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# EFFECTS OF CHEMICAL AND ORGANIC FERTILIZER COMBINATIONS ON BIOACTIVE COMPOUNDS AND MACRO-MICRO NUTRIENTS IN BELL PEPPER (*Capsicum annuum* L.) FRUITS

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## ABSTRACT

This study aimed to identify strategies that are conducive to both sustainable and high-yielding horticulture, with a focus on minimizing ecological damage by reducing dependence on chemical fertilizers. Sumo F1 bell pepper variety was used in an open-field experiment. The effect of three distinct fertilizer types (earthworm vermicompost Yaşa Tarım, organomineral fertilizer Hektaş, chemical fertilizer Gübretaş) and their respective combinations on biochemical, nutrient and color parameters of bell pepper fruits was evaluated. It was observed that biochemical values and nutrient levels were higher in treatments with vermicompost at 25, 50, 75 and 100% rates. The highest levels of organic acids (malic acid, succinic acid, fumaric acid, tartaric acid), polyphenols (chlorogenic acid, ferulic acid), total antioxidants, and nutrient elements (phosphorus, potassium, zinc) were obtained in treatments without chemical fertilizer. The results show that the use of organomineral fertilizer, especially vermicompost, plays a role in reducing the dependence on chemical fertilizer in bell pepper cultivation.

**Keywords:** antioxidants, organic acids, polyphenols, sustainable horticulture, vermicompost

## INTRODUCTION

Pepper (*Capsicum annuum* L.) is a vegetable species belonging to the *Capsicum* genus in the Solanaceae family, with approximately 20–30 species grown in tropical and subtropical regions [Güneş et al. 2023]. It is known that the origin of the pepper, which thrives in temperate climate conditions, is in Central and South America [Başak 2021]. Achieving high yields and quality produce with peppers requires proper nutrition and suitable climatic conditions [Bayram et al. 2019]. Due to its favorable climate conditions, Turkey is one of the most important countries in pepper production.

Antioxidants, phenolic compounds and organic acids, which are considered important bioactive components for human health, are abundantly found in plants, especially in the structure of vegetables and fruits [Saud et al. 2024]. Phenolic compounds, known as phytochemicals, influence the color, taste, ripening, and other characteristics of plants. They exhibit antioxidant effects by preventing oxidation and trapping free radicals within the plant's defense mechanisms and play an essential role in human health [Erdinç et al. 2018].

Peppers, through their carotenoid content and various phytochemicals, are a potent source of antioxidants and possess anti-inflammatory properties. They play a crucial role in reducing the risk of chronic diseases that can lead to genetic damage and mutations. Excessive use of chemical fertilizers in agricultural production has led to water and air pollution, decreased soil fertility, reduced nutritional value and edible

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qualities of fruits, and ultimately poses a threat to human health [Keser 2021]. Considering that the polyphenol content in plants is influenced by growth conditions, ripeness, plant variety, harvesting conditions and cultivation practices, it is important to consider the sustainability of recommended fertilizer doses derived from organic compounds as a significant alternative to improve human health, environmental safety, and soil structure through sustainable agricultural approaches [Ribes-Moya et al. 2020].

Among organic compounds, one of the prominent products is vermicompost, a next-generation organic fertilizer produced through the decomposition processes facilitated by earthworms. Due to its dense population of beneficial bacteria and microorganisms that promote plant growth and development and its low C:N ratio, vermicompost is considered a significant organic fertilizer and soil conditioner [Ilie and Mihalache 2022].

Fertilizers referred to as organominerals are obtained through the combination of mineral fertilizers with organic materials such as manure or other waste products through industrial processes. This combination provides benefits for improving soil conditions and sustaining soil fertility. Organomineral fertilizers have also been reported to play roles in soil pH adjustment, nutrient uptake, increasing organic matter content, and enhancing root exudation in plants [Smith et al. 2020].

Significant differences between organic and conventional farming systems, particularly in soil fertility management, can affect the nutrient composition of plants, including secondary plant metabolites [Ribes-Moya et al. 2020]. Good agricultural practices encompass production systems that are friendly to both humans and the environment.

In the current study, it was hypothesized that the careful selection and combination of organic and chemical fertilizers can significantly influence the biochemical and nutrient composition of bell pepper fruits. Therefore, the aim of this study is to systematically investigate the effects of organic and chemical fertilizers, as well as their combinations, on the nutrient and biochemical profile in pepper fruits. This analysis is intended to provide valuable insights into optimizing fertilizer strategies to enhance both the nutritional quality of bell peppers and the sustainability of agricultural practices.

## MATERIAL AND METHODS

### Experimental setup

The cultivation phase of the study utilized Sumo $F_1$ bell pepper seedlings obtained from a private company. The experiment was organized into three replications with 20 plants in each replicate, following a completely randomized block design. Open-field experimental plots located at Van Yüzüncü Yıl University (38° 34' 25' North latitude and 43° 17' 40" East longitude) were used. Seedlings were planted on 11 June 2021 with inter- and intra-row spacing set at 100 × 50 cm. The ripe fruit samples for the analyses were collected from six plants in the middle of the plots at the third and fourth harvests to eliminate the edge effect. The study area's soil characteristics were assessed before planting, revealing the absence of salts, low organic matter content, rich lime content, and a slightly alkaline pH (Table 1).

Seedlings were irrigated using a drip irrigation system throughout the growing period, ensuring a consistent moisture supply. Climate data for the 2021 growing season, during which the research was conducted, are presented in Table 2.

### Fertilization program

A comprehensive fertilization program consisting of ten treatments was implemented. Three different fertilizer types were employed: chemical fertilizer (Gübretaş), earthworm vermicompost (Yaşa Tarım), and organomineral fertilizer (Hektaş), both individually and in various combinations, including the control group.

Vermicompost, chemical fertilizer and organomineral fertilizers, the contents of which are given in Table 3, were prepared in ten different combinations with varying rates (0, 25, 50, 75, 100%) (Table 4). These fertilizers were applied to the plots on 3 June 2021, one week before the seedling planting. During the growing season, urea was applied twice at intervals of about four weeks to complete the nitrogen deficiency in the plots where chemical fertilizer was applied alone or in combination.

### Laboratory analysis

Chemicals of analytical purity were employed in the present study. The standards of phenolic reagents

**Table 1.** Soil analysis data of the experimental field

| Parameter | Value |
|---|---|
| Phosphorus – P (mg kg$^{-1}$) | 5.50 |
| Pottasium – K (mg kg$^{-1}$) | 11.04 |
| Organic matter (%) | 0.93 |
| Lime (%) | 10.84 |
| pH (%) | 7.83 |
| Electrical conductivity/Salt (%) | 0.01 |
| Structure (%) | sand: 37, clay: 24.3, silt: 38.6 |
| Nitrogen – N (%) | 0.17 |
| Manganese – Mn (mg kg$^{-1}$) | 0.98 |
| Sodium – Na (mg kg$^{-1}$) | 86.35 |
| Iron – Fe (mg kg$^{-1}$) | 1.12 |
| Copper – Cu (mg kg$^{-1}$) | 0.53 |
| Zinc – Zn (mg kg$^{-1}$) | 0.46 |
| Calcium – Ca (mg kg$^{-1}$) | 1025 |
| Magnesium – Mg (mg kg$^{-1}$) | 134 |

**Table 2.** Some climatic parameters of the experimental area in 2021 (14th Regional Directorate of Meteorology)

| Parameter | May | June | July | August | September |
|---|---|---|---|---|---|
| Average temperature (°C) | 19.2 | 21.1 | 24.5 | 26.4 | 22.8 |
| Minimum temperature (°C) | 10.5 | 14.3 | 17.1 | 19.6 | 16.5 |
| Maximum temperature (°C) | 27.8 | 27.9 | 31.8 | 33.2 | 29.1 |
| Sunshine duration | 11.9 | 12.7 | 12.5 | 12.6 | 11.8 |
| Precipitation (mm) | 8.1 | 14.7 | 12.7 | 15.5 | 1.1 |
| Wind (m s$^{-1}$) | 3.1 | 2.7 | 2.1 | 2.3 | 2.1 |
| Relative humidity (%) | 41.8 | 48.3 | 34.2 | 30.9 | 35.8 |
| Evaporation (mm) | 65.2 | 188.5 | 199.4 | 213.4 | 25.0 |

and organic acids were obtained from Sigma–Aldrich (St. Louis, MO, USA). The other chemicals were obtained from Merck (Darmstadt, Germany).

