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Influence of Plant Bio-Regulators on Vegetative Growth, Yield and Fruit Quality of Strawberry (*Fragaria × ananassa* Duch.) cv. Camarosa under Protected Cultivation

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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Abstract

The present investigation was conducted to study the influence of plant bio-regulators on vegetative growth, yield, and fruit quality of strawberry, *Fragaria × ananassa* Duch. cv. Camarosa under protected cultivation. The experiment comprised nine treatments, namely T_0 - Control (0 ppm), T_1 - GA_3 200 ppm, T_2 - GA_3 250 ppm, T_3 - NAA 150 ppm, T_4 - NAA 200 ppm, T_5 - BA 100 ppm, T_6 - BA 150 ppm, T_7 - GA_3 200 ppm + NAA 150 ppm + BA 100 ppm, and T_8 - GA_3 250 ppm + NAA 200 ppm + BA 150 ppm. The treatments were replicated three times in a CRD (Completely randomized design) under protected conditions. Various parameters related to vegetative growth, flowering, yield, and fruit quality were recorded during the study. The findings revealed that treatment T_2 (GA_3 250 ppm) performed significantly better than the other treatments by recording maximum plant height, number of leaves, runners/plant, crowns/plant, number of

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flowers, fruits/plant, fruit length, fruit diameter, yield/plant, TSS, ascorbic acid, total sugars and TSS Acid ratio. The study concluded that the application of plant growth regulators, particularly GA_3 at 250 ppm, can effectively enhance growth, yield, and fruit quality in strawberry under protected cultivation.

Keywords: Strawberry; PGRs; growth; fruit quality; yield.

1. Introduction

Strawberry (*Fragaria × ananassa* Duch.) is an aggregate fruit regarded as one of the most important soft fruits in the world after grapes (Umar *et al*., 2008; Singh, 2020). Botanically, it is an octaploid (2n = 56), dicotyledonous, low-growing herb cultivated widely in diverse agro-climatic regions across the globe (Kumar *et al*., 2012). Strawberry is highly popular because of its attractive appearance, delicate flavour, pleasant aroma, and rich nutritional value. It is an excellent source of vitamins, minerals, and bioactive compounds, and provides quick economic returns within a short cultivation period (Singh & Singh, 2009). The fruits are also rich in natural antioxidants such as carotenoids, phenols, flavonoids, vitamins, glutathione, and other metabolites, which contribute to high antioxidant activity against free radicals (Singh *et al*., 2008; Singh *et al*., 2025).

Several countries, including the US, Canada, France, Italy, and Poland, produce strawberries. It is produced in Jammu & Kashmir, Himachal Pradesh, Nainital, Dehradun, and Mahabaleshwar in India. Due to a successful varietal introduction, Kashmir has become known as a major region for profitable production (Asrey *et al.*, 2003). The fresh strawberry fruits are rich in vitamins, minerals and antioxidants. The berries are non-fat and low in calories, rich in vitamin-C (58 mg/100g), potassium (153 mg/100g), folate (24 µg), dietary fibre (2 %) and vitamin-B6 (0.047 mg/100g). It also contains water (90.95 %), energy (32 kcal), carbohydrates (7.68 %), sugars (4.89 %) and protein (0.67 %) (Giampieri *et al*., 2012).

A temperate fruit crop, strawberries are regarded as short-day plants due to their growth habits and environmental needs. While it may be grown in both plains and hilly areas, higher elevations typically result in better fruit quality and output. The crop grows optimally when the daytime temperature is around 22°C and the temperature at night is between 7°C and 13°C. Fruit results is reduced and plant growth is negatively impacted by severe frost and winter damage. Although strawberries can be grown in a variety of soil types, including light sandy, gravelly, and heavy clay, sandy loam soil that is high in organic matter is thought to be the most ideal. The ideal soil pH for successful cultivation ranges between 5.5-6.5. Strawberry is also regarded as a heavy feeder crop requiring adequate nutrient supply for higher productivity (Singh *et al*., 2025).

