



# Integrated Application of Vermicompost and Vermiwash Enhances Growth, Photosynthetic Pigments, and Essential Oil Yield in Summer Savory (*Satureja hortensis* L.):

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## ARTICLE INFO

## ABSTRACT

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Received: 31 January 2026

Accepted: 31 July 2026

### Keywords:

Organic fertilizers

Vermicompost

Vermiwash

Sustainability

To investigate the effects of different fertilizer management strategies on the production of the medicinal plant *Satureja hortensis* L., a field experiment was conducted during the 2014–2015 growing season at the Research Farm of the Faculty of Agriculture, Shirvan, using a randomized complete block design with three replications. The experimental treatments included: T1 (control), T2 (vermicompost), T3 (complete chemical fertilizer), T4 (vermiwash foliar spray), T5 (50% vermicompost + 50% NPK), T6 (66% vermiwash foliar spray), T7 (33% vermiwash foliar spray), T8 (100% vermiwash + 50% NPK), T9 (66% vermiwash + 50% NPK), and T10 (33% vermiwash + 50% NPK). The results showed that the highest plant height (47.04 cm), largest internode length (4.04 cm), highest number of lateral branches (27.67), essential oil percentage (2.77 g), and essential oil yield (10.93 g m<sup>-2</sup>) were observed under the vermicompost treatment. The highest number of nodes (15.43) was recorded in the 66% vermiwash treatment, while the largest stem diameter (0.60 cm), fresh weight (904.17 g m<sup>-2</sup>), and dry weight (452.09 g m<sup>-2</sup>) were obtained in the 50% NPK + 50% vermicompost treatment. The highest chlorophyll a (1.08 mg g<sup>-1</sup>) and total chlorophyll (1.54 mg g<sup>-1</sup>) contents were recorded under the 100% vermiwash treatment. Overall, the results of this study indicate that the application of organic and biofertilizers positively affected the quantitative and qualitative traits of *Satureja hortensis*. Therefore, the optimal use of natural inputs can support the production of high-quality, sustainable medicinal plants.

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## 1. Introduction

In recent years, the necessity of increasing food production due to global population growth has made agricultural activities more dependent than ever on the use of chemical fertilizers. According to available reports, the global consumption of nitrogen, phosphorus, and potassium fertilizers has consistently increased in recent decades, with average annual growth rates of 2.5%, 3.0%, and 2.8%, respectively (Sharafi et al., 2025). Improper use of chemical fertilizers—either insufficient or excessive—poses significant environmental and human health risks, challenging sustainable agriculture (Peñuelas et al., 2023; Yang et al., 2024). Excessive fertilizer use degrades soil physical and biological properties, causing nutrient imbalances, pH changes, and reduced microbial diversity. It also contributes to greenhouse gas emissions, groundwater contamination,

and eutrophication, posing risks to both ecosystems and human health. (Xing et al., 2025; Li et al., 2025; Elumalai et al., 2025; Adebajo-Aina & Oludoye, 2025; Madjar et al., 2024). In the pursuit of sustainable agriculture, the development and application of alternative fertilizers, such as organic fertilizers, can reduce dependence on chemical fertilizers and minimize environmental impacts (Sharafi et al., 2025). Organic fertilizers provide a slow, stable, and long-term source of macro- and micronutrients and contribute to the recycling of natural resources. In addition to supplying essential nutrients, they improve the chemical and physical properties of the soil (Khan et al., 2024). Among organic fertilizers, vermicompost is considered one of the most effective, as its application enhances soil fertility and crop yield through improvements in the physical, biological, and chemical properties of the soil (Bharti et al., 2025). In recent years, attention has increasingly shifted toward



liquid organic fertilizers, such as extracts from vermicompost, compared to their solid forms. One such extract is vermiwash, a honey-brown liquid containing protease, amylase, urease, and phosphatase enzymes, plant growth hormones, vitamins, earthworm exudates, and other organic compounds (Ganapathy et al., 2025). Vermicompost and vermiwash have immense potential for sustainable agricultural production and can be used as fertilizers to enhance food security (Singh et al., 2024). Several studies have confirmed that the application of compost and vermicompost not only affects soil physical and chemical properties but also enhances plant growth and performance. For example, research on the replacement of chemical fertilizers with vermicompost in tomato (*Solanum lycopersicum*) showed that 40–50% vermicompost application promoted early flowering and fruiting and increased tomato yield (Kist Steffen et al., 2019). Similarly, the effect of vermicompost on the growth and flowering of *Calendula officinalis* under greenhouse conditions revealed that the highest root volume and fresh flower weight were observed with 30% vermicompost, while the greatest overall plant yield occurred with 60% vermicompost (Sardoei, 2014). Likewise, the effect of vermiwash on seedling germination and biochemical traits of *Trigonella foenum-graecum* and *Cyamopsis tetragonoloba* under laboratory conditions demonstrated that the highest germination rate occurred with 50% vermiwash, whereas the maximum growth parameters, chlorophyll content, soluble sugars, total protein, and starch content were recorded with 100% vermiwash treatment (Suthar, 2010). Savory (*Satureja hortensis* L.) is an annual herbaceous plant belonging to the Lamiaceae family (Đurović et al., 2025). Its aerial parts, especially the leaves, are widely used in traditional medicine and the food industry (Fierascu et al., 2018). This plant has been used to treat muscle cramps and spasms, digestive disorders, and pain, and modern studies have demonstrated its antimicrobial, anti-inflammatory, cytotoxic, antidiarrheal, antispasmodic, and anti-protein aggregation properties (Popovici et al., 2019). Savory extracts contain various bioactive compounds, including essential oils (mainly carvacrol), phenolics, flavonoids, and important fatty acids and amino acids (Kavoosi et al., 2025). With the growing demand for natural and healthy products, improving both the quality and yield of this medicinal plant has become increasingly important. The use of organic inputs that enhance plant performance while improving soil properties and reducing environmental impacts is of high significance. Despite the benefits of vermicompost and vermiwash, systematic studies investigating their combined application with chemical fertilizers in savory are still lacking. In particular, there is limited knowledge on whether different ratios of vermicompost and vermiwash can partially or completely replace chemical

