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Differential Responses of Plant Growth Bioregulators on the Quality and Economic Returns of Strawberry Cultivars

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Strawberry productivity and fruit quality are influenced by cultivar selection and exogenous application of plant growth regulators. The present investigation was conducted during 2023–2024 at the research farm of Mata Gujri College, Sri Fatehgarh Sahib, Punjab, India, to assess the responses of Camarosa and Winter Dawn to gibberellic acid (GA3) and naphthalene acetic acid (NAA). The experiment was laid out in a factorial randomised block design with three replications. Treatments comprised control, GA3 at 50 ppm, GA3 at 100 ppm, NAA at 50 ppm, and NAA at 100 ppm. Observations were recorded for vegetative growth, phenology, fruit size, yield, biochemical quality, and economic returns. The treatment PGR2 (GA3 at 100 ppm) recorded the highest mean plant height (21.40 cm), earliest flowering (56.67 days), number of flowers per plant (19.67), berry length (39.40 mm), berry breadth (24.47 mm), total soluble solids (11.02 °Brix), total sugars (6.16%), reducing sugars (4.04%), number of fruits per plant (18.65), and yield per plant (274.56 g). It

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also recorded the lowest titratable acidity (0.63%). Among the interaction treatments, Camarosa with GA3 at 100 ppm (V1PGR2) produced the highest gross income (Rs. 2,421,900 ha-1), net return (Rs. 1,982,540 ha-1), and benefit-cost ratio (4.51). The lowest economic return was observed in Winter Dawn under the control treatment. These findings indicate that foliar application of GA3 at 100 ppm, particularly in Camarosa, improved measured quality, yield, and profitability parameters under the experimental conditions of this field study.

Keywords: Fragaria × ananassa; Camarosa; Winter Dawn; gibberellic acid; naphthalene acetic acid; plant growth regulators; fruit quality; total soluble solids; titratable acidity; yield; benefit-cost ratio.

1. Introduction

The strawberry (*Fragaria × ananassa* Duch.) is a widely appreciated fruit known for its pleasant flavour, freshness and versatility in processing. As a member of the Rosaceae family, it is one of the most important soft fruits globally (Abouelenein et al., 2023). The cultivated strawberry was developed through crossbreeding between two wild strawberry species, *Fragaria virginiana* (meadow strawberry) and *Fragaria chiloensis* (Chilean strawberry). It is an herbaceous perennial plant that can thrive across a range of agro-climatic conditions, from subtropical to temperate regions (Fan & Whitaker, 2024; Paroussi et al., 2002; Sharma & Banyal, 2020). It can be grown at elevations of up to 12,000 feet above sea level under humid and dry climates. Strawberry fruits are attractive, palatable and refreshing, with high concentrations of antioxidants, vitamin C and phenols. They contain vitamin A (60 IU/100 g of edible fruit), vitamin C (30–120 mg/100 g of edible portion), niacin, proteins and minerals such as phosphorus, potassium, calcium and iron. The presence of ellagic acid, which may protect against cancer and heart disease, together with abundant anthocyanins, has increased the value of the fruit (Özcan & Uslu, 2023; Singh & Singh, 2006). Commercial strawberry growers face several challenges, including sporadic freezes and frosts, rising labour costs and concerns about farming in increasingly urbanised areas. Climate variability causes substantial losses in early strawberry production (Singh & Kaur, 2020; Suman et al., 2025).

In recent years, considerable emphasis has been placed on the use of plant growth regulators (PGRs) to modify growth, flowering, fruit quality and production in various fruit crops (Sabir et al., 2021). PGRs are chemical compounds, either synthetic or natural, that affect plant physiological processes at very low concentrations. Several researchers have studied the growth and fruit quality of strawberries and reported that PGRs significantly affect fruit number, fruit yield, fruit weight, fruit diameter and quality parameters such as total soluble solids, ascorbic acid, acidity and sugar content (Katel et al., 2022). Plant growth regulators such as naphthalene acetic acid (NAA) and gibberellic acid (GA3) have been shown to influence the growth, production and quality indices of strawberry fruit (Marwaha et al., 2023; Kumari et al., 2026). Many plant growth-regulating chemicals, including auxins, cytokinins and gibberellins, have been used in crops to increase fruit size, and gibberellic acid helps increase strawberry fruit set, weight, length and girth (Sosnowski et al., 2023; Sharma et al., 2026).

