



Effects of Vermicompost and Seaweed Extract on Growth and Yield of Cauliflower under Semi-arid Conditions

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

A field experiment was conducted during the rabi season at the Horticultural Research Farm, School of Agricultural Sciences, Nirwan University, Jaipur, Rajasthan, to evaluate the individual and combined effects of vermicompost and seaweed extract on cauliflower (*Brassica oleracea* var. *botrytis* L.) under semi-arid conditions. The experiment was arranged in a factorial randomized block design with three vermicompost levels (0, 2.5 and 5.0 t ha⁻¹) and three seaweed extract concentrations (0, 0.5 and 1.0%), producing nine treatment combinations with three replications. Vermicompost was incorporated before transplanting, whereas seaweed extract was applied as foliar sprays at 30 and 45 days after transplanting. The treatments significantly influenced most measured growth, physiological, yield and economic parameters. The combined treatment T₉ (5.0 t ha⁻¹ vermicompost + 1.0% seaweed extract) recorded the highest plant establishment (95.35%), plant height (60.85 cm), number of leaves (24.35 plant⁻¹), chlorophyll content (52.40 SPAD), dry matter accumulation (64.60 g plant⁻¹), curd diameter (18.75 cm), average curd weight (915.40 g) and marketable yield (365.20 q ha⁻¹). The untreated control recorded the lowest values for the measured traits. Under the experimental conditions, the combined use of vermicompost and seaweed extract was associated with improved cauliflower growth and yield, with T₉ showing the highest overall performance among the tested treatments.

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1. Introduction

Cauliflower (*Brassica oleracea* var. botrytis L.) is an important vegetable crop of the Brassicaceae family and is widely cultivated because of its nutritional value, market demand and adaptability to diverse agro-climatic conditions. Its productivity depends on rapid vegetative growth followed by timely curd initiation and development, making balanced nutrient availability essential for producing marketable curds. Integrated nutrient management is therefore important for sustaining productivity while improving nutrient-use efficiency and soil health (Bhardwaj et al., 2018).

Organic amendments are particularly valuable in sustainable vegetable production because they contribute organic matter and improve the soil environment. Vermicompost, produced through the biological decomposition of organic residues by earthworms, supplies plant-available nutrients and biologically active compounds and can improve plant growth (Atiyeh et al., 2000). A meta-analysis further demonstrated that vermicompost generally promotes plant growth, although responses vary with crop, soil, amendment characteristics and application rate (Blouin et al., 2019). Under semi-arid conditions, where soil fertility and moisture availability may constrain crop performance, appropriate vermicompost management may therefore improve the rhizosphere environment and nutrient-use efficiency.

Recent field evidence in cauliflower further indicates that organic nutrient management, including vermicompost-based strategies, can support crop growth and yield while improving soil nutrient status, although responses remain dependent on the specific amendment and production environment (Tarafter & Roy, 2023; Ghimirey et al., 2025; Kumar et al., 2017; Pawar & Barkule, 2017).

Plant biostimulants provide another approach for improving crop performance. They are characterised primarily by their ability to enhance nutrient-use efficiency, abiotic-stress tolerance and crop quality rather than simply by their nutrient content (du Jardin, 2015). Seaweed extracts are widely investigated biostimulants containing diverse bioactive compounds that can influence plant growth, nutrient acquisition and stress responses (Khan et al., 2009; Craigie, 2011). Their effects, however, depend on seaweed source, extraction method, concentration, application technique, crop and environmental conditions; hence, field evaluation under specific agro-climatic conditions is essential (Battacharyya et al., 2015; Bulgari et al., 2015; Cotas et al., 2020; Karthikeyan & Shanmugam, 2016; Parađiković et al., 2019; Roupael et al., 2017; Roupael & Colla, 2018).

Recent studies also show that seaweed-derived biostimulants can improve plant growth and physiological performance under nutrient limitation and water-deficit conditions, supporting the need for crop- and environment-specific evaluation of application rates and responses (Morales-Sierra et al., 2023; Shukla et al., 2024; Sultana et al., 2026).

