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Synergistic Effects of G-GANA and Calcium on Bioactive Compounds, Nutritional Quality, and Antioxidant Potential of Strawberry (Fragaria × ananassa Duch.) Fruits

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ABSTRACT: Strawberry fruits are recognized as an important dietary source of vitamin C, phenolic compounds, flavonoids, and anthocyanins, which contribute to their nutritional and functional value. This study evaluated the individual and combined effects of foliar-applied G-GANA, a commercial growth stimulant containing gibberellic acid, naphthalene acetic acid, and glycine, and organic calcium on the growth, yield, fruit quality, and bioactive compounds of strawberry (Fragaria × ananassa Duch.) cv. Rubygem under greenhouse conditions. Plants were treated with G-GANA at 0, 50, and 100 mg L^{-1} and calcium at 0, 1.5, and 3 mL L^{-1} in a factorial randomized complete block design with three replicates. The combined treatment of 100 mg L^{-1} G-GANA and 3 mL L^{-1} calcium produced the highest leaf area (952.1 cm^2 $plant^{-1}$), average fruit weight (13.57 g), total yield (204.48 g $plant^{-1}$), and marketable yield (92.32%). This treatment also produced the highest total soluble solids (9.13%), total sugars (6.90%), vitamin C (39.57 mg 100 mL^{-1} juice), total phenolic compounds (91.82 mg 100 g^{-1} FW), and total flavonoids (22.40 mg 100 g^{-1} FW). The highest anthocyanin concentration (63.82 mg 100 g^{-1} FW) was obtained with 100 mg L^{-1} G-GANA combined with 1.5 mL L^{-1} calcium. Overall, the combined application of G-GANA and calcium improved strawberry productivity and enhanced the accumulation of nutritionally important bioactive compounds. These findings indicate that integrated foliar application of G-GANA and calcium may be a promising agronomic approach for improving the nutritional and functional quality of strawberry fruits under greenhouse conditions.

Introduction

The cultivated strawberry (*Fragaria* × *ananassa* Duch.) is a herbaceous perennial species belonging to the Rosaceae family and is considered one of the most economically important fruit crops worldwide. It originated from interspecific hybridization between *Fragaria virginiana* and *Fragaria chiloensis* and is characterized by considerable genetic diversity[1]. The extensive cultivation of strawberry worldwide is largely attributed to its broad genetic variability, which has facilitated adaptation to diverse climatic conditions, production systems, and market requirements[2]. Commercial production is mainly concentrated in temperate regions; however, several cultivars can also be successfully grown in tropical and subtropical climates depending on the genotype[3]. Strawberry is cultivated commercially in more than 64 countries, with a global production of approximately 9.29 million tons annually [4]. China is the world's leading producer, followed by the United States, Egypt, Turkey, and Spain. In the Arab region, strawberry cultivation is well established, particularly in Egypt, Syria, Palestine,

Lebanon, and the Maghreb countries. In contrast, strawberry production in Iraq remains relatively limited and is mainly confined to Mosul, Baghdad, and Diyala. Consequently, a substantial proportion of the domestic market demand is met through imports from neighboring countries, particularly Syria, Iran, and Turkey [5].

Strawberry(*Fragaria* × *ananassa* Duch.) is one of the most valuable small fruit crops worldwide because of its high nutritional, medicinal, and economic importance. Its fruits are an excellent source of vitamin C, phenolic compounds, flavonoids, anthocyanins, and other natural antioxidants that contribute to human health by reducing oxidative stress and lowering the risk of several chronic diseases [6]. Although strawberry fruits have a relatively short postharvest life, they remain highly appreciated by consumers because of their attractive appearance, pleasant flavor, high nutritional value, and considerable economic return.

Plant growth regulators play a fundamental role in controlling plant growth, development, and productivity. Gibberellins stimulate cell division and elongation, promote vegetative growth, and enhance flowering and fruit development, whereas auxins regulate cell division, cell expansion, root growth, and fruit set [7]. The coordinated action of these growth regulators improves photosynthetic efficiency, assimilate partitioning, and overall plant performance. Several studies have reported that the application of gibberellins and auxins significantly enhances fruit set, yield, and fruit quality in strawberry plants [8,9].