When applied exogenously to strawberry plants, gibberellic acid (GA3) acts as a growth stimulant by increasing plant height, canopy spread, leaf area, leaf number, petiole length and stem elongation. It also improves the number of flowers per crown, fruit set percentage and total number of fruits per plant (Sharma et al., 2024a, 2024b; Sharma et al., 2026). GA3 also improves fruit quality by producing firmer fruit with increased ascorbic acid and total soluble sugars, while having no significant influence on titratable acidity (Sharma & Singh, 2009).

Application of NAA at an early stage induces cell division in cambium cells, which leads to xylem tissue production in the lower internodes, provides mechanical support to plants and prevents lodging. At low concentrations, it produces profuse and early flowering while also limiting plant height and branching (Vishal et al., 2016). Foliar sprays of NAA have been shown to prevent premature fruit drop while improving fruit size in strawberries (Upadhyay et al., 2023). Strawberry cultivation offers a promising avenue for crop diversification and higher profitability in Punjab.

However, cultivar-specific responses of Camarosa and Winter Dawn to foliar GA3 and NAA under Punjab field conditions, particularly in relation to fruit quality and economic return, remain insufficiently documented in the present production context.

Therefore, the present study was conducted to evaluate the effect of plant growth bioregulators on fruit quality and economic returns of different strawberry cultivars under Punjab conditions.

2. Materials and Methods

The investigation was carried out during 2023–2024. Physical and chemical characteristics of the cultivars were recorded under field and laboratory conditions at the Department of Agriculture, Mata Gujri College, Sri Fatehgarh Sahib, Punjab.

The research farm is situated at 30°56′11.90″N latitude and 76°18′13.18″E longitude, at a mean elevation of 279 metres above sea level. The climate of Sri Fatehgarh Sahib is subtropical, with three distinct seasons: winter, summer and monsoon. During the winter months (December–January), the temperature falls to 4–8 °C or even lower, while in the summer months (May–June) it reaches as high as 42–45 °C. Occasional spells of frost and precipitation may occur during winter. Most of the rainfall is received from mid-July to the end of September, after which the intensity of rainfall decreases. The mean annual rainfall is about 67 cm.

The experiment was laid out in a factorial randomised block design with three replications and comprised ten treatment combinations, with two levels of factor A and five levels of factor B, as shown in Table 1.

Table 1. Treatment combinations

Varieties / Treatments	V_1	V_2
PGR_0	Control	Control
PGR_1	GA_3 @50 ppm	GA_3 @50 ppm
PGR_2	GA_3 @ 100 ppm	GA_3 @ 100 ppm
PGR_3	NAA @50 ppm	NAA @50 ppm
PGR_4	NAA @100 ppm	NAA @100 ppm

Varieties (V), V_1= Camarosa, V_2= Winter Dawn

A foliar spray of an aqueous solution of NAA and GA3 was applied to the upper surface of the plants 15 days after transplanting using a knapsack sprayer equipped with a fine nozzle that produced mist droplets. Data were recorded for vegetative growth, flowering, fruiting, yield and quality attributes. Plant height (cm) was measured using a metre scale and expressed in centimetres, and the leaf area index was measured using a LI-COR LAI-2200C plant canopy analyser equipped with a fisheye sensor to assess light transmission at multiple angles.

Days to first flowering were recorded as the interval between the date of planting and the date of first flower opening. Days to first fruit set were determined from the date of flower opening to the day of fruit setting. Five plants were selected at random to count the number of flowers, fruit set and total fruits. An Erma hand refractometer (0–32 °Brix) and a few droplets of juice on a prism were used to measure total soluble solids in the juice. The refractometer was calibrated with pure water immediately before use. At temperatures above or below 20 °C, a temperature correction was made. Total soluble solids were expressed as a percentage of fresh juice.

