Effect of nutrients and plant growth regulators on growth, yield and fruit quality of strawberry (Fragaria × ananassa Duch.) cv. Winter Dawn

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Research Article

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HIGHLIGHTS

- GA_3 (100 ppm) + 100% RDF maximized vegetative growth: plant height, leaves, spread and petiole length.
- Earliest flowering, highest flowers, fruit set and maximum yield (183.6 g/plant) achieved with GA_3 + full nutrients.
- NAA (100 ppm) + 100% RDF improved fruit sweetness, TSS (7.65°Brix), acidity (0.68%) and TSS:acid ratio (11.25).
- GA_3 enhanced biochemical quality: ascorbic acid, total sugar, reducing and non-reducing sugars.
- Integrating PGRs with full nutrient application boosts growth, yield and fruit quality under subtropical conditions.

ABSTRACT

An investigation was conducted to evaluate the effect of nutrients and plant growth regulators on the performance of strawberry (*Fragaria* × *ananassa* Duch.) cv. Winter Dawn under subtropical conditions in Jabalpur, Madhya Pradesh. The experiment consisted of seven treatments: T_1 – Control, T_2 – 100% RDF + GA_3 (100 ppm), T_3 – 100% RDF + NAA (100 ppm), T_4 – 100% RDF + Triacontanol (10 ppm), T_5 – 75% RDF + GA_3 (100 ppm), T_6 – 75% RDF + NAA (100 ppm) and T_7 – 75% RDF + Triacontanol (10 ppm), each replicated thrice in a Completely Randomized Design (CRD). Among the treatments, the application of GA_3 at 100 ppm with 100% RDF (T_2) stood out, significantly improving plant height, number of leaves, plant spread and ultimately delivering the highest yield per plant (183.6 g). This treatment also enhanced the biochemical composition of the fruit, showing increased levels of ascorbic acid, total sugars and reducing sugars. On the other hand, the combination of NAA at 100 ppm with 100% RDF (T_3) produced the sweetest fruits with the highest TSS (7.65°Brix), lowest acidity (0.68%) and the best TSS:acid ratio (11.25), indicating superior flavor and quality.Among the best treatment combinations, T_2 (100% RDF + GA_3 100 ppm) improved strawberry fruit quality by enhancing ascorbic acid content, total sugars, reducing and non-reducing sugars, increasing TSS and improving the TSS:acid ratio while slightly reducing acidity.These findings suggest that the use of GA_3 with full nutrient application can greatly enhance both the vegetative and reproductive performance of strawberries. Meanwhile, NAA offers a promising approach for improving fruit taste and market appeal. Adopting these treatments could help strawberry growers achieve better yields and improved fruit quality under similar agro-climatic conditions.

Keywords: *Strawberry cv. Winter Dawn, Plant Growth Regulators, Gibberellic Acid, Naphthalene Acetic Acid, Fruit Yield and Quality*

INTRODUCTION

The cultivated strawberry (*Fragaria x ananassa* Duch.), a hybrid derived from two American species, belongs to the Rosaceae family. This fruit is highly prized for its appealing red color, juicy texture, distinctive flavor and sweetness. Beyond its sensory qualities, the strawberry is a highly nutritious food, supplying essential minerals and a significant amount of Vitamin C (40−120 mg/100 g). Furthermore, consuming strawberries may offer health benefits, such as potentially reducing cancer risk by up to 50% (Bakshi *et al.,* 2013). Originally restricted to temperate climates, the development of day-neutral cultivars has allowed its successful commercial cultivation to spread to sub-tropical regions (Lata *et al.,* 2013).

The strawberry is a major, high-value cash crop globally. In India, commercial cultivation spans numerous states, including Haryana, Jammu and Kashmir, Himachal Pradesh, Maharashtra, Tamil Nadu and others (NHB 2021–2022).

While some varieties tolerate subtropical climates, strawberries generally require a calm environment for optimal growth. They are typically short-day plants, needing an 8 to 12-hour period of sunlight for approximately 10 days to stimulate the development of blossoms. During very cold periods, the plants enter a state of dormancy or inactivity. This absorption of sunlight during the required phase significantly boosts flowering. However, in subtropical areas where the winters are milder, varieties exist that continue to develop without a hard rest period (Singh *et al.,* 2022).

Plant growth regulators (PGRs) are widely used to enhance plant growth, yield and fruit quality. They may occur naturally or be synthesized and they influence plant development through various physiological and biochemical pathways. Gibberellic acid (GA_3) has been shown to affect plant height, runner production, flowering, fruit number, fruit size, fruit weight and overall fruit quality (Kumra *et al.,* 2018). In non-chilled strawberry plants, GA_3 application promoted flowering, shortened the cropping period, and improved both vegetative and reproductive growth (Paroussi*et al.,* 2002). GA_3 can also mimic the effects of cold treatment or extended photoperiods (Guttridge, 1970). Moreover, gibberellins act as long-day hormones in short-day plants. However, their application tends to suppress floral initiation while stimulating vegetative growth (Kender*et al.,* 1971).

Naphthalene acetic acid (NAA), a synthetic auxin, is widely used in strawberry cultivation to improve fruit quality by enhancing sugar, ascorbic acid, and acidity levels, while also preventing premature fruit drop and increasing fruit size (Paikra *et al*., 2018; Bhople *et al*., 2020). Triacontanol, first identified as a growth regulator in alfalfa (Ries *et al*., 1977), boosts cellular efficiency and promotes plant growth, leading to higher yields across several crops by improving chlorophyll content, photosynthesis, and overall physiological performance (Perveen *et al*., 2010; Naeem *et al*., 2012). Additionally, nutrient management plays a critical role in strawberry production, as balanced macro- and micronutrient supply ensures better growth, higher yields and superior fruit quality (Barooah & Datta, 2020; Bakshi *et al*., 2013).

