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Research Article

Role of vermicompost and biostimulants in enhancing garlic growth, bulb yield, and quality parameters

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Abstract

Organic fertilizers and biostimulants have been widely studied in vegetable crops, but evidence on their individual and combined effects on growth and quality remains limited. Therefore, this study assessed the effectiveness and synergistic potential of selected organic amendments and biostimulants in improving garlic growth, nutrient composition, allicin content, and total yield. Across two growing seasons, garlic plants received the followed treatment: 1) seaweed extract (SW), 2) garlic extract (GE), 3) yeast extract (YE), 4) vermicompost (VC), biochar, and their combinations. Growth traits, nutrient concentrations, allicin content, bulb characteristics, and yield components were measured and compared with an untreated control. All treatments significantly enhanced plant height, leaf number, and leaf area. The co-application of GE + SW along with vermicompost and biochare produced the highest growth performance and nutrient accumulation. Furthermore, this treatment also markedly increased allicin content, improving bulb quality, and resulted in the greatest bulb weight and total yield. Overall, combining organic fertilizers with biostimulants provides a sustainable strategy to enhance garlic productivity and quality while reducing dependence on synthetic inputs. The study recommends the integrated use of GE + SW with vermicompost and biochar as an effective nutrient management approach.

Keywords: allicin; *Allium sativum*; bioextracts; bulb quality; morphological properties; nutrient content; organic amendments; sustainable agriculture

Introduction

Garlic (*Allium sativum* L.) is a globally important horticultural crop valued for its culinary, medicinal, and economic significance (Kenea *et al*., 2024). Its productivity is strongly influenced by soil fertility, nutrient

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availability, and plant physiological status - factors that can be improved through sustainable soil amendments and foliar biostimulants (Hassan *et al*., 2024). Growing interest in environmentally friendly alternatives to mineral fertilizers has highlighted the potential of organic amendments and natural biostimulants such as yeast extracts, vermicompost, and seaweed-based products (Fajdetić *et al*., 2025). These inputs enhance soil properties, supply nutrients, and activate plant metabolic pathways that ultimately improve garlic growth, yield, and bulb quality (Yakob *et al*., 2024).

Biostimulants encompass a wide group of substances and microorganisms that enhance nutrient-use efficiency, abiotic stress tolerance, and crop quality independent of their nutrient content (Di Sario *et al*., 2025). Among the most widely studied biostimulants are seaweed extracts and yeast-derived products. Seaweed extracts - typically derived from *Ascophyllum, Ecklonia, or Sargassum* species - contain betaines, polysaccharides, phytohormone-like compounds, amino acids, and micronutrients that function as signaling molecules (Jurado-Flores *et al*., 2025). These components stimulate root and shoot development, enhance photosynthesis, and strengthen antioxidant capacity (Gatti *et al*., 2025). Several studies report improvements in vegetative growth, nutrient uptake, and yield across crops, including enhanced bulb size and storage life in garlic following foliar seaweed applications (Arioli *et al*., 2024).

Yeast and yeast extracts, particularly those derived from *Saccharomyces cerevisiae*, represent another effective natural biostimulant. Rich in amino acids, peptides, vitamins, and oligosaccharides (Gao *et al*., 2024), yeast extracts promote cell division, increase chlorophyll synthesis, and influence phytohormonal balance (Johnson *et al*., 2024). Applications to Allium crops and vegetables have consistently improved vegetative growth, leaf area, bulb development, and postharvest attributes, largely due to enhanced nutrient uptake and increased antioxidant enzyme activities (Kumar *et al*., 2025). In garlic, yeast treatments have been associated with significant improvements in yield and bulb quality when combined with appropriate nutrient management (Abdelaal *et al*., 2021).

Vermicompost, a stabilized organic product of earthworm-mediated decomposition, provides a gradual supply of macro- and micronutrients, improves soil structure and water retention, and contributes humic substances and bioactive compounds. In garlic cultivation, vermicompost has been shown to increase bulb weight, clove number, nutrient content, and total yield (Pączka *et al*., 2021). Additionally, it enhances soil microbial activity and nutrient mineralization, promoting long-term soil fertility. Optimal application rates depend on soil properties and cultivar, yet studies consistently demonstrate significant yield advantages over unfertilized or low-input systems (Pączka *et al*., 2021; El-Mogy *et al*., 2024).

Integrating soil-applied amendments with foliar biostimulants may produce additive or synergistic effects on garlic productivity (Hossain *et al*., 2025). Vermicompost improves the physical and biological soil environment and provides a baseline nutrient supply, whereas seaweed and yeast foliar sprays deliver rapid biochemical signals that enhance nutrient uptake, stress resilience, and metabolic activity during critical growth stages (Sarkar *et al*., 2025). Recent trials on vegetables - and limited studies in garlic - show that combined treatments outperform single applications, enhancing vegetative growth and yield components (Rady and Nashwa, 2018; Pączka *et al*., 2021). These synergistic responses are attributed to sustained nutrient release from vermicompost, improved root activity, and bioactive compounds from seaweed and yeast that prime antioxidative and hormone-related pathways during bulb development (Rohith *et al*., 2021). Together, these improvements strengthen photosynthesis, optimize bulb filling, and increase nutrient- and water-use efficiencies (El-Mogy *et al*., 2024; Manzoor *et al*., 2025).

