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EFFECT OF GA_3, TRIACONTANOL, AND HUMIC ACID ON OVERWINTERING, GROWTH, YIELD, AND FRUIT QUALITY OF 'KENT' STRAWBERRY UNDER COLD-TEMPERATE CLIMATES

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ABSTRACT

A two-year study was conducted to investigate the effects of gibberellic acid (GA_3), triacontanol (TRIA), and humic acid (HA) on the overwintering success, growth, yield, and fruit quality of 'Kent' strawberries grown in a temperate climates. In Canada, particularly in regions such as Manitoba, the strawberry growing season is constrained by a short frost-free period and harsh winter conditions, which significantly impact plant growth and yield. This study aimed to evaluate the effects of foliar-applied biostimulators on strawberry growth and productivity under these challenging climatic conditions. Results indicated that triacontanol at 100 ppm consistently yielded the highest total and marketable yields, increased leaf area and chlorophyll content, and improved wintering index. These findings suggest that triacontanol enhances stress tolerance, productivity, and fruit quality. Gibberellic acid also promoted berry size and improved firmness, although to a lesser extent than triacontanol. Humic acid provided moderate benefits for growth and yield improvement. This study offers valuable insights into the potential of biostimulators to enhance strawberry productivity and fruit quality in cold-temperate climates, supporting the optimization of agronomic practices.

Key words: *Fragaria* × *ananassa*, winter hardiness, temperatures, northern climate

INTRODUCTION

Strawberry (*Fragaria* × *ananassa* Duch.) is one of the most economically valuable and widely cultivated small fruit crops across temperate and subtropical regions due to its rich flavor, appealing aroma, and high nutrient content, including vitamins, phenolics, and antioxidants (Giampieri et al. 2012; Newerli-Guz et al. 2023). In Canada, strawberries are among the most important fruit crops in terms of value and production, contributing approximately 2.6% of the total cultivated fruit area and 5% of the value of national fruit export in 2024 (Statistics Canada 2018, 2025). In Canadian agroecological zones, particularly in provinces such as Manitoba, strawberry production is limited by a relatively short growing season of 125–135 frost-free days and harsh wintering conditions (Manitoba Agriculture 2025a). These climatic limitations pose significant challenges to plant survival, vegetative vigor, and fruit productivity.

The 'Kent' strawberry is a widely adapted cultivar, recognized for its cold hardiness and suitability for cultivation in temperate climates (Rao et al. 2020). Nevertheless, yield potential and fruit quality can be severely affected by abiotic stressors such as low temperatures, frost damage, and soil nutrient deficiencies (Bacelar et al. 2024). Optimizing growth and productivity under such constraints has driven interest in the application of plant biostimulants, which can modulate plant physiological processes and enhance stress resilience. Plant biostimulants such as gibberellic acid (GA_3), triacontanol (TRIA), and humic acid (HA) have demonstrated beneficial effects on strawberry growth and productivity.

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Gibberellic acid is a well-known growth promoter that regulates stem elongation, dormancy breaking, flowering induction, and fruit development. In strawberries, GA_3 has been shown to improve vegetative growth, accelerate flowering, and enhance fruit set, even under nonchilled or photoperiod-restricted conditions (Sharma & Singh 2009; Paroussi et al. 2002). Furthermore, GA_3 may delay fruit ripening and extend shelf life, thereby improving marketability (Martínez et al. 1994; Taş et al. 2021).

Triacontanol, a naturally occurring long-chain alcohol, enhances photosynthetic efficiency, promotes root and shoot growth, and stimulates enzyme activity and nutrient uptake. It has been shown to improve growth attributes, yield per plant, and fruit quality in strawberries and other horticultural crops (Katel et al. 2022). Increased photosynthate accumulation and overall plant vigor in response to TRIA application highlight its potential for overcoming seasonal stresses in temperate climates (El-Beltagi et al. 2022; 2025).

