetative to reproductive phases was significantly accelerated in plants treated with GA_3 and boron, resulting in fewer days taken to first flowering. Phytohormones like GA_3 are well-documented to modulate florigenic signals and mobilize stored photoassimilates toward apical buds, thereby expediting flower bud induction.

Furthermore, the simultaneous application of GA_3 and boron exponentially increased the number of flowers, fruit set, fruit size (length and diameter), unit fruit weight, and cumulative yield per plant.

$$\mathrm{GA_3} \rightarrow \mathrm{Peduncle\backslash{:}Elongation} \rightarrow \mathrm{Enhanced\backslash{:}Spatial\backslash{:}Distribution\backslash{:}of\backslash{:}Flowers} \rightarrow \mathrm{Reduced\backslash{:}Mechanical\backslash{:}Abortion}$$

Physiologically, boron plays a critical role in pollen grain germination and pollen tube elongation toward the ovary, thereby ensuring complete fertilization and minimizing misshapen fruits or early fruit drop. The increase in physical fruit dimensions (length and diameter) and subsequent individual mass can be explained by the cumulative effect of GA_3 driven cell expansion and calcium-mediated cell wall stability. Calcium maintains plasma membrane integrity, ensuring that rapid water and solute influx during the cell-enlargement phase of fruit development does not lead to cellular rupture or premature abscission. Consequently, the sink strength of the berries was significantly reinforced, maximizing the translocation of photosynthetic assimilates into high-yielding fruit biomass. These synergistic mechanics align perfectly with the reproductive frameworks outlined by Beniwal et al. (2024) and Verma et al. (2022)

Quality Attributes

Fruit quality indices, including Total Soluble Solids (TSS), sugar fractions (reducing, non-reducing, and total sugars), titratable acidity, and ascorbic acid content, exhibited substantial improvement under the treatments integrated with nano urea, boron, and calcium.

The significant elevation in TSS and carbohydrate fractions is heavily tied to the enhanced source-to-sink relationship. Nano urea provides a sustained, highly bioavailable nitrogen flux that optimizes chlorophyll biosyntheses and net photosynthetic efficiency. Boron acts as a fundamental catalyst in carbohydrate transport by forming highly mobile cis-diol borate complexes with sugars, facilitating their rapid translocation across phloem membranes directly into the ripening fruits. Calcium supplements this by maintaining vacuolar membrane stability, allowing efficient compartmentalization and accumulation of these translocated sugars within the pulp tissue.

Interestingly, titratable acidity and ascorbic acid (Vitamin C) levels were concurrently augmented, primarily driven by nano urea and boron. The optimal nitrogen status from nano urea boosts the synthesis of amino acids and key organic acids (such as citric and malic acids) involved in the tricarboxylic acid (TCA) cycle. Boron preserves the cellular metabolic pathways and enzymatic defense networks that prevent the premature oxidative degradation of ascorbic acid. This biochemical stability successfully maintained a well-balanced sugar-to-acid ratio, optimizing the sensory and commercial value of the berries. This metabolic upgrade matches the foundational physiological responses observed by Singh and Tripathi (2010), Singh et al. (2007), and Suvalaxmi et al. (2016).

Economic Evaluation

From an agronomic production standpoint, maximizing biological yield must be balanced with economic feasibility. Among the tested treatments, Treatment T_7 - GA_3 @ 150 ppm + Boron @ 0.6% + Calcium Nitrate @ 1.0%) emerged as the most economically viable strategy, yielding the maximum net profit and a superior benefit-cost (B:C) ratio. This economic superiority is a direct consequence of the optimal physiological synergy achieved by this specific concentration matrix, which maximized high-grade marketable yield per unit area while keeping input costs realistic. This economic projection validates the cost-benefit paradigms established for high-value strawberry cultivation by Verma (2014).

Correlation Analysis of the Effects of Nano Urea, GA3, Boron, and Calcium on the Vegetative Growth, Fruit Quality, and Profitability of Strawberry

Pearson's correlation coefficient analysis was performed to determine the relationship among growth, yield, and quality attributes of strawberry under different treatment combinations **(**Fig. 1**).** The results revealed a strong association among various morphological, biochemical, and yield parameters.

The data demonstrated that plant growth parameters, viz., plant height, plant spread (E–W and N–S), and number of leaves at 30, 60, and 90 DAP were highly and positively correlated with each other at $P < 0.001$, indicating synchronized vegetative growth. Similarly, these growth traits exhibited a strong positive correlation with yield attributes, including fruit weight, fruit length, fruit diameter, and yield per plant at $P < 0.01$ and $P < 0.001$ levels.

Among yield components, number of fruits per plant and number of flowers per plant showed significant positive correlation with fruit yield and fruit size parameters, suggesting their direct contribution to productivity. The fruit weight was highly positively correlated with fruit diameter, fruit length, and total yield per plant at $P < 0.001$.

