



Influence of Organic Nutrition Regime on Biochemical and Bioactive Compounds in Strawberry

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10.18805/ag.D-6184

ABSTRACT

Background: Strawberries (*Fragaria × ananassa*) are prized worldwide for their unique flavor highly rich nutritional profile, containing various bioactive compounds with potential health benefits. As consumer demand for organic produce rises, there is growing interest in understanding how organic cultivation practices affect strawberry quality and composition. While organic farming is associated with environmental benefits, its impact on fruit quality and nutritional content remains a subject of ongoing research.

Methods: This study advocated the effect of various organic source combinations on biochemical and bioactive compounds in strawberry cv. Flavia. Field trials were carried out over two cultivation seasons (2022-2024) at Lovely Professional University, using different organic inputs including vermicompost, neem cake, biochar, vesicular arbuscular mycorrhiza (VAM), *Panchgavya* and *Amritpani*. The experiment employed randomized block design (RBD) including ten treatments and three replicates. Strawberry fruits were assessed for different bioactive compounds such as total soluble solids (TSS), titratable acidity (TA), sugars, vitamin C, total phenolics, flavonoids, anthocyanins and antioxidant capacity.

Result: Results showed that a balanced combination of organic amendments at 60% RDF through vermicompost (90 g/m²) + neem cake (45 g/m²) + biochar (800 g/m²) + *Panchgavya* (50 ml/plant) + VAM (50 ml/plant) (T₉) significantly enhanced fruit quality parameters compared to control. T₉ exhibited the highest TSS (8.4°Brix), TSS/TA ratio (15.07), total sugars (8.21%), vitamin C (58.03 mg/100 g), total phenolics (268.57 mg GAE/100 g), total flavonoids (187.28 mg QE/100 g), total anthocyanins (50.37 mg/100 g) and total antioxidant capacity (82.99%).

Key words: Bioactive compounds, Fruit quality, Organic amendments, Strawberries.

INTRODUCTION

Globally, strawberries (*Fragaria × ananassa*) reign as the most economically important and extensively cultivated berry fruit, prized for their distinctive flavor, aroma and nutritional value (Agehara *et al.*, 2020). Strawberries contain rich array of bioactive compounds, such as anthocyanins, ellagic acid, vitamin C and flavonoids, which contribute to their antioxidant properties and potential health benefits (Li *et al.*, 2020). These phytochemicals are influenced by several factors, such as genetic composition, climatic conditions and cultivation practices (Nunes *et al.*, 2020; Ganhão *et al.*, 2019). Physiochemical properties such as color, fruit size, firmness, acidity and soluble solids content are crucial determinants of strawberry quality and consumer acceptance. These characteristics are also susceptible to changes in nutrient availability and plant stress responses, which may differ between organic and conventional cultivation systems (Reganold *et al.*, 2010; Rodge *et al.*, 2024).

Since strawberries are typically consumed raw, the buildup of applied synthetic chemicals on them could pose greater health risks. Moreover, the excessive and improper application of these chemicals can disrupt the soil microbial balance, contribute to environmental degradation and lead to groundwater contamination. As a result, the use of synthetic chemicals to boost crop yields should be

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How to cite this article: Sharma, J.B., Wani, A.W., Chauhan, N., Jabroot, K., Chaudhuri, M. and Rodge, R.R. (2024). Influence of Organic Nutrition Regime on Biochemical and Bioactive Compounds in Strawberry. *Agricultural Science Digest*. 1-7. doi: 10.18805/ag.D-6184.