Humic acid, an organic biostimulant derived from decomposed organic matter, improves soil structure, microbial activity, and nutrient bioavailability. It promotes root development and enhances plant resistance to environmental stressors such as drought, salinity, and temperature extremes (Canellas et al. 2015; Suddarth et al. 2019). In strawberry cultivation, HA is associated with increased fruit yield, improved fruit quality, and increased chlorophyll content (Zydlik & Zydlik 2023). The slow release of HA makes it particularly effective in improving long-term plant nutritional status under limited soil conditions (Tahoun et al. 2022; Ma et al. 2024). Although numerous studies have documented the individual effects of biostimulants on strawberry plants, there remains a scarcity of integrated evaluations focusing on the comparative effects on overwintering ability, vegetative growth, yield performance, and fruit quality in the cold-hardy ‘Kent’. Given the increasing demand for high-quality fruit and the unpredictable climate in northern growing regions, there is a pressing need for practical strategies to enhance strawberry productivity and sustainability.

The present study aims to evaluate the influence of foliar-applied GA_3, TRIA, and HA on overwintering success, growth dynamics, yield attributes, and fruit quality parameters of ‘Kent’ strawberry grown under temperate climatic conditions. This research is expected to provide valuable information on optimizing agronomic practices to enhance resilience and profitability in cold-region strawberry production systems.

MATERIALS AND METHODS

Experimental location and climatic conditions

The present 3-year study (2021–2023) was conducted at the Russ Edwards School of Agriculture and Environment, Assiniboine College, Brandon, Manitoba, Canada (latitude: 49°50′48″ N, longitude: 99°57′11″ W).

Brandon experiences a warm season lasting approximately 4.1 months, from May 15 to September 18, with an average daily high temperature exceeding 18 °C. The hottest month is July, with an average high of 25 °C and a low of 13 °C. The cold season spans 3.4 months, from November 25 to March 4, with an average daily high temperature below −4 °C. January is the coldest month, with an average low of −20 °C and a high of −11 °C. The wet season lasts 4.3 months, from May 5 to September 14, with a greater than 20% chance of rainfall on any given day. June has the most wet days, with an average of 9.9 days with at least 1 mm of precipitation. The driest season lasts 7.7 months, from September 14 to May 5, with February having the fewest rainy days (1.9 days with precipitation ≥ 1 mm).

The rainy period spans 7.1 months, from March 30 to November 2, with a sliding 31-day rainfall exceeding 13 mm. June is the rainiest month, with an average rainfall of 73 mm, while January is the driest month with negligible rainfall (0 mm). Snowfall occurs from October 11 to May 7, contributing to an annual average of 1,010 mm (Environment Canada 2025; Manitoba Agriculture 2025b).

Plant material, growth conditions, and treatments

The study used 'Kent' strawberry, a mid-season cultivar that typically bears fruit about a week after early-season cultivars. Plants were hand-planted on June 2, 2021, and the study spanned three growing seasons: 2021 (establishment), 2022, and 2023 (harvest). A total of 10 plants were planted in a single row on the plot, with a plant spacing of 0.45 m and row spacing of 1.5 m. Irrigation was provided using an in-ground micro-drip tape system (Irritec USA) with a dripper rate of 0.95 $L \cdot h^{-1}$. Plants were irrigated twice a week in spring and fall (3 hours per day) and three times a week in summer, depending on rainfall in the preceding week.

Fertigation was performed using a commercial soluble fertilizer blend (18–9–18), supplying 200 ppm nitrogen, with a total of 725 g of nitrogen per 93 m^2 per season. Nitrogen was applied in four doses (181 g per application) using a dosing pump (D125, Dosatron International, USA).

The experiment was conducted using a randomized complete block design (RCBD) with four replications and 10 treatment combinations, yielding a total of 40 experimental units. Commercial formulations of humic acid 0–0–5 (80%) derived from leonardite and potassium hydroxide (EZ-Gro, Ontario, Canada), gibberellic acid (5%), and triacontanol (0.5%) (Growforge, Canada) were used for evaluation.