Plant growth regulators (PGRs) are essential substances that enhance fruit quality, yield, and plant growth. They regulate a variety of physiological and biochemical processes that impact plant growth, development, flowering, fruit set, ripening, and overall productivity. They may be produced artificially or naturally. In strawberry plants, gibberellic acid (GA_3) is essential for regulating vegetative growth and development. Plant height, canopy spread, leaf area, number of leaves, petiole length, and stem elongation are all significantly enhanced by exogenous GA_3 application (Sharma & Singh, 2009; Kaur *et al*., 2026). It also positively influences several reproductive and yield attributes, including the number of runners, flowers, fruit set percentage, fruit number, fruit size, fruit weight, and overall fruit quality (Kumra *et al*., 2018). In non-chilled strawberry plants, GA_3 application promotes early flowering, shortens the cropping period, and enhances vegetative growth and fruit production (Verma *et al*., 2021).

A synthetic auxin termed naphthalene acetic acid (NAA) is frequently used in horticultural crops to regulate a variety of physiological and developmental processes. It influences leaf senescence, fruit abscission, fruit set, and reduced fruit drop in addition to promoting cell elongation, cell division, vascular tissue differentiation, root initiation, and apical dominance (Mehraj *et al*., 2015). Applying NAA to strawberries improves fruit size, delays ripening, and boosts anthocyanin accumulation, all of which contribute to better fruit quality and colour. Additionally, it increases overall fruit yield and quality, delays the flowering time, and promotes vegetative development (Mir *et al*., 2004). Additionally, high-quality strawberries with enhanced total sugars, ascorbic acid content, and titratable acidity percentage are frequently produced using NAA (Bhople *et al*., 2020).

Benzyl Adenine (BA) is an important plant growth regulator that enhances flowering and overall plant development in fruit trees by promoting lateral bud break, lateral shoot growth, and enhanced branching (Shan

et al., 2007). Fruit aging and chlorophyll breakdown are postponed by BA, which also significantly improves fruit size and shape. Additionally, it delays post-harvest senescence by improving mechanical resistance, decreasing respiration rate, delaying ethylene production, and maintaining fruit firmness. It is generally known that cytokinins including BA promote the growth of stems, roots, and side shoots by inducing cell division and elongation. Furthermore, they interrupt the dormancy of seeds and buds and decrease apical dominance carried on by auxins (Al-Taey & Majid, 2018).

1.1 Objectives

1. To study the effect of plant growth regulators on the growth of strawberry cv. Camarosa.
2. To study the effect of plant growth regulators on the yield and fruit quality of strawberry cv. Camarosa.

2. Materials and Methods

2.1 Geographical Location of the Experimental Site

The present investigation entitled "Influence of Plant Bio-Regulators on Vegetative Growth, Yield and Fruit Quality of Strawberry (*Fragaria* × *ananassa* Duch.) cv. Camarosa under Protected Cultivation" was carried out during the years 2025-2026 in the experimental field of department of Horticulture, Guru Kashi University, Bathinda, Punjab. The institution is located at latitude 29°57′ N and longitude 75°07′ E, elevated 213 meters higher mean sea level.

Table 1. Details of the treatments

S. No.	Treatments
1	T_0 (Control 0ppm)
2	T_1 (GA_3 200ppm)
3	T_2 (GA_3 250ppm)
4	T_3 (NAA 150pmm)
5	T_4 NAA (200ppm)
6	T_5 BA (100ppm)
7	T_6 BA (150ppm)
8	T_7 (GA_3 200ppm) + (NAA 150ppm) + (BA 100ppm)
9	T_8 GA_3 (250ppm) + (NAA 200ppm) + (BA150ppm)

Details of field experiment

Cultivar:	Camarosa
Treatments:	9
Replications:	3
Design:	RBD (Randomized Block Design)
Number of plants/replications:	9
Number of plants/treatments:	27

2.2 Planting and Planting Material

Before bed preparation, the land was thoroughly tilled several times using a power tiller to obtain a fine soil texture. Well-decomposed vermi-compost at the rate of 1 kg per plant area was incorporated into the soil before planting. Raised beds measuring 1 × 20 m were prepared, and strawberry cv. Camarosa was planted at a spacing of 40 cm × 40 cm during the first week of December 2025. Black polythene mulch was applied to conserve soil moisture, regulate soil temperature, suppress weed growth, prevent fruit rotting, and improve overall fruit quality.