Despite growing interest in sustainable garlic production, there is a clear lack of integrated studies that compare the individual and combined impacts of different types of compost, and biostumilants, on garlic growth, leaf nutrient composition, and fruitquality. This gap limits the formulation of evidence-based, integrated nutrient and biostimulant strategies for garlic production. Therefore, this study aims to evaluate the individual and combined effects of vermicompost, seaweed extract, and yeast extract on garlic vegetative growth, leaf nutrient status, and bulb quantity and quality.

Materials and Methods

Site and climatic conditions

Two field experiments were conducted at a private farm in Sumusta, Beni-Suief Governorate, Egypt (28°56'02"N 30°50'28"E) during the winters of 2022 - 2023. This study took place in a productive area known for cultivating various vegetable crops in both open fields and greenhouses within the Giza governorate. The region has a desert climate, characterized by an average annual temperature of 22.2 °C and 23.88 °C. Monthly temperatures fluctuate between 32.1 °C in October and 26 °C in March. Overall, the total precipitation during experimentation, ranging from 8 to 11.84 mm, with most precipitation occurring during the wet seasons of 2022 and 2023, which leaves the area dry for the majority of the year.

Preparation of bioextracts

Garlic extract was prepared by mixing 250 g of peeled garlic cloves with 250 mL of distilled water using an electric blender for four minutes. The homogenate was then filtered through multilayered cheesecloth to obtain a clear extract. The filtrate was collected and stored in tightly sealed glass bottles at 4 °C until further use. Baker's yeast (*Saccharomyces cerevisiae*) extract was prepared by dissolving 5 g of commercial dry yeast (Bakmaya) in 1 L of distilled water, with an equal amount of sugar added at a ratio of 1:1 (w/w). The mixture was allowed to sit at room temperature for 12 hours to activate the yeast cells before use. Subsequently, the activated solution was filtered through multilayered cheesecloth and diluted with distilled water to the desired concentration for application. The commercial seaweed extract (BULITEM-MAX, containing *Ascophyllum nodosum*) was utilized as a natural source of biostimulants. This extract was diluted with distilled water at a rate of 5 mL/L to prepare the foliar spray solution used in the treatments.

Experimental layout and data analysis

Before cultivating garlic cloves (*Allium sativum* L cv. 'Sids 40'), we assessed the physicochemical characteristics of the soil (Table 1) and analyzed the chemical properties of the rock phosphate, feldspar, and vermicompost utilized in the study (Tables 2 and 3). The vermicompost, seaweeds, and yeasts were sourced from a private company named Miegos (*https://miegos.com*). Additionally, the rock phosphate and feldspar were obtained from a national company called Al-Ahram (*https://11707-eg.all.biz/*). The seaweed, garlic, and yeast biostimulants were applied to the garlic plants at rate of 5 mL/L, respectively, either individually or in combination. During the experimental setup, rock phosphate, feldspar, vermicompost (VC), and biochar were incorporated into the soil.

Table 1. Physical and chemical properties of the experimental soil during two growing seasons

Physical analysis				Chemical analysis			Soluble cations concentration				Soluble anions concentration		
Sand	Silt	Clay	Texture	OM	pH	EC	Ca^{++}	Mg^{++}	K^{+}	Na^{+}	Cl^{-}	HCO_3^{-}	SO_4^{--}
(%)				(%)		(dS m^{-1})	(meq L^{-1})						
87.16	6.48	6.36		0.8	7.26	4.03	2.2	1.6	0.9	4.3	5.7	1.5	1.8
89.35	5.24	5.41	Sandy loam	0.8	7.29	4.0	2.6	1.8	1.6	4.2	6.2	2.1	2.1

Table 2. Chemical properties of the applied vermicompost and biochar during two growing seasons

Chemical analysis	Vermicompost	Biochar
pH	7.22	8.5
EC	3.5	2.52
Total nitrogen (%)	2.4	1.68
Total phosphorus (%)	1.02	0.8
Total potassium (%)	0.7-1	0.9
Organic carbon (%)	34.75	47.25
Organic matter (%)	20.20	33.6
C/N ratio (%)	12:1	16:1

Table 3. Chemical composition of rock phosphate and Feldspar

Chemical composition	Rock phosphate (%)	Feldspar (%)
SiO_2	12.78	70.56
TiO_2	0.02	0.02
Al_2O_3	0.35	16.23
Fe_2O_3	1.12	0.17
MnO	0.07	0.02
MgO	0.61	0.05
CaO	44.12	0.26
Na_2O	1.12	3.69
K_2O	0.05	8.20
P_2O_5	20.0	0.03

The vermicompost was added at a rate of 100%, 75%, and 50% plus biochar at rate of 25% and 50%. Plots did not receive any organic fertilizers served as control (CON). Furthermore, the treatments were arranged as a split-plot design in a completely randomized block with three replicates; the main plots included four treatments (1) 100 % vermicompost, (2) 75% vermicompost + 25 % biochar, (3) 50% vermicompost + 50 % biochar and (4) and full recommended dose of NPK chemical fertilizers as a control (CON). Each main plot was subdivided into sub-main plots that received the following biostimulants as foliar applications: (1) garlic extract (GE); (2) yeast extract (YE); (3) seaweed extract (Bulitem-Max, SW); and (4) water, serving as a control (CK).