Despite improvements in cultivar development and farming techniques, strawberry production is still highly sensitive to environmental stresses like temperature changes, water shortages, and nutrient imbalances. Combining plant growth regulators (PGRs), proper nutrient management, and suitable cultural practices is therefore crucial for achieving consistent yields and high-quality fruit. Studying how these factors work together offers valuable insights for enhancing strawberry cultivation, especially in subtropical regions with variable climatic conditions.

MATERIALS AND METHOD

Experimental Details

The present investigation entitled "Effect of Nutrients and Plant Growth Regulators on the Performance of Strawberry (*Fragaria* × *ananassa* Duch.) cv. Winter Dawn" was carried out during the 2024–25 growing season at the Fruit Research Station Imaliya (Latitude: 23.10° N; Longitude: 79.58° E), Department of Horticulture, Jawaharlal Nehru Krishi VishwaVidyalaya, Jabalpur, Madhya Pradesh **(Figure 2)**. Graphical representation of week wise meteorological observation during crop season is shown in the **Figure 1.** The investigation followed a completely randomized design, comprising seven unique plant growth regulators treatments, each with three replications. Observations were recorded by selecting representative plants from each treatment to evaluate various parameters related to growth, yield and fruit quality. The study involved seven different treatment **(Table1)** combinations comprising plant growth regulators (GA_3, NAA and Triacontanol) along with Different levels of the recommended dose of fertilizers, as follows: T_1: Control, T_2: 100% RDF + GA_3 (100 ppm), T_3: 100% RDF + NAA (100 ppm), T_4: 100% RDF + Triacontanol (10 ppm), T_5: 75% RDF + GA_3 (100 ppm), T_6: 75% RDF + NAA (100 ppm), T_7: 75% RDF + Triacontanol (10 ppm).

Source of planting material

To carry out the present investigation, uniform tissue culture planting materials of Strawberry cv. winter dawn were purchased from a private organization (BERRIES BIOTECH & FARMS LLP, Pune, Maharashtra, 411041, India).

Table 1 Description of treatments involving Nutrients and Plant Growth Regulators on Performance of Strawberry

Treatments	**Treatments details**
T1	Control
T2	100 % RDF + Spray of GA_3 (100 ppm) at 45, 60 & 75 DAT
T3	100 % RDF + Spray of NAA (100 ppm) at 45, 60 & 75 DAT
T4	100 % RDF + Spray of Triacontanol (10 ppm) at 45, 60 & 75 DAT
T5	75 % RDF + Spray of GA_3 (100 ppm) at 45, 60 & 75 DAT
T6	75 % RDF + Spray of NAA (100 ppm) at 45, 60 & 75 DAT
T7	75 % RDF + Spray of Triacontanol (10 ppm) at 45, 60 & 75 DAT

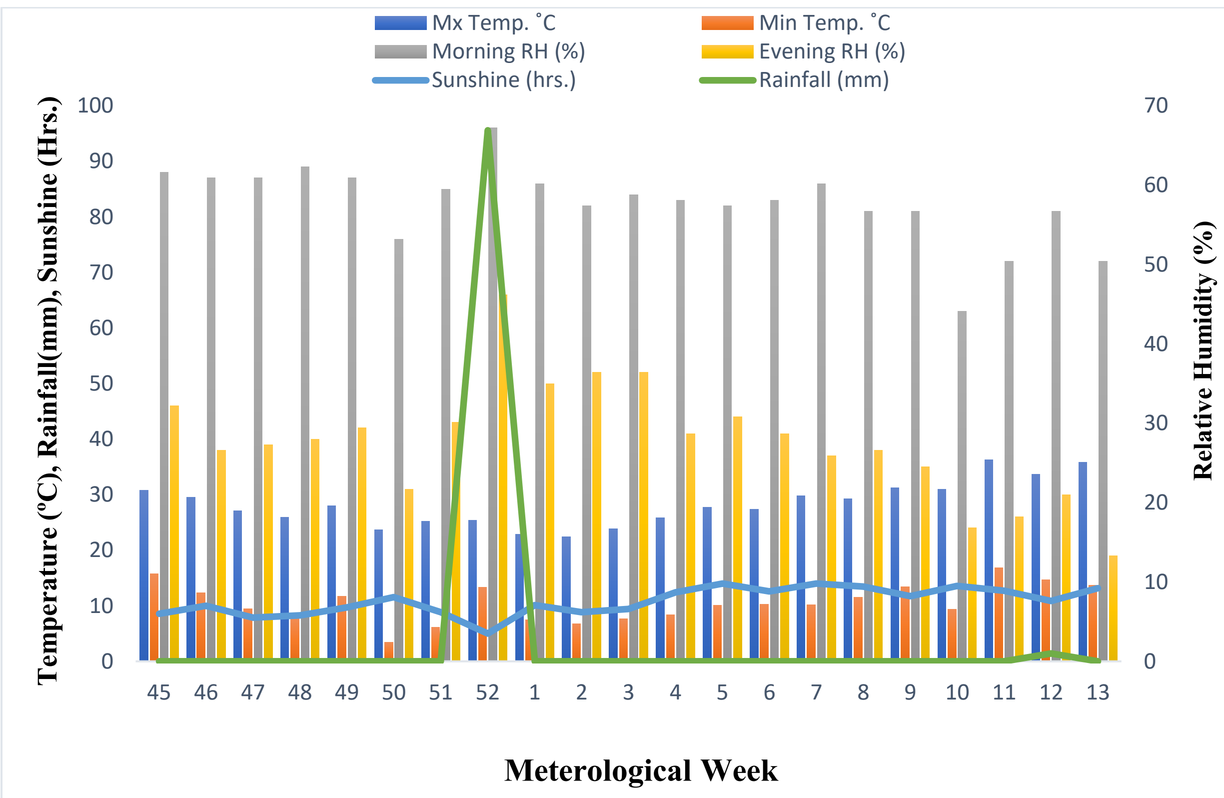


Fig.1 Graphical representation of week wise meteorological observation during crop season 2024-25

Methods of Analysis

TSS - Total Soluble Solid (° Brix): The total soluble solids content in the juice of ripe fruits was determined using a hand-held refractometer with a range of 0–32 °Brix. A few drops of juice were placed on the prism surface to record the TSS reading. Before measurement, the refractometer was calibrated with distilled water. The results were expressed in degrees Brix (°Brix).