Submitted: 04-09-2024 **Accepted:** 11-11-2024 **Online:** 26-12-2024

discouraged due to both consumer health concerns and their harmful environmental impact (Chauhan *et al.*, 2024, Nohong, 2024). Therefore, it is essential to explore and adopt eco-friendly alternatives to enhance crop yield and quality (Negi *et al.*, 2021; Mohanapriya *et al.*, 2024). The organic nutrition regime, which typically relies on vermicompost, compost, FYM and other organic fertilizers, may alter the availability and uptake of nutrients, potentially affecting the synthesis as well as accumulation of these bioactive components (Paul and Mandi, 2024). As consumer demand for organic produce continues to rise, there is

growing interest in understanding how organic cultivation practices affect the quality and composition of strawberries (Saygi, 2022). While organic farming practices are generally associated with environmental benefits and reduced chemical residues in food, their impact on fruit quality and nutritional content remains a subject of ongoing research and debate (Singh *et al.*, 2022).

However, some researches on strawberry cultivation methods suggest potential benefits of organic production (Hernández-Martínez *et al.*, 2023). Several studies have claimed that organically grown strawberries may exhibit higher antiproliferative activity against certain cancer cells, possibly due to increased phenolic compounds (D'Evoli *et al.*, 2010; Olsson *et al.*, 2006). These fruits have also shown elevated levels of ascorbic acid, contributing to enhanced antioxidant capacity (Forbes-Hernandez *et al.*, 2016). Organic strawberries are likely to have greater dry weight, more intense coloration from increased anthocyanin content and a potentially improved flavor profile with higher TSS and titratable acidity compared to conventionally grown counterparts (Mditshwa *et al.*, 2017). However, despite these promising findings, the current body of evidence is not yet sufficient to definitively establish the superior taste, texture, nutritional profile and overall acceptability of organically grown strawberries compared to their conventionally produced counterparts. Therefore, further research is needed to draw more conclusive results from organic strawberry cultivation methods.

By examining these aspects, we seek to contribute to the scientific understanding on influence of various organic amendment combinations on strawberry fruit quality comprised by the levels of different bioactive compounds through field experiments conducted in the Punjab region.

MATERIALS AND METHODS

This research experiment utilized fresh bare-rooted strawberry runners of Flavia cultivar, sourced from Hoshiarpur, Punjab. The field experiment was executed in Lovely Professional University, Phagwara, Punjab, India (30° 57' to 32° 7' N latitude and 75° 4' to 76° 30' E,

longitude) during the cropping years 2022-23 and 2023-24. This location is situated at an elevation of 270-300 m above Mean Sea Level (MSL), characterized by a humid and sub-tropical climate, receiving approximately 2029 mm of precipitation annually. Baseline soil of the experimental site was sandy loam which was well suited for strawberry cultivation. For both the trials, planting was done in the first week of November on raised beds at 30 × 30 cm spacing.

The study employed a randomized block design (RBD) for experimental layout, incorporating a total of ten treatments with three replicates. The details of different treatment combinations are mentioned in Table 1. Nine of these treatments (T₁-T₉) consisted of sole or combined application of vermicompost, neem cake, biochar, VAM, *Panchgavya* and *Amritpani* along with control treatment (T₁₀), which received no fertilizer or manure. Organic formulations like *Panchgavya* and *Amritpani* were prepared 15 days before planting, following the protocols outlined by Raghavendra *et al.* (2014) and Shekh *et al.* (2018), respectively. This involved fermenting various organic materials and byproducts from indigenous cattle, including cow dung, cow urine, ghee, milk and curd, for a two-week period. These materials were sourced from a nearby dairy farm in Phagwara, Punjab. Additionally, supplementary organic amendments such as vermicompost, neem cake, biochar and vesicular-arbuscular mycorrhizae (VAM) were obtained from the experimental input store in Lovely Professional University.

Fresh and fully ripened strawberries were screened visually and collected during April month. The freshly harvested fruits were pre-cooled through hydrocooling and immediately transported to the lab for testing. The fruits were first cleaned, then processed into a smooth puree using a blender and the resulting pulp was preserved at -80°C for subsequent analysis of biochemical characteristics involving sugar content (total, reducing and non-reducing), titratable acidity (TA), total soluble solids (TSS), TSS/TA ratio and total bioactive compounds.