The soil of the experimental land was thoroughly plowed and divided into 48 experimental plots with an area of 10 m^2 for each plot. The garlic cloves were cultivated on October 2nd, with a spacing of 10 cm between plants and 100 cm between rows. A drip irrigation system was employed to irrigate the garlic plants. After 120 days of cultivation, plant samples were selected randomly and uprooted to determine the morphological, biochemical, and physiological characteristics of the garlic plants. The garlic plants were harvested on 20th of April in both 2022 and 2023.

Crop growth and bulb quality parameters

After 120 days from garlic cloves cultivation, a random sample of five plants was taken from each plot to measure plant height, number of leaves/plant, and leaf area.

<u>Total chlorophyll</u>

Four expanded and mature leaves from each experimental plot were selected and measured after 120 days from cultivation of the two seasons using Minolta Chlorophyll Meter (SPAD 502 Minolta Co., Osaka, Japan).

Nutrient content

The leaves and garlic bulb samples were collected from three plants in each replicate for chemical analysis 120 days after cultivation in both seasons. The collected samples were dried at 70 °C before chemical analysis using a forced-air oven. The concentrations of N, P, and K in the dry leaves were assessed. Nitrogen, phosphorous, and potassium were estimated in the acid-digested solution using Micro-Kjeldahle for N determination, colorimetric method (ammonium molybdate) using a spectrophotometer (Model 6300, Jenway, UK) for P determination, and flame photometer to determine potassium (Model PFP7, Jenway, UK) according to methods labelled by Brown and Lilliland (1964). Concentration of micronutrients (Zn, Mn, and Cu) in the garlic bulbs was assessed using an atomic absorption spectrophotometer (Pye Unicam model SP-1900, US) according to the technique stated by Allen *et al*. (1984).

Total yield

After 6 months of garlic cloves cultivation, garlic bulbs from each treatment were harvested and weighed to estimate the total yield, which is reported in t ha^{-1}. Additionally, 15 plants were randomly selected from the harvested samples of each treatment to assess the bulb diameter and bulb weight using an electronic digital caliper (model Mitutoyo 500-197, Kawasaki, Japan) and an electronic table scale (model Tanita KD-200-510, Tokyo, Japan), respectively.

Determination of allicin content

Garlic was peeled and then crushed using either a mortar and pestle or a garlic press to optimize enzymatic yield. Allicin content of garlic bulbs was determined according to the technique described by Bose *et al*. (2014). The ground garlic was subsequently placed into a beaker containing cold water, sealed, and shaken vigorously for 50 seconds. This process was repeated with the addition of more cold water. During shaking, the beaker was held at the top to minimize heat transfer. Finally, the mixture was filtered through a 0.45 µm glass filter. After extraction, high-performance liquid chromatography (HPLC) was typically employed for the detection of analytes. Allicin is rarely detected using the simpler High-Performance Thin-Layer Chromatography (HPTLC) technique (CAMAG Instruments TLC line, Switzerland) due to challenges associated with its unique structure. Pure commercial allicin served as a reference, while the sample was prepared by dissolving fresh garlic cloves in deionized water. This methodology was effectively applied to real Allium samples, yielding results that closely matched HPLC data. A solvent mixture, generally consisting of aqueous and organic solvents like methanol or acetonitrile in a 60:40 (v/v) ratio, was used as the elution solvent. Phosphate buffers, such as potassium dihydrogen phosphate, were often utilized to adjust the solution's pH, typically within the range of 2 to 4. The flow rate was generally maintained at 1.0 mL/min.

Statistical analysis

A factorial split-plot experiment was conducted using a randomized complete design with three replicates for each treatment. Organic fertilizers (vermicompost and biochar) were assigned to the main plots, while biostimulants (garlic extract, seaweed extract, and yeast extract) were allocated to the subplots. The recorded data were subjected to a two-way analysis of variance using the Statistical 7 program after performing a normality (Shapiro - Wilk test) and homogeneity of variance (Levene's test). The Statistics 7 program was used to compare means, and Tukey's multiple range test ($p \leq 0.05$) was used to find significant differences. Additionally, a correlation heatmap, a clustering heatmap and principal component analysis were performed to evaluate the relationships among all studied measurements.