Calcium also plays a key role in many of the plant's physiological processes, as it contributes to building cell walls, maintaining the integrity of cell membranes, and regulating cell signals, as well as its role in improving fruit firmness and reducing post-harvest loss [10]. Because calcium is relatively immobile, only a small percentage of the calcium fertilizer absorbed by the roots reaches the fruit. Therefore, soil fertilization has limited benefits for fruit growth. In recent years, foliar spraying of calcium has been used to improve fertilization efficiency, and good results have been achieved in many fruit trees [11]. Previous studies have confirmed that foliar application of calcium significantly improves growth, fruit quantity and quality in strawberry [12,13,14].

Although the individual effects of calcium and plant growth regulators on strawberry growth have been widely investigated, their combined physiological interactions and synergistic effects remain insufficiently understood. Therefore, further research is needed to evaluate their integrated application in order to optimize vegetative growth, fruit yield, and fruit quality under different environmental conditions. This study aims to evaluate the effect of the interaction between plant growth regulators and calcium in improving growth, fruit quantity and quality in strawberry.

MATERIALS AND METHODS

The study was conducted under greenhouse conditions at the Al-Najaf Research Station, Najaf Governorate, Iraq. Healthy and uniform transplants of strawberry (*Fragaria* × *ananassa* Duch.) cv. Rubygem were transplanted on 5 November 2024. Standard greenhouse production practices, including irrigation, fertilization, weed control, and pest and disease management, were uniformly applied throughout the experimental period according to the recommended cultivation guidelines.

Greenhouse Soil Preparation

The experiment was conducted in a greenhouse measuring 9 × 50 m (450 m²). Before transplanting, the soil was prepared by removing weeds and plant residues, followed by deep tillage to improve soil structure. Well-decomposed sheep manure was incorporated into the soil at a rate of 35 kg greenhouse^{-1} to enhance soil fertility and improve its physical properties. The soil was then leveled and divided into five raised beds. The raised beds were disinfected with Kriptanol® (Spain), a systemic fungicide and bactericide, at a concentration of 3 mL L^{-1} according to the manufacturer's recommendations. After application, the beds were covered with black polyethylene mulch for one week to enhance the effectiveness of soil disinfection. A drip irrigation system was subsequently installed on each raised bed. Before transplanting, a compound NPK fertilizer (15:15:15) was incorporated into the soil at a rate of 2 kg bed^{-1} according to the recommended fertilization program [15]. The irrigation system was then operated to ensure uniform water distribution throughout the greenhouse. After soil preparation, the raised beds were covered with black polyethylene mulch to reduce weed emergence and maintain favorable soil moisture and temperature. Healthy and uniform strawberry (*Fragaria* × *ananassa* Duch.) cv. Rubygem transplants were planted at a spacing of 30 cm between plants. Each experimental unit measured 1.25 × 0.60 m. Guard rows were established along both sides of the greenhouse to minimize border effects, and a 50-cm buffer zone was maintained at each end of the greenhouse to reduce environmental variation among experimental units.

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Experimental Treatments and Experimental Design

The experiment was arranged as a two-factor factorial experiment in a Randomized Complete Block Design (RCBD) with three replicates [16]. The first factor consisted of foliar application of the commercial plant growth stimulant G-GANA (Fabco, Jordan), which contains gibberellic acid (GA_3), naphthalene acetic acid (NAA), and glycine at concentrations of 0.7%, 0.5%, and 40%, respectively. G-GANA was applied at three concentrations: 0, 50, and 100 mg L^{-1}. The second factor consisted of foliar application of calcium at three concentrations: 0, 1.5, and 3 ml L^{-1}.

The combination of the two factors resulted in nine treatment combinations, which were randomly assigned within each block. Each experimental unit consisted of five plants, giving a total of 27 experimental units and 135 plants (9 treatments × 3 replicates × 5 plants). Foliar treatments were applied four times during the growing season. Four application at one-month intervals on 5 December 2024, 5 January 2025, 5 February and 5 March 2025 was done. All spraying treatments were carried out in the early morning using a hand-held sprayer until complete foliage wetting, with Tween-20 added at 0.1% (v/v) as a surfactant to ensure uniform coverage.

Traits studied

All measurements were recorded at the end of the experimental period (1 May 2025).