Acidity (%): To determine the titratable acidity (TA), 5 milliliters of juice were extracted from the fruit sample and diluted to a final volume of 100 milliliters. The diluted juice was then titrated with 0.1 N sodium hydroxide (NaOH), using phenolphthalein as the indicator. The acidity was calculated as a percentage of malic acid using the standard formula outlined by Ranganna (1986).

$$\textbf{Total acidity}\ (\%) = \frac{\text{Titre value} \times \text{Normality of NaOH} \times \text{Vol. mad up} \times \text{eq. weight of acid} \times 100}{\text{Vol. of sample taken for estimation} \times \text{wt. or vol. of sample taken} \times 100}$$

TSS: Acid ratio

The TSS:acid ratio was determined using the following formula.

$$\textbf{TSS}: \textbf{Acidratio} = \frac{\text{TSS (° Brix)}}{\text{Acid (\%)}}$$

Ascorbic acid (mg/100g): Ten milliliters of strawberry juice were diluted to 100 mL with 3% metaphosphoric acid, filtered (Whatman No. 42), and treated with 0.1 mL HCl and 40% formaldehyde to remove sulfur dioxide interference. A 10 mL aliquot was titrated with standard 2,6-dichlorophenol-indophenol dye until a persistent pink endpoint (15 seconds) was reached. Ascorbic acid content was calculated as described by Ranganna (1986):

$$\textbf{Ascorbic acid}\ (\textbf{mg/100g}) = \frac{\text{Titre} \times \text{dye factor} \times \text{Volume made up} \times 100}{\text{Aliquot taken (ml)} \times \text{Weight of sample (g)}}$$

Sugar Estimation: Sugars were estimated following Lane and Eynon (1923) as modified by Ranganna (1986). A 25 mL juice sample was diluted with 100 mL distilled water, neutralized with 1 N NaOH, treated with 2 mL lead acetate for 10 min, and neutralized with 1–2 mL potassium oxalate. The final volume was adjusted to 250 mL.

Fehling's solutions A and B (50 mL each) were mixed; 10 mL of this mixture was titrated with standard invert sugar solution in a 250-mL flask containing 50 mL distilled water, using methylene blue as an endpoint indicator. Titration was completed within one minute.

$$\mathbf{Factor\ of\ Fehling's solution} = \frac{\text{Titre value}}{1000} \times 2.5$$

Reducing sugar (%): A 10 mL sample was diluted to 100 mL with distilled water and used for titration. In a flask, 5 mL each of Fehling's solutions A and B were mixed with 10 mL distilled water, heated, and a few drops of methylene blue were added. Titration was performed with the diluted sample until a brick-red precipitate indicated the endpoint, and the volume was recorded.

$$\mathbf{Reducing\ sugar}\ (\%) = \frac{\text{Dilution} \times \text{Factor of Fehling (gm)}}{\text{Weight of sample} \times \text{Titre}} \times 100$$

Total sugar (%):

$$\mathbf{Total\ sugar}\ (\%) = \frac{\text{Dilution} \times \text{Factor of Fehling (gm)}}{\text{Weight of sample} \times \text{Titre}} \times 100$$

Non-reducing sugar (%): The percentage of non-reducing sugars was calculated by deducting the percentage of reducing sugars from the total sugar content and expressed as a percentage.

$$\mathbf{Non - Reducing\ sugar}(\%) = \text{Total sugar } (\%) - \text{Reducing sugar}(\%)$$

Statical analysis

The data underwent an analysis of variance (ANOVA), and statistical analysis was conducted using Microsoft Excel software packages (Meena *et al*., 2024).