Quality parameters such as total soluble solids (TSS), total sugar, reducing sugar, and non-reducing sugar were also positively and significantly correlated with each other and with yield traits at $P < 0.01$ and $P < 0.001$. The sugar to acid ratio showed a strong positive association with TSS and total sugars, indicating improvement in fruit quality with increased sugar accumulation.

In contrast, titratable acidity exhibited a significant negative correlation with TSS, total sugars, and sugar to acid ratio, suggesting that an increase in sweetness is accompanied by a reduction in acidity. Similarly, days taken to first flowering showed a negative correlation with most growth and yield parameters, indicating that early flowering contributes positively to enhanced vegetative growth and yield performance.

Furthermore, ascorbic acid content showed a moderate positive correlation with quality traits but exhibited non-significant or weak association with some growth parameters.

Overall, the correlation analysis indicated that vegetative growth traits, yield components, and quality parameters are strongly interrelated, and improvement in one set of traits is likely to enhance overall productivity and fruit quality in strawberry.

Evaluating the Effects of Nano Urea, GA_{3}, Boron, and Calcium on Strawberry Growth, Quality, and Profitability Using Hierarchical Cluster Analysis

Hierarchical clustering analysis was performed to assess the similarity and grouping pattern among the seven treatment combinations evaluated under the randomized block design (RBD) in strawberry. The dendrogram **(Figure.2)** revealed distinct clustering of treatments based on their response behavior in terms of growth, yield and quality attributes.

The treatments were broadly grouped into two major clusters. The first cluster comprised T_7, T_4, and T6, indicating a higher degree of similarity among treatments involving the combined application of plant growth regulators and nutrients, particularly those including boron and calcium nitrate. Within this cluster, T_4 (GA_3 150 ppm + Boron 0.6%) and T_6 (Nano urea 0.2% + Boron 0.6% + Calcium nitrate 1.0%) showed closer proximity, suggesting comparable performance, whereas T_7 (GA_3 150 ppm + Boron 0.6% + Calcium nitrate 1.0%) was relatively distinct but remained within the same group.

The second major cluster included T_1, T_2, T_3 and T_5. Among these, T_2 (Nano urea 0.2% + Boron 0.6%), T3 (Nano urea 0.2% + Calcium nitrate 1.0%), and T_5 (GA_3 150 ppm + Calcium nitrate 1.0%) formed a sub-cluster, indicating moderate similarity in their effects on strawberry performance. The control treatment (T_1) was grouped separately within this cluster at a higher linkage distance, reflecting its distinct and comparatively lower performance.

The clustering pattern suggests that treatments involving the combined application of GA_3, boron, and calcium nitrate (T_7) and multi-nutrient combinations (T_6) exhibited superior and more consistent responses in strawberry, distinguishing them from single or dual input treatments. The hierarchical arrangement further indicates that integrated nutrient and growth regulator management significantly influences vegetative growth, fruit yield, and quality parameters in strawberries.

Principal Component Analysis of the Effects of Nano Urea, GA_{3}, Boron, and Calcium on the Vegetative Growth, Fruit Quality, and Profitability of Strawberry

The PCA results illustrated that the first two principal components (PC1 and PC2) accounted for 87.1% of the total variation, with PC1 contributing 75.9% and PC2 contributing 11.2% of the variability (Fig. 3). This indicates that most of the variation among treatments was effectively explained by these two components.

The PCA biplot revealed clear separation of treatment combinations based on their performance. The treatments T_7 and T_6 were positioned on the positive side of PC1, indicating their strong association with growth, yield, and quality attributes. In particular, T_7 (GA_3 + Boron + Calcium nitrate) was located farthest along PC1, suggesting its superior performance across most parameters. Similarly, T_6 (Nano urea + Boron + Calcium nitrate) also showed close proximity to important yield and quality traits, indicating its effectiveness.

In contrast, the control treatment (T_1) was located on the negative side of PC1, far from most of the variables, indicating its poor performance. Treatments T_2 and T_3 were positioned intermediate but closer to the negative side, suggesting moderate to lower effectiveness compared to multi-component treatments. T_5 showed moderate association, while T_4 was more aligned with biochemical traits such as ascorbic acid and titratable acidity.

The distribution of variables on the PCA biplot showed that plant growth parameters (plant height, plant spread, and number of leaves at different stages) had high positive loadings on PC1, along with yield attributes such as fruit weight, fruit length, fruit diameter, number of fruits per plant, and yield per plant. This indicates that PC1 primarily represents overall plant performance and productivity.

Similarly, quality parameters, including total soluble solids (TSS), total sugars, reducing sugar, non-reducing sugar, and sugar to acid ratio, were also positively associated with PC1, suggesting their strong relationship with yield and growth traits. These variables were closely grouped, indicating a high degree of positive correlation among them.

