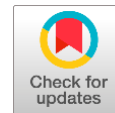


# Role of seaweed extract and vermicompost application on the morphology, yield, phytochemical, and elemental composition of cauliflower plants



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**Abstract** In recent years, the extensive use of agrochemicals for crop production and protection has adversely affected crop productivity, soil health, and the environment. Organic amendments have emerged as promising alternatives to enhance both soil and plant health. This greenhouse study aimed to evaluate the effectiveness of seaweed extract and vermicompost, individually and in combination, on the morphology, yield, phytochemicals, and elemental composition of cauliflower plants. Seaweed extract (2 kg/ha) was applied 21 days after transplanting, while vermicompost was incorporated into the soil around the root zone at rates of 7.5 and 15 tons/ha before planting. The experiment was arranged in a randomized complete block design with three replications. Compared with the other treatments, F5 (seaweed extract combined with vermicompost at a rate of 15 tons/ha) significantly improved plant morphology; yield components; and nitrogen, phosphorus, and calcium contents. F1 (seaweed extract alone) yielded the highest antioxidant activity (TAA) (3.18 µg/g FW) and iron content (280.6 ppm), whereas F2 (7.5 tons/ha vermicompost) resulted in the highest total phenolic content (TPC) (35.49 µg GAE/g FW) and potassium (2.79%) levels. According to the results, the control had the lowest values in this study. These outcomes highlight the potential of using organic amendments and biostimulants to increase crop traits, improve the nutritional quality of plants, and promote sustainable agricultural practices. Consequently, the combination of seaweed extract and vermicompost may serve as an effective strategy for improving the growth and quality of cauliflower, contributing to environmentally friendly and economically viable production systems.

**Keywords:** *Brassica oleracea* var. *botrytis*, curd quality, TAA, organic farming, sustainability

## 1. Introduction

Cauliflower (*Brassica oleracea* var. *botrytis* L.) is one of the most important vegetable crops in the world and originates from the Mediterranean region. Crops belonging to the Brassicaceae family have been extensively studied because of their potential health benefits (Mahmood et al., 2021). Cauliflower is widely cultivated globally for its nutritional value and adaptability to various ecological conditions and is a cold-hardy crop that thrives best in cool and moist climates. It is rich in essential vitamins and minerals, which contribute to the numerous health benefits associated with its consumption (Ogbede et al., 2015). In addition to their nutritional value and productivity, polyphenolic compounds such as myricetin and quercetin, which are flavonoids with high antioxidant activity, may help prevent cancer (El-Saady and Omar, 2018; Chahal et al., 2019). Furthermore, it contains glutathione, which plays a significant role in protecting against bladder cancer (Abbaoui et al., 2018). The growing awareness of food safety has led to an increased demand for organic and biobased alternatives to traditional chemical fertilizers (Shams and Morsy, 2019). In recent years, the use of biostimulants and organic fertilizers to improve both the quantity and quality of crop yields has garnered considerable attention (Hawall et al., 2018). These alternatives are believed to be healthier for both crops and the environment while also reducing the need for mineral fertilizers. Seaweed extracts, classified as biostimulants, are derived from nonblooming marine algae (Mohammed et al., 2022). They contain high concentrations of sterols, polysaccharides, N-containing compounds (e.g., betaines), various nutrients, and plant growth-promoting substances such as auxins, cytokinins, gibberellins, and brassinosteroids (Craigie, 2011). Seaweed extracts have gained increasing importance in recent years for use in a variety of crops, including vegetables. These extracts enhance plant growth, improve plant health, and provide resilience against environmental stresses such as drought, salinity, and extreme temperatures (Lola-Luz et al., 2014; Mughunth et al., 2024). Seaweeds are valuable sources of both organic and inorganic components that can improve plant quantity and quality (Ashour et al., 2021). In addition, vermicompost is the product of mesophilic biodegradation and the stabilization of organic materials through the interactive actions of microorganisms and



earthworms. This product is rich in organic compounds, mineral nutrients, and phytohormones (Yassen et al., 2019). Earthworms play a critical role in altering the physicochemical and biological characteristics of organic matter by reducing the C/N ratio, increasing the surface area, providing more sites for microbial activity, and improving the decomposition process (Rehman et al., 2023). Vermicompost not only promotes healthy and productive crops but also regulates plant development through humic acid and hormones (Wong et al., 2020). More importantly, it stimulates microbial activity in the soil, increases oxygen availability, maintains soil temperature, improves soil porosity and water infiltration, enhances nutrient content, and increases plant growth, yield, and quality (Rekha et al., 2018). Various agricultural strategies have been implemented to improve crop quality and production. However, detailed studies on the application of seaweed extract and vermicompost, as well as their integrated use, are limited. Therefore, the main aim of this study was to investigate the growth, yield, phytochemical properties, and elemental composition of cauliflower under seaweed extract and vermicompost application.