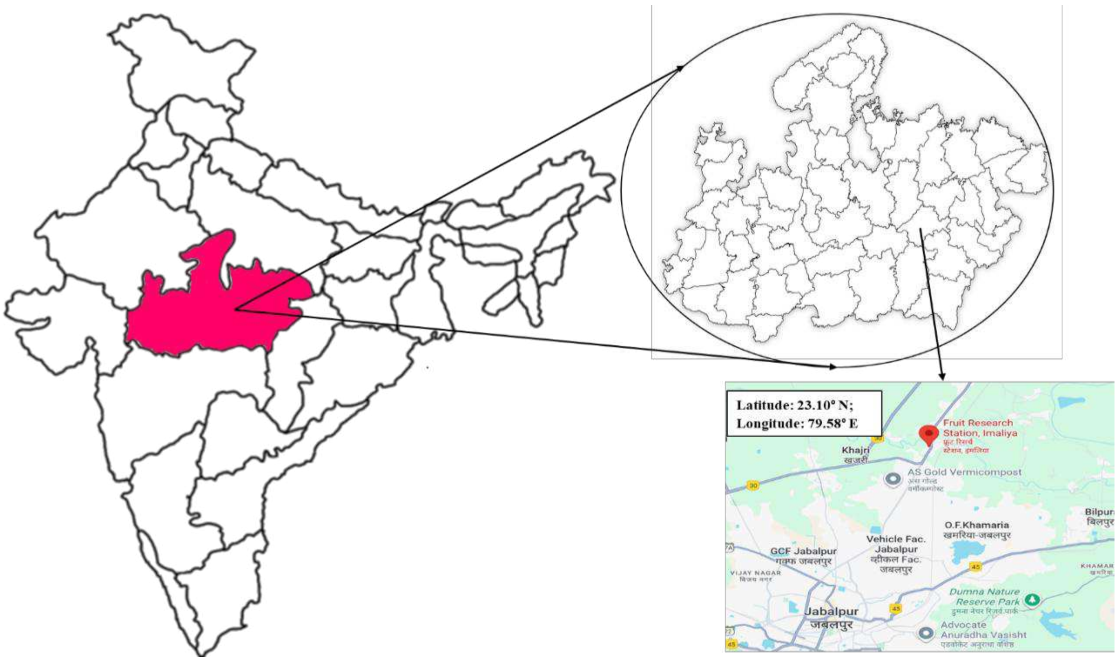


Fig. 2 Geographical location of the study area: Jabalpur, India

RESULTS AND DISCUSSION

1. *Growth parameters*

Application of nutrients in combination with plant growth regulators exerted a significant influence on the vegetative growth of strawberry (*Fragaria* × *ananassa* Duch.) cv. Winter Dawn (Table 2). Among the various treatments, plants treated with GA_3 at 100 ppm along with 100 percent of the recommended dose of fertilizers (T_2) exhibited superior vegetative performance across all parameters. This treatment produced the tallest plants (18.9 cm), the highest number of trifoliate leaves (24.3 per plant), the widest plant spread in both east–west (25.9 cm) and north–south (26.2 cm) directions, and the longest petiole length (14.2 cm). The marked improvement in vegetative growth under GA_3 application can be attributed to its role in stimulating cell division and elongation, which enhances internodal length and canopy development through greater nutrient mobilization and photosynthetic activity (Singh *et al*., 2025; Kumar *et al*., 2025).

In contrast, the control treatment (T_1) consistently recorded the lowest values for all growth attributes—plant height (13.2 cm), number of trifoliate leaves (17.0), plant spread (17.5 cm east–west and 17.2 cm north–south) and petiole length (10.0 cm)—indicating that the absence of growth regulators restricted vegetative development and canopy expansion. Treatments involving NAA (100 ppm) and Triacontanol (10 ppm) also showed moderate improvement over the control, particularly under 100 percent RDF, although their effects were less pronounced than those of GA_3. The positive impact of NAA may be linked to its ability to enhance epidermal and parenchyma cell elongation in the sub-apical meristem regions, while triacontanol is known to improve chlorophyll synthesis, photosynthetic rate and overall metabolic efficiency, thereby promoting vegetative vigor (Tao *et al*., 2025).

The superior performance of GA_3-treated plants observed in this study is in close agreement with the findings of Kharjana *et al*. (2022), Tripathi (2009), Prasad *et al*. (2012) and Paikra *et al*. (2018), who also reported that GA_3 significantly enhances plant height and overall vegetative growth in strawberries. Enhanced plant spread due to GA_3 might be attributed to greater petiole elongation and outward leaf orientation, leading to wider canopy formation, as also reported by Singh and Tripathi (2010) and Paikra *et al*. (2018). Similarly, the increase in petiole length under GA_3 application could be due to its effect on microtubule orientation and the promotion of longitudinal cell expansion, a phenomenon earlier noted by Singh and Kabul (1970), Sharma and Singh (2009), Kumar and Tripathi (2009), Sehkar (2013), Saima *et al*. (2014), Dubey *et al*. (2017), Khunte *et al*. (2020) and Pandey *et al*. (2020).

Overall, it can be concluded that GA_3 at 100 ppm in combination with 100 percent RDF proved most effective for stimulating vegetative growth in strawberry cv. Winter Dawn. The consistent increase in plant height, number of leaves, plant spread, and petiole length under this treatment demonstrates the synergistic influence of nutrient supply and hormonal regulation. These results reaffirm the pivotal role of gibberellic acid in promoting cellular elongation and physiological efficiency, ultimately contributing to vigorous vegetative growth that forms the foundation for higher productivity in strawberries.

Table 2 Effect of Nutrients and Plant Growth Regulators on growth parameters of strawberry

Treatments	**Plant height (cm)**	**Trifoliate leaves per plant**	**Plant spread (E-W)**	**Plant spread (N-S)**	**Petiole length (cm)**
T_1: Control	13.1	17.0	17.5	17.2	10.0
T_2:100% RDF + Spray of GA3 (100 ppm) at 45, 60 & 75 DAT	18.9	24.3	25.9	26.2	14.2
T_3: 100%RDF + Spray of NAA (100 ppm) at 45, 60 & 75 DAT	17.8	23.0	23.1	24.0	13.2
T_4: 100% RDF + Spray of Triacontanol (10 ppm) at 45, 60	15.8	20.2	21.5	22.1	11.7

& 75 DAT					
T_5: 75% RDF + Spray of GA3 (100 ppm) at 45, 60 & 75 DAT	18.1	23.2	24.7	24.7	13.8
T_6: 75% RDF+ Spray of NAA (100 ppm) at 45, 60 & 75 DAT	17.2	22.2	22.4	22.3	12.5
T_7: 75% RDF + Spray of Triacontanol (10 ppm) at 45, 60 & 75 DAT	15.3	20.1	21.5	21.8	11.9
SEm (±)	0.54	0.49	0.69	0.77	0.42
C.D. @ 5%	1.63	1.48	2.10	2.32	1.28

2. *Yield parameters*

The minimum number of days to first flowering (56.0 days) was recorded under treatment T_2 [100% RDF + GA_3 100 ppm], while the maximum number of days to first flowering (67.3 days) was observed in the control (T_1), as presented in Table 3. Early flower initiation indicates that the plant efficiently utilized the essential nutrients provided through a balanced hormone application, resulting in earlier flowering in strawberries. This may be attributed to the synergistic effect of NAA and GA_3, which promote cell division and growth, thereby shortening the flowering duration. Similar results were also reported by Singh and Singh (2006), Prasad *et al.* (2012), Dubey *et al.* (2017) and Sood *et al.* (2018) in strawberry.