The estimation of TSS and TA was done as per the methods followed by Roussos *et al.* (2022) with slight

Table 1: Details of different treatment combinations.

Symbols	Treatment details
T ₁	100% RDF through vermicompost (300 g/m ²)
T ₂	100% RDF through neem cake (150 g/m ²)
T ₃	100% RDF through vermicompost (150 g/m ²) + neem cake (75 g/m ²)
T ₄	80% RDF through vermicompost (240 g/m ²) + biochar (500 g/m ²) + <i>Amritpani</i> (25 ml/plant) + VAM (25 ml/plant)
T ₅	80% RDF through neem cake (120 g/m ²) + biochar (500 g/m ²) + <i>Amritpani</i> (25 ml/plant)
T ₆	80% RDF through vermicompost (120 g/m ²) + neem cake (60 g/m ²) + biochar (500 g/m ²) + <i>Amritpani</i> (25 ml/plant) + VAM (25 ml/plant)
T ₇	60% RDF through vermicompost (180 g/m ²) + biochar (800 g/m ²) + <i>Panchgavya</i> (50 ml/plant) + VAM (50 ml/plant)
T ₈	60% RDF through neem cake (90 g/m ²) + biochar (800 g/m ²) + <i>Panchgavya</i> (50 ml/plant) + VAM (50 ml/plant)
T ₉	60% RDF through vermicompost (90 g/m ²) + neem cake (45 g/m ²) + biochar (800 g/m ²) + <i>Panchgavya</i> (50 ml/plant) + VAM (50 ml/plant)
T ₁₀	Control

alterations. Initially, 2 g of frozen fruit pulp was taken in a centrifuge tube and centrifuged at $5000 \times g$ for 15 min (Remi R-8C plus centrifuge). The resulting clear juice (supernatant) was used for determining the TSS and TA. The measurement of TSS was done with a Hanna Woonsocket RI digital refractometer and values were expressed in oBrix. To determine TA, juice sample was diluted with distilled water in a 1:50 ratio and aliquots of this diluted solution were then titrated using 0.1 N NaOH to a pink endpoint, using phenolphthalein as indicator. The resulting TA value was calculated and expressed in percentage (%). To calculate TSS/TA ratio, the TSS value was divided by the value of TA.

To estimate total and reducing sugar content, procedure described in the A.O.A.C. (1980) was followed using Fehling A and Fehling B solutions and the outcomes were quantified in percentage (%). Additionally, the values of non-reducing sugars were obtained by subtracting the measured value of reducing sugars from the total sugar content. The vit-C content in strawberries was evaluated following the method described by Ranganna (2003), employing the titration of filtered strawberry extracts diluted with 3% metaphosphoric acid against a standardized 2,6-dichlorophenol indophenol dye to pink endpoint.

Using 5 mL of 50% methanol (v/v) and 0.5 g of frozen strawberry pulp, the total phenolic content (TPC) and total flavonoid content (TFC) were calculated in accordance with the methodology followed by Roussos *et al.* (2022). The outcomes were expressed in milligrams of quercetin equivalent (QE) and gallic acid equivalent (GAE) per 100 grams of fresh weight for TPC and TFC, respectively.

The content of total anthocyanin was quantified employing the pH differential method, as suggested by Lee *et al.* (2005) and the results were reported in milligrams of pelargonidin 3-glucoside per 100 g of fresh weight. Similarly, total antioxidant capacity was measured in the juice obtained by centrifuging 1 g of pulp, utilizing DPPH assays (Roussos *et al.*, 2022) and results were expressed as % Radical scavenging activity.

The collected data were presented as mean values and analyzed using one-way ANOVA with SPSS software. Duncan's Multiple Range Test (DMRT) was applied for descriptive analysis to identify homogeneous subsets, aiding in the interpretation of results at a significance level of $P < 0.05\%$. The use of the different letters indicates statistically significant difference between the examined groups.