On the other hand, titratable acidity and ascorbic acid were positioned in the opposite direction of most growth and yield traits, indicating their negative association with these parameters. Likewise, days taken to first flowering was located away from yield and growth traits, suggesting that delayed flowering negatively influences overall plant performance.

The PCA biplot clearly demonstrates that multi-nutrient and growth regulator treatments (T6 and T7) are closely associated with desirable traits, confirming their superiority. The close grouping of growth, yield and quality parameters further indicates that improvement in one set of traits positively influences others.

Overall, the PCA analysis suggests that integrated application of GA_3, nano urea, boron and calcium nitrate significantly enhances growth, yield and quality in strawberry, and these traits collectively contribute to overall plant performance.

Conclusion

Based on the results of the present investigation, it can be concluded that foliar application of T_7-GA_3 (150 ppm) + Boron (0.6%) + Calcium Nitrate (1.0%) at 25, 50 and 75 DAP significantly enhanced vegetative growth, maximized fruit yield, and recorded the highest cost-benefit ratio in Winter Dawn strawberry. Foliar application of T_6-Nano urea (0.2%) + Boron (0.6%) + Calcium Nitrate (1.0%) at 25, 50 and 75 DAP has shown best results for quality parameters.

Considering the superior performance in terms of yield, quality, and economic returns, the foliar application of T_7 and T_6 along with the recommended dose of fertilizers (RDF), can be recommended for adoption by farmers cultivating strawberry cv. *Winter Dawn* under protected conditions.

Declarations

Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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Consent To Participate

-Not applicable.

Consent To Publish-

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Author Contribution

Conceptualization, L.P.; Data curation, A.Y., R.M., and L.P.; Formal analysis, L.P. and K.K.S.; Investigation, L.P. and AY.; Methodology, L.P., Supervision, L.P.; Validation, L.P., and A.Y.; Visualization, A.Y., and L.P.; Writing - original draft, A.Y.; Writing - review and editing, A.Y, L.P. and K. K.S., All authors read and approved the final manuscript.

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Data Availability

All data generated during this study are included in this article.

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Tables

Table-1 Effect of different nutrients and plant growth regulator on plant height at 30, 60 and 90 days after planting in strawberry.

Treatments	Plant height (cm)		
	30 DAP	**60 DAP**	**90 DAP**
T_1-Control	4.79±0.105^{b}	9.18±0.035^{d}	14.3±0.247^{d}
T_2-Nano urea (0.2%) + Boron (0.6%)	5.23±0.071^{b}	10.00±0.080^{c}	16.6±0.191^{c}
T_3-Nano urea (0.2%) + Calcium Nitrate (1.0%)	5.74±0.023^{a}	11.55±0.057^{b}	17.2±0.047^{b}
T_4-GA_3 (150 ppm) + Boron (0.6%)	6.12±0.230^{a}	11.84±0.173^{b}	17.3±0.133^{b}
T_5-GA_3 (150 ppm) + Calcium Nitrate (1.0%)	5.27±0.079^{ab}	9.67±0.123^{c}	16.1±0.125^{c}
T_6-Nano urea (0.2%) + Boron (0.6%) + Calcium Nitrate (1.0%)	6.13±0.325^{a}	12.01±0.173^{b}	18.7±0.174^{a}
T_7-GA_3 (150 ppm) + Boron (0.6%) + Calcium Nitrate (1.0%)	6.19±0.048^{a}	13.29±0.052^{a}	19.1±0.053^{a}
S.E.(m) ±	**0.172**	**0.120**	**0.162**
C.D. at 5%	**0.536**	**0.371**	**0.505**

Table-2 Effect of different nutrients and plant growth regulator on plant spread (E-W) at 30, 60 and 90 days after planting in strawberry

	Plant spread E-W(cm)		
Treatments	**30 DAP**	**60 DAP**	**90 DAP**
T_1-Control	3.50±0.018^{d}	8.07±0.060^{d}	14.99±0.141^{e}
T_2-Nano urea (0.2%) + Boron (0.6%)	3.77±0.046^{c}	9.82±0.083^{c}	17.84±0.293^{cd}
T_3-Nano urea (0.2%) + Calcium Nitrate (1.0%)	3.85±0.030^{c}	10.24±0.108^{c}	18.30±0.249^{c}
T_4-GA_3 (150 ppm) + Boron (0.6%)	3.90±0.047^{c}	10.08±0.043^{c}	18.12±0.324^{c}
T_5-GA_3 (150 ppm) + Calcium Nitrate (1.0%)	4.22±0.099^{b}	10.50±0.040^{c}	18.64±0.133^{bc}
T_6-Nano urea (0.2%) + Boron (0.6%) + Calcium Nitrate (1.0%)	4.25±0.01^{b}	11.00±0.051^{b}	18.88±0.121^{b}
T_7-GA_3 (150 ppm) + Boron (0.6%) + Calcium Nitrate (1.0%)	5.09±0.044^{a}	12.60±0.187^{a}	19.44±0.067^{a}
S.E.(m) ±	**0.043**	**0.101**	**0.171**
C.D. at 5%	**0.135**	**0.310**	**0.530**