Ten treatments were prepared, including a control and three concentrations each of HA, GA_3, and TRIA. All treatments were diluted with water before application. Stock solutions of each treatment were prepared in advance and stored at 20 ± 2 °C until use. For each application, 1.5 L of solution per treatment, calibrated to the experimental row, was applied using industrial hand sprayer (1046, Viton equipped, Chapin International) to ensure uniform foliar coverage of ten plants per row in each replication.

1. Control (without the use of plant biostimulants).
2. Three humic acid (HA) treatments: 1.5 $mL \cdot L^{-1}$, 3.0 $mL \cdot L^{-1}$, and 4.5 $mL \cdot L^{-1}$, referred to as HA 1.5, HA 3.0, and HA 4.5, respectively.
3. Three treatments with gibberellic acid (GA_3): 50 ppm (1.0 $mL \cdot L^{-1}$), 75 ppm (1.5 $mL \cdot L^{-1}$), and 100 ppm (2.0 $mL \cdot L^{-1}$), referred to as GA_3 50, GA_3 75, GA_3 100, respectively.
4. Three triacontanol (TRIA) treatments: 50 ppm (1.0 $mL \cdot L^{-1}$), 75 ppm (1.5 $mL \cdot L^{-1}$), and 100 ppm (2.0 $mL \cdot L^{-1}$), referred to as TRIA 50, TRIA 75, and TRIA 100, respectively.

All treatments were applied as foliar sprays in the late afternoon three times during the growing season: July 12, July 27, and August 10. Standard agricultural practices for soil fertility, pest control, and climate adaptation were followed throughout the experiment, as recommended by the province (Alberta Agriculture 2005). During the overwintering period, when air and soil temperatures dropped below −7 °C and 5 °C, respectively, the experimental plots were covered with a 12–15-cm layer of wheat straw mulch to minimize winter injury.

Measurements

Fruit yield

Fruits were manually harvested at weekly intervals in June and July when fully ripe (red). At harvest, fruits were categorized as marketable (disease-free, regular in shape, and ≥ 25 mm in diameter) and unmarketable (rotten, misshapen, or < 25 mm in diameter). Total yield per plot was obtained by weighing all harvested fruit and dividing it by the number of plants in the plot, expressing as grams per plant.

Berry weight and firmness

Berry weight was determined from five marketable fruits per plot and averaged over the season. Firmness was measured using a fruit texture analyzer (GS-25, GÜSS), assessing the firmness of 20 berries (five from each of four replications) expressed in kg per cm^2.

Total soluble solids

Total soluble solids (TSS) content (0–93%) of berries was measured at room temperature using a digital refractometer (Atago PAL 3).

Leaf area

Leaf area was measured at the end of each growing season by randomly selecting five plants per replication. All leaves were passed through a leaf area meter (AM300, BioScientific) and expressed in cm^2.

Chlorophyll content

At the end of each growing season, chlorophyll content was quantitatively measured in five randomly selected plants per plot using a chlorophyll meter (LEAF CHL PLUS, FT Green, USA) on the youngest, fully expanded leaf. The average chlorophyll content for all five plants was recorded in mg per cm^2.

Overwintering ability

Overwintering ability was assessed by counting plants in the fall (after planting) and in the spring (after removing the straw, when plants started leafing out). Plants were categorized as dead, severely injured (≥50% crown loss), slightly injured (<50% crown loss), or uninjured.

$$\text{Wintering index} = \left(\frac{n_1}{n} \times 1.00\right) + \left(\frac{n_2}{n} \times 0.67\right) + \left(\frac{n_3}{n} \times 0.33\right) + \left(\frac{n_4}{n} \times 0.00\right);$$

where n is the total number of plants, and n_1, n_2, n_3, and n_4 are the numbers of uninjured, slightly injured, severely injured, and dead plants, respectively (Hietaranta & Parikka 2008).