### Extraction of organic acids and determination by HPLC

The method by Bevilacqua and Califano [1989] was modified for organic acid extraction. One-gram fruit samples were transferred to centrifuge tubes, and 10 mL of 0.009 N $H_2SO_4$ was added and homogenized (Heidolph Silent Crusher M, Germany). They were then allowed to mix on a shaker (Heidolph Unimax 1010, Germany) for 1 hour and centrifuged at 15 000 rpm for 15 min. The supernatant was first passed through coarse filter paper, then twice through a 0.45 µm membrane filter (Millipore Millex-HV Hydrophilic PVDF, Millipore, USA), and finally through a SEP-PAK C18 cartridge. The concentration of organic acids was determined by HPLC using an Aminex column (HPX-87H, 300 mm × 7.8 mm, Bio-Rad) fitted on an Agilent 1100 series (HPLC G 1322 A). Organic acids were detected at 214 and 280 nm wavelengths. As the mobile phase, 0.009 N $H_2SO_4$ was passed through a 0.45 µm filter membrane.

**Table 3.** Ingredients of fertilizers used in the plant growing process

| Chemical fertilizer (CF) (20:20:20) (%) | Triple superphosphate (TSP) | Nitrogen fertilizer (%46) | Organomineral fertilizer (OMF) 11:11:11 (%) | Vermicompost (VC) (%) |
|---|---|---|---|---|
| total nitrogen: 20<br>ammonium nitrogen: 3.9<br>nitrate nitrogen: 5.9<br>urea (N-NH$_2$): 10.2<br>water soluble phosphorus pentoxide: 20<br>water soluble potassium oxide: 20<br>water soluble iron: 0.05<br>water soluble copper: 0.02<br>water soluble zinc: 0.02<br>water soluble manganese: 0.02 | water soluble phosphorus pentoxide: 39<br>phosphorus pentoxide soluble in neutral ammonium citrate (P$_2$O$_5$): 42 | urea: 46 | organic matter: 18.00<br>total nitrogen: 11.00<br>ammonium nitrogen: 5.00<br>urea nitrogen: 6.00<br>water soluble potassium oxide: 11.00<br>total phosphorus pentoxide: 11.00<br>water soluble phosphorus pentoxide: 9.00<br>water soluble sulfur trioxide: 7.00<br>total sulfur trioxide: 11.00<br>total zinc: 0.10<br>total humic acid + fulvic acid: 5.00 | organic matter: 35.00<br>total nitrogen: 2.00<br>organic nitrogen: 1.00<br>water soluble potassium oxide: 2.00<br>total phosphorus pentoxide: 0.40<br>total humic acid + fulvic acid: 20.00<br>C/N: 10.04<br>max. EC (dS/m): 2.00<br>max. moisture: 35.00<br>pH: 6–8 |

### Extraction of phenolic compounds and determination by HPLC

The method described by Rodriguez-Delgado et al. [2001] was modified and used to separate phenolic compounds by HPLC. One-gram fruit samples were homogenized by adding 10 mL of methanol (99.9% purity). After homogenization, samples were centrifuged at 15 000 rpm for 15 min. The supernatant was then filtered with 0.45 µm Millipore filters (Millipore Millex-HV Hydrophilic PVDF, Millipore, USA) and injected into the HPLC system (gradient). Chromatographic separation was performed on an Agilent 1100 HPLC system using a DAD detector (Agilent. USA) and a 250 × 4.6 mm, 4 µm ODS column (HiChrom, USA). Solvent A methanol-acetic acid-water (10:2:88) and Solvent B methanol-acetic acid-water (90:2:8) were used as mobile phase, and a gradient elution program was applied. Separation was performed at 254 and 280 nm, the flow rate was 1 mL min$^{-1}$and the injection volume was 20 µL.

### Vitamin C content analysis by HPLC

Five milliliters of the juice obtained from the samples was transferred into a test tube, and 5 mL of 2.5% M-phosphoric acid solution was added. The mixture was centrifuged at 6500 rpm at 40 °C for 10 min. and then 0.5 mL of the supernatant in the tube was taken and refilled to 10 mL with 2.5% M-phosphoric solution. This mixture was filtered through a 0.45 µm Teflon filter and injected into the HPLC device. Readings were taken at 254 nm wavelength on a DAD detector. L-ascorbic acid prepared at different concentrations (50, 100, 500, 1000, and 2000 ppm) was used to identify and quantify the vitamin C peak [Cemeroğlu 2007].

**Table 4.** Doses of fertilizers used in the plant growing process

| Treatment | Fertilizer combinations | Fertilizer doses |
|---|---|---|
| T1 | control | – |
| T2 | CF$_{(100\%)}$ | 19.8 kg da$^{-1}$ N:P:K (20:20:20) + 14.21 kg da$^{-1}$ TSP + 23.63 kg da$^{-1}$ %46 urea |
| T3 | VC$_{(100\%)}$ | 741.5 kg da$^{-1}$ |
| T4 | OMF$_{(100\%)}$ | 134.82 kg da$^{-1}$ |
| T5 | CF$_{(25\%)}$+ VC$_{(75\%)}$ | 4.75 kg da$^{-1}$ N:P:K (20:20:20) + 3.55 kg da$^{-1}$ TSP + 5.91 kg da$^{-1}$ %46 urea + 556.13 kg da$^{-1}$ VC |
| T6 | CF$_{(50\%)}$ + VC$_{(50\%)}$ | 9.9 kg da$^{-1}$ N:P:K (20:20:20) + 7.11 kg da$^{-1}$ TSP + 11.82 kg da$^{-1}$ %46 urea + 370.75 kg da$^{-1}$ VC |
| T7 | CF$_{(75\%)}$+VC$_{(25\%)}$ | 14.85 kg da$^{-1}$ N:P:K (20:20:20) + 10.66 kg da$^{-1}$ TSP + 17.73 kg da$^{-1}$ %46 urea + 185.38 kg da$^{-1}$ VC |
| T8 | OMF$_{(25\%)}$ +VC$_{(75\%)}$ | 33.71 kgda$^{-1}$ OMF + 556.13 kg da$^{-1}$ VC |
| T9 | OMF$_{(50\%)}$ + VC$_{(50\%)}$ | 67.41 kg da$^{-1}$ OMF + 370.75 kg da$^{-1}$ VC |
| T10 | OMF$_{(75\%)}$ + VC$_{(25\%)}$ | 101.12 kg da$^{-1}$ OMF + 185.38 kg da$^{-1}$ VC |

CF – chemical fertilizer, VC – vermicompost, OMF – organomineral fertilizer

### Total antioxidant activity (TE)

The ferric reducing antioxidant power (FRAP) method was used to determine the antioxidant activity [Benzie and Strain 1996]. The absorbance of the prepared solutions was read at 593 nm wavelength in a spectrophotometer (Thermo Scientific-G10S), and the antioxidant activity values were given as µmol Trolox equivalent (TE) g$^{-1}$.

### Total phenolic contents (TP)

The amount of TP was analyzed according to Jang et al. [2007]. Each sample (5 g) was subjected to extraction with 100 mL of a methanol:water solution (80:20 v/v) for 1 hour. The solid was then separated from the extract by vacuum filtration, and 0.15 mL of each extract was added to 0.15 mL of Foline-Ciocalteu reagent (1:10). The mixture was allowed to stand at 25 °C for 3 min before the addition of 0.30 mL of saturated sodium carbonate ($Na_2CO_3$) solution. After 30 min at room temperature, absorbance readings were taken at 725 nm using a UV-Vis spectrophotometer (Thermo Scientific-G10S). The results were expressed as mg 100 g$^{-1}$ fresh weight of gallic acid.

### Nutrient determination

For nutrient analysis, the dry-burning technique was used. Fruit samples of 0.5 g were pre-burned in crucibles with 1 mL of ethyl alcohol (99.9%). Once the crucibles cooled down, they were placed in a muffle furnace and incinerated at 500 °C for approximately 6–9 hours. Subsequently, 4 mL of 3 N HCl was added to the resulting ash samples. The crucibles were then heated on a hot plate (maintained at 80–90 °C) for 15 min until they turned yellow. After the ash samples were prepared, filtrates were created using distilled water.