## 2. Materials and Methods

### 2.1. Experimental site

The experiment was conducted in the Horticulture Department of the College of Agricultural Engineering Sciences at the University of Sulaimani, Sulaymaniyah, Kurdistan Region, Iraq (35° 32' N, 45° 21' E). The study was carried out under greenhouse conditions in a structure measuring 51 m in length, 9 m in width, and 3 m in height and covered with a 200 µm-thick transparent polyethylene plastic film. Soil samples were obtained from a depth of 0–30 cm to assess the initial soil properties. The soil texture was identified (95.6 g/kg sand, 435.9 g/kg silt, and 468.5 g/kg clay), with a pH of 7.56, electrical conductivity of 1.01 dS/m, organic matter content of 10.1 g/kg, calcium carbonate content of 245 g/kg, total nitrogen (N) content of 14.5 mg/kg, available phosphorus (P) content of 6.3 mg/kg, soluble potassium (K) content of 56.1 mg/kg and available iron content of 2.87 mg/kg.

### 2.2. Plant materials and experimental design

The greenhouse area was arranged in parallel terrace lines. Drip irrigation was employed throughout the experiment to ensure an adequate water supply for cauliflower cultivation. Mulching was applied to the terraces for weed control and water conservation. The terraces were spaced 40 cm apart, with 40 cm intervals between plants. The greenhouse was divided into experimental units of 2.1 m<sup>2</sup>, each containing six plants arranged in a zigzag pattern, which were replicated three times. Six treatments were tested, including the application of seaweed extract alone, vermicompost alone, a combination of seaweed extract and vermicompost, and a control. Vermicompost was incorporated into the top 15 cm of soil in the experimental beds before the cultivation of the cauliflower seedlings, with various concentrations applied. Additionally, seaweed extract was applied at a rate of 2 kg/ha 21 days after transplanting, with subsequent applications occurring every 15 days, for a total of four applications. The seaweed extract was produced by the United Kingdom Fertilizers Company (UK). For the seaweed extract and vermicompost applications, 6 treatments were arranged in a randomized complete block design (RCBD) with three replications: control (without any fertilizer-F0), 2 kg/ha seaweed extract (F1), 7.5 ton/ha vermicompost (F2), 15 ton/ha vermicompost (F3), 2 kg/ha seaweed extract and 7.5 ton/ha vermicompost (F4), 2 kg/ha seaweed extract and 15 ton/ha vermicompost (F5).

### 2.3. Data collection

During this study, multiple parameters were measured via various instruments. The chlorophyll content in the leaves was assessed with a chlorophyll meter (SPAD 502 PLUS) (Raheem et al., 2018). To determine the dry matter content (DM%) of the roots, shoots, and curd, the fresh weights of these parts (*W<sub>b</sub>*) were first recorded. These samples were then dried in a forced-air oven at 65°C for 72 hours until they reached a constant weight (*W<sub>a</sub>*) (Ibrahim et al., 2024). The DM% was calculated via the formula:  $DM\% = \frac{W_a}{W_b} \times 100$ .

### 2.4. Plant extraction

For the fruits (curd), the sample extracts for the TPC, TFC, and TAA tests were prepared following the methods described by Ahmed et al. (2024). The procedure involved snap-freezing the fruit samples with liquid nitrogen and then grinding the frozen samples with a mortar and pestle. One gram of the powdered material was placed in 15 mL tubes, and 10 mL of 80% methanol was added. The tubes were shaken in a water bath at 38°C for 3 hours. Afterward, the mixture was centrifuged at 5000 rpm for 15 minutes. The supernatant (extracts) was collected and stored in new tubes, which were kept in a refrigerator at 4°C as the crude extraction solution for further analysis.