Total Leaf Area (cm^2 $plant^{-1}$)

Three fully expanded leaves were randomly collected from each experimental unit and scanned using a digital scanner. Leaf area was measured using ImageJ software, and the average leaf area was calculated. Total leaf area per plant was estimated using the following equation:

Total leaf area (cm^2 $plant^{-1}$) = Average leaf area (cm^2) × Number of leaves $plant^{-1}$

Total Chlorophyll Content

Total chlorophyll content was determined using three fully expanded leaves randomly collected from each experimental unit. Chlorophyll was quantified according to the method described by [17], and the results were expressed as mg 100 g^{-1} fresh weight (FW).

Yield

At harvest, the following yield characteristics were recorded: number of fruits per plant, average fruit weight (g), total yield per plant (g $plant^{-1}$), and marketable yield (%). The average values for each parameter were calculated from the plants within each experimental unit.

Fruit Quality Parameters

Total soluble solids (TSS) %: Total soluble solids were measured using an hand refractometer, and the reading was taken after harvesting to represent (TSS) in the fruit juice.

Total acidity (%) : The total acidity was measured as described in [18], based on the predominant citric acid content in the fruit.

Total sugar content (%) :Sugars in the fruit were estimated as described by [19].

Total sugars to acidity ratio:Calculated by dividing the total sugars by the total acidity in the fruit

Antioidents

Anthocyanin (mg 100g^{-1} fresh weight):The anthocyanin content of the fruit was measured according to the method described by [18],

Ascorbic acid (mg 100 ml^{-1} juice): The ascorbic acid content of the fruits was measured as described in [20].

Total phenols (mg 100 g^{-1} FW): Total phenols in fruit were measured quantitatively using the Ciocalteu–Folin method used by [21].

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Total flavonoids (mg 100 g^{-1} FW) **:** were measured from fruit samples according to the method of [22]. Using a spectrophotometer at a wavelength of 510 nanometers, the standard curve was determined based on the Quercetin compound.

Statistical Analysis

Data were subjected to analysis of variance (ANOVA) and Treatment means were compared using the Least Significant Difference (LSD) test at a probability level of 0.05.

RESULTS

Leaves area and Chlorophyll content

The results presented in Table 1 demonstrated that foliar application of G-GANA growth stimulant and calcium significantly enhanced both leaf area and total chlorophyll content of strawberry plants. Regarding leaf area, the application of G-GANA at 100 mg L^{-1} resulted in the highest value (851.300 cm^2), whereas the lowest leaf area was recorded in the untreated control (693.500 cm^2). Similarly, calcium application significantly improved leaf expansion, with the 3 mL L^{-1} treatment producing the maximum leaf area (914.200 cm^2), representing a 44.38% increase compared with the control treatment. The interaction between G-GANA and calcium exhibited a significant influence on leaf area, as the combined application of 100 mg L^{-1} G-GANA and 3 mL L^{-1} calcium achieved the highest leaf area (952.100 cm^2). A similar trend was observed for total chlorophyll content, where the application of 100 mg L^{-1} G-GANA recorded the highest chlorophyll concentration (63.907 mg 100 g^{-1} fresh weight), which was statistically comparable with the 50 mg L^{-1} treatment and significantly exceeded the control by 0.83%. In addition, foliar calcium application significantly increased chlorophyll content, with the highest value obtained at 3 mL L^{-1} calcium (63.912 mg 100 g^{-1} fresh weight), representing an increase of 0.78% over the control treatment. The interaction effect between G-GANA and calcium was also significant, with the combined treatment of 100 mg L^{-1} G-GANA + 3 mL L^{-1} calcium producing the highest chlorophyll content (64.126 mg 100 g^{-1} fresh weight), while the lowest value was observed in the control treatment (62.603 mg 100 g^{-1} fresh weight).

Table 1. Effect of G-GANA and **ORGANIC CALCIUM** as foliar application on vegetative growth of strawberry plants.