Five grams of fruit juice were extracted and passed through a cotton cloth to measure fruit acidity. The extract was then diluted to a fixed volume of 25 ml using distilled water. The diluted juice was titrated against a standard NaOH solution using phenolphthalein as an indicator. The end point was indicated by the appearance of a pale pink colour and was then recorded. Fruit acidity was expressed as a percentage.

$$\text{Titratable acidity (\%)} = \frac{1 \times \text{Eq. Wt. of acid} \times \text{Normality of NaOH} \times \text{Titre} \times 100}{10 \times \text{weight of sample}}$$

A 25 g sample of fruit pulp was completely homogenised in 250 ml of distilled water to determine total sugar content. The liquid was then stirred, filtered and left for ten minutes before 10 ml of 45% saturated lead acetate was added. Subsequently, 10 ml of 22% potassium oxalate was used to precipitate the excess lead, and distilled water was used to make the final volume up to 250 ml. The mixture was then filtered again, and 100 ml of the filtrate was transferred to a second 250 ml volumetric flask and mixed with 5 ml of concentrated hydrochloric acid. Hydrolysis was completed by leaving it overnight.

Saturated sodium hydroxide was added to neutralise the surplus acid, and distilled water was used to make the total volume up to 250 ml. Next, using methylene blue as an indicator, the hydrolysed aliquot was titrated in a burette against a boiling mixture of 5 ml Fehling A and Fehling B solutions (A.O.A.). The end point was indicated by the appearance of a brick-red colour. Total sugar content was expressed as a percentage.

$$\text{Total sugar (\%)} = \frac{\text{Fehling factor} \times \text{Volume made} \times 100}{\text{Titre value} \times \text{Volume of sample taken for estimation}}$$

2.1 Cost Economics Ratio

Cost of cultivation per hectare was calculated on the basis of expenditure on various inputs and cultural and managerial practices. This expenditure was subtracted from the gross income calculated on the basis of the prevailing market selling rate, which gave the net profit per hectare. The benefit-cost ratio was calculated by dividing net return by the cost of cultivation.

2.2 Cost of Cultivation

After taking into consideration the variable and fixed inputs and their corresponding prices, the cost of cultivation for each treatment was worked out. Similarly, gross income was calculated for each treatment on the basis of the market rate of the produce. Net returns were then computed by deducting the total cost of cultivation from the gross income for each treatment.

Net return = Gross income – Total cost of cultivation.

2.3 Benefit-cost Ratio

The benefit-cost ratio was calculated by dividing net returns by the total cost of production.

$$\text{Benefit: cost ratio} = \frac{\text{Net return}}{\text{Total cost of production}}$$

2.4 Statistical Analysis

The statistical analysis was conducted in R (RStudio version 2022.07.1) by performing a one-way analysis of variance (ANOVA) at a 5% significance level using the stats package. In addition, Duncan's multiple range test (DMRT) was applied as a post-hoc analysis to compare the means of the various treatment combinations using the agricolae package.

3. Results and Discussion

3.1 Plant Height (cm)

Plant height is an important factor for estimating yield because greater plant height may support more lateral branches, fruit set and, ultimately, yield. Plant height increased significantly after the application of GA3 at 100 ppm. The maximum plant height (21.40 cm) was recorded in PGR2 (GA3 100 ppm), followed by PGR1 (GA3 50 ppm) with 19.99 cm, whereas the minimum plant height was observed in PGR0 (control) (Table 2). This increase may be attributed to the well-documented ability of gibberellins to stimulate cell division and expansion in epidermal and parenchyma cells (Bisht et al., 2018). Another possible reason is that GA3 increases vegetative development through active cell division and elongation, as well as a proportional increase in stem length, which could explain the increase in strawberry plant height (Sosnowski et al., 2023).