Collecting and monitoring climate data

Climate conditions were recorded using the Argus Titan system (version 718; Argus Control Systems, Canada) and data from the Brandon weather station (CA005010490, Environment Canada 2025). The Titan WS2 weather station (with the Argus Titan Control System), recorded outdoor temperature (°C), light energy (W per m^2), wind speed and direction.

Statistical analysis

Data were analyzed by one-way analysis of variance (ANOVA) using CoStat software (ver. 6.45, CoHort Software, USA). Treatment means were compared using Fisher's least significant difference (LSD) at $\alpha = 0.05$.

RESULTS

Climate variability

Monthly variations in air temperature, rainfall, and growing degree days (GDD) were observed across three growing seasons (May–September) and overwintering periods (November–April) in 2021, 2022, and 2023 (Table 1, Fig. 1). May 2023 had the highest average temperature (14.6 °C) and GDD (155), followed by June 2023 with an average temperature of 19.7 °C and 292 GDD. May 2023 also had the lowest rainfall (20.1 mm) compared to 2021 (26.2 mm) and 2022 (125 mm). In contrast, rainfall in June (132.6 mm) and September (37.1 mm) was notably higher in 2023 than in the two previous years. July 2021 had the highest maximum temperature (27.8 °C), the highest average temperature (20.3 °C), and the highest number of GDD (321). Similarly, in September 2021, the maximum (23.9 °C) and average (14.8 °C) temperatures and the number of GDD (148) surpassed those in 2022 and 2023. August 2022 had the highest minimum (11.4 °C), average (18.6 °C), and maximum (25.9 °C) temperatures, as well as the highest number of GDD (269) for that month across all years. During the overwintering period (November–April), monthly air temperatures also varied significantly between 2021–2022 and 2022–2023 (Fig. 1). The 2021–2022 winter was relatively mild, with higher average monthly temperatures in November (−3.1 °C), December (−15.5 °C), and March (−7.5 °C). Maximum temperatures were also higher in November (2.3 °C), December (−10.3 °C), and March (−2.4 °C). Minimum temperatures were highest in November (−8.6 °C) and March (−12.6 °C) of the same season.

Plant yield and growth characteristics

Analysis of variance (ANOVA) revealed significant effects ($P \leq 0.05$) for marketable yield, berry weight and firmness, leaf area, soluble solids, and wintering index between treatments (Table 2). Significant interaction effects were also observed for berry weight and leaf area. According to mean-comparison data (Table 3), a trend toward higher values for total yield, marketable yield, leaf area, chlorophyll content, and wintering index was observed in plots treated with 100 ppm (2.0 $mL \cdot L^{-1}$) TRIA, followed by 75 ppm (1.5 $mL \cdot L^{-1}$) TRIA. No significant differences in total yield were detected between the HA (3.0 and 4.5 $mL \cdot L^{-1}$), GA_3 (100 ppm), and TRIA (50–100 ppm) treatments. However, marketable yield showed significant differences ($P \leq 0.05$) for TRIA (75 and 100 ppm) and GA_3 (100 ppm) compared to the control and lower HA treatments.

A trend toward higher unmarketable yields was observed with the 4.5 $mL \cdot L^{-1}$ HA treatment. No significant differences were found between the 75 and 100 ppm TRIA treatments in total yield, marketable yield, chlorophyll content, and wintering index. The TRIA treatments significantly outperformed the HA and GA_3 (50 and 75 ppm) treatments in wintering index and leaf area ($P \leq 0.05$). Among the HA concentrations, only the 4.5 $mL \cdot L^{-1}$ treatment significantly differed in leaf area and wintering index compared to the 1.5 and 3.0 $mL \cdot L^{-1}$ applications. Control plots showed significantly lower leaf area index than the treated plots.

Differences between years were significant only for marketable yield and leaf area (Table 2). In both years, TRIA at 100 ppm had the most beneficial effect.