G-GANA (mg l^{-1})	**Leaves area(cm^2)**			Mean	Total chlorophyll (mg 100g FW^{-1})			Mean
	Organic calcium (ml l^{-1})				**Organic calcium** (ml l^{-1})			
	0	1.5	3		0	1.5	3	
0	480.900	681.700	917.800	693.500	62.603	63.643	63.893	63.380
50	704.600	794.200	873.100	790.700	63.866	63.410	63.716	63.664
100	708.000	893.700	952.100	851.300	63.774	63.820	64.126	63.907
$LSD_{0.05}$	17.210			9.930	0.507			0.293
Average	631.200	789.900	914.200		63.414	63.624	63.912	
$LSD_{0.05}$	9.930				0.293			

Yield and its components

The results presented in Table 2 demonstrated that foliar application of G-GANA significantly improved all quantitative yield characteristics of strawberry plants. The application of G-GANA at 100 mg L^{-1} produced the highest number of fruits per plant (14.409 fruits $plant^{-1}$), representing a 14.40% increase over the control treatment. The same treatment also recorded the highest average fruit weight (12.128 g $fruit^{-1}$), the highest marketable yield (91.62%), and the greatest total yield per plant,

exceeding the control treatment by 17.27%. In contrast, the control treatment produced the lowest values for all measured yield parameters, confirming the positive effect of G-GANA on strawberry productivity.

The results presented in Table 2 demonstrated that foliar application of calcium significantly improved all quantitative yield characteristics of strawberry plants. The application of calcium at 3 mL L^{-1} produced the highest number of fruits per plant, representing a 10.04% increase over the control treatment. The same treatment also recorded the highest average fruit weight, exceeding the control by 17.93%, as well as the highest total yield (193.332 g $plant^{-1}$), corresponding to a 37.95% increase compared with the control. In addition, calcium application significantly enhanced marketable yield, with the highest value obtained at 3 mL L^{-1}, while the 1.5 mL L^{-1} treatment also produced a significantly higher marketable yield than the control.

Table 2. Effect of G-GANA and **ORGANIC CALCIUM** as foliar application on strawberry yield and its components

G-GANA (mg l^{-1})	Fruit number			Mean	Fruit weight(g)			Mean
	Organic calcium (ml l^{-1})				**Organic calcium** (ml l^{-1})			
	0	1.5	3		0	1.5	3	
0	11.273	12.793	13.353	12.473	10.207	12.327	12.973	11.836
50	13.667	12.717	13.220	13.201	11.853	11.590	12.543	11.996
100	12.867	15.330	15.030	14.409	11.083	11.730	13.570	12.128
$LSD_{0.05}$	0.162			0.093	0.109			0.063
Mean	12.602	13.613	13.868		11.048	11.882	13.029	
$LSD_{0.05}$	0.093				0.063			
	Yield per plant(g)				Marketable yield %			
0	**115.796**	**158.191**	**173.405**	149.131	81.280	83.333	84.607	83.073
50	**161.717**	**147.425**	**165.815**	158.319	85.013	89.227	90.627	88.289
100	**142.812**	**180.707**	**204.478**	175.999	90.880	91.670	92.317	91.622
$LSD_{0.05}$	3.512			2.027	0.550			0.318
Average	**140.141**	**162.108**	**193.332**		85.724	88.077	89.183	
$LSD_{0.05}$	2.027				0.318			

The interaction between G-GANA and calcium significantly affected all quantitative yield characteristics of strawberry plants (Table 2). The combined application of G-GANA at 100 mg L^{-1} and calcium at 1.5 mL L^{-1} produced the highest number of fruits per plant (15.330 fruits $plant^{-1}$), significantly exceeding all other treatment combinations, whereas the control treatment (A_0B_0) recorded the lowest value (11.273 fruits $plant^{-1}$). In contrast, the combination of G-GANA at 100 mg L^{-1} and calcium at 3 mL L^{-1} resulted in the highest average fruit weight (13.570 g $fruit^{-1}$), total yield per plant (204.478 g $plant^{-1}$), and marketable yield (92.317%), all of which were significantly higher than those of the other treatment combinations. The corresponding values recorded for the control treatment (A_0B_0) were the lowest, with an average fruit weight of 10.207 g $fruit^{-1}$, a total yield of 115.796 g $plant^{-1}$, and a marketable yield of 81.280%.