### 2.5. Total phenolic content (TPC)

The TPC of each curd extract was determined via a modified Folin–Ciocalteu method (Kakbra et al., 2023). The absorbance of the reaction mixture was measured at 765 nm with a UV–visible spectrophotometer (UVM6100, MAANLAB AB,

Sweden). The TPC values were calculated and expressed as milligrams of gallic acid equivalent (GAE) per gram of fresh weight of the fruit samples ( $\mu\text{g GAE/g FW}$ ) via the following equation:

$$\text{TPC } (\mu\text{g GAE/g FW}) = \frac{V}{W} \times C$$

Where:

C is the gallic acid concentration (mg/mL) calculated via the standard curve,

V is the volume of the extracts (mL), and

W represents the fresh weight of the samples (g).

### 2.6. Total flavonoid content (TFC)

The TFC was assessed via the aluminum chloride ( $\text{AlCl}_3$ ) colorimetric method, following a slightly modified version of the procedure outlined by Kakbra et al. (2023). The absorbance of the reaction mixture was measured at 415 nm with a UV-visible spectrophotometer (UVM6100, MAANLAB AB, Sweden). TFC values were calculated and expressed as micrograms of quercetin equivalent (QE) per gram of fresh weight ( $\mu\text{g QE/g FW}$ ) via the following equation:

$$\text{TFC}(\mu\text{gQE/gFM}) = \frac{V}{W} \times C$$

Where:

C is the concentration of quercetin determined from the standard curve,

V is the volume of the extracts, and

W: fresh weight of the samples

### 2.7. Total antioxidant activity (TAA)

The TAA of the curd extracts was assessed via the DPPH (1-diphenyl-2-picrylhydrazyl) assay, as outlined by Tahir et al. (2022). The absorbance was measured at 517 nm with a UV-visible spectrophotometer (UVM6100, MAANLAB AB, Sweden). Mineral quantification of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and iron (Fe) was conducted following the methods described by Elmer (1996).

### 2.8. Statistical analysis

It was conducted to assess whether the growth, yield, phytochemical, and elemental composition values differed significantly between treatments. An ANOVA was performed, followed by one-way comparisons between control and treated plants via XLSTAT software (version 2019.2.2). Duncan's new multiple range test ( $p \leq 0.05$ ) was applied to compare the means. Additionally, principal component analysis (PCA) was performed.

## 3. Results

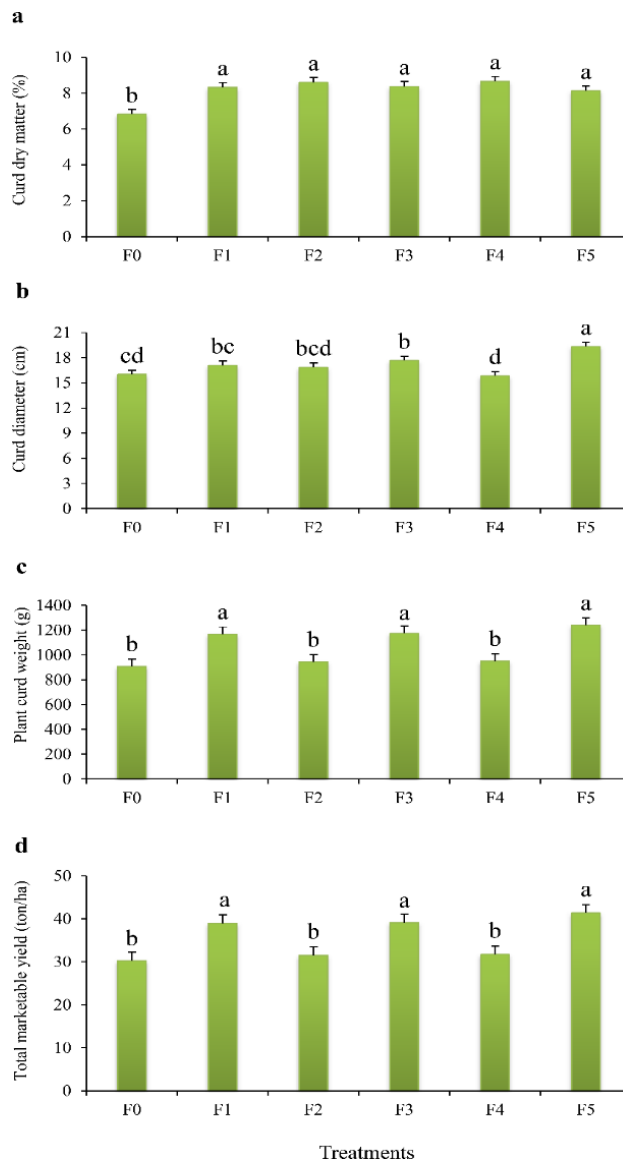
The results of this study revealed that the application of seaweed extract and different rates of vermicompost significantly enhanced all the growth characteristics of the cauliflower plants (Table 1). The F5 treatment was the most effective, resulting in the tallest plants (61.00 cm), thickest stem diameters (24.59 mm), highest plant leaf number (20.20), and maximum leaf chlorophyll content (66.23 SPAD). In contrast, the F0 treatment resulted in the lowest values for plant height (53.86 cm) and plant leaf number (16.16), whereas the F2 treatment resulted in the smallest stem diameter (21.78 mm), and the F1 treatment resulted in the lowest chlorophyll pigment levels (55.26 SPAD). The coapplication of seaweed extract and vermicompost had significant positive effects on the leaf dry matter percentage and root length. The highest percentage (15.72%) and longest root length (32.70 cm) were observed under the F4 treatment. However, the lowest leaf dry matter percentage (13.41%) was recorded under F1, and the shortest root (28.76 cm) was observed under F0. For the root dry matter percentage, the highest value (13.36%) was recorded in F5, which did not differ statistically from that in F4, whereas the lowest percentage (9.69%) was recorded in F0.