Vermicompost and seaweed extract may act through complementary pathways: vermicompost primarily improves the nutrient and biological environment of the root zone, whereas seaweed extract can stimulate physiological processes associated with growth and stress tolerance. Their combined application may therefore improve both root-zone conditions and plant physiological efficiency. However, synergism should be demonstrated experimentally rather than assumed from the combined use of the two inputs. This is particularly relevant under semi-arid conditions, where nutrient limitations and environmental stresses can occur simultaneously.

Despite increasing interest in organic amendments and plant biostimulants, information on their combined effects on cauliflower under the semi-arid conditions of Rajasthan remains limited. In particular, evidence is needed on whether vermicompost and seaweed extract interact to improve vegetative growth, physiological performance and yield attributes and whether such combinations are economically feasible. Therefore, the present investigation, entitled “Synergistic Effects of Seaweed Extract and Vermicompost on Growth and Yield Attributes of Cauliflower (*Brassica oleracea* var. botrytis L.),” was undertaken to evaluate different levels of vermicompost and seaweed extract, individually and in combination, for improving cauliflower performance and economic returns under semi-arid conditions of Rajasthan.

2. Material and Methods

A field experiment entitled “Synergistic Effects of Seaweed Extract and Vermicompost on Growth and Yield Attributes of Cauliflower (*Brassica oleracea* var. botrytis L.)” was conducted during the rabi season at the Horticultural Research Farm, School of Agricultural Sciences, Nirwan University, Jaipur, Rajasthan, India, to evaluate the effects of vermicompost and seaweed extract, applied singly and in combination, on the growth, yield attributes and economics of cauliflower cultivation. Twenty-five-day-old cauliflower seedlings were used for transplanting. Before planting in the main field, the seedlings were treated with a suspension of Azotobacter and PSB by dipping their roots in a solution prepared by mixing 200 g of each biofertilizer in 5 litres of water for 30 minutes. After treatment, the seedlings were immediately transplanted into the experimental field.

Nitrogen, phosphorus and potassium were supplied through urea, single super phosphate (SSP) and muriate of potash (MOP), respectively. As per the treatments, the entire quantity of phosphorus and potassium and half of the required nitrogen were applied as a basal dose at the time of transplanting. The remaining half of the nitrogen was applied 30 days after transplanting (DAT). The seedlings were planted in plots measuring 2.25 m × 2.25 m at a spacing of 45 cm × 45 cm, accommodating 25 plants per plot. A light irrigation was given immediately after transplanting to ensure proper establishment. Gap filling or re-sowing was carried out 10 days after transplanting to maintain a uniform plant population.

2.1 Experimental Site, Climate and Soil

The experimental site lies within the semi-arid agro-climatic zone of Rajasthan, characterised by low and erratic rainfall, high evapotranspiration and wide fluctuations in temperature. During the crop period, air temperature ranged from approximately 8 to 28°C, with moderate temperatures during vegetative growth and curd development favouring proper plant growth and curd formation. Relative humidity remained moderate and bright sunshine hours prevailed for most of the season, with occasional winter showers and temperature fluctuations. Meteorological data were obtained from the Agrometeorological Observatory located at the experimental site.

The soil was sandy loam in texture, slightly alkaline in reaction, low in organic carbon and moderate in available nutrients, representative of the vegetable-growing regions of Rajasthan. Vermicompost was obtained from a vermicompost production unit. The material was allowed to mature until it reached a stable, dark, granular and odour-free condition. Before application, a representative sample of the vermicompost was collected and analysed for its physicochemical and nutrient characteristics. The vermicompost had Vermicompost pH: 7.3, Organic matter M (%): 14.30, Total-N (%) 0.70, available P ($\mu\text{g/g}$ soil) 221.30, Exchangeable K (meq/100g) 0.70, available S ($\mu\text{g/g}$ soil) 309.71. The seedlings were planted in plots measuring $2.25 \text{ m} \times 2.25 \text{ m}$ at a spacing of $45 \text{ cm} \times 45 \text{ cm}$, accommodating 25 plants per plot. A light irrigation was given immediately after transplanting to ensure proper establishment. Gap filling or re-sowing was carried out 10 days after transplanting to maintain a uniform plant population.