Nutrient elements including potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), and phosphorus (P) were quantified using an atomic absorption spectrophotometer (ICE-3000 SERIES-Thermo Scientific). Phosphorus concentration was determined specifically at a wavelength of 430 nm using a spectrophotometer (Thermo Scientific G10S UV-Vis), following the method established by Kacar [1984]. Nitrogen content was determined using the Kjeldahl method, as outlined by Bradstreet [1954]. Upon determining the total nitrogen content of the samples, the amount of crude protein was calculated using a conversion factor of 6.25, which translates % nitrogen to % crude protein, as per the methodology described by Salo-Väänänen and Koivistoinen [1996].

Each sample was subjected to analysis in duplicate to ensure the accuracy and reliability of the obtained results.

### Color analysis

Changes in color values in bell pepper fruits were determined by a Minolta CR-400 colorimeter. The results were expressed as *L*, *a*, *b*, *chroma*, and *hue angle* values. Colors represent *a* (+ red, – green), *b* (+ yellow, – blue), and *L* (from 0 to 100 and brightness increases when it approaches 100) color values [Díaz-Pérez et al. 2020]. *Hue angle* is the color quality that distinguishes one color from another: 0° hue angle indicates red, 90° yellow, 180° green, and 270° blue. *Chroma* value refers to the vividness and dullness of agricultural products. A low chroma value indicates a dull color, while an increase in this value indicates a vivid color [McGuire 1992].

### Statistical analysis

A one-way analysis of variance (ANOVA) was conducted using the SPSS statistical program, adhering to a randomized block experimental design, and significance levels were set at $P \leq 0.05$. To further explore the differences among statistically significant means, the Duncan's multiple comparison test was applied, enabling the grouping of these differences effectively.

An in-depth exploration of the similarities and differences resulting from the various treatments was undertaken using multivariate data analysis methods. Particularly, a robust technique of principal component analysis (PCA) was employed. This method, implemented through the XLSTAT statistical program [Vidal et al. 2020], helped discern the extent to which the observed differences were explained by the characteristics examined in the study.

### Visualization techniques

A heat map clustering was generated to enhance the visualization of independent variables corresponding to fertilizer applications. This visualization tool was created using ClustVis, a comprehensive data visualization platform [Metsalu and Vilo 2015]. The heat map clustering facilitated a comprehensive overview of the relationships and patterns among the variables, offering valuable insights into the experimental outcomes.

## RESULTS AND DISCUSSIONS

### Organic acids and phenolic compounds

In the present study, six organic acids were determined: oxalic acid, citric acid, malic acid, succinic acid, tartaric acid, and fumaric acid (Table 5). It was determined that succinic acid and citric acid were the most abundant organic compounds in the fruits of all fertilizer combinations, and malic acid was the least abundant acid. Significant differences were detected among fertilizer combinations for oxalic acid with the highest value obtained from T7 (448.05 µg $g^{-1}$ FW), and the lowest value obtained from T10 (210.40 µg $g^{-1}$ FW). For succinic acid, significant differences ($P < 0.05$) were determined among fertilizer combinations, and the values between 3494.90 µg $g^{-1}$ FW and 6040.61 µg $g^{-1}$ FW occurred in plants treated with T6 and T4 combinations, respectively. In respect of tartaric acid content, the control group (T1) gave the highest value of 1153.30 µg $g^{-1}$ FW, while T6 provided the lowest value of 662.22 µg $g^{-1}$ FW. Citric acid contents showed significant differences ($P < 0.05$), with the highest value in the T2 (2283.62 µg $g^{-1}$ FW) and the lowest value in the T9 (1254.38 µg $g^{-1}$ FW). Malic acid content was the highest in T4 (121.66 µg $g^{-1}$ FW), and the lowest (54.77 µg $g^{-1}$ FW) in the plants treated only with chemical fertilizer. Fumaric acid content was the highest in T4, with a value of 307.87 µg $g^{-1}$ FW and the lowest in T10, with a value of 174.00 µg $g^{-1}$ FW. Erdinç et al. [2018] determined the citric, fumaric, malic, oxalic, succinic, and tartaric acid contents in fruits in their study on miniature tomato varieties with different combinations of organic and inorganic fertilizers. They noted that different types of organic and inorganic fertilizer combinations, in addition to base fertilizer, showed higher values in all compounds compared to the treatment in which only base fertilizer (diammonium phosphate, DAP) was used. Bavec et al. [2010] reported that statistically significant differences in citric, fumaric, and malic acid contents of red beets grown in conventional, integrated, organic,

**Table 5.** Organic acid (μg $g^{-1}$ FW) and ascorbic acid (mg 100 $g^{-1}$ FW) contents of bell pepper (*Capsicum annuum* L.) fruits grown with organic and chemical fertilizer treatments (mean ±standard deviation)

| Treatment | Oxalic acid | Citric acid | Malic acid | Succinic acid | Fumaric acid | Tartaric acid | Ascorbic acid |
|---|---|---|---|---|---|---|---|
| T1 | 312.43 ±64.28$^{bd}$ | 1958.65 ±317.64$^{ab}$ | 81.99 ±4.64$^{bc}$ | 5422.57 ±628.23$^{ab}$ | 295.35 ±34.00$^{a}$ | 1153.30 ±48.51$^{a}$ | 82.78 ±0.14$^{c}$ |
| T2 | 336.53 ±113.31$^{a–c}$ | 2283.62 ±282.27$^{a}$ | 54.77 ±6.95$^{d}$ | 4947.75 ±963.09$^{a–d}$ | 228.66 ±35.56$^{ab}$ | 832.61 ±186.28$^{b–c}$ | 110.38$^{a–c}$ ±17.10$^{a–c}$ |
| T3 | 288.07 ±88.39$^{cd}$ | 1599.69 ±310.60$^{ab}$ | 80.24 ±14.77$^{bc}$ | 4811.60 ±519.35$^{a–d}$ | 303.85 ±57.04$^{a}$ | 900.32 ±314.74$^{a–c}$ | 93.43 ±5.93$^{bc}$ |
| T4 | 291.81 ±11.83$^{cd}$ | 1570.46 ±338.60$^{ab}$ | 121.66 ±3.53$^{a}$ | 6040.61 ±76.74$^{a}$ | 307.87 ±70.99$^{a}$ | 805.82 ±110.53$^{bc}$ | 120.95 ±17.95$^{ab}$ |
| T5 | 322.90 ±48.27$^{b–d}$ | 1723.80 ±526.08$^{ab}$ | 68.16 ±29.15$^{cd}$ | 5066.17 ±1197.29$^{a–c}$ | 261.83 ±60.89$^{ab}$ | 761.18 ±67.89$^{bc}$ | 141.42 ±26.95$^{a}$ |
| T6 | 422.81 ±79.75$^{ab}$ | 2243.31 ±591.05$^{a}$ | 55.01 ±11.77$^{d}$ | 3494.90 ±158.73$^{d}$ | 243.30 ±53.28$^{ab}$ | 662.22 ±173.21$^{c}$ | 104.44 ±9.45$^{bc}$ |
| T7 | 448.05 ±6.90$^{a}$ | 1769.57 ±623.32$^{ab}$ | 55.29 ±18.95$^{d}$ | 3732.48 ±1155.98$^{cd}$ | 248.49 ±34.193$^{ab}$ | 767.88 ±104.60$^{bc}$ | 90.19 ±4.55$^{bc}$ |
| T8 | 230.78 ±3.08$^{cd}$ | 1710.24 ±179.30$^{ab}$ | 77.52 ±5.46$^{b–d}$ | 4416.06 ±717.60$^{b–d}$ | 272.57 ±41.75$^{a}$ | 809.17 ±81.48$^{bc}$ | 108.88 ±6.75$^{a–c}$ |
| T9 | 302.80 ±66.58$^{b–d}$ | 1254.38 ±99.44$^{b}$ | 83.59 ±6.93$^{bc}$ | 4753.87 ±834.08$^{a–d}$ | 284.61 ±37.35$^{a}$ | 1040.20 ±210.21$^{ab}$ | 101.51 ±0.71$^{bc}$ |
| T10 | 210.40 ±59.85$^{d}$ | 1390.74 ±123.13$^{b}$ | 93.56 ±5.27$^{b}$ | 4582.11 ±651.44$^{a–d}$ | 174.00 ±16.91$^{b}$ | 779.04 ±151.05$^{bc}$ | 120.20 ±32.02$^{ab}$ |

* Different letters indicating significant differences among the means in the column at $p \leq 0.05$ (according to Duncan's multiple comparison test.), FW – fresh weight