2.3 Preparation of Bio-regulators

For preparing GA_3 at 200 ppm, weigh 200 mg of gibberellic acid (GA_3) and dissolve it in a small amount of ethyl alcohol (5-10 ml). After complete dissolution, transfer the solution into a one-litre volumetric flask or

measuring container and make the volume up to one litre with distilled water. Similarly, for GA_3 at 250 ppm, dissolve 250 mg of GA_3 in a small quantity of alcohol and then dilute to one litre with water.

For NAA solution preparation, weigh 150 mg NAA for 150 ppm or 200 mg NAA for 200 ppm. Dissolve the chemical in a few drops of NaOH or alcohol because NAA is not readily soluble in water. After dissolution, transfer the solution into a measuring flask and add distilled water to make one litre. In the same manner, BA solutions can be prepared by dissolving 150 mg BA for 150 ppm and 200 mg BA for 200 ppm in a small amount of alcohol or dilute NaOH, followed by dilution to one litre with distilled water. Proper stirring should be done before spraying or application.

2.4 Observation Recorded

Plant height was measured using a scale and reported in centimeters. Using a Vernier caliper, the fruit's diameter and length were measured and reported in millimeters. A weighing balance was used to determine the average weight of the fruit, which was then expressed in grams. Fruit yield per plant, represented in grams per plant, was calculated by multiplying the number of fruits per plant by the average fruit weight. Titratable acidity, ascorbic acid, and TSS were measured using the A.O.A.C. (2019) method.

2.5 Statistical Analysis

The Completely randomized design (CRD) was used for statistical analysis of the data produced during the current study. To accurately establish the treatment effects, the significance of differences between treatments for different parameters was examined at the five percent significance level (Gomez & Gomez, 1984).

3. Results and Discussion

3.1 Plant Growth and Yield Parameters

The current study found that the application of various plant growth regulators produced a significant effect on the height of the strawberry cultivar Camarosa. The maximum plant height (8.67cm, 15.16cm, 25.08 cm, 33.48cm at 30, 60, 90 and 120 days after planting, respectively) was observed in GA_3 250 ppm (T_2) and the lowest plant height was recorded in Control (T_0) (4.87 cm, 7.44 cm, 14.53 cm at 22.62 cm and 120 days after planting respectively). The treatment of GA_3 at 250 ppm, which stimulates cell elongation and vegetative growth, may be responsible for the increase in plant height reported during this experiment. According to Singh *et al.* (2005), the maximum plant height noticed under polythene mulch may be attributed to its effective surface-covering capacity, which improves moisture conservation and increases nutrient availability for plants. The results presented by Kaur and Mirza (2018) closely match these findings.

The current study found that the application of multiple plant growth regulators showed a significant effect on the height of the strawberry cultivar Camarosa. The highest number of leaves (6.19, 10.12, 20.00 and 35.08 at 30, 60, 90 and 120 DAP, respectively) was observed in GA_3 250 ppm (T_2). The lowest number of leaves/plant was recorded in control i.e., T_0 (3.47, 5.25, 10.82 and 22.25at 30, 60, 90 and 120 DAP, respectively). Increased photosynthetic activity in plants treated with GA_3 at 250 ppm and black polythene mulch may be responsible for the increase in leaves observed during the current study. Increased dry matter accumulation and vegetative development may have been encouraged by this increased photosynthetic efficiency (Sharma & Singh, 2009; Saima *et al*., 2014).

Significantly, treatment T_2 (GA_3 250 ppm) has the minimum number of days to first flowering (63.52 days), while treatment T0 (control) had the highest number of days to first flowering (76.16 days). Gibberellic acid's beneficial effects on vegetative development and floral initiation may be responsible for the treatment T_2 minimum number of days to first flowering. GA_3 promotes cell division, elongation, and metabolic processes, which quicken plant growth and cause early flowering. Additionally, it increases photosynthetic efficiency and nutrient mobilization toward bud development, which accelerates up the emergence of flowers (Tripti & Shukla, 2010).