fertilizers while maintaining or enhancing plant growth, photosynthetic pigments, and essential oil yield. Therefore, this study aimed to investigate the potential to reduce chemical fertilizer use and partially replace it with organic amendments, such as vermicompost and vermiwash, and to evaluate their effects on the growth and biochemical traits of savory.

## 2. Materials and Methods

The experiment was conducted during the 2016 cropping season at the experimental farm of the Shirvan faculty agriculture, Iran, located at 37.436492° N latitude and 57.821893° E longitude, with an elevation of 1051 m above sea level. The experimental design was a randomized complete block design (RCBD) with three replications. The experiment consisted of ten nutrient management treatments: T1 (control), T2 (vermicompost application), T3 (complete chemical fertilizer, NPK), T4 (foliar application of vermiwash), T5 (combined application of 50% of T2 and 50% of T3), T6 (foliar application of vermiwash at 66% of the T4 rate), T7 (foliar application of vermiwash at 33% of the T4 rate), T8 (foliar application of vermiwash at 100% of the T4 rate combined with 50% of T3), T9 (foliar application of vermiwash at 66% of the T4 rate combined with 50% of T3), and T10 (foliar application of vermiwash at 33% of the T4 rate combined with 50% of T3). In the initial stage prior to planting, soil samples were collected from the field to determine its physical and chemical properties, as well as fertilization requirements. For this purpose, samples were randomly taken from a soil depth of 0–30 cm and transferred to the laboratory for the determination of physical and chemical characteristics. The results obtained from the physical and chemical analyses of the soil are presented in Table 1, while the results of the vermicompost sample analysis are shown in Table 2.

Land preparation steps included primary plowing and secondary tillage operations, which involved two passes with a disk harrow perpendicular to each other, leveling the field with a land leveler, and creating furrows and ridges using a furrower before planting. Based on the defined treatments, vermicompost and complete chemical fertilizers were applied before planting. For this purpose, the rate of complete NPK chemical fertilizer was set at 450 kg per hectare (N: 100 kg, P<sub>2</sub>O<sub>5</sub>: 150 kg, K<sub>2</sub>O: 100 kg), and vermicompost at 5 tons per hectare (Joshi et al., 2013). The amount for each treatment was calculated according to the plot size and added to the soil. For the experiment, 10 plots, each measuring 3 by 2 meters with an area of 6 m<sup>2</sup>, were established. The distance between planting rows was set at 25 cm (planting on both sides of the ridge). The distance between plants within a row was set at 10 cm.

**Table 1.** Physical and chemical properties of the soil at the experimental site

| PH   | EC      | SP    | TNV   | N     | P     | K     | O C   | Sand | Clay | Silt |
|------|---------|-------|-------|-------|-------|-------|-------|------|------|------|
|      | (ms/Cm) | (%)   | (%)   | (%)   | (ppm) | (ppm) | (%)   | (%)  | (%)  | (%)  |
| 7.77 | 5.08    | 50.54 | 16.25 | 0.069 | 19.10 | 415   | 0.581 | 20   | 42   | 38   |

OC, organic carbon; K, available potassium; P, available phosphorus; N, total nitrogen; TNV, total neutralizing value (calcium carbonate equivalent); SP, saturation percentage; EC, electrical conductivity; pH, soil reaction.

**Table 2.** Physical and chemical properties of the vermicompost

| PH   | EC      | Humidity | SP     | N     | P     | K     | O.C   | O/M   | C/N   |
|------|---------|----------|--------|-------|-------|-------|-------|-------|-------|
|      | (ms/Cm) | (%)      | (%)    | (%)   | (%)   | (%)   | (%)   | (%)   |       |
| 8.95 | 2.40    | 43.37    | 136.25 | 0.839 | 0.689 | 1.079 | 22.37 | 38.03 | 26.66 |

C/N, carbon-to-nitrogen ratio; OM, organic matter (%); OC, organic carbon (%); K, total potassium (%); P, total phosphorus (%); N, total nitrogen (%); SP, saturation percentage (%); Humidity, moisture content (%); EC, electrical conductivity (mS cm<sup>-1</sup>); pH, hydrogen ion concentration (soil/acidity-alkalinity index).

**Table 3.** Analysis of variance of the effects of chemical fertilizer, vermicompost and vermiwash on the quantity characters of *Satureja hortensis*

| SOV       | df | Plant height        | Number of nodes    | Number of lateral stems | Stem diameter        | Shoot fresh weight     | Shoot dry weight       |
|-----------|----|---------------------|--------------------|-------------------------|----------------------|------------------------|------------------------|
| Block     | 2  | 11.69 <sup>ns</sup> | 0.91 <sup>ns</sup> | 1.90 <sup>ns</sup>      | 0.0158 <sup>ns</sup> | 55742.02 <sup>ns</sup> | 13935.51 <sup>ns</sup> |
| Treatment | 9  | 14.36*              | 1.69**             | 5.74**                  | 0.0064**             | 40018.29**             | 10004.57**             |
| Error     | 18 | 5.73                | 0.52               | 1.83                    | 0.0017               | 12583.50               | 3145.88                |
| CV (%)    | -  | 5.41                | 4.92               | 5.34                    | 7.94                 | 15.75                  | 15.47                  |

ns, \*, \*\*: non-significant and significant at 0.05 and 0.01 probability levels, respectively