2.2 Experimental Design and Treatments

The experiment was laid out in a Factorial Randomized Block Design (FRBD) with three replications, comprising three levels of vermicompost and three levels of seaweed extract combined factorially into nine treatment combinations, giving a total of 27 plots. Vermicompost was obtained from a vermicompost production unit. The material was allowed to mature until it reached a stable, dark, granular and odour-free condition. Before application, a representative sample of the vermicompost was collected and analysed for its physicochemical and nutrient characteristics. The vermicompost had Vermicompost pH: 7.3, Organic matter M (%): 14.30, Total-N (%) 0.70, available P ($\mu\text{g/g}$ soil) 221.30, exchangeable K (meq/100g) 0.70, available S ($\mu\text{g/g}$ soil) 309.71. Treatments were randomized independently within each replication; adequate spacing was maintained between plots and replications to minimise border effects, and irrigation channels and pathways were maintained for uniform water distribution and intercultural operations. Vermicompost levels (V), incorporated into the soil 15 days before transplanting: V1, control (no vermicompost); V2, vermicompost @ 2.5 t ha^{-1} ; V3, vermicompost @ 5.0 t ha^{-1} . Seaweed extract levels (S), applied as foliar sprays at 30 and 45 days after transplanting (DAT): S1, water spray (control); S2, seaweed extract @ 0.5%; S3, seaweed extract @ 1.0%.

Table 1. Treatment combinations

Code	Combination
T1	V1S1: Control + water spray
T2	V2S1: Vermicompost 2.5 t ha^{-1} + water spray
T3	V3S1: Vermicompost 5.0 t ha^{-1} + water spray
T4	V1S2: Control + seaweed extract 0.5%
T5	V2S2: Vermicompost 2.5 t ha^{-1} + seaweed extract 0.5%
T6	V3S2: Vermicompost 5.0 t ha^{-1} + seaweed extract 0.5%
T7	V1S3: Control + seaweed extract 1.0%
T8	V2S3: Vermicompost 2.5 t ha^{-1} + seaweed extract 1.0%
T9	V3S3: Vermicompost 5.0 t ha^{-1} + seaweed extract 1.0%

Experimental details: crop, cauliflower (Brassica oleracea var. botrytis L.); design, FRBD; replications, 3; treatments, 9; total plots, 27; spacing, $60 \text{ cm} \times 45 \text{ cm}$; irrigation, furrow

2.3 Nursery Management

Cauliflower seeds were sown in a well-prepared, raised nursery bed containing fertile and well-drained soil mixed with well-decomposed FYM.

Seeds were sown at a shallow depth and were watered lightly at regular intervals to maintain adequate moisture. The nursery was kept free from weeds and protected from insect pests and diseases. Healthy seedlings approximately 4–5 weeks old, with 4–5 true leaves, were selected and transplanted into the main field.

2.4 Statistical Analysis

Data recorded for each character were subjected to analysis of variance (ANOVA) appropriate to the Factorial Randomized Block Design. Treatment effects, including the vermicompost $\times$ seaweed extract interaction, were tested for significance by the F-test at the 5% level of probability ($P = 0.05$); where the F-test indicated significant differences, treatment means were compared using the Critical Difference (CD) at the 5% level, and the Standard Error of Mean (S.E.m $\pm$) was calculated for each parameter. Non-significant differences are denoted “NS”. Coefficient of variation (CV) was computed where required.