The highest number of runners per plant (9.29) recorded under treatment T_2 (GA_3 250 ppm) may be attributed to the stimulatory effect of gibberellic acid on vegetative growth and stolon formation in strawberry. GA_3 promotes

rapid cell division, cell elongation, and internodal elongation, which enhance the development of axillary buds into runners. It also increases the synthesis and translocation of carbohydrates and other metabolites towards actively growing regions, thereby encouraging vigorous runner production. The enhanced vegetative growth under GA_3 application may have created favorable physiological conditions for the initiation and growth of stolons (Verma *et al*., 2021).

The quantity of flowers per plant varied significantly among the different treatments. According to Table 2 data, treatment T_2 (GA_3 250 ppm) produced the most flowers per plant (31.17). The application of gibberellic acid, which stimulated the formation of differentiated inflorescence and enhanced floral initiation, may be responsible for the increased number of flowers and early flowering. GA_3 improves metabolic and physiological processes, which results in improved vegetative development and more flowers. Additionally, black polyethylene mulch increased flowering and plant growth by supporting in the maintenance of ideal soil moisture and temperature conditions. Singh and Singh (2009) reported similar results about the combined effect of GA_3 and black plastic mulch on strawberry flowering.

The largest number of fruits per plant (25.07) under treatment T_2 (GA_3 250 ppm) may have resulted from GA_3's beneficial impacts on flowering, fruit set, and improved photosynthate translocation towards developing fruits. GA_3 increased fruit development and retention by increasing physiological activity. Black polythene mulch maintained the soil at the ideal temperature, moisture content, and weed control, which promoted plant development and fruit production. The findings support Singh and Singh (2005) observation.

Notably, treatment T_2 (GA_3 250 ppm) produced the largest fruit length (53.69 mm) and fruit diameter (37.24 mm), while the control treatment (T_0) produced the smallest fruit length (36.40 mm) and fruit diameter (26.33 mm). The increased photosynthetic efficiency of plants treated with GA_3 and black polythene mulch, which stimulated larger accumulation and transfer of dry matter towards the fruits, may be responsible for the increase in fruit size during the current experiment. Similar findings were also reported by Tripathi and Shukla (2010) in strawberry.

The data provided in Table 3 demonstrated that various plant growth regulator treatments have significant effects on strawberry fruit weight. Significantly better than all other treatments, treatment T_2 (GA_3 250 ppm) produced the maximum fruit weight (23.56 g). This might be explained by the treatment's promotion of vigorous vegetative growth and increased development of flower clusters, which raised the quantity of flowers and improved the berry set %. It might also be the result of improved water retention in the growing medium and improved nutrient and water intake, which increased the rate of photosynthetic activity and ultimately increased fruit weight. Kharjana *et al*. (2022) reported similar findings in strawberries.

The largest fruit size (45.46 mm) was recorded by treatment T_2 (GA_3 250 ppm), which was statistically comparable to the best treatment and significantly better than all other treatments. On another side, the minimum fruit size of 31.36 mm was obtained by the control treatment (T_0). This might be attributed to greater leaves producing more photosynthates, which improved blooming and fruit set. Better reproductive development and yield characteristics were probably supported by the increased assimilate supply. Thakur *et al*. (2017) similarly reported similar results.

Table 2. Effect of bio-regulators on Plant Height (cm) and number of leaves of strawberry cv. Camarosa

Treatments	Plant Height (cm)				No of leaves			
	30 Days	60 Days	90 Days	120 Days	30 Days	60 Days	90 Days	120 Days
T_0	4.866^{d}	7.44^{f}	14.53^{e}	22.62^{f}	3.47^{e}	5.25^{d}	10.82^{f}	22.25^{h}
T_1	7.863^{a}	12.92^{c}	21.50^{c}	28.40^{e}	4.97^{b}	7.38^{c}	13.78^{e}	28.82^{fg}
T_2	8.670^{a}	15.16^{a}	25.08^{a}	33.48^{a}	6.19_{a}	10.12^{a}	20.00^{a}	35.08^{a}
T_3	6.823^{bc}	11.29^{e}	19.44^{d}	30.59^{c}	4.45_{c}	7.06^{c}	15.55^{c}	30.82^{cd}
T_4	8.097^{a}	14.06^{b}	24.48^{a}	30.63^{c}	5.12^{b}	8.26^{b}	18.04^{b}	31.86^{bc}
T_5	7.720^{ab}	12.50^{cd}	20.50^{cd}	29.26^{d}	5.10^{b}	9.11^{b}	14.04^{de}	29.30^{ef}
T_6	6.413^{c}	11.70^{de}	19.60^{d}	30.64^{c}	4.19^{cd}	7.15^{c}	13.56^{e}	28.04^{g}
T_7	7.673^{ab}	13.07^{c}	23.18^{b}	31.16^{c}	4.16^{d}	8.32^{b}	14.24^{cde}	32.86^{b}
T_8	6.693^{c}	12.61^{cd}	20.92^{c}	28.67^{de}	5.15^{b}	8.52^{b}	15.26^{cd}	30.12^{de}
CD at 5 %	0.929	0.902	1.257	0.713	0.2661	0.8187	1.2466	1.1675
SE (m) ±	0.31	0.301	0.4196	0.238	0.0888	0.2731	0.4158	0.3894