**Table 4.** Analysis of variance of the effects of chemical fertilizer, vermicompost and vermiwash on the quality characters of *Satureja hortensis*

| SOV       | df | Chlorophyll a        | chlorophyll b        | Carotinoeids         | Total chlorophyll    | Essential oil        | Essential oil yield |
|-----------|----|----------------------|----------------------|----------------------|----------------------|----------------------|---------------------|
| Block     | 2  | 0.0011 <sup>ns</sup> | 0.0029 <sup>ns</sup> | 0.0025 <sup>ns</sup> | 0.0031 <sup>ns</sup> | 0.1212 <sup>ns</sup> | 13.54 <sup>ns</sup> |
| Treatment | 9  | 0.0123**             | 0.0058*              | 0.0020*              | 0.0285*              | 0.0964*              | 8.41**              |
| Error     | 18 | 0.0024               | 0.0047               | 0.0009               | 0.0104               | 0.0348               | 1.94                |
| CV (%)    | -  | 5.04                 | 16.10                | 7.11                 | 7.33                 | 7.39                 | 15.42               |

ns, \*, \*\*: non-significant and significant at 0.05 and 0.01 probability levels, respectively

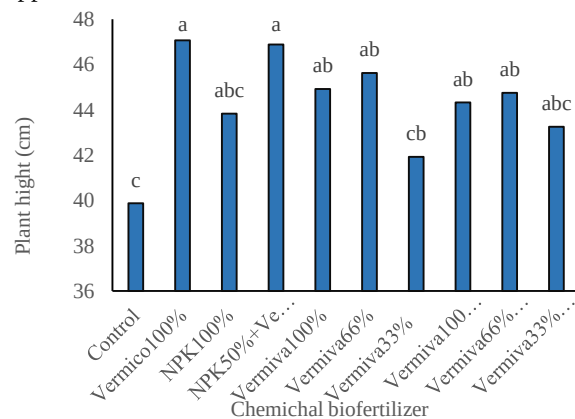
### 3. Results

#### 3.1 Plant Height

The results showed that, although there were no significant differences among the fertilizer treatments, they all exhibited significantly greater plant height compared to the control. Specifically, mean comparison (Figure 1) revealed that the greatest plant height (47.04 cm) was associated with the 100% vermicompost treatment, placing it in the highest statistical group. The 100% NPK treatment resulted in a height of 43.88 cm, while the 50% NPK + 50% vermicompost treatment achieved a height of 46.88 cm.

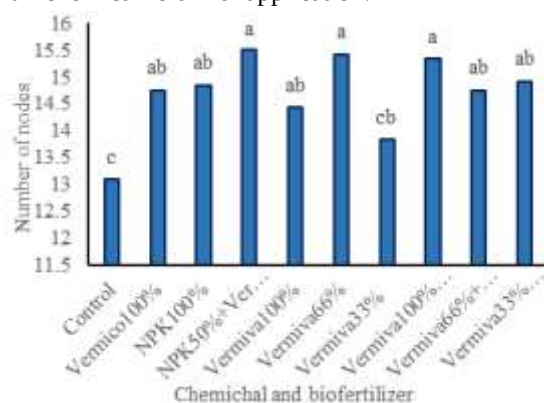
This treatment not only showed no significant decrease compared to 100% NPK, but actually resulted in greater plant height, placing it in the same statistical group as the 100% vermicompost treatment. This indicates that a 50% reduction in chemical fertilizer combined with vermicompost substitution can enhance plant height growth. Among the vermiwash-based treatments, both 100% vermiwash (44.92 cm) and 66% vermiwash (45.63 cm) resulted in greater plant heights than the 100% NPK treatment; however, no significant difference was observed between these two treatments. However, reducing the vermiwash concentration to 33% decreased plant height to 41.92 cm, a value closer to that of the control.

In the combined vermiwash and chemical fertilizer treatments, plant heights were 44.33 cm for 100% vermiwash + 50% NPK, 44.75 cm for 66% vermiwash + 50% NPK, and 43.25 cm for 33% vermiwash + 50% NPK. Statistically, none of these differed significantly from the 100% NPK treatment. In summary, the results demonstrate that reducing the share of chemical fertilizer and utilizing vermicompost or vermiwash, particularly in combined applications, can maintain or even increase plant height at a level comparable to or exceeding that achieved with full chemical fertilizer application.

**Fig1.** Mean comparison of the effects of different ratios of chemical and biofertilizer on plant height.

### 3.2 Number of Nodes

Based on the comparison of mean node numbers across different treatments (Figure 2), the control treatment exhibited the lowest number of nodes, with a mean of 13.08. The highest node numbers were observed in the NPK 50% + vermicompost 50% treatment (15.50) and the 66% vermiwash treatment (15.42), which were classified in the highest statistical group. The NPK 100% treatment, with a mean of 14.84 nodes per plant, was statistically similar to the combined treatments. Reducing the proportion of chemical fertilizer and replacing it with vermicompost in the NPK 50% + vermicompost 50% treatment not only prevented a noticeable decrease compared to NPK 100% but also resulted in the highest node number, indicating the positive effect of a 50% replacement of chemical fertilizer with vermicompost. In the combined vermiwash and chemical fertilizer treatments, the 100% vermiwash + 50% NPK, 66% vermiwash + 50% NPK, and 33% vermiwash + 50% NPK treatments, with mean node numbers of 15.33, 14.75, and 14.92 respectively, were statistically similar to NPK 100%. Moreover, reducing the vermiwash concentration to 33% led to a decrease in node number to 13.83, which was not significantly different from the control. Overall, the results indicate that reducing the share of chemical fertilizer and using vermicompost or vermiwash, particularly in combined treatments, can maintain or even enhance node numbers to levels comparable with full chemical fertilizer application.