**Table 6.** Phenol (µg g$^{-1}$ FW), total phenolic (mg GAE 100 g$^{-1}$ FW), and antioxidant (Trolox µmol TE g$^{-1}$ FW) contents of bell pepper (*Capsicum annuum* L.) fruits grown with organic and chemical fertilizer treatments (mean ±standard deviation)

| Treatment | Gallic acid | Chlorogenic acid | Rutinic acid | Ferulic acid | Hydroxycinnamic acid | Total phenols | Total antioxidants |
|---|---|---|---|---|---|---|---|
| T1 | 11.11 ±0.53$^{d*}$ | 58.72 ±17.44$^{c}$ | 40.27 ±0.88 | 2.24 ±0.47$^{c}$ | 3.20 ±0.28 | 30.31 ±1.54 | 228.33 ±98.69 |
| T2 | 11.04 ±0.60$^{d}$ | 70.57 ±20.37$^{bc}$ | 40.64 ±0.89 | 2.18 ±0.57$^{c}$ | 3.16 ±0.37 | 26.87 ±1.56 | 275.83 ±23.78 |
| T3 | 13.15 ±1.64$^{b–d}$ | 112.02 ±5.43$^{a}$ | 41.93 ±1.26 | 1.82 ±0.24$^{c}$ | 3.38 ±0.15 | 28.09 ±0.43 | 276.67 ±7.10 |
| T4 | 12.56 ±0.78$^{cd}$ | 79.04 ±8.89$^{bc}$ | 40.53 ±0.79 | 2.31 ±0.27$^{c}$ | 3.07 ±0.24 | 29.35 ±0.61 | 245.00 ±28.27 |
| T5 | 20.38 ±1.34$^{a}$ | 72.77 ±13.03$^{bc}$ | 42.31 ±2.05 | 2.43 ±0.39$^{c}$ | 3.56 ±0.60 | 30.35 ±2.06 | 318.75 ±75.82 |
| T6 | 18.84 ±2.95$^{ab}$ | 59.15 ±3.92$^{c}$ | 39.96 ±0.32 | 2.62 ±0.19$^{bc}$ | 2.93 ±0.05 | 25.45 ±5.60 | 281.11 ±36.57 |
| T7 | 13.48 ±5.49$^{b–d}$ | 87.02 ±11.27$^{b}$ | 40.84 ±0.41 | 3.58 ±0.82$^{a}$ | 3.04 ±0.00 | 28.03 ±2.55 | 270.83 ±16.14 |
| T8 | 17.68 ±4.39$^{a–c}$ | 59.55 ±3.93$^{c}$ | 40.60 ±0.50 | 3.56 ±0.57$^{a}$ | 3.02 ±0.12 | 28.86 ±4.24 | 291.39 ±20.62 |
| T9 | 15.79 ±3.86$^{a–d}$ | 71.20 ±11.97$^{bc}$ | 41.60 ±1.98 | 3.48 ±0.03$^{a}$ | 3.22 ±0.20 | 29.70 ±2.07 | 324.44 ±22.19 |
| T10 | 17.04 ±4.06$^{a–c}$ | 87.96 ±14.19$^{b}$ | 41.41 ±1.75 | 3.26 ±0.52$^{ab}$ | 3.14 ±0.23 | 28.13 ±0.46 | 265.97 ±26.75 |

* Different letters indicating significant differences among the means in the column at $p \leq 0.05$ (according to Duncan's multiple comparison test), FW – fresh weight

biodynamic, and control farming systems were found only for malic acid with the highest content of this acid in the control group and red beets grown in the biodynamic farming system. Although there were no significant differences in citric and fumaric acid contents, the highest values were obtained in fruits from plants grown in the biodynamic farming system. However, Kazimierczak et al. [2021] did not detect any significant differences between organic acids in onions grown with organic and inorganic fertilizers. In the present study, significant results in terms of organic compounds were observed in the groups where organic fertilizer was used in combination, which can be considered positive for good agricultural principles.

The polyphenol content in plants is influenced by plant variety, harvesting conditions, and cultivation. Significant differences between organic and conventional production systems, especially soil fertility management, can affect the nutrient composition of plants, including secondary plant metabolites [Keser 2021]. In the present study, five phenolic compounds were determined: gallic acid, chlorogenic acid, rutin acid, ferulic acid, and hydroxycinnamic acid (Table 6). In all combinations, chlorogenic acid was the dominant phenolic compound, and ferulic was the least abundant compound. Significant differences were observed between treatments for chlorogenic acid. The highest content of this acid was determined in T3 (112.02 μg $g^{-1}$ FW), and the lowest content was determined in the control group (58.72 μg $g^{-1}$ FW). In a study of five chicory cultivars, it was reported that chlorogenic and hydroxycinnamic acid contents obtained from the leaves of the plants were higher in the control group compared to the treatments using organic and mineral fertilizers [Sinkovič et al. 2015]. In the present study, although hydroxycinnamic acid contents were not significantly different between different fertilizer applications, the highest content of this acid was obtained from T5 with 3.56 μg $g^{-1}$ FW. In *Brassica rapa* subsp. *chinensis* (L.) Hanelt under organic and conventional cultivation conditions, chlorogenic acid and ferulic acid contents were recorded in higher amounts in organic cultivation [Zhao et al. 2009]. Guilherme et al. [2020] examined the phenol contents of sweet pepper at the green and red stages under conventional and organic cultivation conditions and noted that the chlorogenic acid content increased in conventional cultivation at the green stage and in organic cultivation at the red stage. In the rutin acid content, an increase was observed in organically cultivated fruits at both maturity stages. In a study on sweet bell peppers using organic and conventional fertilizers, gallic and chlorogenic acid contents were higher in plants receiving organic fertilizers [Hallmann and Rembialkowska 2012]. Gholami et al. [2018] reported that the gallic acid content of chicory plants was higher when humic acid and vermicompost were applied together than in the control plants without fertilizer. In the present study, gallic acid content in bell peppers cultivated under different fertilization conditions showed significant statistical differences. The highest value was determined in T5 (20.38 μg $g^{-1}$ FW) and the lowest in T2 (11.04 μg $g^{-1}$ FW). The highest ferulic acid contents were found in T7 (3.58 μg $g^{-1}$ FW), T8 (3.56 μg $g^{-1}$ FW) and T9 (3.48 μg $g^{-1}$ FW) combinations, while T3 had the lowest content of this acid (1.82 μg $g^{-1}$ FW). There were no significant differences noted for rutin and hydroxycinnamic acid contents among different fertilizer combinations in the multiple comparison tests, and all treatments, including the control, had similar values of these compounds.

### Total phenolic, antioxidant and ascorbic acid contents

There were no significant differences between treatments in terms of total phenolic and antioxidant contents. When the total phenolic content was determined in bell peppers in different fertilizer combinations, the highest similar values were observed in T5 (30.35 mg GAE 100 $g^{-1}$ FW) and control (30.31 mg GAE 100 $g^{-1}$ FW) treatments, while the lowest value was recorded in T6 (25.45 mg GAE 100 $g^{-1}$ FW) – Table 6. As a result of the application of organic and chemical fertilizers in celery cultivation, it was revealed that organic fertilizers did not make a difference in total phenolic content in the vegetable compared to the control. However the content of these compounds decreased when high doses of chemical fertilizer were applied and it increased in celery fertilized with low doses of this type of fertilizer [Daneshvar et al. 2022]. Vinha et al. [2014] examined the total phenolic content of the Redondo tomato cultivar grown in two different greenhouses and the study concerned pest control and soil fertilizer. In conventional production, a synthetic fertilizer (Diamant) was applied weekly, while an organic fertilizer NPK (Agrimartin) was used in organic production. The total phenolic content of 149 mg GAE 100 $g^{-1}$ was determined in conventional production and 196 mg GAE 100 $g^{-1}$ in organic production. In the present study, fertilizer combinations did not produce statistically significant results concerning the total phenolic content.