The maximum number of flowers per plant (20.3) was recorded under treatment T_2 [100% RDF + GA_3 100 ppm], while the minimum number of flowers per plant (13.0) was observed in the control (T_1), as shown in Table 3. The increase in the number of flowers may be attributed to the hormonal treatment, which accelerated the development of differentiated inflorescences and promoted flowering. Additionally, it could be due to increased carbohydrate accumulation resulting from enhanced photosynthesis, encouraging the plant to produce more flowers. Similar results were also reported by Prasad *et al.* (2012), Kaur *et al.* (2018) and Dubey *et al.* (2017) in strawberry.

The maximum number of fruits set per plant (15.3) was recorded under treatment T_2, while the minimum number of fruits per plant (10.7) was observed in the control (T_1), as shown in Table 3. The increase in fruit set with GA_3 application may be attributed to its stimulatory role in fruit development, which is influenced by both pollen and ovary activity. It is possible that the pollen component functions as a co-enzyme or activator of enzymatic systems within the ovary, facilitating the release of active hormones from stored reserves. Similar results were also reported by Singh and Singh (2006) and Kumar and Tripathi (2009) in strawberry.

The results in Figure 4 and 5 show that fruit dimensions were significantly influenced by the treatments. The maximum fruit length (25.0 mm) was recorded under T_2 (100% RDF + GA_3 100 ppm), whereas the minimum (16.1 mm) occurred in the control (T_1). The increase in fruit length may be due to enhanced carbohydrate accumulation and the stimulatory effect of GA_3 on cell division and elongation, resulting in better fruit development. Similar findings were reported by Thakur *et al*. (2015), Sevan *et al*. (2014) and Yadav *et al*. (2017) in strawberry.

Likewise, the maximum fruit diameter (20.1 mm) was observed in T_2, while the minimum (14.9 mm) was recorded in T_1. The increase in fruit diameter could be attributed to improved photosynthetic efficiency and better assimilate translocation in GA_3-treated plants, which enhanced total solid accumulation and nutrient allocation to each fruit. These results are in agreement with the observations of Yadav *et al*. (2017) in strawberry.

The maximum fruit weight (13 g) was recorded under treatment T_2 [100% RDF + GA_3 100 ppm], whereas the minimum fruit weight (10.33 g) was observed in the control (T_1), as shown in **Figure 4 and 5**. The application of GA_3 likely enhanced fruit growth and final size by promoting cell elongation and expansion, leading to increased fruit weight. GA_3 also stimulated the growth of vegetative parts, resulting in greater production of assimilates that supported fruit development. Additionally, the improved photosynthetic capacity of plants treated with GA_3 at 100 ppm may have contributed to the increase in fruit size and weight. Similar results were reported by Singh and Singh (2009), Prasad *et al.* (2012) and Rajbahar *et al.* (2015) in strawberry.

The data on yield per plant under different treatments are presented in Table 3. The results indicate that plants treated with T_2 produced the highest yield per plant (183.6 g), which was statistically significant, while the minimum yield (93 g) was observed in the control (T_1). The increased yield in GA_3-treated plants may be attributed to enhanced vegetative growth, which supports better fruit set and increased fruit weight. Throughout the plant's life cycle, vegetative development influences yield by affecting the crop's sink capacity. Vigorous vegetative growth enhances nutrient absorption, and larger leaves along with higher photosynthetic activity likely produced more assimilates, contributing to the higher yield. These findings are in agreement with the results of Sison and Marcelino, (2025), Jasrotia *et al.* (2014), and Saima *et al.* (2014) in strawberry.