The data (Figure 1) revealed that the application of seaweed extract and vermicompost as soil amendments increased the yield components of the cauliflower plants compared with those of the control (without treatment). The curd dry matter percentage increased with the application of F2; however, there was no statistically significant difference among the treatments, except for the untreated plants (F0), whose dry matter percentage was the lowest (6.82%) (Figure 1a). Both treatments significantly influenced curd diameter, with the maximum value (19.33 cm) recorded under F5, whereas F4 had the minimum diameter (15.83 cm) (Figure 1b). The plant curd weight and total marketable yield responded positively to the various treatments throughout the growing season. F5 produced the highest harvest for both yield components (1240.33 g/plant and 41.34 ton/ha, respectively), although it did not differ statistically from F3 and F1. In contrast, the lowest curd weight (908.33 g/plant) and total marketable yield (30.27 ton/ha) were recorded in the F0 treatment (untreated plants) (Figure 1c, d).

**Table 1** Effects of seaweed extract and vermicompost on the morphological attributes.

Treat	Plant height (cm)	Stem diameter (mm)	Plant leaf number	Leaf chlorophyll content (SPAD)	Leaf dry matter (%)	Root dry matter (%)	Root length (cm)
F0	53.86 ± 0.98 c	22.73 ± 0.48 bc	16.16 ± 0.17 c	60.43 ± 2.18 bc	12.95 ± 0.26 cd	9.69 ± 0.06 c	28.76 ± 0.27 c
F1	56.66 ± 1.20 bc	22.78 ± 0.38 bc	17.20 ± 0.42 bc	55.26 ± 0.88 d	13.41 ± 0.42 c	11.01 ± 0.47 b	30.23 ± 0.50 b
F2	59.33 ± 0.67 ab	21.78 ± 0.41 c	18.70 ± 0.15 ab	63.50 ± 2.30 ab	15.06 ± 0.26 ab	10.78 ± 0.19 b	30.26 ± 0.56 b
F3	57.10 ± 1.24 bc	24.49 ± 0.56 a	18.66 ± 1.20 ab	58.46 ± 0.74 cd	12.09 ± 0.22 d	10.71 ± 0.40 b	30.40 ± 0.40 b
F4	55.00 ± 0.58 c	24.04 ± 0.31 ab	18.00 ± 0.29 bc	63.00 ± 1.53 abc	15.72 ± 0.40 a	12.67 ± 0.40 a	32.70 ± 0.25 a
F5	61.00 ± 1.53 a	24.59 ± 0.50 a	20.20 ± 0.76 a	66.23 ± 0.50 a	14.70 ± 0.16 b	13.36 ± 0.28 a	32.23 ± 0.23 a