The antioxidant content in peppers depends on genetics, chemical structure and concentration, and environmental conditions [Chatterjee et al. 2021, Daneshvar et al. 2022]. In a study on broccoli in which chicken manure compost was applied with organic and bioorganic fertilizers, the determined antioxidant contents were as follows: 9.15 mg $g^{-1}$ DW in the control group without fertilizer, 13.83 mg $g^{-1}$ DW in organic fertilizer application, and 11.56 mg $g^{-1}$ DW in bioorganic fertilizer application [Naguib et al. 2012]. In the present study, although the differences in antioxidant content were not significant between treatments, increased amounts of these compounds were observed in bell peppers grown with fertilizer combinations compared to the control. The highest content of these compounds was found in T9 (324.44 Trolox μmol TE $g^{-1}$ FW), and the lowest in the control (228.33 Trolox μmol TE $g^{-1}$ FW) – Table 6. Chatterjee et al. [2021] reported that the highest antioxidant content in green bell peppers was obtained from plants treated with vermicompost containing 91% rabbit manure. As a result of organic and chemical fertilizer applications in celery, it was determined that antioxidant contents increased in plants treated with organic fertilizer compared to both control and plants treated with chemical fertilizer [Daneshvar et al. 2022]. Daneshvar et al. [2022] and Ibrahim et al. [2013] stated that the macro-micro nutrients released as a result of organic fertilizer applications can cause an increase in total phenolic and antioxidant contents, whereas chemical fertilizers only release N.

Peppers are significantly higher in vitamin C compared to citrus fruits and other vegetables known to be rich in vitamin C [Marin et al. 2004, Antonious 2014]. In the present study, vitamin C content in bell peppers showed significant differences between experimental treatments. The highest ascorbic acid content was recorded in T5 with 141.42 mg 100 $g^{-1}$ FW, and the lowest in the control treatment with 82.78 mg 100 $g^{-1}$ FW (Table 5). Chatterjee et al. [2021] applied vermicompost obtained from varied biological waste in bell pepper cultivation and found that the applications of this type of fertilizer caused an increase in vitamin C contents compared to the control group, and the highest vitamin C content was obtained in fruits from the group treated with poultry litter vermicompost. Densilin et al. [2010], in a study conducted on the content of vitamin C in chili peppers by creating different organic and inorganic fertilizer combinations, observed increases in the content of this vitamin compared to the control, with the highest content obtained in the combination of vermicompost and triple-17 complex (inorganic fertilizer). Chouhan [2015] and Aminifard et al. [2012] also reported that organic fertilizer applications increased the content of ascorbic acid in pepper fruits. Joshi and Vig [2010] applied various dosages of vermicompost to tomatoes and obtained the highest ascorbic acid content in the treatment with a 45% dose of vermicompost. The use of vermicompost in tomatoes [Murmu et al. 2013, Meena et al. 2014] and in celery [Daneshvar et al. 2022] enhanced ascorbic acid content in plants. However, Pereira et al. [2021] found that there was no significant increase in vitamin C content in *Capsicum chinense* Jacq. treated with mineral fertilizer and biofertilizer compared to the control. Pérez-López et al. [2007] examined vitamin C contents in sweet peppers at three ripening stages (immature green, green, and red) under organic and conventional cultivation conditions and reported that vitamin C contents were higher in fruits obtained from organic cultivation at all stages. In the present study, an increased content of vitamin C was noted in all treatments compared to the control, and the treatment combining 25% chemical fertilizer and 75% vermicompost showed the highest vitamin C content (Table 5).

## Fruit color analysis

The color of agricultural products is an important quality criterion for consumers [Rizzo and Muratore 2009]. According to the comparative test, $b^*$ and *chroma* values showed significant differences among the fertilizer combinations in the present study (Table 7). Their highest values were obtained from T4, while the lowest value was obtained from T6 treatment. Pérez-López et al. [2007] found the highest $b^*$ and *chroma*

**Table 7.** Color properties of bell pepper (*Capsicum annuum* L.) fruits grown with organic and chemical fertilizer treatments (mean ±standard deviation)

| Treatment | L | a | b | Chroma | Hue |
|---|---|---|---|---|---|
| T1 | 55.47 ±1.35 | –15.71 ±0.08 | 35.88 ±1.68$^{b}$ | 39.18 ±1.52$^{b}$ | 113.72 ±1.03 |
| T2 | 53.81 ±1.99 | –16.21 ±0.56 | 36.45 ±1.13$^{b}$ | 39.92 ±1.03$^{b}$ | 114.08 ±1.04 |
| T3 | 54.97 ±0.50 | –16.08 ±0.49 | 36.30 ±0.56$^{b}$ | 39.72 ±0.62$^{b}$ | 113.94 ±0.57 |
| T4 | 55.87 ±2.17 | –16.62 ±0.34 | 40.49 ±1.82$^{a}$ | 43.79 ±1.54$^{a}$ | 112.40 ±1.33 |
| T5 | 53.95 ±1.85 | –15.91 ±0.49 | 36.13 ±1.19$^{b}$ | 39.51 ±1.21$^{b}$ | 113.85 ±0.73 |
| T6 | 54.27 ±1.65 | –15.61 ±0.73 | 35.31 ±2.03$^{b}$ | 38.62 ±2.04$^{b}$ | 113.88 ±1.06 |
| T7 | 54.34 ±2.00 | –16.24 ±0.79 | 36.66 ±1.09$^{b}$ | 40.13 ±1.10$^{b}$ | 113.98 ±1.09 |
| T8 | 55.55 ±1.27 | –15.31 ±1.22 | 35.98 ±0.41$^{b}$ | 39.14 ±0.35$^{b}$ | 113.13 ±1.78 |
| T9 | 55.77 ±1.02 | –15.65 ±0.25 | 37.02 ±1.51$^{b}$ | 40.22 ±1.49$^{b}$ | 112.97 ±0.58 |
| T10 | 54.62 ±1.84 | –16.33 ±0.81 | 36.25 ±0.42$^{b}$ | 39.77 ±0.67$^{b}$ | 114.27 ±0.83 |

* Different letters indicating significant differences among the means in the column at $p \leq 0.05$ (according to Duncan's multiple comparison test)

values in immature green, green, and red sweet pepper fruits cultivated organically. In the present study, *hue* and $a^*$ values did not show statistical significance between the treatments (Table 7). Pereira et al. [2021] applied mineral fertilizer and biofertilizer to Biquinho pepper (*C. chinense*) and reported that brightness and *hue* values did not show significant differences between treatments. In the present study, $L^*$ values were similar and the highest was determined for T4 (55.87) and the lowest for T2 (53.81). Murmu et al. [2013] reported that 100% vermicompost application resulted in the highest color ratio of tomatoes compared to chemical fertilizers and their combinations.

### Macro-micro nutrients

In the current study, protein content and five macronutrients (N, P, K, Ca and Mg) were determined in bell pepper fruits. Potassium was the macro element with the highest concentration. Other macronutrients, except N and protein, demonstrated significant differences in fertilizer treatments. The highest P content in bell pepper fruits (0.87 mg kg$^{-1}$) was found in T9 with 50% inorganic fertilizer and 50% vermicompost mixture, and the lowest (0.63 mg kg$^{-1}$) in the control group. Sharma et al. [2020] reported that N, P and K uptake in bell peppers was not affected by fertilizer applications to a considerable degree. However, the supply of nutrients from organic and inorganic sources tended to increase the nutrient content of the plant. In the current study, K content in fruits was the highest in T8 (5.23 mg kg$^{-1}$) and the lowest in T2 (4.24 mg kg$^{-1}$) treatment. Calcium content in bell peppers was the highest in the control group (0.38 mg kg$^{-1}$) and the lowest in T2 (0.24 mg kg$^{-1}$). Magnesium content in pepper fruits was the highest in treatment T7 (0.40 mg kg$^{-1}$) and the lowest in T6 (0.34 mg kg$^{-1}$). These findings underscore the significant impact of different fertilizer combinations on the nutrient composition of pepper fruits. Furthermore, the results emphasize the effectiveness of vermicompost and organo-mineral fertilizer combinations in increasing the nutrient content of pepper plants. Comparing the current study with previous research conducted by Zheljazkov et al. [2011], where different rates of vermicompost and chemical fertilizers were applied to pepper plants, interesting contrasts emerge. While Zheljazkov et al.[2011] found that vermicompost did not significantly increase the nutrient contents of pepper except for potassium, while the current study demonstrated significant increases in the content of various nutrient elements in pepper fruits grown with the combined use of vermicompost. Specifically, T9 resulted in the highest phosphorus content (0.87%) and zinc content (154.56 mg kg$^{-1}$). Additionally, T8 exhibited the highest K content (5.23%), while T7 yielded the highest magnesium content. Furthermore, T5 produced the highest iron (115.92 mg kg$^{-1}$) and manganese contents (22.46 mg kg$^{-1}$). Upon a comprehensive analysis of the nutrient element results, it is evident that treatments incorporating vermicompost, particularly those ranking second or third in nutrient content, significantly contribute to increased nutrient contents in pepper fruits. This underscores the positive impact of vermicompost application and emphasizes its potential as a valuable component in optimizing nutrient composition in agricultural practices. These findings highlight the importance of thoughtful fertilizer combinations and reinforce the potential benefits of integrating organic components like vermicompost into agricultural systems, promoting sustainable and nutrient-rich crop production.