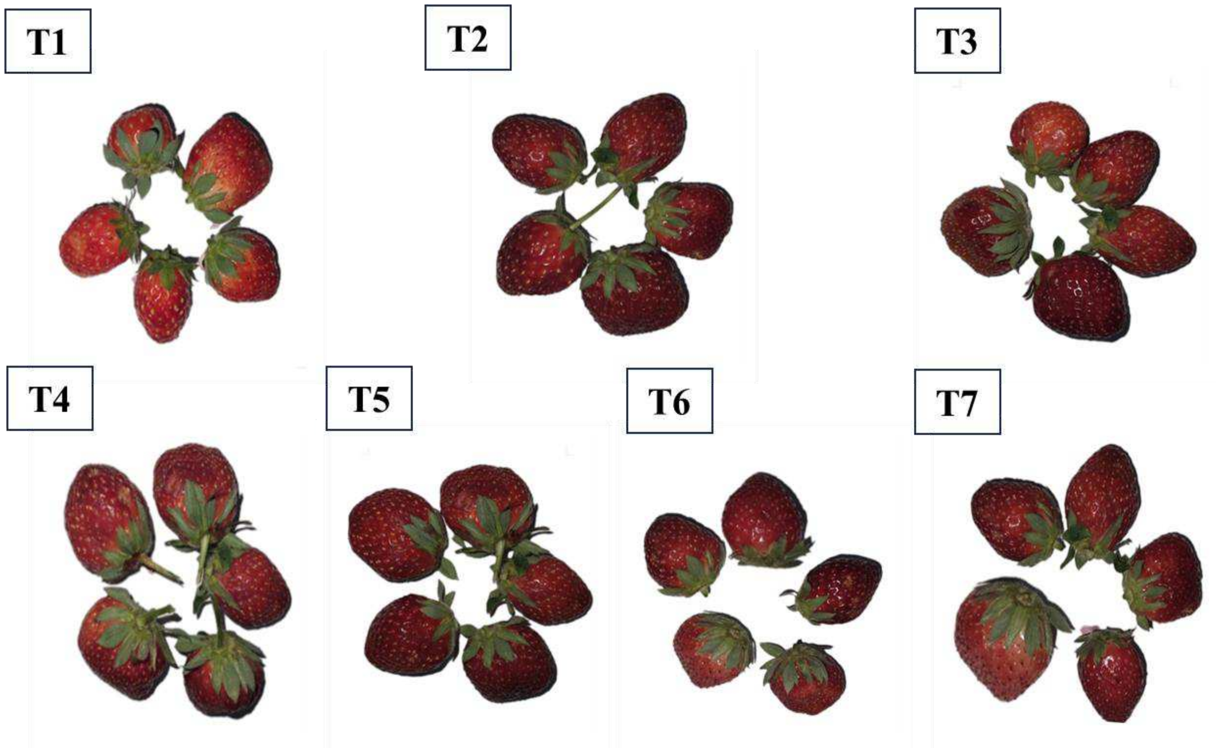


Fig. 3 Effect of nutrients and plant growth regulators on strawberry

T_1

T_2

T1 T2

T1 T2

Fig. 4 Effect of nutrients and plant growth regulators on fruit weight (g), fruit length (mm), diameter (mm) strawberry

Table 3 Effect of nutrients and plant growth regulators on growth parameters of strawberry

Treatments	**No. Days to 1st flowering**	**Number of flowers per plant**	**Number of fruits per plant**	**Fruit yield/ plant (g)**
T1: Control	67.3	13.0	10.7	93.0
T2:100% RDF + Spray of GA3 (100 ppm) at 45, 60 & 75 DAT	56.0	20.3	15.3	184
T3: 100%RDF + Spray of NAA (100 ppm) at 45, 60 & 75 DAT	58.3	17.8	14.0	174
T4: 100%RDF + Spray of Triacontanol (10 ppm) at 45, 60 & 75 DAT	61.2	16.2	12.2	148
T5: 75% RDF + Spray of GA3 (100 ppm) at 45, 60 & 75 DAT	61.6	16.6	14.0	182
T6: 75% RDF+ Spray of NAA (100 ppm) at 45, 60 & 75 DAT	57.7	19.1	14.3	173
T7: 75% RDF + Spray of Triacontanol (10 ppm) at 45, 60 & 75 DAT	61.5	15.3	11.8	127
SEm (±)	1.15	0.56	0.35	4.79

C.D. @ 5%	3.48	1.71	1.07	14.54

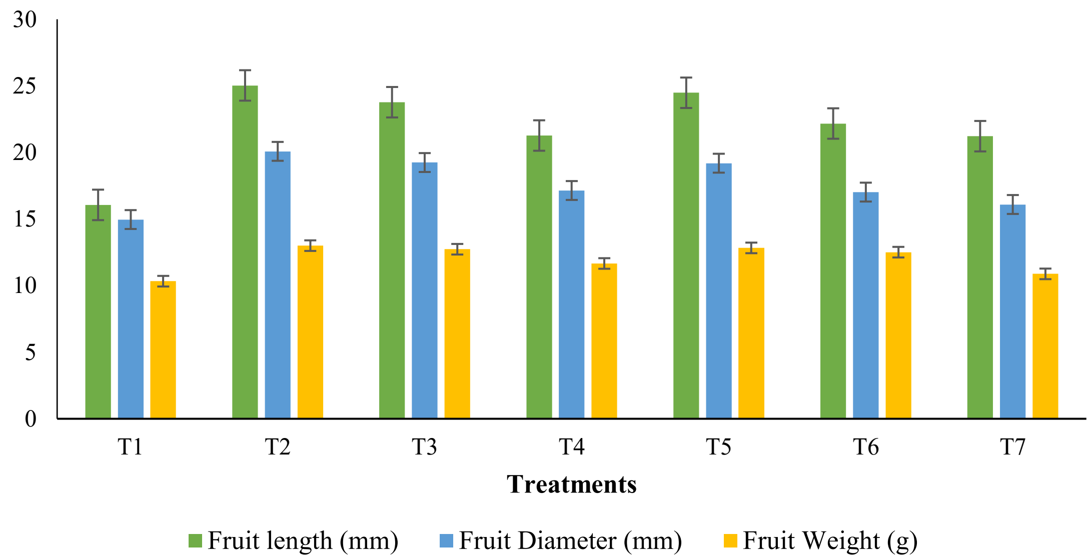


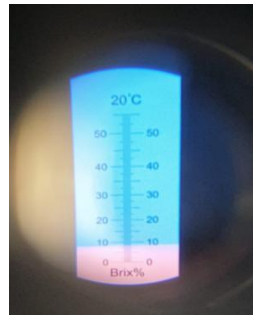
Fig. 5 Effect of nutrients and plant growth regulators on fruit length, diameter and weight of strawberry

3. Chemical quality parameters

3.1 Total soluble solids (°Brix)

The highest fruit TSS (7.65° Brix) was recorded in plants treated with T_3 [100% RDF + NAA spray (100 ppm) at 45, 60, and 75 DAT], whereas the lowest TSS (6.41° Brix) was observed in the control (T_1), as shown in **Table 4 and Fig. 6.**The increase in total soluble solids with NAA application may be due to the accelerated metabolic conversion of starch and pectin into soluble sugars, along with enhanced translocation of sugars from the leaves to the developing fruits (Brahamchari and Rani, 2001). Similar findings were also reported by Kumar *et al*. (2009) and Meena *et al*. (2024).