RESULTS AND DISCUSSION

TSS, TA and TSS/TA ratio

Significant variations were noted among all the treatments regarding TSS, TA and the TSS/TA ratio in strawberries, as shown in Table 2. Among all the treatments, T_9 i.e. 60% RDF through vermicompost (90 g/m^2) + neem cake (45 g/m^2) + biochar (800 g/m^2) + *Panchgavya* (50 ml/plant) + VAM (50 ml/plant) exhibited the most favorable results. The data

Table 2: Effect of organic nutrition regime on total soluble solids, titratable acidity and TSS/Acid ratio in strawberries.

Treatments	Total soluble solids (°Brix)			Titratable acidity (%)			TSS/Acid ratio		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T_1	6.4±0.072 ^{bc}	6.7±0.036 ^b	6.5±0.468 ^{bc}	0.71±0.016 ^{ef}	0.68±0.020 ^a	0.69±0.011 ^e	9.04±0.213 ^{bc}	9.92±0.326 ^b	9.47±0.260 ^b
T_2	6.5±0.225 ^c	6.8±0.261 ^{bc}	6.6±0.221 ^c	0.69±0.022 ^a	0.67±0.026 ^d	0.68±0.010 ^e	9.37±0.317 ^c	10.21±0.369 ^b	9.78±0.165 ^b
T_3	6.1±0.271 ^{ab}	6.5±0.217 ^{ab}	6.3±0.076 ^{ab}	0.73±0.027 ^a	0.73±0.201 ^f	0.73±0.010 ^f	8.37±0.445 ^a	8.96±0.269 ^a	8.66±0.158 ^a
T_4	6.9±0.170 ^d	7.1±0.253 ^c	7.0±0.199 ^d	0.65±0.003 ^d	0.60±0.020 ^c	0.63±0.010 ^d	10.6±0.263 ^d	11.73±0.754 ^c	11.19±0.475 ^c
T_5	7.7±0.137 ^e	8.1±0.109 ^{de}	7.9±0.018 ^f	0.63±0.016 ^{bcd}	0.63±0.001 ^c	0.63±0.010 ^d	12.3±0.159 ^e	12.93±0.172 ^d	12.65±0.916 ^d
T_6	7.9±0.262 ^{ef}	8.2±0.148 ^{de}	8.0±0.112 ^f	0.60±0.027 ^a	0.56±0.261 ^{ab}	0.58±0.25 ^{ab}	13.2±0.975 ^f	14.67±0.551 ^e	13.92±0.744 ^e
T_7	7.1±0.035 ^d	7.9±0.090 ^d	7.5±0.048 ^e	0.64±0.158 ^{cd}	0.57±0.004 ^{ab}	0.60±0.057 ^c	11.0±0.209 ^d	13.95±0.964 ^e	12.41±0.158 ^d
T_8	7.8±0.213 ^e	8.4±0.377 ^{ef}	8.1±0.213 ^f	0.62±0.018 ^{bc}	0.57±0.005 ^b	0.60±0.005 ^{bc}	12.5±0.509 ^f	14.65±0.656 ^e	13.58±0.291 ^e
T_9	8.2±0.289 ^f	8.7±0.342 ^f	8.4±0.264 ^g	0.58±0.025 ^a	0.54±0.008 ^a	0.56±0.152 ^a	14.0±0.100 ^g	16.20±0.646 ^f	15.07±0.312 ^f
T_{10}	5.0±0.127 ^a	5.1±0.201 ^a	5.0±0.582 ^a	0.86±0.014 ^g	0.83±0.019 ^f	0.84±0.011 ^f	5.90±0.173 ^a	6.14±0.172 ^a	6.02±0.160 ^a

*Differences marked by distinct letters in the same column are statistically significant ($P < 0.05$). Treatment details: Refer to Table 1.