Moreover, the use of chemical fertilizer alone did not cause an increase in nutrient contents compared to vermicompost and control treatments. Abu-Zahra et al. [2013] used conventional fertilizer (50 kg ha$^{-1}$ week$^{-1}$ of NPK 20:20:20) as fertigation and 118 kg ha$^{-1}$ of ammonium nitrate as a supplementary fertilization treatment, and mixed manure of cattle, poultry and sheep (1:1:1) as organic matter source in the cultivation of bell pepper. They reported that Zn and Fe levels were higher in bell pepper fruits treated with conventional fertilizer. In the present study, the highest levels for the same elements were generally obtained from the treatments in which vermicompost was used as a fertilization component. In addition, fruits from both the control group and the group in which only chemical fertilizer was used had lower mineral contents than the other treatments (Table 8). Micronutrients such as Zn and Mn play vital roles in the production of chlorophyll, facilitating the essential process of photosynthesis in plant leaves [Sokhela 2021].

Pérez-López et al. [2007], Peyvast et al. [2008] and Das et al. [2016] emphasized that vermicomposts, especially those derived from animal waste, contain abundant macronutrients and various trace elements.

**Table 8**. Macro-micro nutrient contents of bell pepper (*Capsicum annuum* L.) fruits grown with organic and chemical fertilizer treatments (mean ±standard deviation)

| Treatments | N (%) | P (%) | K (%) | Ca (%) | Mg (%) | Protein (%) | Fe (mg kg$^{-1}$) | Zn (mg kg$^{-1}$) | Cu (mg kg$^{-1}$) | Mn (mg kg$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|
| T1 | 2.26 ±0.07 | 0.63 ±0.01$^{D}$ | 4.93 ±0.30$^{AB}$ | 0.38 ±0.12$^{A}$ | 0.36 ±0.03$^{B-D}$ | 14.14 ±0.42 | 92.17 ±1.44$^{E}$ | 76.53 ±0.67$^{E}$ | 29.36 ±1.07$^{A}$ | 19.59 ±0.59$^{BC}$ |
| T2 | 2.70 ±0.59 | 0.72 ±0.01$^{BC}$ | 4.24 ±0.17$^{E}$ | 0.24 ±0.02$^{B}$ | 0.34 ±0.01$^{D}$ | 16.85 ±3.70 | 105.95 ±0.51$^{BC}$ | 29.90 ±0.36$^{H}$ | 24.08 ±0.47$^{C}$ | 18.48 ±0.66$^{DE}$ |
| T3 | 2.41 ±0.01 | 0.74 ±0.02$^{B}$ | 4.36 ±0.24$^{DE}$ | 0.25 ±0.03$^{B}$ | 0.35 ±0.02$^{D}$ | 15.07 ±0.10 | 102.19 ±1.95$^{C}$ | 29.79 ±0.66$^{H}$ | 19.63 ±1.41$^{FG}$ | 18.08 ±0.38$^{E}$ |
| T4 | 3.19 ±1.17 | 0.70 ±0.02$^{B-D}$ | 4.56 ±0.11$^{C-E}$ | 0.29 ±0.04$^{B}$ | 0.34 ±0.02$^{D}$ | 19.92 ±7.33 | 105.92 ±1.51$^{BC}$ | 90.13 ±0.70$^{C}$ | 17.89 ±0.68$^{G}$ | 19.46 ±0.25$^{B-D}$ |
| T5 | 2.42 ±0.19 | 0.65 ±0.04$^{CD}$ | 4.63 ±0.33$^{B-D}$ | 0.28 ±0.03$^{B}$ | 0.35 ±0.02$^{CD}$ | 15.15 ±1.20 | 115.92 ±1.59$^{A}$ | 34.88 ±0.18$^{F}$ | 27.31 ±0.53$^{B}$ | 22.46 ±0.98$^{A}$ |
| T6 | 3.25 ±0.89 | 0.69 ±0.04$^{B-D}$ | 4.25 ±0.17$^{E}$ | 0.26 ±0.01$^{B}$ | 0.33 ±0.01$^{D}$ | 20.29 ±5.51 | 98.23 ±2.80$^{D}$ | 31.16 ±0.50$^{Ğ}$ | 18.93 ±0.76$^{FG}$ | 18.95 ±0.66$^{C-E}$ |
| T7 | 2.16 ±0.23 | 0.76 ±0.03$^{B}$ | 4.79 ±0.19$^{BC}$ | 0.29 ±0.05$^{B}$ | 0.40 ±0.01$^{A}$ | 13.51 ±1.45 | 84.84 ±2.03$^{F}$ | 32.77 ±0.85$^{G}$ | 20.52 ±0.95$^{EF}$ | 20.28 ±0.22$^{B}$ |
| T8 | 2.65 ±0.14 | 0.73 ±0.06$^{BC}$ | 5.23 ±0.01$^{A}$ | 0.31 ±0.01$^{AB}$ | 0.38 ±0.00$^{AB}$ | 16.57 ±0.92 | 108.57 ±4.41$^{B}$ | 83.84 ±0.85$^{D}$ | 22.47 ±1.11$^{CD}$ | 20.45 ±0.26$^{B}$ |
| T9 | 2.45 ±0.02 | 0.87 ±0.07$^{A}$ | 4.95 ±0.05$^{AB}$ | 0.30 ±0.02$^{B}$ | 0.37 ±0.01$^{BC}$ | 15.36 ±0.09 | 95.23 ±1.42$^{DE}$ | 154.56 ±1.35$^{A}$ | 21.64 ±1.51$^{DE}$ | 19.93 ±0.69$^{BC}$ |
| T10 | 2.83 ±0.86 | 0.70 ±0.05$^{B-D}$ | 4.80 ±0.07$^{BC}$ | 0.31 ±0.01$^{AB}$ | 0.34 ±0.01$^{D}$ | 17.71 ±5.41 | 105.98 ±2.98$^{BC}$ | 95.77 ±0.54$^{B}$ | 18.47 ±0.92$^{G}$ | 19.49 ±0.62$^{B-D}$ |

* Different letters indicating significant differences among the means in the column at $p \leq 0.05$ (according to Duncan's multiple comparison test)

**Table 9.** PCA results on biochemical-color characteristics of bell pepper (*Capsicum annuum* L.) fruits grown with organic and chemical fertilizer treatments

| Items | PC1 | PC2 | PC3 | PC4 | PC5 | PC6 |
|---|---|---|---|---|---|---|
| Eigenvalue | 6.10 | 3.61 | 2.83 | 2.43 | 1.57 | 1.25 |
| Variation (%) | 32.09 | 18.99 | 14.91 | 12.78 | 8.25 | 6.57 |
| Cumulative Var. (%) | 32.09 | 51.08 | 65.99 | 78.77 | 87.03 | 93.60 |
| factor loadings of parameters | | | | | | |
| L | 0.304 | –0.104 | **0.328** | –0.085 | 0.152 | 0.010 |
| a | –0.158 | 0.040 | **0.518** | 0.053 | –0.142 | –0.005 |
| b | **0.331** | –0.092 | –0.192 | –0.236 | –0.072 | 0.180 |
| CHROMA | **0.324** | –0.089 | –0.235 | –0.225 | –0.051 | 0.169 |
| HUE | **–0.297** | 0.076 | –0.210 | 0.269 | 0.195 | –0.232 |
| Total phenolics | **0.272** | 0.192 | 0.211 | 0.162 | –0.085 | –0.048 |
| Total antioxidants | –0.109 | **0.388** | 0.159 | –0.107 | –0.101 | 0.347 |
| Vit. C | 0.040 | 0.336 | –0.196 | –0.272 | **–0.398** | –0.185 |
| Oxalic acid | –0.203 | –0.205 | –0.102 | 0.020 | –0.114 | **0.572** |
| Citric acid | –0.240 | –0.290 | –0.109 | 0.122 | **–0.406** | –0.060 |
| Malic acid | **0.366** | 0.015 | –0.018 | –0.150 | 0.070 | –0.218 |
| Succinic acid | **0.347** | 0.010 | –0.081 | 0.158 | –0.268 | –0.217 |
| Fumaric acid | 0.235 | –0.107 | 0.197 | 0.198 | –0.216 | **0.459** |
| Tartaric acid | 0.185 | –0.083 | 0.296 | **0.403** | 0.121 | –0.087 |
| Gallic acid | –0.157 | **0.345** | 0.141 | –0.287 | –0.172 | –0.015 |
| Chlorogenic acid | 0.089 | 0.154 | –0.340 | 0.158 | **0.456** | 0.233 |
| Rutin | 0.068 | **0.475** | –0.090 | 0.180 | 0.116 | 0.162 |
| Ferulic acid | –0.077 | 0.089 | 0.272 | **–0.383** | 0.371 | 0.036 |
| Hydroxycinnamic acid | 0.083 | 0.380 | –0.078 | **0.386** | –0.174 | 0.062 |