Results

Morphological properties of garlic plants

The results in Table 4 demonstrate that both fertilizer sources and biostimulants significantly influenced garlic vegetative growth across both seasons. The highest plant height resulted from the foliar application of garlic extract (GE) and seaweed extract (SW), whether used individually or combined with vermicompost. In the first season, plants treated with CON + GE + SW achieved a height of 74.6 cm, compared to 65.3 cm in the control (CON - CK), representing a 14.2% increase. In the second season, the same treatment reached 77 cm, whereas the control measured 67.66 cm, resulting in a 13.8% increase. Additionally, the number of leaves per plant increased with the GE + SW treatments. The highest leaf count, ranging from 9 to 10 leaves, was observed with GE + SW in both seasons. In contrast, the control group had 7 leaves in the first season and only 5 leaves in second season, indicating increases of 28.6% and 100% over the control, respectively. A leaf area exhibited a similar trend. The CON + GE + SW treatment produced the largest leaves, measuring 229 cm^2 in season 1 and 235 cm^2 in season 2, while the controls recorded 202 cm^2 and 215.66 cm^2. The improvements in leaf areas were 13.3% in the first season and 9.0% in the second season. Overall, the application of foliar GE + SW, whether alone or in combination with vermicompost and biochar, enhanced all measured vegetative growth traits.

Table 4. Effect of organic fertilizers and biostimulants on the vegetative growth parameters of garlic plants over two seasons

Treatment	Seasons 1				Seasons 2		
	Biostimulants	Plant height (cm)	Number of leaves (leave/plant)	Leaf area (cm^2)	Plant height (cm)	Number of leaves (leave/plant)	Leaf area (cm^2)
CON	CK	65.3bc	7a	202cb	67.66d	5d	215.66c
	GE	68.6b	8a	211.3ab	70.66bc	7b	222.66b
	GE + YE	74a	8a	216.6ab	73.33ab	10a	227.66a
	GE + SW	74.6a	9a	229a	77a	10a	235a
50 % VC + 50% Biochar	CK	61c	7a	184ef	63.33gh	6c	206.7ef
	GE	65.3bc	8a	190.3d	67.33e	7cb	210.66e
	GE + YE	49e	8a	196.6c	72.66ab	9ab	217.7bc
	GE + SW	73.3a	9a	207b	75.33a	10a	225ab
75% VC + 25% Biochar	CK	58.6d	6b	175gh	61.33ij	6cd	188.66i
	GE	61.3c	6b	181.3fg	64.66fg	7.33b	195.7hi
	GE + YE	68.6ab	8a	187.66e	69.66cd	7.33b	205.66f
	GE + SW	70ab	9a	194 cd	72.66ab	7.66b	213d
100 % VC	CK	51.6e	5b	164.6i	54.66k	5d	182.66g
	GE	56d	5b	171hi	58.33jk	5d	189.66i
	GE + YE	60c	7a	177.3g	62hi	5d	196.66h
	GE + SW	67.6b	8a	183.6ef	66.66ef	6c	204g

Means followed by different letter (s) indicate significant differences between the treatments according to Tukey's multiple range test ($p \leq 0.05$). CON=control, VC= vermicompost, CK= control, GE=garlic extract, YE= yeast extract, and SW=seaweed extract

Leaf nutrient content of garlic plants

The mineral composition of garlic leaves, specifically nitrogen (N), phosphorus (P), and potassium (K), was significantly affected by the combination of organic fertilizer regimes and the applied stimulants across both growing seasons (Table 5). The nitrogen concentration in the leaves exhibited a consistent upward trend with increasing organic inputs, especially in treatments that combined vermicomposting with biochar and biostimulants. During the first season, leaf nitrogen ranged from 1.82% in the control group to 3.66% under the GE + SW treatment utilizing 100% vermicompost. In the second season, nitrogen levels also went up, reaching 3.72%. Phosphorus concentration also increased significantly in response to the amendments, with the highest values associated with the GE + YE treatment under the 50% VC + 50% biochar combination (0.50% in Season 1). The potassium concentration displayed a comparable response pattern. In the first season, potassium content varied between 0.47% and 0.66%, with the highest values found in the GE + SW and GE +

YE treatments. In the second season, potassium concentration ranged from 0.51% to 0.71%, with GE + SW recording the maximum value. For all nutrients (N, P, and K), the combined application of vermicompost, biochar, and biostimulants resulted in higher concentrations than those observed in the corresponding untreated controls.