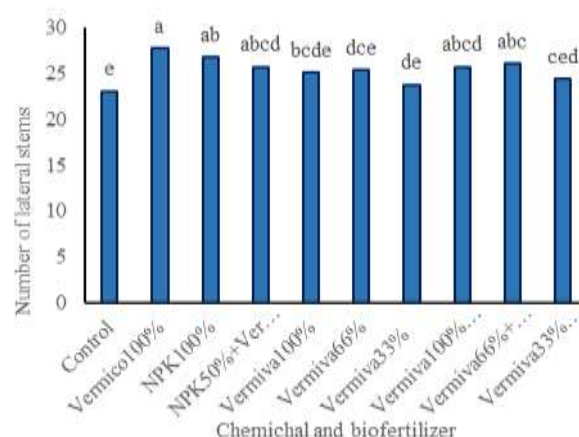


**Fig2.** Mean comparison of the effects of different ratios of chemical and biofertilizer on number of nodes.

### 3.3 Number of Lateral Stems

Based on the comparison of the mean number of lateral stems (Figure 3), the highest count (27.67) was observed in the 100% vermicompost treatment, placing it in the highest statistical group. The 100% NPK treatment (26.67), 50% NPK + 50% vermicompost (25.67), 50% NPK + 100% vermiwash (25.67), and 50% NPK + 66% vermiwash (26.00) treatments all belonged to the same statistical group. Reducing the chemical fertilizer share and substituting it with organic amendments did not create a significant difference in the number of lateral

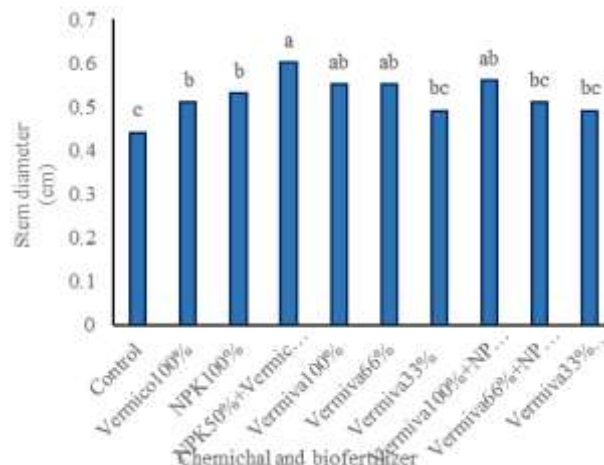
stems. In the combined vermiwash and NPK treatments, values of 25.67 and 26.00 were recorded for the 100% vermiwash + 50% NPK and 66% vermiwash + 50% NPK treatments, respectively. None of these differed significantly from the 100% NPK treatment. These results indicate that the integrated use of organic fertilizers can maintain the number of lateral stems at a desirable level. Among the sole vermiwash treatments, 100 % vermiwash and 66 % vermiwash produced acceptable lateral stem counts of 25.00 and 25.33, respectively. However, reducing the vermiwash concentration to 33% decreased this trait to 23.67, which was not significantly different from the control.



**Fig3.** Mean comparison of the effects of different ratios of chemical and biofertilizer on number of lateral stems.

### 3.4 Stem Diameter

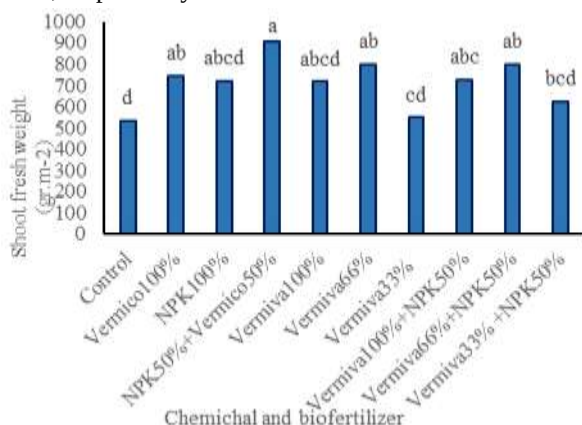
The results (Figure 4) showed that the highest stem diameter was observed in the NPK 50% + vermicompost 50% treatment, measuring 0.60 cm. This value was not significantly different from those of the 100% vermiwash, 66% vermiwash, and 100% vermiwash + 50% NPK treatments, which had mean diameters of 0.55, 0.55, and 0.56 cm, respectively. The lowest stem diameter was recorded in the control treatment, with a mean of 0.23 cm.



**Fig4.** Mean comparison of the effects of different ratios of chemical and biofertilizer on steam diameter.

### 3.5 Shoot Fresh Weight

Comparison of the mean data (Figure 5) revealed that the highest shoot fresh weight was recorded for the 50% NPK + 50% Vermicompost treatment at 904.17 grams per square meter (a 69% increase compared to the control). The 100% Vermicompost, 100% NPK, and 100% Vermiwash treatments, with averages of 744.80, 721.89, and 719.29 grams per square meter, respectively, were placed in the same statistical group. The lowest values were obtained in the Control and 33% Vermiwash treatments, with the lowest averages of 533.33 and 549.20 grams per square meter, respectively.