This type of vermicompost converts these elements into plant-accessible forms, such as nitrates, exchangeable phosphorus, and soluble potassium, calcium, and magnesium. Several studies have corroborated the positive impact of vermicompost on plant nutrient content and stress tolerance. For instance, Demir and Kıran [2020] reported significant increases in macro and micronutrients in lettuce plants treated with vermicompost. In another study on spinach, Syed et al. [2022] found that vermicompost applications

**Table 10.** PCA results on nutrient properties of bell pepper (*Capsicum annuum* L.) fruits grown with organic and chemical fertilizer treatments

| Items | PC1 | PC2 | PC3 | PC4 |
|---|---|---|---|---|
| Eigenvalue | 4.06 | 2.09 | 1.75 | 1.05 |
| Variation (%) | 40.64 | 20.90 | 17.54 | 10.51 |
| Cumulative Var. (%) | 40.64 | 61.54 | 79.08 | 89.60 |
| factor loadings of parameters | | | | |
| N | **0.421** | 0.100 | 0.333 | –0.073 |
| P | –0.099 | **0.588** | –0.114 | 0.368 |
| K | **–0.392** | 0.116 | 0.390 | 0.048 |
| Ca | –0.329 | –0.073 | 0.382 | **–0.521** |
| Mg | **–0.416** | 0.188 | –0.161 | 0.176 |
| Protein | **0.420** | 0.102 | 0.337 | –0.071 |
| Fe | 0.205 | –0.330 | 0.321 | **0.529** |
| Zn | –0.163 | 0.385 | **0.512** | –0.016 |
| Cu | –0.271 | **–0.483** | –0.004 | –0.109 |
| Mn | –0.243 | –0.298 | 0.270 | **0.507** |

not only enhanced mineral content but also reduced high concentrations of toxic elements like Cd and Pb. Furthermore, Bellitürk et al. [2017] observed elevated levels of P and K in pepper plants treated with vermicompost, emphasizing the positive effects of vermicompost on nutrient uptake. Researchers such as Atiyeh et al. [2000] and Paul and Metzger [2005] have suggested that humic acids present in vermicompost enhance nutrient uptake and potentially exert hormone-like effects on plants. Additionally, the use of vermicompost has been associated with a reduced need for inorganic fertilizers. Notably, research has consistently shown the positive effects of vermicompost on plant germination, growth, and yield [Arancon and Edwards 2005]. These findings collectively highlight the potential of vermicompost in sustainable agriculture, not only as a nutrient-rich organic amendment but also as a means to reduce reliance on chemical fertilizers, promoting environmentally friendly and sustainable farming practices.

### Principal component analysis, heat map

In the current study, principal component analysis (PCA) was employed to identify the key traits responsible for variations among different fertilizer combinations. The PCA performed on the biochemical data, which included 19 different parameters, revealed that the first six components with eigenvalues greater than 1.00 explained 93.59% of the total variation (Table 9). The PCA conducted on the nutrient data, which included 10 different parameters, indicated that the first four components with eigenvalues greater than 1.00 accounted for 89.59% of the total variation (Table 10). This high percentage indicates a robust model, as it captures the majority of the variability in the data. The first two components alone explained 51.08% of the total variation, which is consistent with the recommendations by Seymen et al. [2019] and Bicer et al. [2022], who stated that the first two components should account for at least 25% of the variation for a reliable PCA.

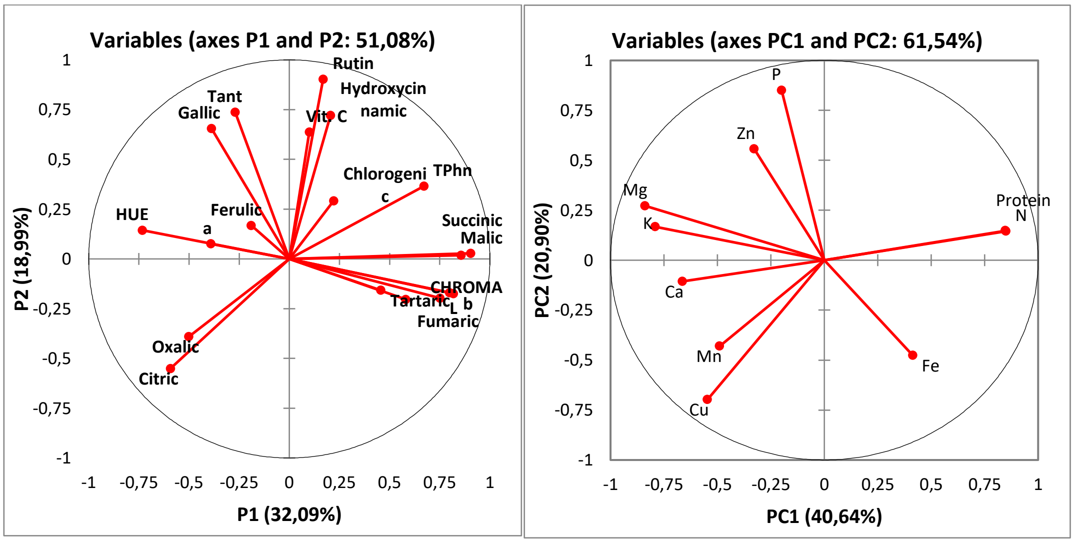

**Fig. 1.** Loading plot based on PC 1 and PC 2 obtained from PCA using biochemical, color and nutrient characteristics of bell pepper fruits (*Capsicum annuum* L.)

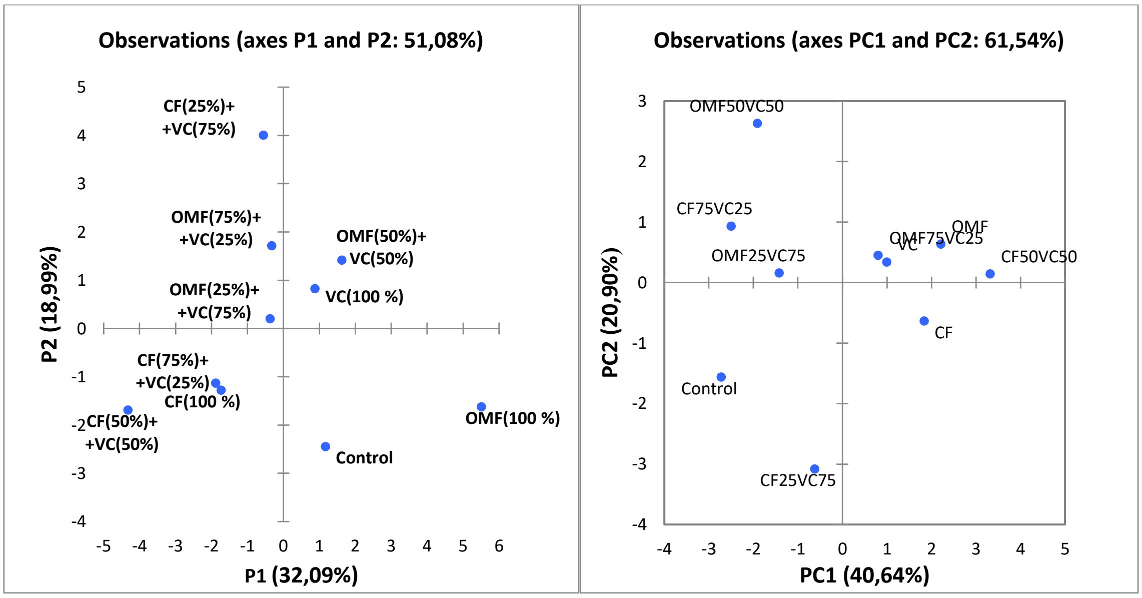

**Fig. 2.** Score plot based on PC 1 and PC 2 obtained from PCA using biochemical, color and nutrient characteristics of bell pepper fruits (*Capsicum annuum* L.)