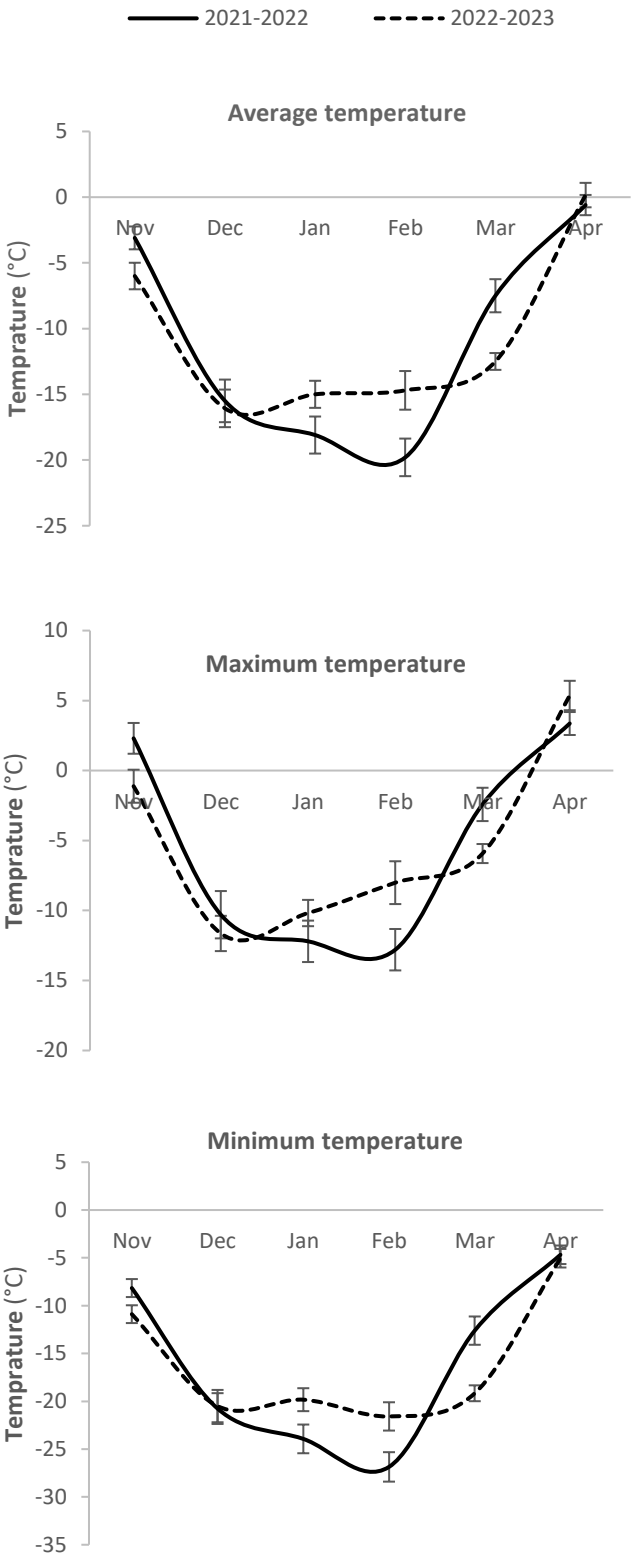


Figure 1. Changes in outdoor air temperature during the winter months (November–April) in the 2021–2022 and 2022–2023 seasons
Vertical bars ±SE (n = 240 for November, 248 for December, 248 for January, 224 for February, 248 for March, and 240 for April)

Table 1. Temperatures, total rainfall, and growing degree days (base 10 °C) for the 2021, 2022 and 2023 growing season in Brandon

Month	2021					2022					2023				
	Temperature (°C)			Total rainfall (mm)	Growing degree days	Temperature (°C)			Total rainfall (mm)	Growing degree days	Temperature (°C)			Total rainfall (mm)	Growing degree days
	maximum	minimum	month average			maximum	minimum	month average			maximum	maximum	month average		
May	18.0	1.2	9.6	26.2	66	15.6	4.3	10.0	125.0	46	22.4	7.0	14.6	20.1	155
June	25.8	10.5	18.2	102.6	247	22.9	9.9	16.4	102.0	196	26.4	13.0	19.7	132.6	292
July	27.8	12.8	20.3	29.8	321	25.3	12.9	19.1	85.7	283	24.3	9.4	16.9	29.3	214
August	20.0	10.1	17.1	161.9	220	25.9	11.4	18.6	28.6	269	25.0	10.0	17.5	27.3	234
September	23.9	5.8	14.8	20.7	148	21.1	5.5	13.4	23.8	110	22.5	6.6	14.6	37.1	138