Table 5. Effect of organic fertilizers and biostimulants on the leaf macronutrient content of garlic plants over two seasons

Treatment	Biostimulants	Seasons 1			Seasons 2		
		N %	P %	K %	N %	P %	K %
CON	CK	1.82d	0.23b	0.53bcd	2.04e	0.28de	0.59bc
	GE	2.6c	0.29b	0.57abc	2.61d	0.32bc	0.62b
	GE + YE	2.89bc	0.33b	0.61ab	3.65ab	0.37ab	0.65ab
	GE + SW	3.27b	0.38b	0.66a	3.72a	0.42a	0.71a
50 % VC + 50% Biochar	CK	2.5c	0.21b	0.5bcd	2.54d	0.26e	0.54f
	GE	2.4c	0.25b	0.54abcd	2.58d	0.31cd	0.58c
	GE + YE	3.09bc	0.50a	0.57abc	3.69ab	0.33bc	0.62b
	GE + SW	3.60a	0.31b	0.62a	3.72a	0.37ab	0.65a
75% VC + 25% Biochar	CK	2.48c	0.18c	0.49cd	2.63d	0.21he	0.52gh
	GE	2.53c	0.21b	0.52bcd	2.57d	0.25fg	0.55df
	GE + YE	3.58a	0.24b	0.58abc	3.61b	0.29d	0.58cd
	GE + SW	3.62a	0.28b	0.61ab	3.66ab	0.34b	0.62b
100 % VC	CK	3.37b	0.176c	0.47d	2.43g	0.2e	0.51h
	GE	3.46ab	0.21b	0.51bcd	3.07c	0.23gh	0.53fg
	GE + YE	3.53ab	0.22b	0.54abcd	3.49bc	0.31c	0.56cd
	GE + SW	3.66a	0.25b	0.57abc	3.61b	0.26ef	0.59bc

Means followed by different letter (s) indicate significant differences between the treatments according to Tukey's multiple range test ($p \leq 0.05$). CON=control, VC= vermicompost, CK= control, GE=garlic extract, YE= yeast extract, and SW=seaweed extract

Total yield of garlic plant

The productivity traits of garlic, including bulb weight, total yield, clove fresh weight, and bulb diameter, were significantly impacted by the combination of organic fertilizers and stimulants across both seasons (Table 6). In the control treatment, a progressive enhancement was recorded with the addition of stimulants. The GE + SW combination produced the heaviest bulbs (93.6 g and 100.33 g in seasons 1 and 2, respectively), the highest clove fresh weight (4.04 and 4.28 g), and the largest bulb diameter (5.89 and 6.07 cm), leading to the greatest total yield (28.25 and 32.5 t ha^{-1}). This treatment was statistically superior to the untreated control (81.3 and 85 g bulb weight; 24.38 and 25 t ha^{-1} total yield). For the 50% VC + 50% biochar regime, the foliar addition of biostimulants also obviously enhanced bulb productivity compared with CK. The GE + SW treatment achieved 81.3 and 91 g bulb weight, 20.9 and 30 t ha^{-1} total yield, and clove fresh weight of 3.74 and 4.17 g, with significantly larger bulb diameters (5.61 and 5.76 cm) in both seasons. Similarly, under 75% VC + 25% biochar, stimulant application improved bulb traits, with the GE + SW treatment again outperforming others (76.6 and 85 g bulb weight; 24.25 and 30 t ha^{-1} yield; 3.55 and 3.74 g clove fresh weight; 5.29 and 5.62 cm bulb diameter). In contrast, the 100% vermicompost treatment without stimulants produced the smallest bulbs (63.3 and 67.66 g) and the lowest total yields (20.5 and 25 t ha^{-1}). However, stimulant addition, particularly GE + SW, improved performance under this regime, reaching 71 and 76.66 g bulb weight and 23.33 and 27.5 t ha^{-1} yield, alongside improves in clove fresh weight and bulb diameter.

Table 6. Effect of organic fertilizers and biostimulants on the yield and its components of garlic plants over two seasons

Treatment	Biostimulants	Seasons 1				Seasons 2			
		Bulb weight (g)	Total yields (t ha^{-1})	Clove Fw (g)	Bulb diameter (cm)	Bulb weight (g)	Total yields (t ha^{-1})	Clove FW (g)	Bulb diameter (cm)
CON	CK	81.3b	24.38c	3.42b	5.25ab	85b	25c	3.5ab	5.57a
	GE	81.6a	25.7b	3.61a	5.45a	89a	30ab	3.76a	5.91a
	GE + YE	82.3a	27.03a	3.92a	5.65a	94.33a	32.5a	4.17a	5.97a
	GE + SW	88.6a	28.25a	4.04a	5.89a	100.3a	32.5a	4.28a	6.07a
50 % VC + 50% Biochar	CK	74c	23.15d	3.08cd	4.84c	78.3de	25c	3.41b	5.09bc
	GE	75.6bc	24.2c	3.44ab	5.14ab	83.3bc	30ab	3.71a	5.35b
	GE + YE	78.6b	25.43bc	3.55ab	5.48a	86.66b	30ab	3.91a	5.63a
	GE + SW	86.3a	25.9b	3.74a	5.61a	91a	30ab	4.17a	5.756a
75% VC + 25% Biochar	CK	68e	20.9f	2.55d	4.62cd	70g	25c	3.07c	5.04cd
	GE	68.6ed	22e	3.09c	4.92c	77e	27.5b	3.57a	5.39b
	GE + YE	72.6 cd	23.43cd	3.21bc	5.0bc	80.7cd	30ab	3.54a	5.63a
	GE + SW	78.6b	24.25c	3.55ab	5.29a	85b	30ab	3.74a	5.62a
100 % VC	CK	63.3g	20.5f	2.41d	4.41d	67.66h	25c	2.75d	4.84d
	GE	64.6fg	20.9ef	2.77d	4.63cd	69h	27.5b	3.1cd	5.15b
	GE + YE	67.6ef	22.08e	2.83d	4.81c	72.3fg	27.5b	3.3bc	5.38b
	GE + SW	71cd	23.32d	3.17c	4.99bc	76.7ef	27.5b	3.54a	5.55ab