Table 2. Effect of GA_3 and NAA on plant height and leaf area of strawberry cvs. Camarosa and Winter Dawn

Varieties	Plant height (cm)			Leaf area index		
Treatments	V_1	V_2	Mean (PGR)	V_1	V_2	Mean (PGR
PGR_0	16.2^{e}	15.79^{e}	15.99	4.90ab	4.75abc	4.83
PGR_1	22.73^{b}	17.26^{de}	19.997	4.38bc	4.75abc	4.70
PGR_2	24.57^{a}	18.23^{d}	21.40	4.20c	5.21a	4.56
PGR_3	21.40^{bc}	16.54^{e}	18.97	4.83ab	4.91ab	4.87
PGR_4	20.67^{c}	16.43^{e}	18.55	5.08a	4.80ab	4.94
Mean (V)	21.11	16.85		4.68	4.88	
Factors	CD $_{(0.05)}$	SE(m)±		CD $_{(0.05)}$	SE(m)±	
Factor(V)	0.68	0.23		N/S	0.08	
Factor (PGR)	1.07	0.36		N/S	0.12	
Factor (V × PGR)	1.52	0.51		0.51	0.17	

V_1= Camarosa, V_2= Winter Dawn

3.2 Leaf Area Index

The minimum leaf area index (4.56) was recorded in PGR2 (GA3 100 ppm), and the maximum leaf area index was observed in PGR4 (NAA 100 ppm). The interaction between plant growth regulators and variety also showed a non-significant difference (Table 2).

3.3 Phenological Attributes

3.3.1 Days to First Flowering

In the experiment, the application of GA3 resulted in earlier flowering. The minimum number of days to first flowering (56.67 days) was recorded in PGR2 (GA3 100 ppm), followed by PGR1 (GA3 50 ppm) with 58.17 days, whereas the maximum number of days to first flowering was observed in PGR0 (control) (Table 3). Earlier flowering and fewer days to first fruiting may be attributed to the ability of GA3 to mobilise assimilates to the site of application, which is responsible for increased fruit set. The increased fruit set may be due to the involvement of the GA3 stimulus in fruit set, which comes not only from pollen but also from the ovary. This result corroborates the findings of Saima et al. (2014) in strawberry. Another possible explanation is that early flower initiation occurs when the plant receives the necessary nutrients from a balanced hormone spray, allowing early flowering in strawberry. This could be related to the reduced flowering duration caused by the increased effects of NAA and GA3 on cell division and growth (Sosnowski et al., 2023).

Table 3. Effect of GA3 and NAA on days to first flowering and number of flowers per plant of strawberry cvs. Camarosa and Winter Dawn

Varieties	Days taken to first flower			Number of flowers per plant		
	V_1	V_2	Mean (PGR)	V_1	V_2	Mean (PGR
Treatments						
PGR_0	66.33ab	67.33a	66.83	13.00ef	12.00f	12.50
PGR_1	53.67f	62.67cd	58.17	21.00b	15.67cd	18.33
PGR_2	51.00f	62.33cd	56.67	22.67a	16.67c	19.67
PGR_3	57.00e	63.33bcd	60.17	20.67b	14.67d	17.67
PGR_4	61.33d	65.00abc	63.17	19.67b	14.33de	17.00
Mean (V)	57.87	64.13		19.40	14.67	
Factors	CD $_{(0.05)}$	SE(m)±		CD $_{(0.05)}$	SE(m)±	
Factor(V)	1.40	0.47		0.67	0.23	
Factor (PGR)	2.21	0.74		1.07	0.36	
Factor (V × PGR)	3.13	1.04		1.51	0.51	

V_1= Camarosa, V_2= Winter Dawn

3.3.2 Number of Flowers Per Plant

The maximum number of flowers per plant (19.67) was recorded in PGR2 (GA3 100 ppm), followed by PGR1 (GA3 50 ppm) with 18.33, whereas the minimum number of flowers per plant was observed in PGR0 (control) (Table 3). The possible reason for maximum flowering might be that hormone treatment hastened the development of differentiated inflorescences and stimulated flowering. It could also be due to carbohydrate accumulation resulting from increased photosynthesis, which caused the plant to produce more flowers (Lee et al., 2021; Sosnowski et al., 2023).