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Fruit Quality

The results presented in Table 3 demonstrated that foliar application of G-GANA significantly improved the chemical quality attributes of strawberry fruits. The application of G-GANA at 100 mg L^{-1} resulted in the highest total soluble solids (8.864%) and total sugars (6.453%), representing increases of 20.50% and 14.80%, respectively, compared with the control treatment. In addition, the TS/TA ratio was significantly enhanced by the same treatment, showing a 12.97% increase over the control. Conversely, total acidity was significantly reduced by G-GANA application, with the lowest value (3.111%) recorded at 50 mg L^{-1}. These findings indicate that G-GANA effectively enhanced fruit sweetness and overall eating quality while reducing fruit acidity**.** The results presented in Table 3 also demonstrated that foliar application of calcium significantly improved the chemical quality of strawberry fruits. The application of calcium at 3 mL L^{-1} produced the highest total soluble solids and total sugars, exceeding the control treatment by 5.07% and 9.89%, respectively. Furthermore, the same treatment significantly increased the TS/TA ratio by 10.30% compared with the control, while recording the lowest total acidity (3.236%). These findings suggest that calcium application at 3 mL L^{-1} enhanced fruit sweetness and overall fruit quality by increasing soluble solids and sugars while reducing acidity. he results presented in Table 3 revealed that the interaction between G-GANA and calcium significantly influenced the chemical quality attributes of strawberry fruits. The combination of 100 mg L^{-1} G-GANA with 3 mL L^{-1} calcium produced the highest total soluble solids (9.130%) and total sugars (6.900%), compared with the control treatment, which recorded the lowest values. In contrast, the lowest total acidity (3.056%) was obtained from the combination of 50 mg L^{-1} G-GANA and 1.5 mL L^{-1} calcium, whereas the highest acidity (3.753%) was recorded in the control treatment. Moreover, the combination of 100 mg L^{-1} G-GANA and 3 mL L^{-1} calcium significantly enhanced the TS/TA ratio, reaching the highest value (2.190), compared with the control treatment (1.303). These results indicate that the synergistic interaction between G-GANA and calcium effectively improved fruit sweetness and overall quality by increasing soluble solids and sugars while reducing acidity**.**

Table 3. Effect of G-GANA and **ORGANIC CALCIUM** as foliar application on strawberry fruit quality

G-GANA (mg l^{-1})	TSS%			Average	Total sugar%			Average
	Organic calcium (ml l^{-1})				**Organic calcium** (ml l^{-1})			
	0	1.5	3		0	1.5	3	
0	7.086	7.526	7.456	7.356	4.780	5.110	5.473	5.121
50	7.946	8.053	8.256	8.085	6.133	5.737	6.157	6.009
100	8.610	8.853	9.130	8.864	5.950	6.510	6.900	6.453
$LSD_{0.05}$	0.069			0.039	0.0948			0.0547
Average	7.881	8.144	8.281		5.621	5.786	6.177	
$LSD_{0.05}$	0.039				0.0547			
	Acidity%				Sugar- Acidity			
0	3.753	3.586	3.403	3.581	1.300	1.470	1.620	1.470
50	3.140	3.056	3.136	3.111	1.950	1.870	1.960	1.930
100	3.326	3.270	3.170	3.255	1.830	2.000	2.190	2.010
$LSD_{0.05}$	0.040			0.023	0.293			0.169
Average	3.406	3.304	3.236		1.69	1.78	1.93	
$LSD_{0.05}$	0.0236				0.169			

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Antioxidant

The results presented in Table 4 demonstrated that foliar application of G-GANA significantly enhanced the biochemical quality of strawberry fruits. The application of 50 mg L^{-1} G-GANA produced the highest anthocyanin content, representing a 6.55% increase compared with the control treatment. In contrast, the highest vitamin C content (36.486 mg 100 mL^{-1} juice), total phenolic content (81.636 mg 100 g^{-1} FW), and total flavonoid content (21.664 mg 100 g^{-1} FW) were recorded at 100 mg L^{-1} G-GANA, significantly exceeding the control treatment, which showed the lowest flavonoid content (20.433 mg 100 g^{-1} FW). These findings indicate that G-GANA effectively enhanced the antioxidant capacity and nutritional quality of strawberry fruits by promoting the accumulation of bioactive compounds. Results presented in Table 4 also demonstrated that foliar application of calcium significantly improved the biochemical quality of strawberry fruits. The application of calcium at 3 mL L^{-1} resulted in the highest anthocyanin content (56.15 mg 100 g^{-1} juice), representing a 10.89% increase compared with the control treatment. The same treatment also produced the highest vitamin C content (36.113 mg 100 mL^{-1} juice) and significantly increased the total flavonoid content compared with the control. These findings indicate that calcium application at 3 mL L^{-1} enhanced the antioxidant potential and nutritional quality of strawberry fruits through the accumulation of health-promoting bioactive compounds. Results in Table 4 revealed that the interaction between G-GANA and calcium significantly enhanced the biochemical quality of strawberry fruits. The combination of 100 mg L^{-1} G-GANA with 1.5 mL L^{-1} calcium produced the highest anthocyanin content (63.820 mg 100 g^{-1} FW), whereas the control treatment recorded the lowest value (44.133 mg 100 g^{-1} FW). In contrast, the combination of 100 mg L^{-1} G-GANA with 3 mL L^{-1} calcium resulted in the highest vitamin C content (39.567 mg 100 mL^{-1} juice), total phenolic content (91.820 mg 100 g^{-1} FW), and total flavonoid content (22.400 mg 100 g^{-1} FW), while the control treatment recorded the lowest corresponding values of 28.193 mg 100 mL^{-1} juice, 62.947 mg 100 g^{-1} FW, and 19.420 mg 100 g^{-1} FW, respectively. These findings demonstrate a synergistic effect between G-GANA and calcium in promoting the accumulation of antioxidant compounds and improving the nutritional and functional quality of strawberry fruits