Table-3 Effect of different nutrients and plant growth regulator on plant spread (N-S) at 30, 60 and 90 days after planting in strawberry

Treatments	Plant spread N-S(cm)		
	30 DAP	60 DAP	90 DAP
T_1-Control	9.84±0.237[d]	14.45±0.056[c]	18.12±0.48[c]
T_2-Nano urea (0.2%) + Boron (0.6%)	10.87±0.057[b]	16.50±0.246[b]	19.91±0.417[bc]
T_3-Nano urea (0.2%) + Calcium Nitrate (1.0%)	10.66±0.080[c]	16.85±0.134[b]	20.26±0.670[abc]
T_4-GA_3 (150 ppm) + Boron (0.6%)	10.69±0.179[bc]	16.55±0.133[b]	20.61±0.396[ab]
T_5-GA_3 (150 ppm) + Calcium Nitrate (1.0%)	10.88±0.067[b]	16.82±0.023[b]	20.52±0.426[ab]
T_6-Nano urea (0.2%) + Boron (0.6%) + Calcium Nitrate (1.0%)	10.98±0.037[b]	17.42±0.091[a]	21.44±0.395[b]
T_7-GA_3 (150 ppm) + Boron (0.6%) + Calcium Nitrate (1.0%)	11.74±0.144[a]	17.72±0.119[a]	22.16±0.341[a]
S.E.(m) ±	**0.098**	**0.120**	**0.301**
C.D. at 5%	**0.304**	**0.381**	**0.931**

Table-4 Effect of different nutrients and plant growth regulator on no. of leaves at 30, 60 and 90 days after planting in strawberry.

Treatments	Number of leaves plant^{-1}		
	30 DAP	60 DAP	90 DAP
T_1-Control	4.73±0.267[d]	8.2±0.001[d]	13.73±0.291[f]
T_2-Nano urea (0.2%) + Boron (0.6%)	5.07±0.176[bc]	9.8±0.305[c]	14.40±0.004[e]
T_3-Nano urea (0.2%) + Calcium Nitrate (1.0%)	5.13±0.067[bc]	10.97±0.200[b]	17.60±0.231[b]
T_4-GA_3 (150 ppm) + Boron (0.6%)	4.93±0.176[bc]	10.01±0.400[c]	16.07±0.240[d]
T_5-GA_3 (150 ppm) + Calcium Nitrate (1.0%)	4.80±0.000[cd]	10.53±0.240[bc]	17.27±0.291[c]
T_6-Nano urea (0.2%) + Boron (0.6%) + Calcium Nitrate (1.0%)	5.33±0.176[b]	11.2±0.200[b]	17.80±0.115[b]
T_7-GA_3 (150 ppm) + Boron (0.6%) + Calcium Nitrate (1.0%)	5.80±0.115[a]	12.6±0.115[a]	18.60±0.115[a]
S.E.(m) ±	**0.170**	**0.231**	**0.162**
C.D. at 5%	**0.521**	**0.701**	**0.483**

Table-5 Effect of different nutrients and plant growth regulator on days taken to first flowering, number of flowers plant^{-1} and number of fruits plant^{-1} in strawberry.

Treatments	Days taken to first flowering	Number of flowers plant^{-1}	Number of fruits plant^{-1}
T_1-Control	78.33±0.240^{g}	19.20±0.116^{g}	16.67±0.176^{c}
T_2-Nano urea (0.2%) + Boron (0.6%)	66.87±0.266^{d}	23.33±0.067^{d}	19.33±0.133^{b}
T_3-Nano urea (0.2%) + Calcium Nitrate (1.0%)	74.13±0.177^{e}	21.60±0.115^{e}	18.60±0.115^{b}
T_4-GA_3 (150 ppm) + Boron (0.6%)	58.47±0.068^{a}	27.93±0.133^{a}	21.60±1.168^{a}
T_5-GA_3 (150 ppm) + Calcium Nitrate (1.0%)	76.33±0.240^{f}	20.60±0.200^{f}	18.00±0.902^{bc}
T_6-Nano urea (0.2%) + Boron (0.6%) + Calcium Nitrate (1.0%)	63±0.115^{c}	24.73±0.176^{c}	19.87±0.240^{ab}
T_7-GA_3 (150 ppm) + Boron (0.6%) + Calcium Nitrate (1.0%)	61.20±0.231^{b}	25.73±0.134^{b}	20.73±0.067^{a}
S.E.(m) ±	**0.213**	**0.115**	**0.622**
C.D. at 5%	**0.665**	**0.360**	**1.910**

Table-6 Effect of different nutrients and plant growth regulator on fruit length, fruit diameter, fruit weight and yield plant^{-1} in strawberry.