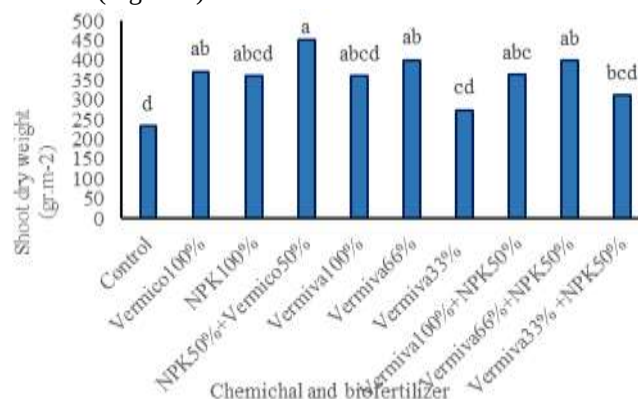
**Fig5.** Mean comparison of the effects of different ratios of chemical and biofertilizer on shoot fresh weight.

### 3.6 Shoot dry weight

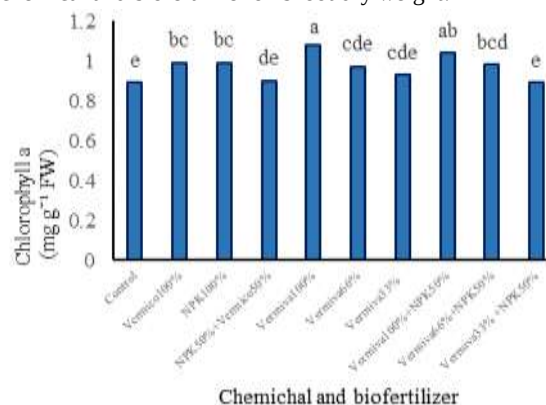
According to the results (Figure 6), the highest shoot dry weight was recorded in the NPK 50% + vermicompost 50% treatment, measuring 452.09 g m<sup>-2</sup>, representing a 70% increase compared to the control. The 100% vermicompost, 100% NPK, and 66% vermiwash treatments, with mean values of 744.80, 721.89, and 800.51 g m<sup>-2</sup>, respectively, ranked next, although no significant differences were observed among them. The lowest shoot dry weight was recorded in the control treatment, with 266.67 g m<sup>-2</sup>. Among the treatments, 100% vermicompost significantly increased shoot dry weight to 372.40 g m<sup>-2</sup> compared to the control and was statistically similar to the top-performing treatments. The NPK 100% treatment yielded 360.95 g m<sup>-2</sup>, showing a noticeable increase relative to the control, while 100% vermiwash recorded 359.65 g m<sup>-2</sup>, which was comparable to NPK 100% and significantly higher than the control. Overall, the combination of vermicompost and chemical fertilizer had the greatest effect on shoot dry weight. In particular, the NPK 50% + vermicompost 50% treatment, with 452.09 g m<sup>-2</sup>, produced the highest aerial dry biomass and was classified in the top statistical group.

### 3.7 Chlorophyll a

Analysis of photosynthetic pigments revealed that the lowest chlorophyll a content (0.89 mg per g of solution) was recorded in the control treatment. Among the experimental treatments, both 100% Vermicompost and 100% NPK showed a value of 0.99 mg per g, indicating an increase compared to the control. In contrast, the 100% Vermiwash treatment, with a content of 1.08 mg per g of solution, registered the highest value for this trait and was placed in the highest statistical group. Reducing the vermiwash concentration led to a decrease in Chlorophyll a content, with 66% Vermiwash declining to 0.97 mg per g and 33% vermiwash to 0.93 mg per g. This indicates that reducing the vermiwash percentage resulted in a gradual decrease in this trait. In the combined treatments, the Chlorophyll a content in 100% Vermiwash + 50% NPK was 1.04 mg per g, showing an increase over the control. However, reducing the vermiwash level in the presence of NPK (66% and 33%) led to a decrease in this trait (Figure 7).



**Fig6.** Mean comparison of the effects of different ratios of chemical and biofertilizer on shoot dry weight.

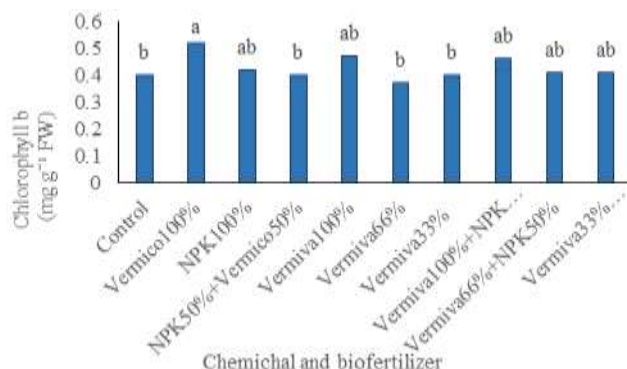


**Fig7.** Mean comparison of the effects of different ratios of chemical and biofertilizer on chlorophyll a.

### 3.8 Chlorophyll b

The comparison of mean values (Figure 8) showed that the highest chlorophyll b content was observed in the 100% vermicompost treatment, with 0.52 mg.g<sup>-1</sup> fw of extract, whereas the lowest value was recorded in the 66% vermiwash treatment, at 0.37 mg g<sup>-1</sup>. In the control treatment, chlorophyll b content was 0.40 mg g<sup>-1</sup>, and