The first component (PC1), which explained 32.09% of the variation, was heavily influenced by traits such as *b**, *chroma*, *hue*, total phenolic content, malic acid, and succinic acid. These traits are crucial in determining the biochemical quality of pepper fruits, indicating that the selection of fertilizers can significantly impact these parameters. The second component (PC2), which accounted for 18.99% of the variation, was primarily associated with total antioxidant content, gallic acid, and rutin. This suggests that the combination of fertilizers also plays a significant role in enhancing the antioxidant properties of the peppers.

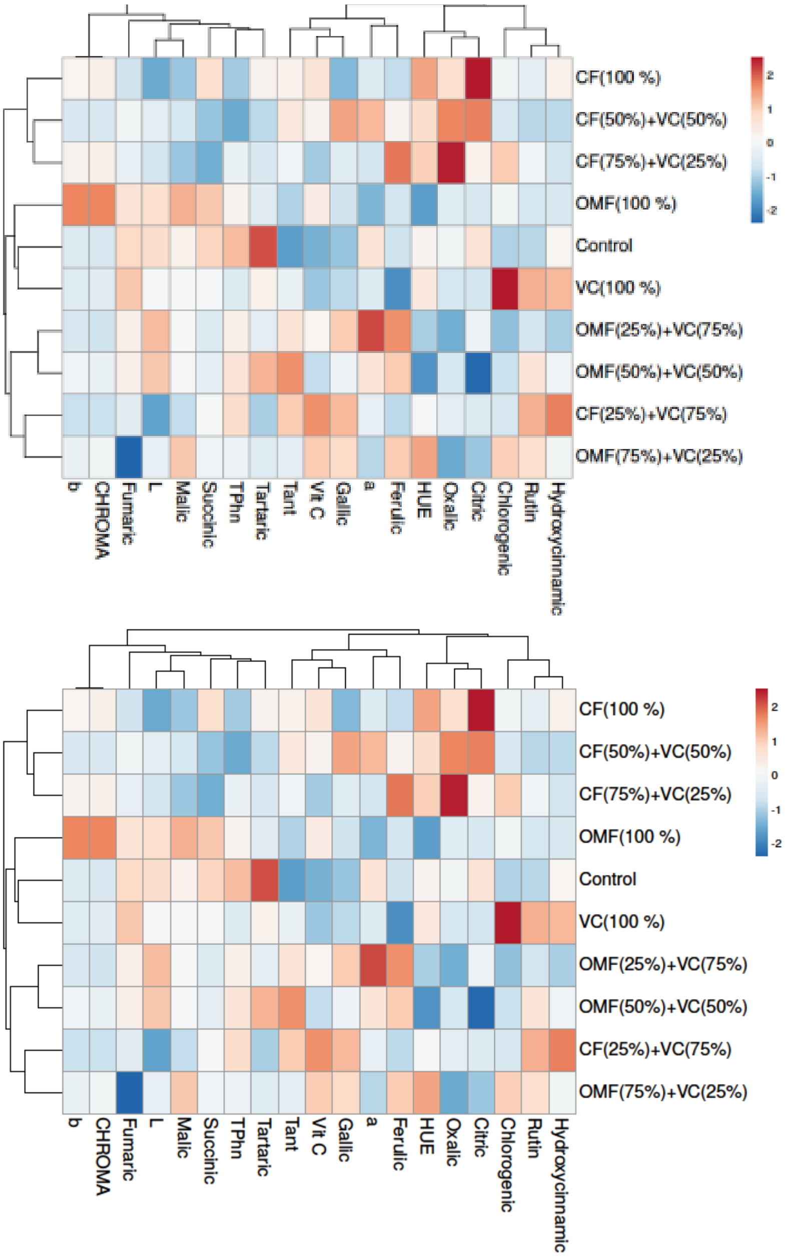

**Fig. 3.** Clustering of fertilizer combinations in terms of biochemical, color and nutrient traits - Heat Map of traits (color scale from blue to red representing low (blue) to high (red) values)

A loading plot based on the first two components (PC1 and PC2) was created to visualize the interrelationships between the 19 traits (Fig. 1). There was a strong positive correlation between rutinic, ascorbic and hydroxycinnamic acids. Similarly, succinic acid and malic acid were positively correlated, which could be attributed to their roles in the metabolic pathways of the plant. In contrast, negative correlations were observed between certain traits, such as total phenolic and chlorogenic acid contents, suggesting that the fertilizers influence these parameters differently. The presence of both positive and negative correlations emphasizes the complexity of the biochemical responses in pepper fruits to different fertilizer combinations.

The score plot (Fig. 2) provided insights into the effects of different fertilizer treatments. For example, T3 and T9, which were located in the positive region of both PC1 and PC2, had similar nutrient compositions, suggesting that these treatments might be optimal for enhancing certain biochemical traits. On the other hand, T5 and T6, located in the negative regions, showed distinct nutrient profiles, which might indicate that these combinations are less effective or have different impacts on pepper quality.

These findings align with previous research. For instance, Chatterjee et al. [2021] also reported the positive effects of vermicompost on yield and quality parameters in pepper. Similar positive impacts of organic fertilizers have been documented in other studies [Das et al. 2016, Rekha et al. 2018], reinforcing the potential benefits of integrating organic materials into fertilization strategies.

The heatmap analysis (Fig. 3) further illustrated the complex relationships between the fertilizer treatments and the biochemical parameters. Treatments using chemical fertilizers were clustered together, while combinations involving organomineral fertilizers formed a separate group. This division suggests that the type of fertilizer significantly influences the biochemical profile of the pepper fruits. Chatterjee et al. [2021], Rekha et al. [2018], and Peyvast et al. [2008] stated that fertilization treatments cluster in direct proportion to fertilizer contents, and this is important in determining the relationships between yield and fertilizer types. In the current study, T3 treatment showed a strong association with the content of chlorogenic acid, a compound known for its antioxidant properties, while T7 was closely related to the content of oxalic acid. These associations highlight the potential for specific fertilizer combinations to enhance particular health-promoting compounds in peppers. The PCA and heatmap analyses reveal that the careful selection and combination of organic and chemical fertilizers can significantly influence the biochemical and nutrient composition of pepper fruits. The current study provides valuable insights for optimizing fertilizer strategies to improve the nutritional quality of pepper and the sustainability of agricultural practices.

## CONCLUSIONS

The current study provides valuable insights into the effects of various fertilizer treatments on bell pepper fruits, with a particular emphasis on vermicompost. The results reveal that vermicompost, used alone or in combination with chemical fertilizers, significantly enhances the levels of organic acids, phenolic compounds, and vitamin C in bell peppers. This suggests that vermicompost plays a crucial role in improving both the nutritional and biochemical quality of pepper fruits.

Vermicompost enhances nutrient availability and uptake, contributing to superior fruit quality. Conversely, treatments with only chemical fertilizers generally resulted in lower levels of certain phenolic compounds and antioxidants. Organomineral fertilizers might be more effective for achieving optimal fruit coloration. The study also highlighted significant variations in nutrient contents across different fertilizer treatments, except for nitrogen and protein, which remained relatively stable. This underscores the importance of selecting appropriate fertilizer combinations to influence nutrient composition effectively.

Based on these findings, it is recommended to incorporate vermicompost into fertilization strategies for bell peppers to enhance the nutritional and biochemical quality of the fruits.

Future research should investigate the long-term effects of vermicompost on soil health and its impact on various crops beyond bell peppers. Exploring different doses of vermicompost and chemical fertilizers, and their interactions with other agricultural practices, could provide further insights into optimizing fertilizer use for sustainable horticulture.

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## DECLARATIONS

The corresponding author affirms that there is no conflict of interest related to this research study. The study was conducted with the sole objective of advancing scientific knowledge, and the authors declare no competing interests that might have influenced the outcomes or interpretations presented in this research.

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