Treatments	Fruit length (cm)	Fruit diameter (cm)	Fruit weight (gm)	Yield plant^{-1} (gm)
T_1-Control	2.86±0.062^{g}	1.97±0.023^{g}	12.53±0.063^{f}	208.91±3.256^{c}
T_2-Nano urea (0.2%) + Boron (0.6%)	3.48±0.021^{e}	2.53±0.020^{d}	13.72±0.127^{d}	265.31±1.427^{b}
T_3-Nano urea (0.2%) + Calcium Nitrate (1.0%)	3.06±0.005^{f}	2.13±0.019^{f}	13.22±0.068^{e}	245.79±0.885^{b}
T_4-GA_3 (150 ppm) + Boron (0.6%)	4.15±0.014^{b}	3.09±0.027^{b}	15.26±0.075^{a}	313.53±19.011^{a}
T_5-GA_3 (150 ppm) + Calcium Nitrate (1.0%)	3.73±0.036^{d}	2.26±0.018^{e}	14.09±0.035^{c}	264.90±13.390^{b}
T_6-Nano urea (0.2%) + Boron (0.6%) + Calcium Nitrate (1.0%)	3.97±0.014^{c}	2.76±0.039^{c}	14.90±0.028^{b}	296.07±3.756^{a}
T_7-GA_3 (150 ppm) + Boron (0.6%) + Calcium Nitrate (1.0%)	4.91±0.051^{a}	3.45±0.027^{a}	15.46±0.060^{a}	320.47±2.214^{a}
S.E.(m) ±	**0.031**	**0.017**	**0.072**	**9.746**
C.D. at 5%	**0.095**	**0.054**	**0.224**	**30.63**

Table-7 Effect of different nutrients and plant growth regulator on TSS, Titrable acidity and Ascorbic acid in strawberry.

Treatments	Total Soluble Solids (º Brix)	Titrable Acidity (%)	Ascorbic acid (mg 100gm^{-1})
T_1-Control	7.57±0.145^c	0.66±0.012^d	53.60±0.208^c
T_2-Nano urea (0.2%) + Boron (0.6%)	8.47±0.273^b	0.82±0.009^{ab}	58.17±0.441^b
T_3-Nano urea (0.2%) + Calcium Nitrate (1.0%)	7.80±0.379^c	0.74±0.009^{bc}	56.67±0.333^{bc}
T_4-GA_3 (150 ppm) + Boron (0.6%)	9.20±0.058^{ab}	0.78±0.009^b	57.70±0.473^b
T_5-GA_3 (150 ppm) + Calcium Nitrate (1.0%)	8.13±0.088^{bc}	0.72±0.006^c	54.73±0.120^c
T_6-Nano urea (0.2%) + Boron (0.6%) + Calcium Nitrate (1.0%)	10.27±0.120^a	0.86±0.006^a	61.10±0.099^a
T_7-GA_3 (150 ppm) + Boron (0.6%) + Calcium Nitrate (1.0%)	9.77±0.384^a	0.73±0.004^a	55.30±0.173^c
S.E.(m) ±	**0.256**	**0.01**	**0.317**
C.D. at 5%	**0.799**	**0.03**	**0.987**

Table-8 Effect of different nutrients and plant growth regulator on Reducing sugar, Non-reducing, Total sugar and Sugar : Acid ratio in strawberry.

Treatments	Reducing Sugar (%)	Non- reducing Sugar (%)	Total Sugar (%)	Sugar to Acid Ratio
T_1-Control	3.17±0.120^d	1.67±0.120^b	4.83±0.233^c	7.37±0.411^b
T_2-Nano urea (0.2%) + Boron (0.6%)	4.13±0.145^b	1.93±0.120^b	6.07±0.240^b	7.40±0.225^b
T_3-Nano urea (0.2%) + Calcium Nitrate (1.0%)	3.77±0.120^c	2.03±0.240^{ab}	5.80±0.351^b	7.81±0.552^b
T_4-GA_3 (150 ppm) + Boron (0.6%)	4.30±0.145^b	2.17±0.058^a	6.77±0.233^{ab}	8.71±0.330^a
T_5-GA_3 (150 ppm) + Calcium Nitrate (1.0%)	3.93±0.115^c	1.80±0.145^b	5.73±0.260^b	7.96±0.329^b
T_6-Nano urea (0.2%) + Boron (0.6%) + Calcium Nitrate (1.0%)	4.87±0.033^a	2.33±0.120^a	7.2±0.173^a	8.37±0.149^{ab}
T_7-GA_3 (150 ppm) + Boron (0.6%) + Calcium Nitrate (1.0%)	4.53±0.145ab	2.23±0.088a	6.47±0.176a	9.08±0.277a
S.E.(m) ±	**0.128**	**0.117**	**0.243**	**0.34**
C.D. at 5%	**0.400**	**0.365**	**0.750**	**1.04**

Table-9 Effect of different nutrients and plant growth regulator on Economics of strawberry cultivation (per hectare).