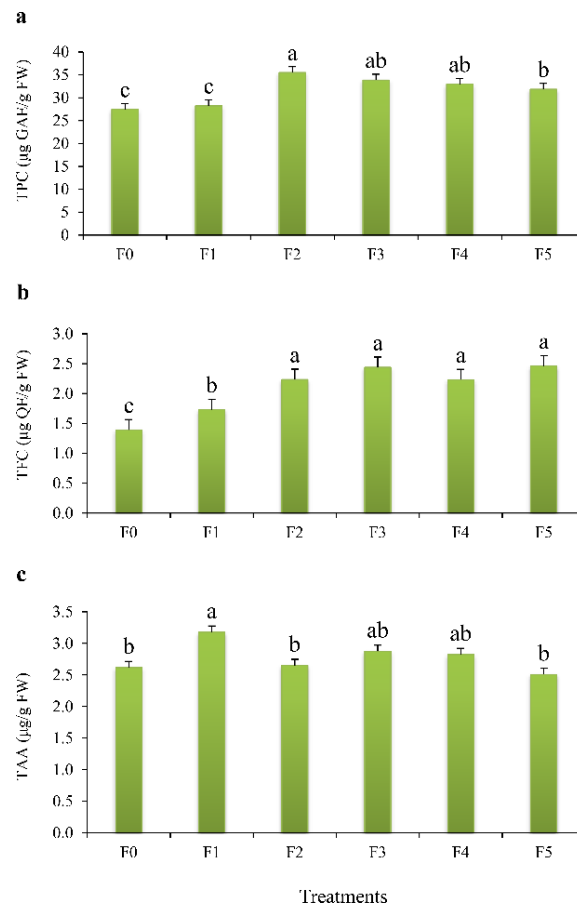
\*Control (F0), seaweed extract 2 kg/ha (F1), vermicompost at 7.5 ton/ha (F2), vermicompost at 15 ton/ha (F3), seaweed extract and vermicompost at 7.5 ton/ha (F4), seaweed extract and vermicompost at 15 ton/ha (F5).



**Figure 1** Effects of seaweed extract (2 kg/ha) and different doses of vermicompost (0, 7.5, and 15 ton/ha) on the studied variables in cauliflower curds. The data are expressed as the means ± SEs ( $n = 3$ ), with different letters indicating significant differences based on Duncan's multiple range test ( $p \leq 0.05$ ).

The phytochemical content was significantly influenced by the seaweed extract and vermicompost concentrations (Figure 2). The F2 treatment notably increased the total phenolic content (TPC) in the cauliflower curd, resulting in the highest TPC value (35.49  $\mu\text{g GAE/g FW}$ ). In contrast, the F0 treatment resulted in the lowest TPC value (27.45  $\mu\text{g GAE/g FW}$ ) (Figure 2a). The TFC increased with increasing seaweed extract content and vermicompost content. The highest value (2.46  $\mu\text{g QE/g FW}$ ) was observed in the F5 treatment, which was not significantly different from those of F4, F3, and F2. Conversely, the lowest value (1.39  $\mu\text{g QE/g FW}$ ) was recorded in the F0 (control) treatment (Figure 2b). Furthermore, the radical scavenging activity increased with the application of the seaweed extract alone. The maximum activity (3.18  $\mu\text{g/g FW}$ ) was observed in the

F1 treatment. However, this activity decreased as the concentrations of seaweed extract and vermicompost increased, with the lowest activity (2.51  $\mu\text{g/g}$  FW) recorded in the F5 treatment. This value was not significantly different from those in F0 and F2 (Figure 2c).



**Figure 2** Effects of seaweed extract (2 kg/ha) and different doses of vermicompost (0, 7.5, and 15 ton/ha) on the studied variables in cauliflower curds. The data are expressed as the means  $\pm$  SEs ( $n = 3$ ), with different letters indicating significant differences based on Duncan's multiple range test ( $P \leq 0.05$ ).