Table 2. F ratios of yield, growth and berry quality characteristics of two different June bearing strawberry cultivars grown during 2022 and 2023

Source of variation	DF	Total yield (g per plant)	Marketable yield (g per plant)	Unmarketable yield (g per plant)	Berry weight (g per berry)	Berry firmness ($kg \cdot cm^{-2}$)	Soluble solids (Brix %)	Leaf area index	Chlorophyll ($mg \cdot cm^{-2}$)	Wintering index
Main effects										
Treatment (TRT)	9	1.60 ns	3.11**	0.49 ns	7.08***	4.78***	3.95***	14.68***	0.89 ns	8.43***
Year	1	2.56 ns	6.37*	0.32 ns	0.16 ns	1.47 ns	0.86 ns	10.79**	2.24 ns	6.31*
Interaction										
TRT × year	9	0.42 ns	1.01 ns	0.26 ns	2.20*	0.69 ns	1.02 ns	6.99***	1.11 ns	0.42 ns
Error mean square	60	19557	4207	11259	1.36	0.275	0.121	0.0023	4.743	3.329

*, **, *** represents P = 0.05, 0.01, 0.001 respectively; ns – not significant

Table 3. Effect of the treatment on the yield and quality of berry and growth traits of strawberry plants (average from two growing seasons – 2022 and 2023)

Treatment	Total yield (g per plant)	Marketable yield (g per plant)	Unmarketable yield (g per plant)	Berry weight (g per berry)	Berry firmness ($kg \cdot cm^{-2}$)	Soluble solids (Brix %)	Leaf area index	Chlorophyll ($mg \cdot cm^{-2}$)	Wintering index
Control	420.7^{c}	270.3^{d}	178.1^{a}	8.2^{e}	0.58^{c}	7.9^{c}	0.76^{e}	0.013^{b}	0.922^{c}
HA 1.5 $mL \cdot L^{-1}$	490.9^{bc}	317.1^{bcd}	173.8^{a}	10.0^{d}	0.90^{b}	8.1^{bc}	0.69^{f}	0.016^{b}	0.928^{c}
HA 3.0 $mL \cdot L^{-1}$	502.6^{abc}	329.2^{bcd}	173.4^{a}	10.2^{cd}	0.83^{b}	8.0^{c}	0.69^{f}	0.017^{ab}	0.932^{c}
HA 4.5 $mL \cdot L^{-1}$	559.0^{abc}	328.2^{bcd}	230.8^{a}	10.8^{bcd}	0.88^{b}	8.1^{bc}	0.77^{de}	0.016^{b}	0.955^{b}
GA_3 50 ppm	489.1^{bc}	310.9^{cd}	178.1^{a}	11.4^{ab}	0.85^{b}	8.1^{bc}	0.82^{bcd}	0.016^{b}	0.932^{c}
GA_3 75 ppm	481.8^{bc}	316.0^{bcd}	165.7^{a}	10.6^{bcd}	0.86^{b}	7.9^{c}	0.79^{cde}	0.03^{a}	0.955^{b}
GA_3 100 ppm	579.3^{ab}	378.2^{ab}	201.0^{a}	11.6^{ab}	0.98^{ab}	8.4^{ab}	0.83^{abc}	0.018^{ab}	0.957^{b}
TRIA 50 ppm	520.9^{abc}	340.1^{bc}	180.7^{a}	11.1^{abcd}	0.91^{ab}	8.4^{ab}	0.85^{ab}	0.012^{b}	0.965^{ab}
TRIA 75 ppm	585.7^{ab}	372.8^{abc}	212.9^{a}	11.2^{abc}	0.97^{ab}	8.4^{ab}	0.85^{ab}	0.018^{ab}	0.963^{ab}
TRIA 100 ppm	634.0^{a}	412.3^{a}	221.7^{a}	12.1^{a}	1.0^{a}	8.6^{a}	0.88^{a}	0.021^{ab}	0.978^{a}
LSD (0.05)	139.8	64.8	106.1	1.16	0.16	0.34	0.048	0.021	0.018