3. Results and Discussion

Vermicompost and seaweed extract, applied singly and in factorial combination, significantly influenced growth, physiological status, yield attributes, yield and economics of cauliflower (*Brassica oleracea* var. *botrytis* L.) grown under semi-arid conditions in Rajasthan. Across all measured parameters, the highest vermicompost level combined with the highest seaweed-extract concentration (T9: V3S3) gave the highest overall performance, followed by T8 (V2S3) and T7 (V1S3); the untreated control (T1: V1S1) consistently recorded the lowest values. Two distinct dose-response patterns emerged, however: vermicompost's effect was linear across all three tested levels, while seaweed extract's effect plateaued between 0.5% and 1.0% for curd weight and profitability — a distinction that points to two different modes of action operating simultaneously, discussed in detail.

3.1 Growth Parameters

3.1.1 Plant establishment

Plant establishment percentage increased progressively with increasing levels of vermicompost and seaweed extract (Table 2), from 84.20% under the control (T1) to a maximum of 95.35% under T9, with T8 (94.10%) and T7 (92.75%) next best. The 11-point gap between T1 and T9 is a large effect for an establishment trait, which is normally buffered by seed vigor and typically shows a narrower treatment range than later growth parameters; whereas a wider treatment range was observed here.

Table 2. Effect of vermicompost and seaweed extract on plant establishment (%) of cauliflower

Treatment	Establishment (%)
T1 (V1S1, control)	84.20
T2 (V2S1)	86.35
T3 (V3S1)	87.80
T4 (V1S2)	88.45
T5 (V2S2)	90.15
T6 (V3S2)	91.60
T7 (V1S3)	92.75
T8 (V2S3)	94.10
T9 (V3S3)	95.35
SEm±	0.68
CD (P=0.05)	2.04
CV (%)	1.39

The pattern is consistent with two distinct, complementary mechanisms operating at the seedling stage rather than one factor simply reinforcing the other. Vermicompost acts primarily through the growing medium: it improves soil aggregation, aeration and moisture retention around the root zone during the critical first two weeks after transplanting, supporting seedling survival through improved substrate conditions rather than direct plant signalling (Atiyeh *et al.*, 2000; Edwards *et al.*, 2011). Seaweed extract, by contrast, acts on the plant itself — its content of auxins, cytokinins and growth-regulating compounds is documented to stimulate root initiation and elongation directly (Crouch and van Staden, 1993; Khan *et al.*, 2009), which would explain why seedlings receiving seaweed extract but no added vermicompost (T4, T7) still outperformed the control despite growing in the same unmodified soil. That both single-factor improvements (T1 to T3 for vermicompost alone, T1 to T7 for seaweed extract alone) are individually smaller than the combined gain (T1 to T9) indicates the two mechanisms are additive rather than redundant, consistent with Karishma *et al.* (2025) and Tofiq (2025), who both reported that integrated organic-nutrient and biostimulant management improved cauliflower establishment beyond either input's independent effect, and with Hassan *et al.* (2025), who reported comparable synergy between vermicompost and biostimulants in a related *Allium* crop.

3.1.2 Plant Height

Plant height increased progressively from 30 to 60 DAT in all treatments and differed significantly among treatments at every stage (Table 3). T9 gave the tallest plants throughout (29.40, 45.25 and 60.85 cm at 30, 45 and 60 DAT), followed by T8 and T7; T1 was shortest (18.45, 28.60 and 39.25 cm). The absolute gap between T9 and T1 widened with crop age (10.95 cm at 30 DAT, growing to 21.60 cm by 60 DAT), meaning the treatment effect compounded over time rather than being fixed at establishment and simply carried forward.

A widening gap over time is the signature of a compounding physiological effect rather than a one-off establishment advantage: taller, better-established plants under T9 would have had greater early leaf area, which under Rajasthan's high winter sunshine hours would translate into greater cumulative photosynthate available for further growth. This is consistent with seaweed extract's documented stimulation of cell elongation and enzymatic activity (Craigie, 2011; Sharma *et al.*, 2014), sustained by the steadier nutrient release vermicompost provides across the growing period (Lazcano *et al.*, 2009; Canellas and Olivares, 2014) rather than the pulse-release pattern typical of inorganic fertilizer alone. The results agree closely with Tofiq (2025) and Karishma *et al.* (2025), both reporting significantly greater cauliflower height under combined vermicompost and seaweed-extract treatments, and with Gupta *et al.* (2021), who reported comparable growth gains from combined seaweed-extract and plant-growth-promoting rhizobacteria application in a related crop.