Statistical analysis revealed significant differences in the mineral content of cauliflower curds treated with seaweed extract and varying doses of vermicompost (Table 2). Compared with those in the other treatments, the nitrogen, phosphorus, and calcium levels were significantly greater in the plants in the F5 treatment (3.12%, 0.97%, and 0.19%, respectively). The lowest nitrogen (2.25%) and phosphorus (0.77%) levels were recorded in the untreated plants (F0), whereas the minimum calcium content (0.12%) was detected in the F0 plants, although these values did not differ significantly from those of the F2, F3, and F4 plants at  $p \leq 0.05$ . In addition, the application of vermicompost at a rate of 7.5 ton/ha (F2) resulted in the highest concentration of K (2.787%). The F5 treatment had the lowest concentration (2.367%). Compared with the control treatment, F0 (without any fertilizer) was used. In terms of iron content, different fertilizer treatments had notable impacts, with F1 (seaweed extract) resulting in the highest iron level (280.6 ppm), which was significantly greater than that of the control (F0) but not substantially different from those of F2 and F3. The lowest iron content (110 ppm) was observed in F0.

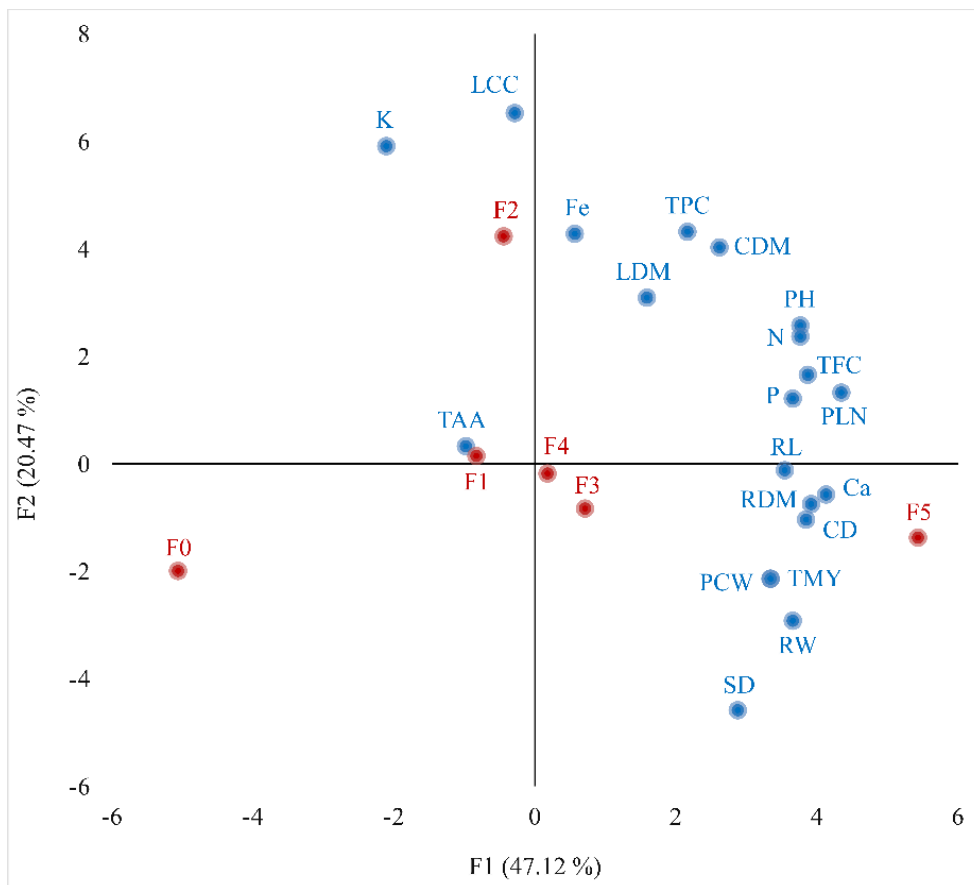
**Table 2** Effects of seaweed extract and vermicompost on element attributes.

Treat	Nitrogen (%)	Phosphorus (%)	Potassium (%)	Calcium %	Fe (ppm)
F0	2.25 $\pm$ 0.07 d	0.77 $\pm$ 0.02 c	2.53 $\pm$ 0.06 ab	0.12 $\pm$ 0.007 b	110.0 $\pm$ 4.62 c
F1	2.86 $\pm$ 0.05 ab	0.88 $\pm$ 0.01 b	2.67 $\pm$ 0.18 ab	0.13 $\pm$ 0.006 b	280.6 $\pm$ 6.98 a
F2	2.80 $\pm$ 0.01 abc	0.87 $\pm$ 0.02 b	2.79 $\pm$ 0.09 a	0.14 $\pm$ 0.003 b	271.6 $\pm$ 2.21 a
F3	2.60 $\pm$ 0.09 bc	0.79 $\pm$ 0.02 c	2.49 $\pm$ 0.03 ab	0.14 $\pm$ 0.006 b	265.3 $\pm$ 7.80 a
F4	2.57 $\pm$ 0.06 c	0.83 $\pm$ 0.02 bc	2.55 $\pm$ 0.07 ab	0.13 $\pm$ 0.003 b	151.0 $\pm$ 4.18 b
F5	3.02 $\pm$ 0.12 a	0.97 $\pm$ 0.03 a	2.37 $\pm$ 0.04 b	0.19 $\pm$ 0.015 a	156.0 $\pm$ 5.12 b