Table 3: Effect of organic nutrition regime on total sugars, reducing sugars and non-reducing sugars in strawberries.

Treatments	Total sugars (%)			Reducing sugars (%)			Non-reducing sugars (%)		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T ₁	6.56±0.458 ^b	6.71±0.117 ^b	6.63±0.750 ^b	4.50±0.045 ^b	4.70±0.264 ^a	4.60±0.030 ^b	2.06±0.045 ^{bc}	2.01±0.110 ^a	2.03±0.080 ^{bc}
T ₂	6.97±0.624 ^c	7.22±0.242 ^c	7.09±0.873 ^c	4.92±0.036 ^c	5.03±0.000 ^c	4.97±0.020 ^c	2.05±0.052 ^{bc}	2.19±0.242 ^b	2.12±0.104 ^{bc}
T ₃	6.37±0.458 ^b	6.97±0.216 ^c	6.67±0.953 ^b	4.98±0.208 ^c	5.12±0.072 ^c	5.05±0.028 ^{cd}	1.38±0.041 ^a	1.85±0.190 ^a	1.61±0.090 ^a
T ₄	7.41±0.294 ^d	7.65±0.134 ^d	7.53±0.160 ^d	5.12±0.108 ^d	5.20±0.513 ^d	5.15±0.047 ^d	2.29±0.258 ^{cd}	2.45±0.100 ^b	2.37±0.140 ^c
T ₅	7.53±0.170 ^{de}	7.71±0.153 ^e	7.62 ±141 ^d	5.30 ±0.180 ^e	5.64±0.08 ^e	5.47 ±0.115 ^e	2.23 ±0.350 ^{cd}	2.07±0.132 ^a	2.15 ±0.236 ^{bc}
T ₆	8.03±0.355 ^f	8.24±0.152 ^f	8.13±0.181 ^{ef}	5.85±0.170 ^f	6.23±0.117 ^g	6.04±0.138 ^g	2.18±0.525 ^{bcd}	2.01±0.127 ^a	2.09±0.321 ^{bc}
T ₇	7.81±0.776 ^f	8.04±0.314 ^f	7.92±0.120 ^e	5.31±0.123 ^e	5.84±0.117 ^f	5.58±0.108 ^f	2.49±0.201 ^{cd}	2.20±0.337 ^b	2.34±0.136 ^c
T ₈	7.93±0.216 ^f	7.97±0.984 ^f	7.95±0.141 ^e	5.35±0.036 ^e	5.91±0.045 ^f	5.63±0.010 ^f	2.58±0.220 ^d	2.05±0.142 ^a	2.32±0.138 ^c
T ₉	8.12±0.278 ^f	8.30±0.19 ^f	8.21±0.233 ^f	5.87±0.015 ^f	6.41±0.56 ^h	6.14±0.020 ^g	2.24±0.265 ^{cd}	1.89±0.242 ^a	2.07±0.255 ^{bc}
T ₁₀	6.02±0.117 ^a	6.23±0.19 ^a	6.12±0.051 ^a	4.28±0.128 ^a	4.29±0.015 ^a	4.29±0.072 ^a	1.73±0.058 ^{ab}	1.93±0.206 ^a	1.83±0.118 ^{ab}

*Differences marked by distinct letters in the same column are statistically significant (P<0.05). Treatment details: Refer to Table 1

Table 4: Effect of organic nutrition regime on total phenolic content, total flavonoid content and vitamin-C content in strawberries.