3.4 Fruit Quality Attributes

3.4.1 Berry Length and Breadth

Fruit size is an important characteristic for consumer appeal, as larger fruits contribute to higher yield and are preferred by consumers. The maximum berry length (39.40 mm) was recorded in PGR2 (GA3 100 ppm), followed by PGR1 (GA3 50 ppm) with 34.17 mm, whereas the minimum berry length was observed in PGR0 (control). The increase in fruit length could be due to higher carbohydrate levels, and GA3 might have encouraged cell division and cell elongation, resulting in maximum fruit length (Table 4).

The maximum berry breadth (24.47 mm) was recorded in PGR2 (GA3 100 ppm), followed by PGR1 (GA3 50 ppm) with 22.26 mm, whereas the minimum berry breadth was observed in PGR0 (control) (Table 4). The increase in fruit breadth observed in this study could be attributed to the enhanced photosynthetic ability of GA3-treated plants, which favoured increased dry matter accumulation (Abbas et al., 2020; Chandel et al., 2023; Chandra et al., 2025).

Table 4. Effect of GA_3 and NAA on berry length (mm) and berry breadth (mm) of strawberry cvs. Camarosa and Winter Dawn

Varieties	Berry length (mm)			Berry breadth (mm)		
Treatments	V_1	V_2	Mean (PGR)	V_1	V_2	Mean (PGR
PGR_0	24.02f	22.09g	23.06	15.45fg	14.8g	15.12
PGR_1	38.72b	29.61d	34.17	26.01b	18.51e	22.26
PGR_2	45.19a	33.61c	39.40	28.25a	20.69d	24.47
PGR_3	38.22b	26.68e	32.45	23.54c	17.83e	20.69
PGR_4	37.85b	26.06e	31.95	22.03cd	16.98ef	19.51
Mean (V)	36.80	27.61		23.06	17.76	
Factors	CD $_{(0.05)}$	SE(m)±		CD $_{(0.05)}$	SE(m)±	
Factor(V)	0.71	0.24		0.83	0.28	
Factor (PGR)	1.12	0.38		1.31	0.44	
Factor (V × PGR)	1.59	0.53		1.85	0.62	

V_1= Camarosa, V_2= Winter Dawn

3.5 Fruit Chemical Characteristics

3.5.1 Total Soluble Solids (° brix)

The present investigation revealed that the maximum total soluble solids (11.02 °Brix) were recorded in PGR2 (GA3 100 ppm), followed by PGR1 (GA3 50 ppm) with 10.72 °Brix, whereas the minimum total soluble solids were observed in PGR0 (control) (Table 5). The possible reason for the increase in total soluble solids might be that the use of NAA and GA3 influenced physiological processes, hydrolysed starch and aided metabolic activity during the conversion of available starch to sugar, possibly increasing TSS. Similar findings were also reported by Kumar et al. (2013) in strawberry, who observed that the application of GA3 at 50 ppm resulted in a significant improvement in total soluble solids (°Brix).

3.5.2 Titratable Acidity (%)

The minimum titratable acidity (0.63%) was recorded in PGR2 (GA3 100 ppm), followed by PGR1 (GA3 50 ppm) with 0.66%, whereas the maximum titratable acidity was observed in PGR0 (control) (Table 5). The decrease in acidity caused by growth regulators could be attributed to metabolic processes involving the rapid conversion of organic acids to sugars and sugar derivatives (Kumar et al., 2013; Prasad et al., 2013; Matsuane et al., 2016; Sharma et al., 2025).

Table 5. Effect of GA_3 and NAA on TSS (°Brix) and titratable acidity (%) of strawberry cvs. Camarosa and Winter Dawn

Varieties	TSS (°Brix)			Titratable acidity (%)		
Treatments	V_1	V_2	Mean (PGR)	V_1	V_2	Mean (PGR
PGR_0	7.77ef	7.23f	7.50	0.75ab	0.77a	0.76
PGR_1	12.01ab	9.35d	10.72	0.62ef	0.70bcd	0.66
PGR_2	12.67a	9.37d	11.02	0.58f	0.67cde	0.63
PGR_3	11.23bc	8.76de	9.99	0.63ef	0.71abc	0.67
PGR_4	10.57c	8.76de	9.53	0.65de	0.72abc	0.69
Mean (V)	10.87	8.64		0.65	0.72	
Factors	CD $_{(0.05)}$	SE(m)±		CD $_{(0.05)}$	SE(m)±	
Factor(V)	0.43	0.14		0.015	0.145	
Factor (PGR)	0.69	0.23		0.023	0.229	
Factor (V × PGR)	0.97	0.32		0.033	0.324	