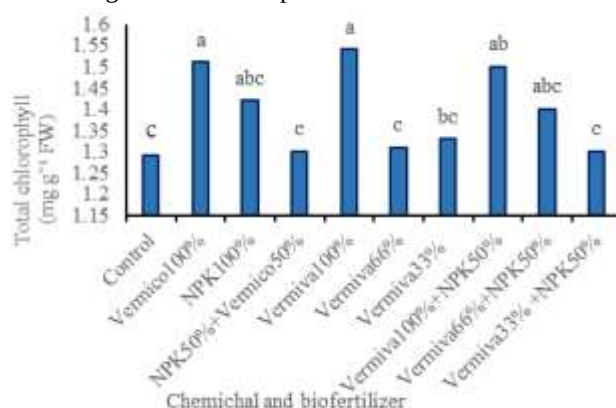
the NPK 100%, 100% vermiwash, and combined vermiwash + NPK treatments were statistically similar to the control. A decrease in vermiwash concentration resulted in a gradual decline in chlorophyll b content, although no significant difference was observed between the 33% vermiwash treatment and the control. Among the combined treatments, particularly 100% vermiwash + 50% NPK, chlorophyll b content was relatively higher than that of the single-factor treatments.



**Fig8.** Mean comparison of the effects of different ratios of chemical and biofertilizer on chlorophyll b.

### 3.9 Total chlorophyll

The obtained results (Figure 9) showed that the highest total chlorophyll content was achieved in the 100% Vermiwash treatment with 1.54 mg per g of solution and the 100% Vermicompost treatment with 1.51 mg per g of solution. The lowest value (1.29 mg per g) was recorded in the control treatment. The 100% NPK treatment showed a value of 1.42 mg per g of solution. Reducing the vermiwash percentage led to a decrease in total chlorophyll content, with the 66% and 33% Vermiwash treatments showing values close to that of the control. The combined treatments, particularly 100% Vermiwash + 50% NPK, exhibited higher values compared to the control.

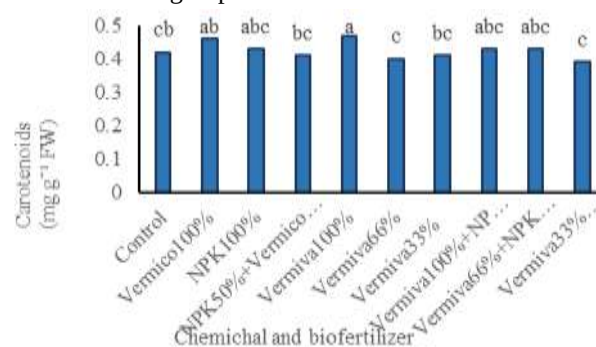


**Fig9.** Mean comparison of the effects of different ratios of chemical and biofertilizer on total chlorophyll.

### 3.10 Carotenoids

According to the results (Figure 10), the highest carotenoid content was observed in the 100% vermiwash treatment, with 0.47 mg g<sup>-1</sup> leaf,

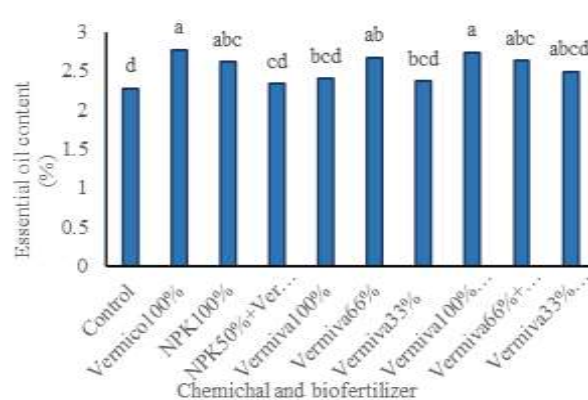
representing a 12% increase compared to the control. The lowest value was recorded in the 33% vermiwash + 50% NPK treatment, at 0.39 mg g<sup>-1</sup>. Carotenoid contents in the 100% vermicompost (0.46 mg g<sup>-1</sup>) and 100% NPK (0.43 mg g<sup>-1</sup>) treatments were numerically higher than the control (0.42 mg g<sup>-1</sup>); however, no significant differences were observed among the treatments. A reduction in vermiwash concentration resulted in a decrease in carotenoid content, with the 66% and 33% vermiwash treatments being classified in lower statistical groups.



**Fig10.** Mean comparison of the effects of different ratios of chemical and biofertilizer on carotenoids.

### 3.11 Essential oil content

Comparison of mean showed that the highest essential oil content was found in the 100% Vermicompost treatment, with a value of 2.77 % solution, followed by the 100% Vermiwash + 50% NPK treatment, at 2.73 %. In contrast, the lowest value for this trait was recorded in the control treatment, at 2.27% (Figure 11). The essential oil content in the 100% NPK treatment was 2.61%, reflecting an increase relative to the control. Reducing the vermiwash percentage in the combined treatments of vermiwash and NPK, resulted in a gradual decline in essential oil content, as illustrated by the value of 2.49 mg per g solution observed in the 33% Vermiwash+NPK50% treatment.