Means followed by different letter (s) indicate significant differences between the treatments according to Tukey's multiple range test ($p \leq 0.05$). CON=control, VC= vermicompost, CK= control, GE=garlic extract, YE= yeast extract, and SW=seaweed extract

Nutrient composition of garlic bulb

Bulb macronutrient composition

The findings indicated that the levels of nitrogen, phosphorus, and potassium in garlic bulb (cloves) were considerably influenced by the applied stimulants and organic amendments (Table 7). At both seasons, the lowest value of clove N concentration (C.N) was observed in the untreated plants (Con + CK). Overall, the application of biostimulants (GE, YE, and SW) across all soil amendment levels resulted in higher N concentrations compared to their corresponding CK treatments. Phosphorus concentration also showed significant differences among treatments. The amount of P in the first season ranged from 0.37% (100% VC - CK) to 0.60% (GE + SW under the control soil). In the second season, clove P concentration (C.P) ranged from 1.84% to 2.44%, with GE + SW consistently achieving the highest values for each amendment level. Potassium concentration exhibited a similar response pattern. In the first season, K values ranged from 1.71% to 2.35%, with the highest values recorded under both GE + SW and GE + YE treatments. In the second season, clove K concentration (C.K) varied between 1.84% and 2.44%, again with GE + SW producing the highest values. Biostimulants generally led to increased P and K concentrations across all soil amendments compared to their CK treatment.

Table 7. Effect of organic fertilizers and biostimulants on bulb macronutrient content over two seasons

Treatment	Biostimulants	Seasons 1			Seasons 2		
		N %	P %	K %	N %	P %	K %
CON	CK	0.93g	0.47c	2.00a	0.89 h	2.1de	2.04 a
	GE	1.60cd	0.51bc	2.14a	1.38e	2.19bc	2.19 a
	GE + YE	1.76bc	0.56b	2.26a	1.82 ab	2.3ab	2.32 a
	GE + SW	1.86ab	0.60a	2.35a	1.98 ab	2.44a	2.44 a
50 % VC + 50% Biochar	CK	1.29f	0.42cd	1.93a	1.10g	2.01e	2.01 a
	GE	1.59cde	0.45c	2.14a	1.42de	2.14cd	2.13 a
	GE + YE	1.69c	0.50bc	2.22a	1.78 bc	2.26bg	2.26 a
	GE + SW	1.76bc	0.54b	2.27a	1.84 ab	2.37ab	2.37 a
75% VC + 25% Biochar	CK	1.32f	0.39d	1.79b	1.25 f	1.91he	1.87b
	GE	1.57de	0.43cd	1.91a	1.44de	2.06de	2.05 a
	GE + YE	1.67c	0.48bc	2.02a	1.69cd	1.48bc	1.47 a
	GE + SW	1.81ab	0.52b	2.18a	1.74bc	2.26b	2.26 a
100 % VC	CK	1.48e	0.37d	1.71b	1.21f	1.84e	1.84 b
	GE	1.55de	0.39cd	1.77b	1.52d	1.94de	1.9 ab
	GE + YE	1.89a	0.44c	1.83ab	1.83 ab	2.05cd	2.04 a
	GE + SW	1.93a	0.47bc	2.00a	2.02 a	2.13c	2.03 a

Means followed by different letter (s) indicate significant differences between the treatments according to Tukey's multiple range test ($p \leq 0.05$). CON=control, VC= vermicompost, CK= control, GE=garlic extract, YE= yeast extract, and SW=seaweed extract