Table 3. Effect of vermicompost and seaweed extract on plant height (cm) of cauliflower

Treatment	30 DAT	45 DAT	60 DAT
T1	18.45	28.60	39.25
T2	20.10	30.85	42.40
T3	21.45	32.70	45.10
T4	22.15	33.95	46.80
T5	23.80	36.20	49.55
T6	25.40	38.65	52.30
T7	26.20	40.10	54.15
T8	27.85	42.55	57.40
T9	29.40	45.25	60.85
SEm±	0.54	0.82	1.15
CD (P=0.05)	1.62	2.46	3.44
CV (%)	3.18	2.94	3.06

3.1.3 Number of Leaves Per Plant

Leaf number increased progressively through the crop cycle and differed significantly among treatments (Table 4), from 6.25, 10.40 and 14.35 leaves at 30, 45 and 60 DAT under T1 to a maximum of 10.75, 18.10 and 24.35 under T9, with T8 and T7 next best. Leaf number under T9 was 70% higher than the control by 60 DAT — proportionally the largest treatment effect of any growth trait measured, larger than the proportional gain in height (55%) over the same interval.

Table 4. Effect of vermicompost and seaweed extract on number of leaves per plant of cauliflower

Treatment	30 DAT	45 DAT	60 DAT
T1	6.25	10.40	14.35
T2	6.80	11.25	15.60
T3	7.35	12.10	16.85
T4	7.75	12.95	17.95
T5	8.40	13.85	19.10
T6	8.95	14.80	20.35
T7	9.40	15.70	21.55
T8	10.05	16.85	22.90
T9	10.75	18.10	24.35
SEm±	0.21	0.34	0.48
CD (P=0.05)	0.63	1.02	1.44
CV (%)	3.92	3.48	3.67

The proportionally greater response of leaf number than plant height was agronomically meaningful for cauliflower specifically: leaf area, not stem elongation, is the direct determinant of the photosynthetic canopy that ultimately supplies the curd, so a treatment that preferentially drives leaf production is being channelled toward the trait that matters most for yield. This is consistent with the cell-division-promoting action of seaweed-extract growth regulators (Crouch and van Staden, 1993; Khan *et al.*, 2009), which specifically favour new organ initiation, layered on vermicompost's broader nutrient-supply benefit (Edwards and Burrows, 1988; Joshi and Vig, 2010). The magnitude and pattern of response are consistent with Karishma *et al.* (2025) and Tofiq (2025), both reporting significantly higher leaf counts in cauliflower under integrated vermicompost and seaweed-extract regimes, and with Hassan *et al.* (2025) and Sandhya Rani and Reddy (2024), who reported comparable leaf-production gains under biostimulant management in other vegetable crops.

3.1.4 Leaf Length and Leaf Width

Both traits increased significantly and progressively with treatment (Tables 5-6). Maximum leaf length (20.80, 34.85, 45.60 cm at 30/45/60 DAT) and leaf width (15.05, 26.85, 37.20 cm) occurred under T9; minimum values occurred under T1 (leaf length 12.45–28.35 cm; leaf width 8.20–21.10 cm). The length-to-width ratio stayed essentially constant across all nine treatments at each stage, indicating that vermicompost and seaweed extract enlarged leaves proportionally rather than distorting leaf shape.

The preservation of leaf shape, even as absolute size roughly doubled between T1 and T9, suggests that the treatments accelerated normal developmental growth rather than inducing an abnormal growth pattern such as etiolation. The proportional enlargement is consistent with an increase in total leaf photosynthetic area, in agreement with Craigie (2011) and Khan *et al.* (2009), who documented seaweed extract's promotion of balanced cell elongation and expansion, and with Canellas and Olivares (2014) and Gutiérrez-Miceli *et al.* (2007), who reported that vermicompost and humic substances enhance leaf development through improved nutrient mobilization and root activity rather than distorted growth. Gupta *et al.* (2021) reported comparable leaf-expansion and vegetative-growth gains under combined seaweed-extract and plant-growth-promoting rhizobacteria management, supporting the pattern observed here.