a, b – means within a column followed by the same letter are not significantly different at $P < 0.05$ according to LSD

Characteristics of berries

Berry attributes such as average weight, firmness, and TSS were significantly influenced by the treatments. A trend towards higher values of berry weight (12.1 g), firmness (1.0 kg·cm^{-2}), and TSS (8.6°Bx) was observed after treatment with 100 ppm TRIA followed by 100 ppm GA_3, corresponding to values of 11.6 g, 0.98 kg·cm^{-2}, and 8.4°Bx (Table 3).

No significant differences were observed between the HA and GA_3 (50 and 75 ppm) treatments for berry weight and firmness. However, both the TRIA (50–100 ppm) and GA_3 (100 ppm) treatments showed significantly higher values ($P \leq 0.05$) for all three berry quality attributes compared with the control and treatments with lower HA concentrations (Table 3). Annual comparison confirmed that the highest berry weight in 2023 (12.2 g) was recorded for the 100 ppm GA_3 treatment, closely followed by TRIA (12.18 g). Maximum berry firmness was recorded in 2022 (1.13 kg·cm^{-2}) and 2023 (1.03 kg·cm^{-2}) for 100 ppm TRIA. Similarly, in both years with the same treatment TSS were the highest (8.73°Bx in 2022 and 8.72°Bx in 2023), followed by 75 ppm TRIA in the respective years.

DISCUSSION

Observed variations in air temperature, rainfall, and growing degree days (GDD) during the growing seasons (May–September) and overwintering periods (November–April) in 2021–2023 underscore the complexity of climate influences on strawberry phenology and productivity. Notably, 2023 had the highest mean temperatures in May (14.6 °C) and June (19.7 °C), contributing to an increase in the number of GDD (155 and 292, respectively). These thermal accumulations are critical for accelerating strawberry vegetative growth and fruiting, confirming previous findings showing that higher GDD correlate with enhanced strawberry development (Lee et al. 2022).

However, rainfall distribution was inconsistent. For instance, low rainfall in May 2023 (20.1 mm) may have stressed early plant development, while heavy rainfall in June (132.6 mm) could have increased vegetative vigor or even disease susceptibility. Such variability underscores the need for adaptive agronomic practices, particularly in regions experiencing erratic precipitation patterns due to climate change (Palencia et al. 2009). Overwintering temperature patterns also differed significantly between the 2021–2022 and 2022–2023 periods. Higher average and minimum temperatures in November, December, and March of 2021–2022 may have mitigated cold stress, improving plant survival and vigor for spring regrowth, a vital aspect for perennials like strawberries (Ledesma et al. 2008). This could explain some of the performance differences observed in subsequent growing seasons. Application of TRIA, GA_3, and HA significantly affected strawberry yield components, growth characteristics, and overwintering success. Analysis of variance (ANOVA) results clearly indicated that TRIA, particularly at 100 ppm, consistently provided the highest total and marketable yields, leaf area, chlorophyll content, and wintering index. These findings align with previous research showing that TRIA enhanced photosynthetic efficiency, enzymatic activity, and carbohydrate accumulation in strawberries and other horticultural crops (Katel et al. 2022; El-Beltagi et al. 2025).