Bulb micronutrient composition

The results presented that the concentrations of zinc, manganese, copper, and iron in garlic bulb (cloves) were markedly influenced by the combined application of stimulants and organic amendments across both seasons (Table 8). In the control treatment, the foliar application of GE + SW resulted in the greatest micronutrient contents, particularly for clove Mn, Cu, and Fe content (C.Mn, C.Cu, and C.Fe). Although, Zn remained relatively stable with no significant differences among treatments. For the combination of 50% vermicompost + 50% biochar, nutrient concentrations improved when stimulants were applied, with GE + SW again showing superior performance, recording 14.00 ppm Mn, 12.85 ppm Cu, and 10.61 ppm Fe in the first season, and 14.11 ppm Mn, 13.09 ppm Cu, and 10.74 ppm Fe in the second season. Similarly, under 75% VC + 25% biochar, the addition of stimulants significantly increased micronutrient uptake, with GE + SW being the most effective treatment (13.77 ppm Mn, 12.79 ppm Cu, and 0.64 ppm Fe in the first season, and 13.84 ppm Mn, 13.05 ppm Cu, and 0.72 ppm Fe in the second season). On the other hand, the 100% vermicompost treatment recorded the lowest values overall. Nevertheless, the stimulants, particularly GE + SW, improved micronutrient concentrations, reaching 13.48 ppm Mn, 12.69 ppm Cu, and 0.64 ppm Fe in the first season, and 13.63 ppm Mn, 12.84 ppm Cu, and 0.66 ppm Fe in the second season. Overall, these results show that the levels of zinc did not change much, but the combination of GE + SW with organic amendments greatly increased the amount of Mn, Cu, and Fe in garlic cloves. The most significant enhancements were noted with GE + SW treatments, especially when vermicompost and biochar were combined, emphasizing their synergistic effect in maximizing micronutrient absorption.

Table 8. Effect of organic fertilizers and biostimulants on bulb micronutrient content over two seasons

Treatment	Biostimulants	Seasons 1			Seasons 2		
		Zn (ppm)	Mn (ppm)	Cu (ppm)	.Zn (ppm)	Mn (ppm)	Cu (ppm)
CON	CK	10.73a	13.51efg	12.58cd	10.89a	13.69cd	12.69gh
	GE	10.87a	13.72cd	12.77c	10.97a	13.85c	12.89d
	GE + YE	10.97a	13.9b	12.95b	11.07a	14.11b	13.29b
	GE + SW	11.15a	14.05a	13.21a	11.33a	14.31a	13.54a
50 % VC + 50% Biochar	CK	10.66a	13.41hg	12.44eg	10.8a	13.44gh	12.66h
	GE	10.77a	13.58def	12.60de	10.88a	13.61de	12.79ef
	GE + YE	10.84a	13.72cd	12.76c	10.81a	13.75cd	12.93cd
	GE + SW	10.96a	14cd	12.85cb	11.18a	14.11b	13.09c
75% VC + 25% Biochar	CK	10.44a	13.26i	12.34g	10.55a	13.31ih	12.57ig
	GE	10.56a	13.43gh	12.50ef	10.72a	13.52ef	12.72fg
	GE + YE	10.66a	13.6cde	12.65cd	10.92a	13.72cd	12.88de
	GE + SW	10.78a	13.77c	12.79c	10.91a	13.84c	13.05c
100 % VC	CK	10.34a	13.06j	12.28h	10.46a	13.23i	12.49g
	GE	10.42a	13.17ij	12.40f	10.61a	13.48f	12.63hi
	GE + YE	10.51a	13.3hi	12.57e	10.69a	13.47fg	12.756f
	GE + SW	10.61a	13.48fg	12.69cd	10.79a	13.63d	12.84e

Means followed by different letter (s) indicate significant differences between the treatments according to Tukey's multiple range test ($p \leq 0.05$). CON=control, VC= vermicompost, CK= control, GE=garlic extract, YE= yeast extract, and SW=seaweed extract

Correlation heatmap

The correlation heatmap illustrates the relationships among nutrient concentrations, growth parameters, and yield-related traits (Figure 1). Strong positive correlations were observed among most macronutrient contents in garlic cloves (C.N, C.P, and C.K) and between these nutrients and agronomic traits. Plant growth characteristics such as number of leaves, leaf area (LA), bulb fresh weight (Bulb FW), bulb diameter, and clover fresh weight (Clover FW) exhibited strong positive associations with yield (r = 0.79 - 0.96), highlighting the importance of vegetative growth in determining final productivity. In particular, bulb fresh weight (r = 0.91) and clover fresh weight (r = 0.96) showed the highest correlations with yield, followed by leaf area (r = 0.81) and bulb diameter (r = 0.79). This indicates that vigorous vegetative growth and efficient biomass accumulation directly contribute to improved yield performance. On the other hand, some negative associations were observed. Leaf nitrogen (LN) showed negative correlations with several traits, especially with C.Mn (r = - 0.58) and C.Fe (r = - 0.56). Similarly, leaf phosphorus (L.P) was negatively correlated with plant height (r = - 0.76). These results suggest that nutrient imbalances may adversely affect plant growth and should be carefully managed.