Economics

Treatments	Cost of cultivation (₹ ha^{-1})	Gross returns (₹ ha^{-1})	Net returns (₹ ha^{-1})	Benefit cost ratio (B:C)
T_1-Control	540680	1410149	869469	1:1.61
T_2-Nano urea (0.2%) + Boron (0.6%)	556730	1770931	1214201	1:2.18
T_3-Nano urea (0.2%) + Calcium Nitrate (1.0%)	541105	1640662	1099557	1:2.03
T_4-Gibberellic acid (150 ppm) + Boron (0.6%)	565573	2092839	1527265	1:2.70
T_5-Gibberellic acid (150 ppm) + Calcium Nitrate (1.0%)	549948	1768241	1218292	1:2.22
T_6-Nano urea (0.2%) + Boron (0.6%) + Calcium Nitrate (1.0%)	563605	1976274	1412669	1:2.51
T_7-Gibberellic acid (150 ppm) + Boron (0.6%) + Calcium Nitrate (1.0%)	572448	2139170	1566721	1:2.74

Figures

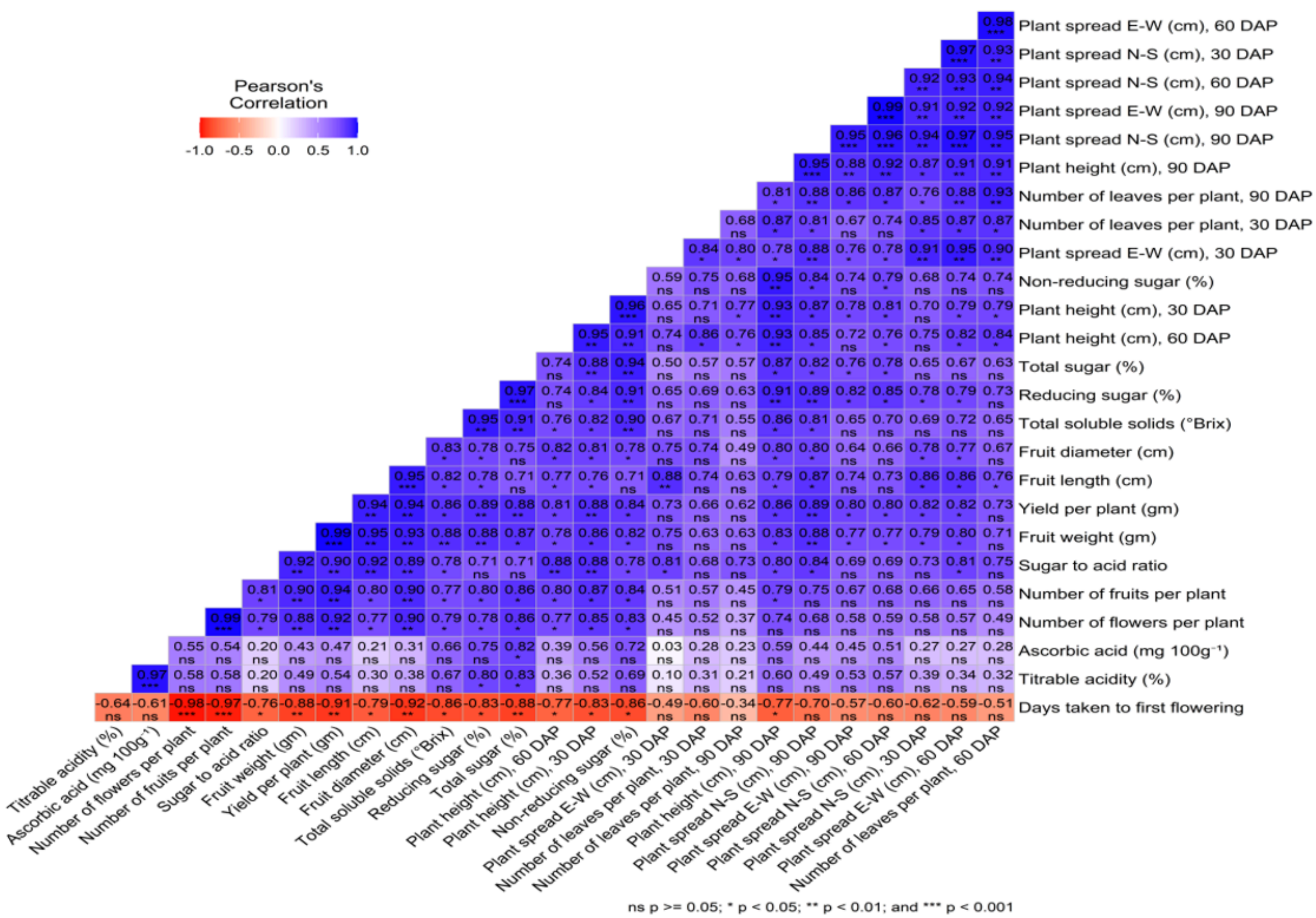

Figure 1

Correlation matrix depicting relationship among various traits in strawberry.

PH30, PH60, PH90- Plant height at 30, 60 and 90 DAP; PS(E-W)30, 60, 90 - Plant spread East-West at 30, 60 and 90 DAP; PS(N–S)30, 60, 90 - Plant spread North-South at 30, 60 and 90 DAP; NL30, NL90 - Number of leaves per plant at 30 and 90 DAP; NF - Number of flowers per plant; NFr - Number of fruits per plant; FW - Fruit weight (g); FL - Fruit length (cm); FD -Fruit diameter (cm); YPP - Yield per plant (g); TSS -Total soluble solids (°Brix);

TS - Total sugar (%); RS – Reducing sugar (%); NRS - Non-reducing sugar (%); SAR -Sugar to acid ratio; AA- Ascorbic acid (mg $100g^{-1}$); TA- Titratable acidity (%); DFF- Days to first flowering.