Treatments	Total phenolic content (mg GAE/100 g)			Total flavonoid content (mg QE/100 g)			Vitamin-C (mg/100 g)		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T ₁	234.03±0.907 ^d	237.76±7.715 ^e	235.89±3.652 ^f	148.13±4.753 ^f	151.63±6.574 ^e	149.88±1.622 ^g	48.64±1.174 ^{bc}	52.72±0.994 ^{bc}	50.68±1.117 ^b
T ₂	242.36±4.369 ^{cd}	248.92±3.366 ^d	245.64±3.359 ^e	154.21±1.251 ^{ef}	160.52±5.643 ^d	157.37±2.287 ^f	49.15±0.838 ^c	52.30±0.252 ^b	50.73±0.330 ^b
T ₃	246.65±6.225 ^{bcd}	257.86±5.346 ^{cd}	252.26±2.918 ^{de}	159.6±3.453 ^{de}	167.251.357 ^c	163.43±2.147 ^e	47.33±1.406 ^{ab}	50.13±0.707 ^{ab}	48.73±0.015 ^{ab}
T ₄	248.61±6.051 ^{abc}	260.47±1.174 ^{bc}	254.54±2.548 ^{cde}	165.25±6.703 ^{cd}	170.12±1.687 ^{bc}	167.69±3.843 ^d	51.32±1.432 ^d	53.55±0.973 ^{bcd}	52.43±0.576 ^c
T ₅	252.36±5.004 ^{abc}	265.38±11.243 ^{abc}	258.87±6.240 ^{bcd}	171.34±4.633 ^{bc}	175.26±5.371 ^b	173.3±1.432 ^c	52.18±0.278 ^d	55.22±0.802 ^{de}	53.70±1.442 ^{cd}
T ₆	258.12±10.005 ^{ab}	271.84±9.556 ^{ab}	264.98±6.783 ^{ab}	178.22±2.570 ^b	183.31±0.165 ^a	180.77±1.203 ^b	53.12±0.190 ^{de}	55.53±0.571 ^{de}	54.32±0.952 ^d
T ₇	257.36±10.903 ^{ab}	269.74±4.620 ^{ab}	263.55±7.508 ^{abc}	172.56±2.955 ^{bc}	176.61±2.000 ^b	174.59±2.460 ^c	52.11±1.596 ^d	55.71±0.435 ^{de}	53.91±1.859 ^d
T ₈	255.13±10.119 ^{abc}	265.3±3.348 ^{abc}	260.22±5.268 ^{abcd}	171.66±3.404 ^{bc}	174.35±1.100 ^b	173.01±1.271 ^c	52.77±0.618 ^d	54.74±1.04 ^{cd}	53.76±2.00 ^{cd}
T ₉	262.65±7.76 ^a	274.49±0.247 ^a	268.57±3.893 ^a	185.32±4.176 ^a	189.23±2.729 ^a	187.28±3.012 ^a	55.72±0.690 ^e	60.34±0.352 ^f	58.03±0.153 ^e
T ₁₀	185.11±5.173 ^e	187.37±0.169 ^f	186.24±2.661 ^g	109.56±1.778 ^h	111.35±0.301 ⁱ	110.46±0.824 ^h	41.57±0.252 ^a	43.61±1.007 ^a	42.59±1.874 ^a

*Differences marked by distinct letters in the same column are statistically significant (P<0.05). Treatment details: Refer to Table 1.

reveal a consistent upward trend in the TSS and TSS/TA ratio while, a decreasing trend in TA over the two-year period, indicating the positive impact of this treatment (T_9). In contrast, the control group (T_{10}) displayed less-desirable characteristics, including lower TSS content, reduced TSS/TA ratio and elevated TA. The pooled data for TSS and TSS/TA ratio show a trend of $T_9 > T_6 > T_8 > T_7 > T_5 > T_4 > T_1 > T_2 > T_3 > T_{10}$ whereas, TA showed a reverse pattern as $T_9 < T_6 < T_8 < T_7 < T_5 < T_4 < T_2 < T_1 < T_{10}$.