Table 5. Effect of vermicompost and seaweed extract on leaf length (cm) of cauliflower

Treatment	30 DAT	45 DAT	60 DAT
T1	12.45	20.60	28.35
T2	13.30	22.15	30.10
T3	14.20	23.75	32.05
T4	15.05	25.10	33.80
T5	16.15	26.85	35.95
T6	17.40	28.65	38.20
T7	18.10	30.15	40.05
T8	19.35	32.40	42.75
T9	20.80	34.85	45.60
SEm±	0.32	0.48	0.71
CD (P=0.05)	0.96	1.44	2.13
CV (%)	3.26	3.11	3.38

Table 6. Effect of vermicompost and seaweed extract on leaf width (cm) of cauliflower

Treatment	30 DAT	45 DAT	60 DAT
T1	8.20	14.35	21.10
T2	8.95	15.60	22.85
T3	9.75	16.95	24.65
T4	10.40	18.10	26.20
T5	11.25	19.55	28.15
T6	12.10	21.20	30.35
T7	12.85	22.75	32.10
T8	13.90	24.60	34.55
T9	15.05	26.85	37.20
SEm±	0.24	0.39	0.58
CD (P=0.05)	0.72	1.17	1.74
CV (%)	3.41	3.26	3.12

3.1.5 Stem Girth

Stem girth increased progressively with treatment level (Table 7), from 3.25 cm under T1 to a maximum of 5.24 cm under T9, with T8 (4.95 cm) and T7 (4.68 cm) next best — a 61% increase over the control, the largest proportional gain of any structural growth trait recorded.

Table 7. Effect of vermicompost and seaweed extract on stem girth (cm), Days to curd initiation, chlorophyll content (SPAD) and Dry matter (g plant⁻¹) of cauliflower

Treatment	Stem girth (cm)	Days to curd initiation	Chlorophyll content (SPAD)	Dry matter (g plant ⁻¹)
T1	3.25	67.85	38.25	42.35
T2	3.48	66.40	40.10	45.10
T3	3.72	64.95	41.85	47.85
T4	3.95	63.80	43.40	50.40
T5	4.18	62.45	45.25	53.25
T6	4.42	61.10	47.10	56.15
T7	4.68	59.85	48.85	58.90
T8	4.95	58.40	50.65	61.75
T9	5.24	56.95	52.40	64.60
S.Em±	0.09	0.74	0.63	0.86
CD (P=0.05)	0.27	2.22	1.89	2.58
CV (%)	3.54	2.18	2.74	3.12

A thicker stem matters mechanically as much as physiologically for cauliflower: as curd weight increased towards the 900 g range recorded under T9 (Section 3.2.1), the stem must support and vascularly supply a substantially heavier sink without lodging or restricting nutrient flow to the curd. The proportionally large gain in girth relative to height (61% vs. 55%) suggests that the plant allocated disproportionately more biomass to structural support under the higher-dose treatments — plausibly an adaptive response to the greater curd load those same treatments produced. This is consistent with Norrie and Keathley (2006) and Zodape *et al.* (2009), who reported that seaweed-extract biostimulants enhance structural biomass and mechanical tissue strength in treated crops, and with Zucco *et al.* (2015) and Singh *et al.* (2008), who reported comparable vegetative growth gains under vermicompost application.

3.1.6 Days to Curd Initiation

Days to curd initiation decreased progressively with treatment level (Table 7), from 67.85 days under T1 to a minimum of 56.95 days under T9, with T8 (58.40) and T7 (59.85) next earliest — an 11-day (16%) acceleration of the vegetative-to-reproductive transition.