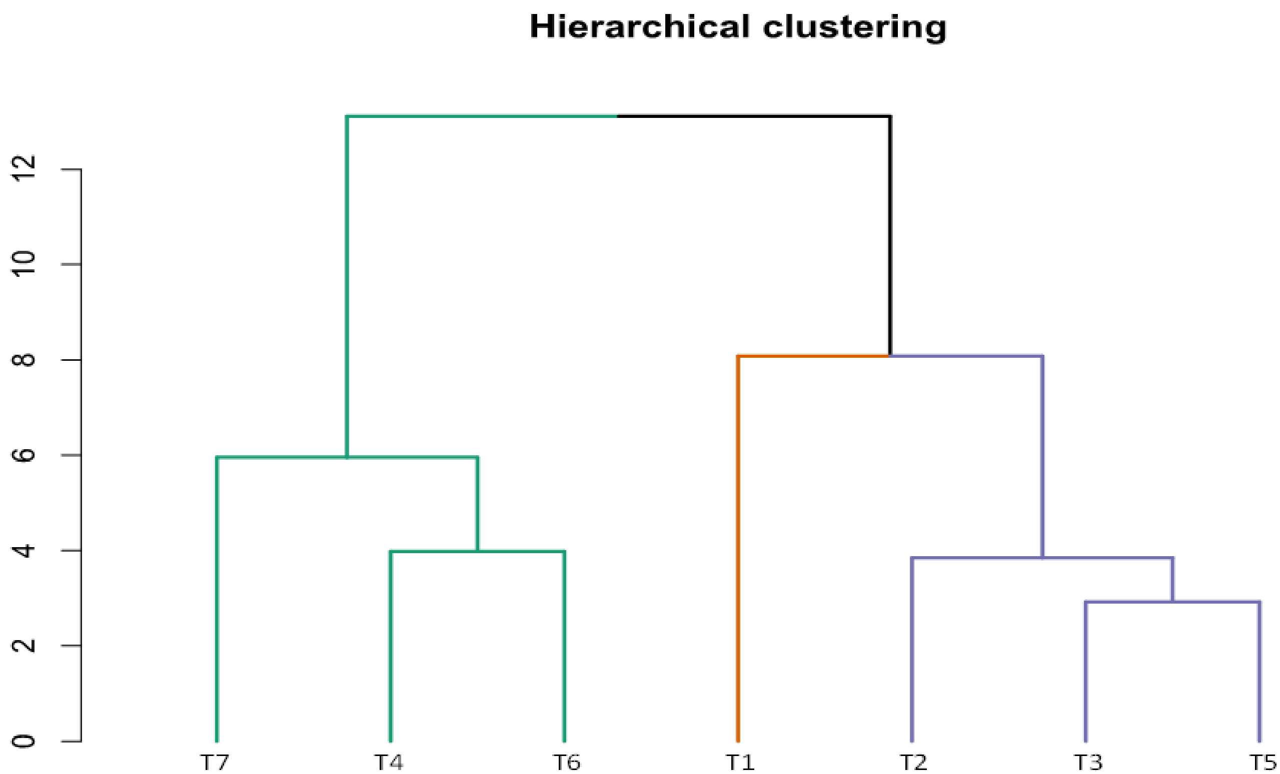

Figure 2

Hierarchical clustering

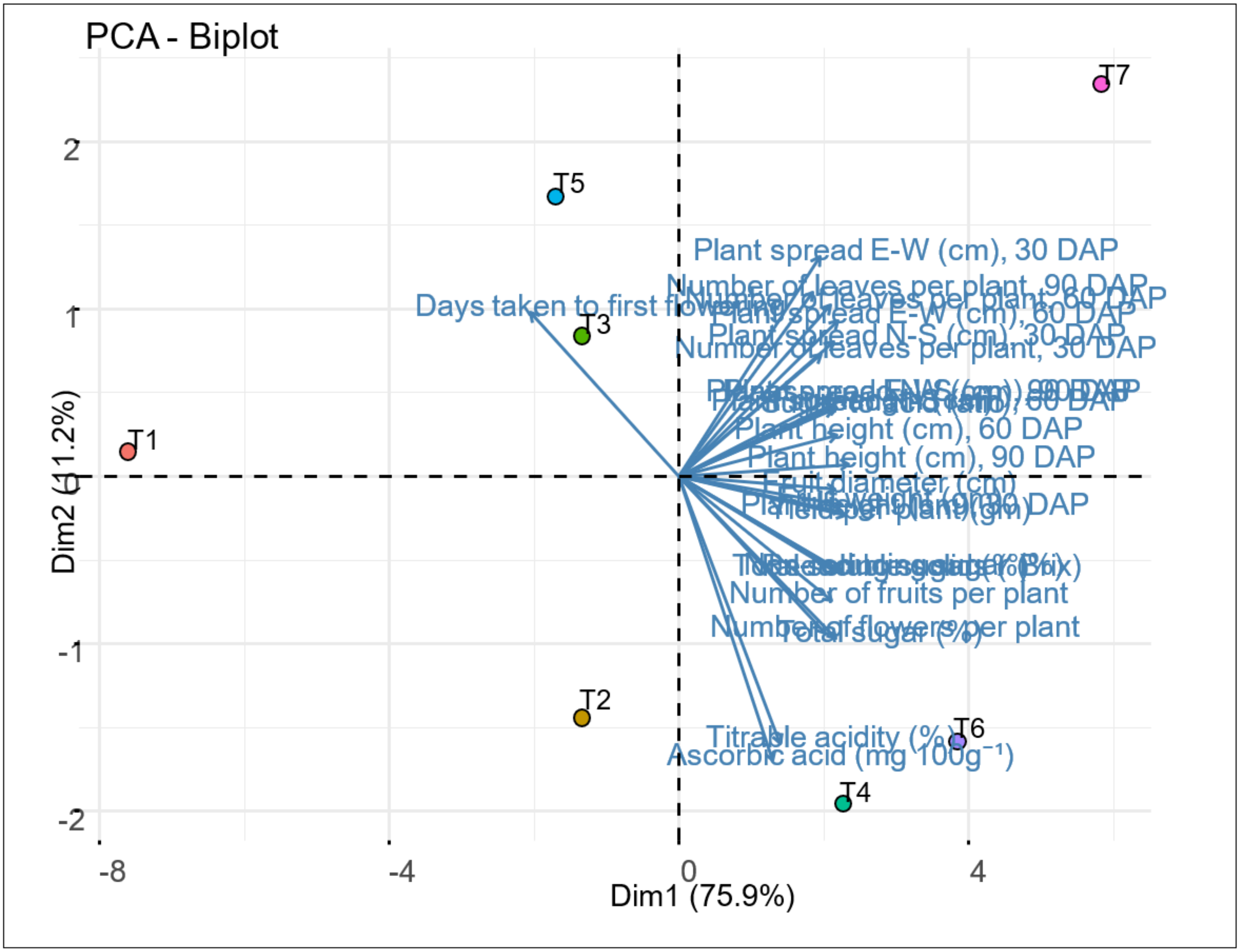

Figure 3

Principal component analysis (PCA)-biplot based on the variance in growth, yield and quality traits of strawberry under different treatment combinations. PH: Plant height; PS: Plant spread (E-W and N-S); NL: Number of leaves per plant; NF: Number of flowers per plant; NFr: Number of fruits per plant; FW: Fruit weight; FL: Fruit length; FD: Fruit diameter; YPP: Yield per plant; TSS: Total soluble solids; TS: Total sugar; RS: Reducing sugar; NRS: Non-reducing sugar; SAR: Sugar to acid ratio; AA: Ascorbic acid; TA: Titratable acidity; DFF: Days to first flowering.