Sugar content

Table 3 shows the effect of organic amendments on total sugars, reducing sugars and non-reducing sugars in strawberry, with significant differences in all the treatments. T_9 consistently yielded the highest values for total sugars and reducing sugars over two years and in the pooled data, which were significantly higher than the other treatments and control (T_{10}). For non-reducing sugars, T_4 (80% RDF through vermicompost + biochar + *Amritpani* + VAM) recorded significantly higher results than other treatments while, control showed the least values. However, T_9 was closely followed by T_6 , T_8 and T_7 which showed statistical similarity among themselves across the pooled average for total sugars, while it (T_9) was statistically comparable to T_6 for reducing sugars. For non-reducing sugars, T_4 exhibited the statistical similarity with T_7 and T_8 , while, T_5 , T_2 , T_9 and T_1 were statistically comparable among themselves.

TPC, TFC and vitamin C content

Pooled results from Table 4 reveal significant differences among the treatments for TPC, TFC and vitamin C content among various organic treatment combinations in strawberries. The values for TPC, TFC and vitamin C among all treatments ranged from 186.24 to 268.57 mg GAE/100 g, 110.46 to 187.28 mg QE/100 g and 42.59 to 58.03 mg/100 g, respectively, with T_9 recording the highest and T_{10} recording the lowest. However, T_9 was closely followed by T_6 , showing the effectiveness of combination of multiple organic amendments at low concentration over the single or less number of sources.

Total anthocyanin and total antioxidant capacity

Table 5 reveal striking contrasts in strawberry anthocyanin content and antioxidant capacity across all the treatments. Maintaining the consistent behavior, T_9 emerged as an innovative combination yielding peak anthocyanin levels (50.37 mg/100 g) and antioxidant capacity, significantly outperforming the other treatments. Conversely, the control treatment (T_{10}) lagged far behind, exhibiting lower total anthocyanin content and total antioxidant capacity. Intriguingly, superiority of T_9 over treatments with higher RDF percentages, such as T_1 (100% RDF via vermicompost) and T_6 at 80% RDF underscored a paradigm shift.

The application of organic amendments has been shown to significantly enhance fruit quality and increase levels of bioactive compounds. The present research demonstrates that a well-balanced combination of organic resources in T_9 including vermicompost, neem cake, biochar, *Panchgavya*, *Amritpani* and VAM, can lead to notable improvements in various quality attributes.

Several other mechanisms have been proposed to explain the enhancement in the fruit quality and bioactive compound profile associated with organic amendments. Vermicompost, rich in humic acids and trace elements, has been associated with increased vitamin C content in fruits (Zuo *et al.*, 2018), which was also observed in our study. Biochar acts as a biostimulant, leading to enhancement in soil structure and promoting plant stress tolerance, growth and product quality (Garza-Alonso *et al.*, 2022). The presence of arbuscular mycorrhizal fungi (AMF) along with organic manures has been associated with increased synthesis of secondary metabolites, particularly phenolics and flavanols, primarily through enhanced phosphorus uptake (Ansari *et al.*, 2018). Additionally, neem cake serves a dual role as both a biopesticide and biofertilizer, further contributing to improved fruit quality (Devi and Gogoi, 2023).

Our findings are in line with studies demonstrating the benefits of organic amendments on fruit quality (Vilhena *et al.*, 2024; Fan *et al.*, 2023). Similarly, research shows

Table 5: Effect of organic nutrition regime on total anthocyanin content and total antioxidant capacity in strawberries.