Significantly, treatment T_2 ($GA_3$250ppm) produced the highest yield per plant (516.77g). Larger leaves produced more metabolites, which encouraged rapid vegetative growth, abundant blooming, and improved fruit setting, which may have contributed to the higher output. These plants may have produced better fruit development and total output due to increased photosynthetic activity. The current results are consistent with those of Anwar and Hafiz (1990). In the same way, Lal and Seth (1980) found a favorable correlation between strawberry fruit output and characteristics including days to runner development, fruit quantity, fruit length, fruit diameter, and number of achenes.

Table 3. Effect of bio-regulators on growth and yield characteristics of strawberry cv. Camarosa

Treatments	Days to first flowering	Runner /Plant	No of flowers	Crown /plant	No of fruit/Plant	Fruit length (mm)	Fruit diameter (mm)	Fruit weigh t (g)	Yield /plant (g)
T_0	76.16^{a}	5.29^{f}	17.74^{e}	2.51^{e}	12.20^{g}	36.40^{f}	26.33^{f}	15.21^{f}	345.706^{d}
T_1	70.49^{b}	7.45^{c}	27.90^{cd}	3.48^{d}	20.15^{cde}	45.82^{d}	31.20^{d}	20.24^{c}	436.236^{c}
T_2	63.52^{d}	9.29^{a}	31.17^{a}	5.25^{d}	25.07^{a}	53.69^{a}	37.24^{a}	23.56^{a}	516.766^{a}
T_3	71.16^{b}	6.47^{e}	26.88^{d}	4.35^{c}	19.24^{def}	46.48^{d}	32.16^{c}	18.20^{e}	455.426^{c}
T_4	64.63^{d}	8.23^{b}	29.33^{b}	5.14^{a}	22.56^{b}	50.80^{b}	33.20^{b}	21.76^{b}	504.126^{ab}
T_5	67.78^{c}	7.31^{cd}	27.31^{d}	5.03^{ab}	20.21^{cd}	48.24^{c}	30.46^{e}	19.55^{d}	467.580^{bc}
T_6	68.20^{c}	6.90^{d}	29.08^{bc}	4.32^{c}	18.48^{f}	46.26^{d}	32.16^{c}	20.24^{c}	459.956^{c}
T_7	72.49^{b}	7.15^{cd}	30.21^{ab}	4.71^{b}	21.11^{c}	45.27^{d}	30.2^{e}	18.26^{e}	502.266^{ab}
T_8	70.83^{b}	7.06^{cd}	27.67^{d}	4.07^{c}	19.18^{ef}	43.31^{e}	31.08^{d}	17.84^{e}	471.383^{bc}
CD at 5 %	2.050	0.396	1.230	0.355	0.937	1.604	0.624	0.510	38.495
SE (m) ±	0.683	0.132	0.410	0.118	0.312	0.535	0.208	0.170	12.87

3.2 Quality Parameters

The current study indicates that the foliar application of various plant growth regulators was a significant impact on the fruit's Total Soluble Solids (TSS) content. Of all the treatments, T2 (GA3 250 ppm) was the highest TSS value of 8.86%, which was statistically superior to all other treatments. The control treatment is inferior to the treatment T2 (GA3 250 ppm) because it showed the lowest TSS Content of 6.57%. The absence of weeds, improved moisture retention, and improved nutrient absorption under black polythene mulch treatment may all contribute to higher fruit quality. Improved fruit quality may have resulted from enhanced physiological and metabolic processes under these conditions. These results are consistent with those published by Singh *et al*. (2007). Growth regulators may also be important in metabolic processes related to improved strawberry fruit quality, according to Thakur *et al*. (1991). Kumar and Tripathi (2009) also observed similar findings.