Table 4. Effect of G-GANA and ORGANIC CALCIUM as foliar application on some antioxidant in strawberry fruit

G-GANA (mg l^{-1})	**Anthocyanin** (mg 100 g^{-1} FW)			Average	Vitamin C(mg 100 mL^{-1} juice)			Average
	Organic calcium (ml l^{-1})				**Organic calcium** (ml l^{-1})			
	0	1.5	3		0	1.5	3	
0	44.133	53.357	55.113	50.868	28.193	31.587	32.710	30.830
50	54.940	50.763	54.367	57.613	30.080	34.353	36.063	33.499
100	52.853	63.533	58.997	54.204	33.537	36.353	39.567	36.486
$LSD_{0.05}$	0.789			0.455	0.518			0.299
Average	50.642	55.884	56.159		30.603	34.098	36.113	
$LSD_{0.05}$	0.455				0.299			
	Total Phenols(mg 100 g^{-1} FW)				Flavonoids(mg 100 g^{-1} FW)			
0	62.947	66.797	66.230	65.324	19.420	20.783	21.097	20.433
50	71.477	70.780	73.583	71.947	20.447	20.577	21.327	20.783
100	76.590	76.497	91.820	81.636	20.510	22.083	22.400	21.664
$LSD_{0.05}$	0.851			0.491	0.089			0.051
Average	70.338	71.358	77.211		20.126	21.148	21.608	
$LSD_{0.05}$	0.491				0.051			

DISCUSSION

Strawberry is highly responsive to nutrient management and plant growth regulators, which play an essential role in improving fruit development and yield [23]. The present results in Table 1 showed that both G-GANA and calcium, applied individually or in combination, significantly enhanced leaf area and total chlorophyll content. These improvements indicate a positive

interaction between the two treatments. The beneficial effect of G-GANA is mainly attributed to its bioactive components, including gibberellins, auxins, and glycine. Gibberellins stimulate cell division, cell elongation, and leaf expansion, resulting in increased leaf area and enhanced photosynthetic capacity [7]. Larger leaves intercept more light and produce more assimilates, leading to greater biomass accumulation [24]. Auxins promote vascular differentiation and root development, thereby improving water and nutrient uptake [25]. Glycine also contributes to chlorophyll biosynthesis and nitrogen metabolism, enhancing photosynthetic efficiency and plant vigor [26]. Similar responses have been reported in strawberry following the application of gibberellins, NAA, and glycine, which improved vegetative growth, chlorophyll accumulation, and biomass production [27,28].

Calcium also significantly improved vegetative growth (Table 1). It regulates cell division and elongation and strengthens cell walls through the formation of calcium pectate, promoting leaf expansion, also Calcium further maintains membrane stability and improves water and nutrient uptake, supporting leaf development and increasing leaf area [29]. In addition, calcium regulates the activity of growth hormones involved in leaf development and activates enzymes required for chlorophyll biosynthesis. The resulting increase in leaf area and chlorophyll enhances photosynthetic efficiency and carbohydrate production, providing more assimilates for fruit growth and yield. These findings agree with [30, 31], who reported significant improvements in leaf area and chlorophyll content following calcium application in strawberry.