Although total yield was statistically similar between treatments at $P \leq 0.05$, marketable yield, which is critical for commercial production, was significantly higher in the TRIA-treated plots, especially at 75 ppm and 100 ppm. A recent study by El-Beltagi et al. (2022) provides evidence that TRIA enhances fruit quality and reduces physiological disorders in strawberries, thereby increasing the proportion of harvestable produce. In this 2022 field experiment, researchers applied foliar TRIA treatments (0.5 and 1 ppm) to strawberry plants under

varying irrigation levels. Results demonstrated that TRIA application increased chlorophyll content, net photosynthetic rate, stomatal conductance, and water use efficiency. This suggests that TRIA may improve fruit quality and reduce physiological disorders, thereby increasing the proportion of harvestable produce. Moreover, the highest unmarketable yield recorded for plots treated with HA at 4.5 $mL \cdot L^{-1}$ may indicate overuse or suboptimal effect on fruit quality attributes.

GA_3 also improved several traits, particularly at 100 ppm, including berry weight, firmness, and leaf area, albeit to a lesser extent than TRIA. Mosa et al. (2022) also found that foliar applications of GA_3 at 100 and 150 ppm to 'Le Conte' pear trees significantly improved fruit weight, firmness, and leaf area. These enhancements were attributed to the role of GA_3 in promoting cell elongation and expansion, thereby increasing fruit size. However, the study noted that while GA_3 improved these physical traits, it did not necessarily enhance postharvest quality parameters such as shelf life or decay resistance. HA had a more moderate effect, with less pronounced effects on total and marketable yields and growth parameters. While humic substances are known to enhance nutrient uptake and soil structure (Nardi et al. 2002), efficacy can be strongly dose-dependent, which could explain the inconsistencies between application rates in this study.

TRIA at 100 ppm again demonstrated superior performance on berry quality, such as weight, firmness, and TSS, in both years. These attributes are essential for consumer acceptability and marketability. The higher berry firmness and TSS with TRIA treatment suggest improved cell wall structure and sugar accumulation, possibly due to enhanced photosynthate translocation and hormonal balance. Pang et al. (2020) observed that TRIA promoted sugar accumulation by enhancing the activity of starch-degrading enzymes such as α-amylase and β-amylase, leading to increased sucrose, glucose, and fructose levels in the fruit. Additionally, TRIA treatment delayed fruit softening, suggesting improved cell wall structure and integrity. Interestingly, GA_3 at 100 ppm had the highest average berry weight in 2023 (12.20 g), similar to TRIA (12.18 g), indicating the effect of GA_3 on fruit enlargement. However, its lower TSS and firmness compared to TRIA highlight the trade-off between size and internal quality, a known limitation of GA_3 in fruit crops (Yamaguchi 2008). In both 2022 and 2023, treatment effects were consistent, with TRIA repeatedly outperforming other biostimulants. Slight year-to-year variations in yield and physiological traits may reflect climatic influences, particularly interactions between biostimulant efficacy and environmental conditions such as rainfall and temperature. This reinforces the need to integrate agronomic inputs with climate-responsive management strategies.

CONCLUSION

This study demonstrates the efficacy of triacontanol in enhancing plant growth, yield, fruit quality, and stress resilience in 'Kent' strawberries under diverse weather conditions. Gibberellic acid, humic acid, and triacontanol consistently outperformed the control, in multiple agronomic and quality traits, indicating a broad spectrum of physiological benefits. These effects are likely related to enhanced photosynthetic activity, hormonal regulation, and improved tolerance to abiotic stressors. To advance this research, future studies should investigate the long-term effects of repeated applications of plant growth regulators across different growing seasons. They should also explore the molecular and biochemical pathways involved in triacontanol-mediated physiological responses. In addition, evaluating the economic feasibility of triacontanol use by cost–benefit analyses of input investment versus yield gains would provide valuable information for its commercial application.

Author contribution statement

SR – A – Research concept and design, B – Collection and/or assembly of data, C – Data analysis and interpretation, D – Writing the article, E – Critical revision of the article, F – Final approval of the article

AM – E – Critical revision of the article

PS – D – Writing the article

JP – D – Writing the article

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