T$_1$(Control)



T$_2$(100%RDF + NAA100 PPM)

Fig. 6 Effect of nutrients and plant growth regulators on TSS (˚brix)

3.2 Acidity (%)

The lowest fruit acidity (0.68%) was observed in plants treated with T$_3$ [100% RDF + NAA spray (100 ppm) at 45, 60, and 75 DAT], while the highest acidity (0.78%) was recorded in the control (T$_1$), as shown in Table 4. The reduction in titratable acidity with increasing NAA concentration may be attributed to accelerated fruit ripening induced by the treatment, during which organic acids are either consumed through respiration or rapidly converted into sugars. Supporting this, Agnihotri *et al.* (2013) reported a minimum acidity of 0.27% in guava following foliar application of NAA at 300 ppm. Similar findings were also reported by Xiao *et al.* (2005), Singh *et al.* (2017) and Garasiya *et al.* (2013).

3.3 TSS: Acid ratio (%)

The highest TSS:acid ratio (11.25%) was recorded in fruits from plants treated with T$_3$ [100% RDF + NAA spray (100 ppm) at 45, 60 and 75 DAT], whereas the lowest ratio (8.21%) was observed in the control (T$_1$), as shown in Table 4. These results indicate that T$_3$ was the most effective treatment for improving fruit quality by enhancing the TSS:acid ratio. The increase in NAA concentration likely contributed to a reduction in titratable acidity, possibly due to accelerated fruit ripening, during which organic acids are either consumed in respiration or converted rapidly into sugars. Supporting this, Agnihotri *et al.* (2013) reported the lowest acidity (0.27%) in guava following foliar application of NAA at 300 ppm. Similar observations were also made by Kumar *et al.* (2009), Xiao *et al.* (2005), Singh *et al.* (2017) and Garasiya *et al.* (2013).

3.4 Ascorbic acid (mg/100 g)

The highest ascorbic acid content in fruits (57.14 mg/100 g) was recorded under treatment T_2 [100% RDF + GA_3 spray (100 ppm) at 45, 60 and 75 DAT], while the lowest content (51.38 mg/100 g) was observed in the control (T_1), as shown in Table 4. The increase in ascorbic acid may be attributed to the catalytic effect of gibberellins and auxins, which promote its biosynthesis from precursors such as glucose-6-phosphate, or by inhibiting its degradation into dehydroascorbic acid through suppression of the enzyme ascorbic acid oxidase (Brahamachari and Rani, 2001). These findings are in agreement with the observations of Singh and Singh (2009), Kumar *et al.* (2012), Paikra *et al.* (2018), Kong *et al.* (2019) and Bairwa *et al.* (2020).

3.5 Reducing sugar (%)

The highest reducing sugar content (2.81%) was observed in treatment T_2 [100% RDF + GA_3 spray (100 ppm) at 45, 60 and 75 DAT], whereas the lowest reducing sugar content (2.18%) was recorded in the control (T_1) (**Fig. 7**). The increase in total soluble solids and reduction in acidity may be attributed to the accelerated conversion of starch into sugars (both reducing and non-reducing) during rapid fruit ripening. Paikra *et al.* (2018) also reported an increase in reducing sugar content in Strawberry cv. Sabrina with the application of 75 ppm GA_3, and similar results were observed by Sehkar (2013) using the same GA_3 concentration.

3.6 Total sugar (%)

The highest total sugar content (7.30%) was recorded in treatment T_2 [100% RDF + GA_3 spray (100 ppm) at 45, 60 and 75 DAT], whereas the lowest total sugar content (5.29%) was observed in the control (T_1) (**Fig. 7**). Gibberellins are known to enhance the activity of α-amylase, an enzyme responsible for breaking down starch into sugars, thereby promoting greater sugar accumulation in fruits. Similar results were reported by Singh and Singh (2009), who observed maximum total sugars with GA_3 application in strawberries. These findings are further supported by Thakur *et al.* (2015) and Paikra *et al.* (2018).

3.7 Non-reducing sugar (%)

The maximum non-reducing sugar content (4.49 %) was recorded in treatment T_2 [100 % RDF + Spray of GA3 (100 ppm) at 45, 60 & 75 DAT], while the minimum non-reducing sugar (3.11 %)

was observed in the control treatment T_1(Control) (**Fig. 7)**. The increase in non-reducing sugars in GA_3-treated plants could be attributed to accelerated fruit ripening triggered by hydrolytic enzymes. These enzymes facilitate intense metabolic activity, leading to the breakdown of complex polysaccharides and organic acids into simpler sugars through enhanced respiration. Similar findings were reported by Kumar *et al.* (2012), Khunte *et al.* (2014) and Thakur *et al.* (2015) in strawberries.

Table 4 Effect of Nutrients and Plant Growth Regulators on TSS, Acidity, TSS: Acidity ratio and Ascorbic acid (g) of Strawberry fruit

Treatments	TSS (˚Brix)	Acidity (%)	TSS: Acidity ratio	Ascorbic acid (g)
T1: Control	6.41	0.78	8.21	51.4
T2:100% RDF + Spray of GA3 (100 ppm) at 45, 60 & 75 DAT	7.40	0.70	10.57	57.1
T3: 100%RDF + Spray of NAA (100 ppm) at 45, 60 & 75 DAT	7.65	0.68	11.25	54.8
T4: 100%RDF + Spray of Triacontanol (10 ppm) at 45, 60 & 75 DAT	7.11	0.75	9.48	53.4
T5: 75% RDF + Spray of GA3 (100 ppm) at 45, 60 & 75 DAT	7.56	0.69	10.95	55.6
T6: 75% RDF+ Spray of NAA (100 ppm) at 45, 60 & 75 DAT	7.38	0.73	10.10	54.2
T7: 75% RDF + Spray of Triacontanol (10 ppm) at 45, 60 & 75 DAT	6.54	0.77	8.49	53.8
SEm (±)	0.15	0.01	0.14	1.02
C.D. @ 5%	0.46	0.04	0.42	3.09