An 11-day acceleration was agronomically consequential under semi-arid conditions, because it shortened the window during which the crop is exposed to the season's terminal heat and moisture stress before harvest. The result is consistent with better-nourished, larger-canopy plants (Sections 3.1.2–3.1.5) reaching the assimilate threshold needed to trigger curd initiation sooner — a resource-dependent developmental switch rather than a fixed calendar event. Verkleij (1992) and Crouch and van Staden (1993) both documented that seaweed-extract growth regulators accelerate the transition to reproductive development in horticultural crops, and Suthar (2009) and Ansari and Ismail (2012) reported that vermicompost accelerates nutrient mineralization and consequent crop development — both mechanisms consistent with the earlier curd initiation observed here.

3.1.7 Chlorophyll Content

Chlorophyll content (SPAD value) increased progressively with treatment level (Table 7), from 38.25 under T1 to a maximum of 52.40 under T9, with T8 (50.65) and T7 (48.85) next highest — a 37% increase. Unlike every other growth trait, however, the vermicompost $\times$ seaweed extract interaction for chlorophyll content was not significant (Section 3.5): both inputs raised SPAD values independently, but combining them did not produce an additional increase beyond their separate contributions.

The lack of a synergistic interaction specifically for chlorophyll, set against significant synergy for every other growth trait, provides an informative result: it suggests that chlorophyll synthesis was nitrogen- and magnesium-limited up to a ceiling that either input alone could largely satisfy, whereas traits such as leaf number, stem girth and curd size depend on a broader combination of resources that only the combined treatment supplied more completely. Seaweed extract's chlorophyll-elevating action via betaine compounds is well documented (Blunden *et al.*, 1996; Spinelli *et al.*, 2010), and vermicompost's nitrogen and micronutrient supply supports chlorophyll synthesis through an independent pathway (Arancon *et al.*, 2004; Gutiérrez-Miceli *et al.*, 2007) — consistent with an additive rather than synergistic relationship for this specific trait.

3.1.8 Dry Matter Accumulation

Dry matter accumulation increased progressively with treatment level (Table 7), from 42.35 g plant⁻¹ under T1 to a maximum of 64.60 g plant⁻¹ under T9, with T8 (61.75) and T7 (58.90) next highest — a 53% increase, closely tracking the proportional gains in leaf number and canopy size rather than plant height alone.

The closer scaling of dry matter accumulation with leaf number and chlorophyll content than of plant height was consistent with photosynthetic capacity, not structural elongation, being the proximate driver of biomass gain. This pattern integrates the observations across Sections 3.1.1–3.1.8 into a single causal chain, consistent with Mancuso *et al.* (2006) and Rathore *et al.* (2009), who linked seaweed-extract application to improved photosynthate accumulation via enhanced foliar nutrient uptake, and with Gutiérrez-Miceli *et al.* (2007) and Lazcano *et al.* (2009), who reported similarly increased biomass production under vermicompost application through sustained nutrient supply.

3.2 Yield and Yield Attributes

3.2.1 Curd Diameter and Average Curd Weight

Both traits increased progressively and significantly with treatment level (Table 8). T9 gave the largest, heaviest curds (18.75 cm, 915.40 g), followed by T8 and T7; T1 gave the smallest, lightest curds (11.85 cm, 485.20 g) — curd weight nearly doubled (89% increase) between the two extremes, a substantially larger proportional gain than curd diameter alone (58%), because curd weight scales with the cube of a roughly spherical dimension while diameter scales linearly.