Treatments	Total anthocyanin content (mg/100 g)			Total antioxidant capacity (%)		
	2023	2024	Pooled	2023	2024	Pooled
T_1	31.54±0.76 ^b	32.15±1.34 ^b	31.84±0.92 ^b	71.36±0.134 ^b	73.65±2.93 ^b	72.50±1.43 ^b
T_2	39.45±0.17 ^c	42.63±1.84 ^c	41.04±0.92 ^c	72.65±0.91 ^{bc}	74.99±141 ^{bc}	73.82±0.62 ^{bc}
T_3	39.75±0.71 ^c	43.15±0.66 ^c	41.45±0.66 ^{cd}	72.25±2.14 ^{bc}	74.69±2.15 ^{bc}	73.46±2.06 ^{bcd}
T_4	41.76±1.80 ^{de}	44.15±1.32 ^c	43.22±1.56 ^e	74.13±3.13 ^{bcd}	76.35±3.10 ^{bc}	75.24±2.99 ^{cde}
T_5	40.12±0.36 ^{cd}	45.36±1.34 ^d	42.74±0.60 ^e	73.20±0.45 ^{bcd}	77.02±0.41 ^{bc}	75.11±0.31 ^{bcd}
T_6	47.39±1.99 ^f	50.16±1.58 ^f	48.77±0.53 ^g	79.23±1.21 ^e	81.36±3.15 ^{de}	80.29±1.11 ^f
T_7	42.76±1.00 ^e	47.65±0.42 ^e	45.20±0.63 ^f	75.62±0.00 ^d	78.66±3.04 ^{cd}	77.14±1.52 ^e
T_8	43.05±1.39 ^e	49.65±0.17 ^f	46.35±0.62 ^f	74.99±0.87 ^{cd}	77.56±0.20 ^{bcd}	76.27±0.40 ^{de}
T_9	48.12±0.08 ^f	52.63±0.90 ^g	50.37±0.49 ^h	81.63±1.39 ^e	84.36±0.83 ^e	82.99±0.60 ^g
T_{10}	28.57±0.90 ^a	30.15±0.86 ^a	29.36±0.85 ^a	60.13±2.11 ^a	62.31±1.96 ^a	61.22±0.49 ^a

*Differences marked by distinct letters in the same column are statistically significant ($P < 0.05$). Treatment details: Refer to Table 1.

that organic manures enhance soil organic matter, nutrients, hormones and microbial populations, creating a favorable rhizosphere for nutrient absorption, which boosts plant growth, fruit quality and nutrient content Chaudhary *et al.*, 2022). Similarly, Negi *et al.* (2021) reported a significantly higher concentration of ascorbic acid, total sugars, total phenolic content and antioxidant capacity in strawberries treated with a combination of 50% FYM, 50% vermicompost, *Azotobacter* and *Pseudomonas*. Comparative studies have shown that organically grown strawberries have higher levels of anthocyanins, total sugars, TSS and TS/TA ratios compared to conventionally grown ones (Pešaković *et al.*, 2023). Similarly, Roussos *et al.* (2022). found that organic strawberries contain more flavanols, phenolics and antioxidants than those from integrated farming. These findings suggest that organic agriculture can produce high-quality products with enhanced nutritional profiles under optimal conditions, however future research should examine the long-term effects of these organic amendments on strawberry quality across cultivars and conditions, as well as their economic viability and sustainability for broader adoption. The major limitation of adopting organic farming is that preparing organic inputs can be time-consuming and these inputs take longer to mineralize compared to inorganic fertilizers. This slower process may result in reduced plant growth during the early stages.

CONCLUSION

This study highlights the benefits of using a balanced organic mix of vermicompost, neem cake, biochar, *Panchgavya*, *Amritpani* and VAM at 60% RDF to improve total soluble solids, sugar content, vitamin C and other bioactive compounds in strawberries. These enhancements were achieved without higher fertilizer doses, demonstrating the effectiveness of a synergistic organic approach that boosts soil health, nutrient availability and plant metabolism. Vermicompost provides nutrients, biochar improves soil structure and water retention and mycorrhizal fungi increase nutrient uptake, creating an optimal environment for bioactive compound synthesis. This study paves the way for further research into sustainable, high-quality organic strawberry production.

ACKNOWLEDGEMENT

The support provided by Lovely Professional University for carrying out this research is duly acknowledged.

Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article. No funding or sponsorship influenced the design of the study, data collection, analysis, decision to publish, or preparation of the manuscript.

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