Yield components, including fruit number, average fruit weight, marketable yield, and total yield per plant, are key indicators of strawberry productivity. The present results (Table 2) demonstrated that foliar application of G-GANA and calcium, individually and in combination, significantly improved all quantitative yield traits. These improvements indicate a positive interaction between the two treatments in promoting fruit growth and productivity.The beneficial effect of G-GANA is mainly attributed to the combined action of gibberellins and auxins. Gibberellins stimulate ovary development by promoting cell division and elongation, resulting in larger fruits and greater fruit weight. They also improve hormonal balance during the early stages of fruit development, enhancing fruit set and increasing the number of fruits per plant [7].Auxins play an essential role in fruit set by regulating ovary growth and reducing flower and young fruit abscission. They also enhance the translocation of photoassimilates toward developing fruits, ensuring a greater supply of carbohydrates required for fruit growth [29]. The combined activity of gibberellins and auxins therefore promotes fruit enlargement and increases fruit weight, marketable yield, and total yield. G-GANA also stimulates flower bud differentiation by enhancing nucleic acid and protein synthesis and increasing cell division. These physiological responses improve nutrient and hormone transport to developing floral tissues, resulting in higher flower production and improved fruit set [32]. Furthermore, the increase in leaf area and chlorophyll content observed in the present study (Table 1) enhanced photosynthetic efficiency and carbohydrate production, providing more assimilates for developing fruits. Auxins further reduce fruit drop by inhibiting the formation of the abscission layer through suppression of cell wall-degrading enzymes such as cellulose, in addition, gibberellins and auxins act synergistically to increase cell expansion and improve cell wall extensibility, allowing greater water and nutrient uptake into fruit tissues. Consequently, fruit size, length, diameter, and fresh weight increase, leading to higher fruit yield per plant [33]. Similar findings have been reported by [27,34,35].

Calcium also significantly improved yield components (Table 2). It enhances cell membrane stability, strengthens cell walls, and regulates cellular signaling associated with fertilization and ovary development, thereby improving fruit set [36]. Calcium further facilitates carbohydrate transport from source leaves to developing fruits, supporting fruit growth and increasing both fruit number and fruit weight. Moreover, calcium-induced improvements in leaf area and chlorophyll content (Table 1) increased photosynthetic capacity and assimilate production. The greater availability of carbohydrates and other metabolites supported fruit development and ultimately increased marketable yield and total yield per plant. These findings are consistent with [37,38,39,40]results, who reported significant improvements in fruit set, fruit number, fruit weight, and total strawberry yield following calcium application

The results presented in Table 3 showed that foliar application of G-GANA and calcium significantly improved the chemical quality attributes of strawberry fruits during both growing seasons. The greatest improvement was obtained with the combined application of G-GANA (100 mg L^{-1}) and calcium (3 mL L^{-1}), indicating a positive interaction between the two treatments. The improvement in fruit quality can be attributed to the enhancement of photosynthetic efficiency resulting from the increases in leaf area and chlorophyll content (Table 1). These changes promoted carbon dioxide fixation and carbohydrate production, increasing dry matter accumulation and the translocation of photoassimilates to developing fruits.

Consequently, fruit chemical quality was markedly improved. The beneficial effect of G-GANA is mainly associated with the activity of gibberellins, auxins, and glycine. Gibberellins promote fruit enlargement by stimulating cell elongation, whereas auxins enhance cell division and direct the transport of assimilates toward developing fruits. These processes increase the accumulation of soluble solids and improve the balance between sugars and organic acids, which are important indicators of strawberry fruit quality [41]. Similar improvements in fruit quality following the application of gibberellins and auxins have been reported by [23,35,42].Glycine also contributes to fruit quality by serving as an organic nitrogen source and a precursor for chlorophyll and amino acid biosynthesis. This enhances photosynthetic activity and carbohydrate production, thereby increasing sugar accumulation and improving the nutritional and sensory quality of the fruits. These results agree with those reported by [43,44,45].

Calcium also played a significant role in improving fruit quality. It enhances fruit firmness through the formation of calcium pectate in the cell wall, strengthening cell structure and reducing tissue breakdown during ripening and storage [46]. Calcium also maintains membrane stability, reducing cellular leakage and preserving fruit tissue integrity.Furthermore, calcium improved total soluble solids, total sugars, and the TSS/TA ratio (Table 3). These improvements are attributed to its role in enhancing photosynthetic efficiency, facilitating carbohydrate transport from leaves to fruits, and promoting sugar accumulation while reducing organic acid concentration [47].Similar results have been reported by [40,48,49], who demonstrated that calcium application significantly improved strawberry fruit quality.