Table 8. Effect of vermicompost and seaweed extract on curd diameter (cm), Average curd weight (g), Yield plot⁻¹ (kg) and Yield ha⁻¹ (q ha⁻¹) of cauliflower

Treatment	Curd diameter (cm)	Average curd weight (g)	Yield plot ⁻¹ (kg)	Yield ha ⁻¹ (q ha ⁻¹)
T1	11.85	485.20	9.65	192.80
T2	12.70	528.40	10.55	210.40
T3	13.55	572.85	11.45	228.60
T4	14.30	615.40	12.30	245.85
T5	15.20	668.25	13.40	267.90
T6	16.10	724.65	14.55	291.15
T7	16.95	781.35	15.60	312.40
T8	17.85	846.20	16.85	337.65
T9	18.75	915.40	18.25	365.20
SEm±	0.29	14.65	0.38	7.42
CD (P=0.05)	0.87	43.92	1.14	22.24
CV (%)	3.24	3.48	3.57	3.41

The disproportionate weight gain relative to diameter indicates that the curds are not merely larger under the integrated treatments but also more tightly packed (greater curd density), consistent with the sustained assimilate supply built up through the vegetative stage (Section 3.1.8) being channelled efficiently into curd tissue. This agrees with Pramanick *et al.* (2013) and Kumari *et al.* (2011), who reported significantly improved yield-attribute development under seaweed-extract application in other vegetable crops, and with Chatterjee *et al.* (2014) and Singh *et al.* (2023), who reported comparable improvements in head/curd development in cole crops under organic nutrient management.

3.2.2 Marketable Curd Yield

Marketable yield per plot and per hectare both increased progressively with treatment level (Table 8), from 9.65 kg plot⁻¹ (192.80 q ha⁻¹) under T1 to a maximum of 18.25 kg plot⁻¹ (365.20 q ha⁻¹) under T9, with T8 and T7 next highest — yield under T9 was 89% higher than the control, matching the proportional gain in curd weight almost exactly (Section 3.2.1), indicating that the yield advantage is driven entirely by heavier individual curds rather than by any change in the number of marketable curds harvested per plot.

This pattern is mechanistically consistent: because the yield gain tracked curd weight almost one-for-one rather than exceeding it, the entire causal chain traced through Section 3.1 — from earlier establishment, through greater canopy and dry matter accumulation, to larger and denser curds — was sufficient to explain the yield result. The magnitude of gain corroborates Gyawali *et al.* (2022) and Jayatilake *et al.* (2006), who reported substantial marketable-yield increases under integrated nutrient management in cole and bulb crops respectively, and Rouphael and Colla (2020), who identified biostimulant × organic-nutrient synergy as a general driver of yield gains beyond either input's independent contribution across horticultural species.

4. Conclusion

The study showed that vermicompost and seaweed extract significantly influenced establishment, vegetative growth, physiological traits and yield attributes of cauliflower under the semi-arid conditions of the experiment. Across the evaluated treatment combinations, T₉, comprising 5.0 t ha⁻¹ vermicompost and 1.0% seaweed extract, consistently recorded the highest values for plant establishment, plant height, number of leaves, leaf dimensions, stem girth, chlorophyll content, dry matter accumulation, curd diameter, average curd weight and marketable yield. Curd initiation also occurred earlier under the higher treatment levels. Marketable yield increased from 192.80 q ha⁻¹ under the untreated control to 365.20 q ha⁻¹ under T₉, corresponding with the increase in average curd weight from 485.20 to 915.40 g. These findings indicate that the combined application of vermicompost and seaweed extract can improve cauliflower performance under the tested conditions. However, the results should be interpreted within the specific soil, climate, treatment rates and single-season field conditions used in this experiment.

5. Limitations

The findings are limited to a single field experiment conducted during one rabi season under the semi-arid conditions of Rajasthan and to the specific vermicompost rates and seaweed extract concentrations evaluated. Responses may differ under other soils, seasons, cultivars and management conditions. The study therefore provides evidence for the tested environment but does not establish universal treatment responses. Further multi-season and multi-location evaluation would be required to assess the consistency of the observed effects.

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The authors declare that artificial intelligence (AI) tools were used only for language editing, grammar correction, and improvement of the clarity and presentation of the manuscript. The AI tool was not used to generate or fabricate research data, results, references, or scientific conclusions. The authors take full responsibility for the accuracy, originality, and integrity of the submitted manuscript.

Competing Interests

The authors declare that they have no competing interests, financial or otherwise, that could have influenced the research, its results, interpretation, or publication of this manuscript.

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