The lowest acidity (0.823%) was observed in T_2 ($GA_3$250ppm). These treatments indicate a significant reduction in acidity compared to the control, which observed the highest acidity of (0.903%). Among all the treatments T_2 (GA_3 250ppm) was observed the maximum ascorbic content of (95. 533 mg/100g), which was statically superior and significantly higher than all other treatments. In contrast, the control treatment (T_0) showed the lowest ascorbic acid content of (63.276mg/100g). The growth of bigger plants with more leaves, which improved photosynthetic activity and promoted greater formation of carbohydrates under ideal soil moisture conditions, may be the cause of an increase in total acidity. Increased fruit acidity may also have been caused by growth regulators' participation in a number of physiological, biochemical, and metabolic processes. These results agree with the findings of Wang et al. (1996). Similar findings in strawberries were also reported by Kumar *et al*. (2013) and Kaur and Mirza (2018).

The highest total sugar level of 8.74% was found in T_2 (GA_3 250 ppm), which was statically better than all other treatments. At 7.73%, the control treatment T_0 showed the lowest total sugar level. According to data, the T_2 (GA3 250 ppm) treatment produced the greatest TSS: Acid ratio (10.77), whereas the T_0 (Control) treatment showed the lowest TSS: Acid ratio (7.27). higher photosynthetic activity, improved assimilate translocation, and Increased enzymatic conversion of starch into soluble sugars could all contribute to the increase in total sugar content following GA_3 treatment (Mir *et al*., 2004).

Table 4. Effect of bio-regulators on fruit quality characteristics of strawberry cv. Camarosa

Treatments	TSS	Acidity %	Ascorbic acid	Total sugar	TSS Acid ratio	Fruit size (mm)
T_0	6.57^{e}	0.903^{a}	63.276^{h}	7.73^{e}	7.27^{e}	31.36^{g}
T_1	8.15^{b}	0.825^{c}	74.5133^{f}	8.22^{d}	9.90^{b}	38.35^{de}
T_2	8.86^{a}	0.823^{c}	95.533^{a}	8.74^{a}	10.77^{a}	45.46^{a}
T_3	7.84^{bc}	0.834^{b}	73.686^{g}	8.38^{cd}	9.39^{c}	39.32^{c}
T_4	7.74^{c}	0.836^{b}	92.173^{b}	8.52^{bc}	9.27^{c}	42.00^{b}
T_5	7.76^{c}	0.833^{b}	82.173^{e}	8.46^{bc}	9.31^{c}	39.37^{c}
T_6	8.20^{c}	0.832^{b}	84.226^{d}	8.39^{bcd}	9.85^{b}	39.19^{cd}
T_7	7.52^{c}	0.825^{c}	85.350^{c}	8.56^{b}	9.11^{c}	37.73^{ef}
T_8	7.12^{d}	0.823^{c}	84.096^{d}	8.54^{bc}	8.67^{d}	37.19^{f}
CD at 5 %	0.3478	0.0052	0.4454	0.1672	0.3984	0.8628
SE (m) ±	0.116	0.0017	0.1486	0.0558	0.1879	0.2878

4. Conclusion

The present investigation revealed that the application of bio-regulators significantly affected the growth, yield, and fruit quality of strawberry. Among all the treatments, T_2 (GA_3 at 200 ppm) proved to be the most effective in improving vegetative growth, flowering, fruit set, yield, and quality attributes. The treatment enhanced plant vigour, promoted early and better flowering, and resulted in higher fruit production compared to the other treatments. Improved fruit quality parameters such as TSS, total sugars, and ascorbic acid were also observed under this treatment. Therefore, the study concluded that the application of GA_3 at 200 ppm can be successfully used to enhance strawberry productivity and fruit quality under protected cultivation conditions.

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this 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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