V_1= Camarosa, V_2= Winter Dawn

3.6 Total Sugar (%)

The maximum total sugar content (6.16%) was recorded in PGR2 (GA3 100 ppm), followed by PGR1 (GA3 50 ppm) with 5.82%, whereas the minimum total sugar content was observed in PGR0 (control) (Table 6). The increase in sugar content might be due to the rapid transformation of starch into sugar in the presence of enzymes following the application of hormones to strawberry plants. Gibberellins increase total sugars by inducing the synthesis of α-amylase, which is responsible for the conversion of starch into sugars in fruits (Thakur et al., 2015; Sharma et al., 2024a, 2024b).

3.7 Reducing Sugar (%)

The maximum reducing sugar content (4.04%) was recorded in PGR2 (GA3 100 ppm), followed by PGR1 (GA3 50 ppm) with 3.80%, whereas the minimum reducing sugar content was observed in PGR0 (control) (Table 6). Increased TSS and reduced acidity might be attributed to the high conversion of starch into reducing and non-reducing sugars during the rapid ripening process (Thakur et al., 2015).

Table 6. Effect of GA_3 and NAA on total sugar (%) and reducing sugar (%) of strawberry cvs. Camarosa and Winter Dawn

Varieties	Total sugar (%)			Reducing sugar (%)		
Treatments	V_1	V_2	Mean (PGR)	V_1	V_2	Mean (PGR
PGR_0	4.85d	4.79d	4.82	3.21e	3.15e	3.18
PGR_1	6.41b	5.23d	5.82	4.11ab	3.49de	3.80
PGR_2	7.02a	5.29cd	6.16	4.38a	3.69cd	4.04
PGR_3	6.00b	5.19d	5.60	4.06b	3.39de	3.72
PGR_4	5.85bc	5.14d	5.49	3.96bc	3.28e	3.62
Mean (V)	6.03	5.13		3.94	3.40	
Factors	CD $_{(0.05)}$	SE(m)±		CD $_{(0.05)}$	SE(m)±	
Factor(V)	0.26	0.09		0.14	0.05	
Factor (PGR)	0.41	0.14		0.22	0.07	
Factor (V × PGR)	0.58	0.19		0.31	0.10	

V_1= Camarosa, V_2= Winter Dawn

3.8 Yield Attributes

3.8.1 Number of Fruits Per Plant and Yield Per Plant

Number of fruits per plant is an important character because it ultimately reflects yield. It is a major yield-contributing character, as a greater number of fruits per plant increases yield and returns. In the present investigation, the maximum number of fruits per plant (18.65) was recorded in PGR2 (GA3 100 ppm), followed by PGR1 (GA3 50 ppm) with 17.41, whereas the minimum number of fruits per plant was observed in PGR0 (control) (Table 7). The maximum yield per plant (274.56 g) was recorded in PGR2 (GA3 100 ppm), followed by PGR1 (GA3 50 ppm) with 238.22 g, whereas the minimum yield per plant was observed in PGR0 (control) (Table 7). This may be attributed to faster translocation and mobilisation of stored metabolites or photosynthates from source to sink, which could explain how GA3 increased the number of fruits per plant. The increase in yield might be due to increased fruit set per plant, fruit length, fruit width and fruit weight (Jha et al., 2022; Sharma et al., 2026).