\*Control (F0), seaweed extract 2 kg/ha (F1), vermicompost at 7.5 ton/ha (F2), vermicompost at 15 ton/ha (F3), seaweed extract and vermicompost at 7.5 ton/ha (F4), seaweed extract and vermicompost at 15 ton/ha (F5).

Principal component analysis (PCA) was performed to evaluate the relationships among the variables. The first two principal components, F1 and F2, accounted for 67.59% of the observed variation and were displayed in two dimensions (Figure

3). F1, represented on the horizontal axis, explained the largest proportion of variance at 47.12%, whereas F2, shown on the vertical axis, accounted for approximately 20.47% of the total variation. The PCA results revealed a strong relationship between F5 and most variables, including PH, SD, PLN, LCC, RDM, CD, PCW, TMY, TFC, N, P, and Ca. Additionally, F4 significantly affected LDM, RL, and CDM, whereas F2 influenced TPC and K. F1 demonstrated a strong correlation with TAA and Fe. However, no significant relationships were observed between F0 or F3 and any of the variables.



**Figure 3** A PCA biplot shows the distributions of seaweed extract and varying doses of vermicompost across the analyzed variables: plant height (PH), stem diameter (SD), plant leaf number (PLN), leaf chlorophyll content (LCC), leaf dry matter (LDM), root dry matter (RDM), root length (RL), curd dry matter (CDM), curd diameter (CD), plant curd weight (PCW), total marketable yield (TMY), TPC, TFC, TAA, nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and iron (Fe).

#### 4. Discussion

On the basis of these findings (Table 1), the combination of seaweed extract and varying concentrations of vermicompost, particularly at the highest rates, significantly improved most of the morphological attributes. These results may be attributed to the synergistic effects of both treatments. The beneficial impact of seaweed extract can be attributed to its ability to increase cell membrane permeability, thereby improving the absorption of nutrients, particularly nitrogen, which is closely associated with the leaf chlorophyll concentration (El Boukhari et al., 2020). Seaweed extract also helps delay leaf aging by reducing chlorophyll degradation due to its cytokinin content (Carrasco-Gil et al., 2018). It contributes to soil organic matter and supplies plants with hormones and essential nutrients, all of which play a critical role in plant growth (Khan et al., 2009).

The application of biostimulants resulted in a significant increase in chlorophyll content, likely due to the presence of cytokinins, which promote cell division and stimulate chlorophyll biosynthesis. Additionally, certain biostimulants slow chlorophyll degradation, thereby delaying leaf senescence (Halshoy and Sadik, 2024). As a biostimulant, seaweed extract enhances root system development by increasing root biomass, length, and diameter, which in turn improves nutrient uptake and overall plant health (Di Mola et al., 2019). Seaweed extract modifies soil properties and root architecture, further facilitating efficient nutrient absorption (Battacharyya et al., 2015). On the other hand, vermicompost is rich in readily available minerals, stimulating plant growth (Sinha et al., 2010). It improves soil structure, porosity, and water-holding capacity (Jahan et al., 2014) and promotes soil microbial populations that increase nutrient availability and plant hormone production, further enhancing plant health (Yassen et al., 2019). The superior performance of the combined application of seaweed extract and vermicompost may be due to the high content of enzymes, such as protease, peroxidase, and amylase, in the vermicompost. These enzymes increase the activity of soil microorganisms, breaking down organic matter and making nutrients more



accessible to plants (Bottinelli et al., 2010). Additionally, humic acids from vermicompost stimulate root elongation and the formation of lateral roots and root hairs (Canellas and Olivares, 2014).