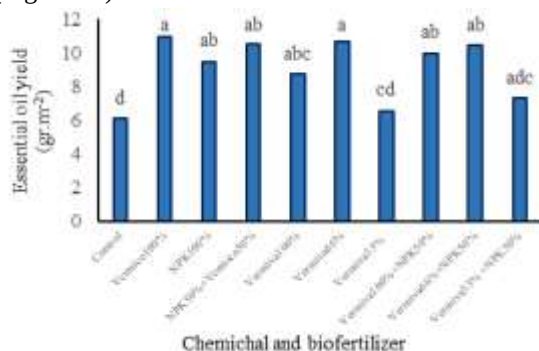


**Fig11.** Mean comparison of the effects of different ratios of chemical and biofertilizer on essential oil content.

### 3.12 Essential oil yield

The results indicated that the highest essential oil yield was recorded in the 100% vermicompost treatment

(10.93 mg g<sup>-1</sup> of extract) and the 66% vermiwash treatment (10.64 mg g<sup>-1</sup>), while the lowest value was observed in the control treatment (6.10 mg g<sup>-1</sup>). The 100% NPK treatment yielded 9.47 mg g<sup>-1</sup>, showing a noticeable increase compared to the control. Reducing the vermiwash concentration to 33% led to a decline in essential oil yield to 6.53 mg g<sup>-1</sup>. However, combining vermiwash with 50% NPK, particularly at the 66% level, resulted in a renewed increase in essential oil yield (Figure 12).



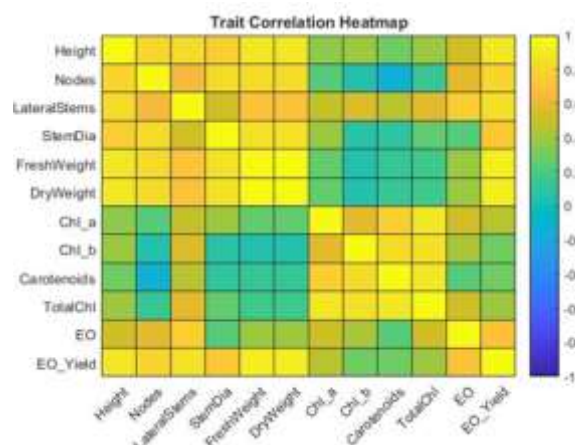
**Fig12.** Mean comparison of the effects of different ratios of chemical and biofertilizer on essential oil yield.

### 3.13 Correlation analysis

The correlation analysis among the studied traits revealed complex and significant interrelationships, providing a deeper understanding of the plant's response to various fertilizer treatments. Based on the results, shoot dry weight exhibited a strong positive correlation ( $r \approx 0.85^*$ ) with essential oil yield, confirming that dry matter accumulation serves as the primary foundation for the plant's essential oil production potential. Physiologically, total chlorophyll content was found to be intensely correlated ( $r > 0.95^*$ ) with its constituent pigments, indicating high integrity and stability of the photosynthetic system across different nutritional conditions. Additionally, a substantial positive correlation ( $r \approx 0.80^*$ ) between plant height and the number of nodes suggests a precise synchronization between vertical stem elongation and the structural development of vegetative sites. Finally, the extremely high correlation ( $r \approx 0.90^*$ ) between fresh weight and dry weight demonstrates that biomass accumulation and water uptake processes operate in full alignment, both serving as reliable key indicators for evaluating the success of combined vermicompost and vermiwash applications.

## 4. Discussion

The obtained results clearly demonstrate the impact of organic fertilizers on the growth characteristics of summer savory (*Satureja hortensis* L.). The evaluation of quantitative traits indicated that the vegetative growth of the plant was significantly influenced by the type and combination of fertilizers used.



**Fig13.** Pearson correlation coefficients among growth parameters, physiological traits, and essential oil yield under different fertilizer treatments.

The application of organic fertilizers and integrated treatments was able to improve various growth indices and, in many cases, produce performance equal to or superior to that of complete chemical fertilizer. For traits such as node number, number of lateral branches, and stem diameter, no significant difference was observed among vermicompost, chemical fertilizer, and combined treatments. Regarding plant height, among the experimental treatments, the application of vermicompost resulted in the greatest plant height. The highest fresh and dry weights of the aerial parts were obtained in the combined chemical fertilizer and vermicompost treatment, indicating a synergistic effect between organic and chemical fertilizers and increased nutrient uptake efficiency. Numerous studies have shown that the application of vermicompost and vermiwash as organic fertilizers increases plant growth and improves quantitative and qualitative performance in various plant species. These organic compounds, due to their content of plant hormones, humic acids, and bioactive enzymes, stimulate growth processes and cell division in plants (Ganapathy et al., 2025). Research reported that the use of vermiwash led to significant changes in plant growth parameters, including increased stem height, number of leaves, number of branches, stem diameter, and number of flowers in *Capsicum annum* (Chandukishore et al., 2023). Studies on two varieties of flax (*Linum usitatissimum* L.) also showed that the use of vermicompost and vermiwash increased plant growth (Cinny Makkar et al., 2017). It has been reported that the use of vermiwash and vermicompost in *Linum usitatissimum* increases the number of branches, the number of capsules, plant dry weight, and improves growth indices (Cinny Makkar et al., 2017). Another report stated that the consumption of vermicompost along with chemical fertilizers resulted in the best tomato yield, emphasizing that combined nutrient supply maintains soil fertility and plant performance in an environmentally friendly manner.

(Singh et al., 2010). Another study reported the positive effect of vermiwash and vermicompost on the physiological characteristics of *Abelmoschus esculentus* L. (Gupta et al., 2018). A study on lettuce reported that the application of vermicompost combined with vermiwash foliar spraying improved vegetative growth, plant height, fresh and dry leaf weight, and total yield of lettuce plants (Yassen et al., 2020). The increase in soil nitrogen and phosphorus content after vermicompost application is linked to the high activity of protease and acid phosphatase enzymes in vermicompost. Furthermore, the wellbeing of soil is significantly enhanced by the diverse biochemical makeup of vermicompost, characterized by hormones (auxins, cytokinins), macronutrients (amino acids, vitamins), and enzyme cocktails (Gudeta et al., 2021). Complementing this, vermiwash provides a rich source of secondary metabolites and beneficial microorganisms, including saprophytes, actinomycetes, fungi, nitrogen-fixing strains such as *Agrobacterium*, *Azotobacter*, and *Rhizobium*, and phosphate-solubilizing bacteria (Das et al., 2014; Tripathi et al., 2005).