The results presented in Table 3 demonstrated that foliar application of G-GANA and calcium significantly improved the chemical quality attributes of strawberry fruits in both growing seasons. The combined application of G-GANA (100 mg L^{-1}) and calcium (3 mL L^{-1}) produced the highest values of anthocyanins, vitamin C, total phenolics, and flavonoids, indicating a complementary effect of plant growth regulators and calcium on fruit biochemical composition.The improvement in fruit quality can be primarily attributed to the enhancement of photosynthetic efficiency resulting from the significant increases in leaf area and chlorophyll content (Table 1). The greater photosynthetic capacity increased carbon assimilation and carbohydrate production, providing more photoassimilates for developing fruits. These carbohydrates serve not only as energy sources but also as essential carbon skeletons for the biosynthesis of secondary metabolites, including phenolic compounds, flavonoids, anthocyanins, and ascorbic acid [29].

The positive effect of G-GANA is mainly associated with the physiological functions of gibberellins, auxins, and glycine. Gibberellins stimulate cell elongation and fruit growth while enhancing carbohydrate metabolism and assimilate translocation toward developing fruits. They also promote the activity of enzymes involved in the phenylpropanoid pathway, particularly phenylalanine ammonia-lyase (PAL), leading to increased biosynthesis of anthocyanins and other phenolic compounds [50]. Furthermore, preharvest application of gibberellic acid has been reported to preserve vitamin C and enhance the accumulation of phenolic compounds during strawberry fruit development and storage [51]. Auxins contribute to fruit quality by regulating cell division, fruit set, and assimilate partitioning. They facilitate the transport of sugars and other metabolites into developing fruits, thereby providing substrates required for the synthesis of anthocyanins, flavonoids, phenolics, and ascorbic acid. The interaction between auxins and gibberellins therefore enhances both fruit growth and antioxidant metabolism, resulting in fruits with improved nutritional quality [29]. Glycine also contributes to these responses by serving as an organic nitrogen source and as a precursor for chlorophyll and amino acid biosynthesis. Enhanced chlorophyll formation improves photosynthetic efficiency and carbohydrate accumulation, while increased amino acid availability supports the synthesis of antioxidant metabolites, including phenolic compounds and flavonoids, thereby improving the nutritional and antioxidant properties of strawberry fruits.

Calcium also played a crucial role in improving fruit biochemical quality. Besides strengthening cell walls and maintaining membrane integrity, calcium functions as an important secondary messenger regulating numerous metabolic pathways associated with fruit ripening and antioxidant metabolism [46]. Calcium has been shown to stimulate the expression of genes involved in the flavonoid biosynthetic pathway and to increase anthocyanin accumulation through enhanced phenylpropanoid metabolism [52]. Moreover, calcium reduces oxidative stress by preserving membrane stability and limiting the degradation of ascorbic acid and phenolic compounds, thereby increasing vitamin C concentration and total antioxidant capacity.

The increase in total soluble solids observed in the present study(table 3) also provided additional substrates for the synthesis of phenolic compounds and anthocyanins. Consequently, the combined enhancement of photosynthesis, carbohydrate accumulation, assimilate translocation, and antioxidant metabolism explains the significant increases in anthocyanins, vitamin

C, total phenolics, and flavonoids recorded in strawberry fruits. Similar improvements in fruit biochemical quality following the application of gibberellins and calcium have been reported by [51,52,53].

CONCLUSION

The present study demonstrated that foliar application of G-GANA and calcium, particularly their combined application, improved both strawberry productivity and fruit nutritional quality under greenhouse conditions. The treatment consisting of 100 mg L^{-1} G-GANA and 3 mL L^{-1} calcium produced the greatest improvements in fruit yield, total soluble solids, total sugars, vitamin C, total phenolic compounds, and total flavonoids, while the combination of 100 mg L^{-1} G-GANA and 1.5 mL L^{-1} calcium resulted in the highest anthocyanin concentration. The enhancement of these bioactive compounds highlights the potential of integrated G-GANA and calcium application to increase the nutritional and functional value of strawberry fruits. However, because the present study did not directly determine antioxidant enzyme activities, reactive oxygen species, or molecular responses, further investigations are needed to clarify the physiological and biochemical mechanisms underlying these responses.

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