Compared with the control treatment, the application of seaweed extract and vermicompost, either individually or in combination, significantly increased the cauliflower yield (Figure 1). The positive effects of biostimulants on yield can be attributed to their rich content of macro- and micronutrients, as well as their ability to stimulate plant growth, such as auxins, gibberellins, polysaccharides, and amino acids (Halshoy et al., 2023). Seaweed extracts, in particular, contain these components, which promote growth, increase productivity, and enhance nutrient absorption while also improving resistance to environmental stress, extending postharvest shelf-life, and reducing fungal and insect infestations (Bulgari et al., 2019; Priyadarshini and Madhanakumari, 2021). Seaweed extract contains beneficial substances such as polyphenols, polyamines, pigments, and vitamins (Stirk et al., 2014; Attallah et al., 2021). By improving water and nutrient absorption and enhancing photosynthesis efficiency, seaweed extracts support strong vegetative growth and contribute to increased curd weight (Ali et al., 2021). The presence of cytokinins in algae extracts further stimulates chlorophyll production, increasing photosynthesis and leading to increased yields (Yassen et al., 2019; Kakbra et al., 2023). Vermicompost, on the other hand, serves as an excellent nutrient source, providing growth regulators, beneficial microorganisms, and essential elements that enhance cauliflower growth, particularly curd production (Islam et al., 2021). The increased curd weight and total yield of cauliflower under vermicompost can be attributed to improved nutrient availability, carbohydrate synthesis, vegetative growth, and efficient nutrient partitioning and translocation (Jahan et al., 2014).

The biochemical composition of the cauliflower curds was positively influenced by the seaweed extract and vermicompost (Figure 2 and Table 2). Notably, there was a significant increase in the total phenolic content, total flavonoid content, and antioxidant activity. This can be attributed to the plant hormone activities induced by seaweed application (Ghaderiardakani et al., 2019). The enhancement of metabolic pathways, including nitrogen metabolism and antioxidative capacity, by seaweed extracts leads to increased levels of total soluble protein and antioxidant content (Fan et al., 2013). The humic and fulvic acids of vermicompost also contribute to the synthesis of phenolic compounds and flavonoids, which are precursors of endogenous plant phenolics (Luján-Hidalgo et al., 2017).

Additionally, the combined use of seaweed extract and vermicompost significantly increased the nitrogen, phosphorus, calcium, and iron contents in cauliflower plants (Table 2). This effect can be explained by the ability of both treatments to increase soil organic matter, improve water retention, and provide essential nutrients for plant growth. Seaweed extracts contain polyuronides such as alginates and fucoidans, with alginic acid conditioning the soil and chelating metal ions, thus benefiting nutrient uptake (Battacharyya et al., 2015). The large organic molecules in seaweed extracts also chelate micronutrients, increasing their availability to plants and enhancing nutrient uptake efficiency (Halpern et al., 2015). Vermicompost is rich in macro- and microelements that are gradually released to plants, promoting sustained growth and development (Ebrahimi et al., 2021). Its application also increases the population of beneficial soil microorganisms, which increases the production of essential nutrients such as nitrogen, phosphorus, magnesium, and potassium, which are crucial for plant growth (Namazi et al., 2015). The humic acids in vermicompost improve soil physical conditions and stimulate soil microflora growth, solubilizing minerals and increasing the availability of nutrients to plants throughout their growth period (Lim et al., 2015). The integrated use of seaweed extract and vermicompost enhances plant growth, yield, and biochemical properties in cauliflower by improving nutrient availability, stimulating root development, and supporting physiological processes that lead to greater productivity and resilience.

## 5. Conclusions

The experimental results clearly demonstrated that the application of seaweed extract and vermicompost, both individually and in combination, significantly enhanced the growth and productivity of cauliflower plants, with the control plants showing the lowest performance. On the basis of these findings, the application of F5 (seaweed extract at 2 kg/ha and vermicompost at 15 tons/ha) to improve the morphological traits, yield, and curd quality of cauliflower is recommended. The long-term benefits of using seaweed extract and vermicompost as organic fertilizers could help mitigate the negative effects of chemical inputs and reduce the cost of mineral fertilizers. Additionally, further research across different crops is needed to explore the potential of these organic amendments fully.

### Ethical considerations

Not applicable.

### Conflict of Interest

The author(s) declare no conflicts of interest.

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