Another study reported increased growth indices of *Amaranthus viridis* L. under the influence of different concentrations of vermiwash (Deepthi et al., 2021). Vermicompost and vermiwash are suitable substitutes for chemical fertilizers. In the vermicomposting process, organic materials are exposed to bacteria and enzymes in the earthworm gut, which alter nutrient compounds and impart a unique character and consistency to vermicompost. Chemically, vermicompost and vermiwash contain proteins, hormones, enzymes, macro and micronutrients, and several microorganisms. One of the positive effects of using vermicompost extract is the increased population of Plant Growth-Promoting Bacteria (PGPB) (Pathma and Sakthivel, 2012). These bacteria can improve plant growth through mechanisms such as auxin production, ACC deaminase enzyme activity, cytokinin and gibberellin production, nitrogen fixation, phosphorus solubilization, and iron uptake via bacterial siderophores (Olanrewaju et al., 2017). The results of this research provide the possibility of reducing chemical fertilizer use without compromising plant growth and for planning within the framework of organic production of medicinal plants and sustainable agriculture. At the same time, the obtained results on the quantitative traits of summer savory under the influence of organic treatments, especially vermicompost and vermiwash, indicate the potential for replacing common chemical fertilizers with organic ones. The increased number of lateral branches in organic and combined treatments indicates improved plant architecture and increased potential for producing aerial biomass, which is of particular importance in medicinal plants. From an

organic agriculture perspective, the results show that through gradual planning to reduce chemical fertilizer use and reliance on organic resources, optimal growth of summer savory can be maintained without dependence on chemical inputs. Thus, the exclusive use of vermicompost and vermiwash as sustainable options, while preserving quantitative growth traits, improves soil quality and reduces environmental impacts, providing a suitable path for the organic and sustainable production of summer savory.

The results showed that the type of plant nutrition source significantly influenced photosynthetic pigment production and photosynthetic performance in summer savory. Since photosynthesis provides the carbon skeletons and energy required for secondary metabolite biosynthesis, improvements in photosynthetic traits may subsequently enhance essential oil production.

The use of organic fertilizers, alone or in combination with chemical fertilizers, showed a marked superiority in many traits compared with the control and even the full chemical fertilizer treatment. The results indicated that the highest levels of chlorophyll a, carotenoids, and total chlorophyll pigments were observed in the vermiwash treatment, pure vermicompost, and the combination of vermiwash and chemical fertilizer. This suggests an improvement in the plant's nutritional status and increased photosynthetic efficiency resulting from the application of organic fertilizers.

In line with these findings, a study investigating the effects of vermicompost and vermiwash on *Trigonella foenum-graecum* demonstrated that, in addition to quantitative traits, chlorophyll a and b content, as well as essential oil percentage and yield, were significantly increased (Tadayyon et al., 2018). In another study, it was reported that treatment with vermicompost and vermiwash in *Aphanus sativus* L. led to increased chlorophyll content in the leaves (Muthukannan et al., 2024). Vermicompost appears to improve soil quality, enhance the availability of essential nutrients, provide humic acids, growth-regulating hormones, and enzymes, thereby improving plant nutrition, photosynthesis, and overall product quality (Oyege and Balaji Bhaskar, 2023). Moreover, the highest essential oil content and yield observed under pure vermicompost and vermiwash treatments indicate that organic fertilizers, in addition to support vegetative growth, play an important role in stimulating secondary metabolite synthesis and improving product quality—an aspect of particular importance in medicinal plants. Comparisons between integrated treatments and sole chemical fertilizer application showed that reducing chemical fertilizer use and partially replacing it with organic fertilizers can achieve high levels of photosynthetic pigments and essential oil yield without significant reductions in overall performance. Within the

framework of sustainable agriculture, these results highlight the potential to reduce dependence on chemical fertilizers, increase input-use efficiency, and mitigate environmental impacts (Yang et al., 2024). In the context of organic farming, the exclusive use of organic fertilizers may serve as an effective strategy for the organic cultivation of savory (*Satureja hortensis*), maintaining yield while enhancing physiological and medicinal quality. In another study, vermicompost application improved plant biomass, phytochemical characteristics, and essential oil content in the medicinal plant *Dracocephalum kotschyi* Boiss (Bohlouli et al., 2024). Likewise, Esfahani et al. (2023) demonstrated that the use of organic fertilizers such as vermicompost increased flavonoid content in medicinal mullein plants.

## 5. Conclusion

Overall, the results of this study indicate that the application of organic and biofertilizers, including vermicompost and vermiwash, as well as their combination with complete chemical fertilizers, had positive effects on the growth, physiological traits, and essential oil yield of *Satureja hortensis* L. The cultivation of medicinal plants without chemical inputs is essential for producing safe and natural products. Given the favorable response of *Satureja hortensis* to organic and biological fertilizers, their application appears to be a viable strategy for producing medicinal plants under low-input and sustainable agricultural systems. Organic and biofertilizers can meet plant nutritional requirements without environmental hazards, maintain soil and agroecosystem health, and promote the establishment of beneficial soil microorganisms. Therefore, these treatments can be considered an effective alternative to chemical fertilizers in ecological nutrient management systems, supporting both sustainable production and the quality of medicinal plants.

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