Table 7. Effect of GA_3 and NAA on number of fruits per plant and yield per plant of strawberry cvs. Camarosa and Winter Dawn

Varieties / Treatments	Number of fruits per plant (g)			Yield per plant (g)		
	V_1	V_2	Mean (PGR)	V_1	V_2	Mean (PGR
PGR_0	12.33fg	11.23g	11.78	138.91fg	117.49g	128.20
PGR_1	20.17b	14.65de	17.41	296.70b	179.75de	238.22
PGR_2	22.27a	15.03d	18.65	359.09a	190.03d	274.56
PGR_3	19.4bc	13.5ef	16.45	268.94c	158.85ef	213.89
PGR_4	18.73c	12.87f	15.80	244.91c	146.81fg	195.86
Mean (V)	18.58	13.46		261.71	158.59	
Factors	CD $_{(0.05)}$	SE(m)±		CD $_{(0.05)}$	SE(m)±	
Factor(V)	0.59	0.20		11.82	3.95	
Factor (PGR)	0.94	0.31		18.69	6.24	
Factor (V × PGR)	1.32	0.44		26.43	8.83	

V_1= Camarosa, V_2= Winter Dawn

3.9 Economic Returns

Examination of the data revealed that the highest cost of cultivation (Rs. 439,360 ha-1), gross return (Rs. 2,421,900 ha-1) and net return (Rs. 1,982,540 ha-1) were obtained in treatment V1PGR2 (Camarosa + GA3 @ 100 ppm), whereas the lowest cost of cultivation (Rs. 435,960 ha-1), gross return (Rs. 840,029.67 ha-1) and net return (Rs. 404,069.67 ha-1) were found under treatment V2PGR0 (Winter Dawn + control). Similarly, the highest benefit-cost ratio (4.51) was recorded in V1PGR2 (Camarosa + GA3 @ 100 ppm), whereas the lowest benefit-cost ratio (0.93) was found under treatment V2PGR0 (Winter Dawn + control) (Table 8).

Table 8. Effect of GA3 and NAA on economic returns of strawberry cultivars

Treatment combinations	Total cost of cultivation (Rs. /ha)	Gross income (Rs. /ha)	Net return (Rs. /ha)	B:C Ratio
V_1PGR_0	435960	993192.2	557232.2	1.28
V_1PGR_1	438255	2121447.9	1683192.9	3.84
V_1PGR_2	439360	2421900	1982540	4.51
V_1PGR_3	436483	1922894.8	1486411.8	3.41
V_1PGR_4	437007	1751139.9	1314132.9	3.01
V_2PGR_0	435960	840029.67	404069.67	0.93
V_2PGR_1	438255	1285192.2	846937.24	1.93
V_2PGR_2	439360	1358719.3	919359.27	2.09
V_2PGR_3	436483	1135791.8	699308.8	1.60
V_2PGR_4	437007	1049724.9	612717.87	1.40

V_1= Camarosa, V_2= Winter Dawn

4. Conclusions

The present investigation showed that strawberry cultivars differed in their responses to foliar application of GA3 and NAA under the experimental conditions of Sri Fatehgarh Sahib, Punjab. Among the evaluated treatments, GA3 at 100 ppm produced the most favourable response for several measured traits, including plant height, earliness of flowering, flower number, berry length, berry breadth, total soluble solids, total sugars, reducing sugars, number of fruits per plant and yield per plant. This treatment also recorded the lowest titratable acidity among the plant growth regulator treatments. At the interaction level, Camarosa treated with GA3 at 100 ppm gave the highest economic performance, with a gross income of Rs. 2,421,900 ha-1, net return of Rs. 1,982,540 ha-1 and benefit-cost ratio of 4.51. The control treatment in Winter Dawn recorded the lowest economic return. The findings suggest that GA3 at 100 ppm may improve the measured quality, yield and economic parameters of strawberry, particularly in Camarosa, under similar field conditions.

5. Limitations

This study was conducted during a single growing season at one experimental location in Sri Fatehgarh Sahib, Punjab. Only two strawberry cultivars and four plant growth regulator treatments, in addition to the control, were evaluated. The findings are limited to selected vegetative, flowering, fruit quality, yield and economic parameters. Multi-season validation, post-harvest storage behaviour, sensory evaluation and residue-related assessment were not included. Economic returns may also vary with market price and input costs.

Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s) acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement and reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgment of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified, and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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