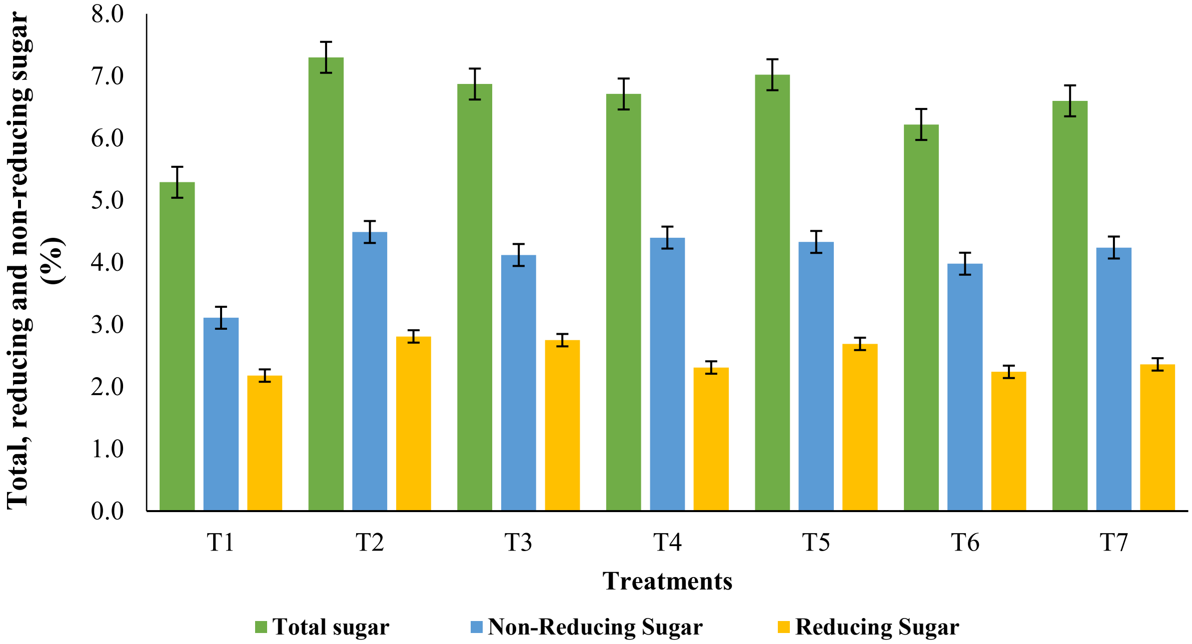


Fig. 7 Effect of Nutrients and Plant Growth Regulators on Total Sugar (%), Reducing Sugar (%) and Non-Reducing Sugar (%) of Strawberry fruit

Conclusions

The present study clearly demonstrated that the combined use of nutrients and plant growth regulators exerts a marked influence on the vegetative growth, yield, and fruit quality of strawberry (*Fragaria* × *ananassa* Duch.) cv. Winter Dawn under the subtropical conditions of Jabalpur, Madhya Pradesh. Among the treatments, the application of GA_3 at 100 ppm along with 100 % of the recommended dose of fertilizers (RDF) consistently performed best across most parameters.Plants treated with GA_3 (100 ppm + 100 % RDF) exhibited superior vegetative growth, reflected in greater plant height, more trifoliate leaves, wider plant spread, and longer petioles. This treatment also promoted earlier flowering, a higher number of flowers and fruits per plant, and ultimately produced the highest yield per plant. These effects can be attributed to the physiological role of gibberellins in enhancing cell elongation, photosynthetic efficiency, and assimilate translocation, which collectively support both vegetative and reproductive development. With respect to fruit quality, the NAA (100 ppm + 100 % RDF) treatment proved most effective in improving the sweetness and flavor profile of fruits, as indicated by higher total soluble solids and TSS:acid ratio, along with lower acidity. Meanwhile, GA_3 application further enhanced biochemical quality through increased ascorbic acid and total sugar content. Taken together, the results indicate that integrating GA_3 at 100 ppm with the full recommended nutrient dose can serve as an effective strategy to improve growth, productivity, and fruit quality in strawberry cv. Winter Dawn under central Indian conditions. Adoption of this treatment combination could therefore be beneficial for farmers seeking higher economic returns and better fruit quality from strawberry cultivation.

Author contributions

Vijay Ram Meena: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Rajnee Sharma: Data curation, Investigation, Methodology, Supervision, Writing – review & editing. Chandra Shekhar: Investigation, Methodology, Writing – review & editing. Atma Ram Meena: Data curation, Investigation, Methodology, Writing – review & editing. Narotam Nagar: Writing – review & editing. Devkumar Sareyam: Writing – review & editing. Siyaram Meena: Data curation, Investigation, Methodology, Resources, Writing – review & editing. Latesh Kumar: Methodology, Writing – review & editing. Harshit Jangid: Writing – review & editing.

Conflict of interest

Vijay Ram Meena, Rajnee Sharma, Chandra Shekhar Pandey, Atma Ram Meen, Narotam Nagar, Devkumar Sareyam, Siyaram Meena, Latesh Kumar and Harshit Jangid declare that they have no competing interests.

Consent for publication

All authors have read and agreed to the published version of the manuscript.

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Ethical standards

For this article no studies with human participants or animals were performed by any of the authors. All studies mentioned were in accordance with the ethical standards indicated in each case.

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