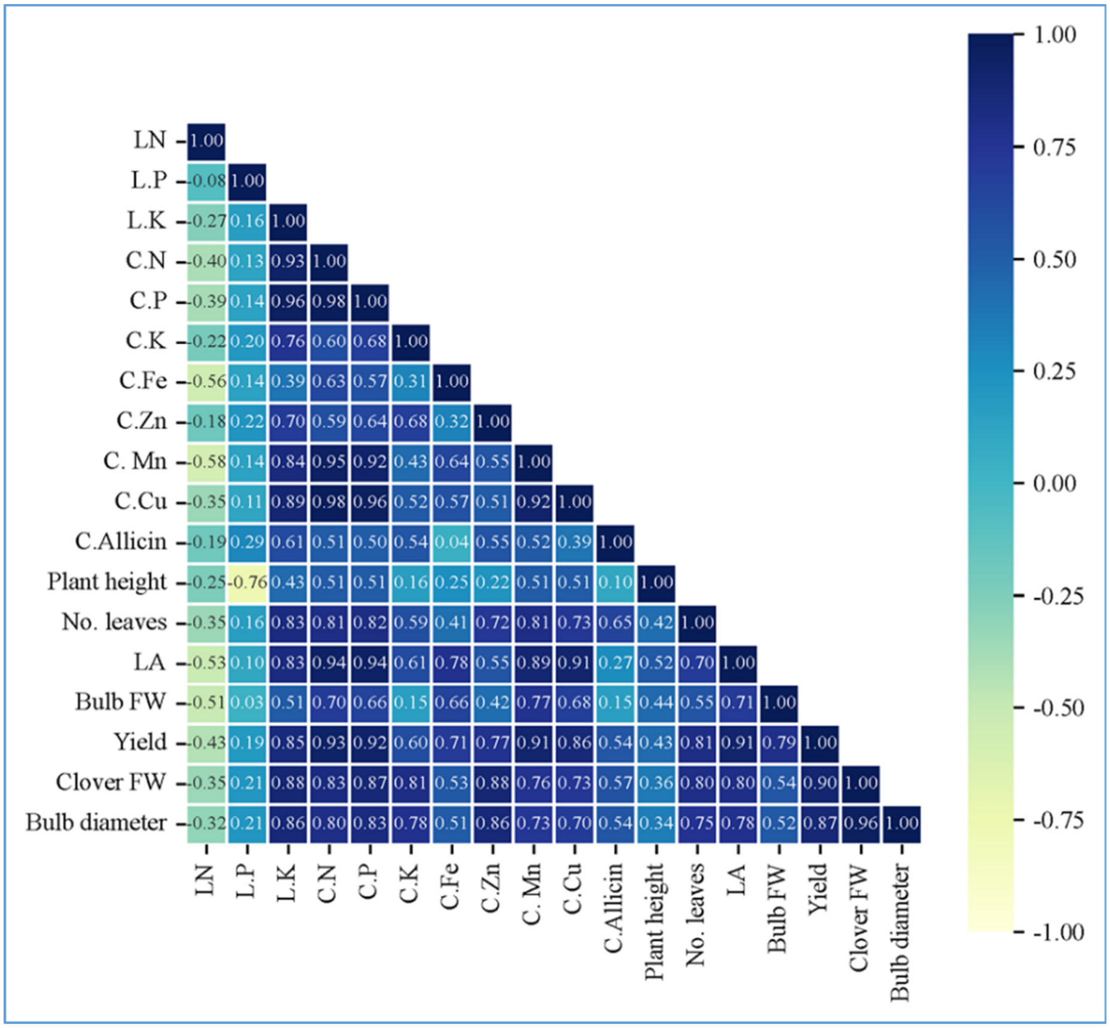

Figure 1. Correlation analysis between morphological and chemical properties of garlic plants treated with organic fertilizers (vermicompost and biochar), and bio-stimulants

Abbreviations: LA, leaf area; Bulb FW, bulb fresh weight; L.N, leaf nitrogen; L.P, leaf phosphorus content; leaf; L.K; leaf potassium; C.N, clove nitrogen content; C.K, clove potassium content; C.Fe, clove iron content; C.Mn, Clove manganese content; C.Cu, clove copper content

Bulb allicin concentration

The results presented in Figure 2 indicate that the Allicin content in garlic cloves was significantly influenced by the interaction between organic amendments and biostimulant applications during both growing seasons. Across all treatments, the application of GE + SW consistently yielded the highest allicin concentrations. Specifically, under the treatment of 75% VC + 25% biochar, GE + SW recorded maximum values of 4.2 mg g^{-1} FW in the first season and 4.6 mg g^{-1} FW in the second season, outperforming all other treatments. Similarly, in the 50% VC + 50% biochar system, GE + SW also achieved superior allicin levels, ranging from approximately 4.0 to 4.3 mg.g^{-1} FW. In contrast, the control treatments - those without stimulants - typically exhibited the lowest allicin contents, particularly under the sole application of 100% vermicompost or 100% control, where values ranged from 3.3 to 3.6 mg g^{-1} FW across both seasons. Nevertheless, the application of stimulants, especially GE+YE and GE + SW, significantly enhanced allicin accumulation compared to the untreated CK. The data illustrate that the combined application of vermicompost and biochar, particularly at the ratio of 75% VC + 25% biochar, along with the GE + SW biostimulant treatment, was the most effective strategy for maximizing allicin content in garlic. These findings underscore the synergistic effects of organic fertilization and natural stimulants in improving garlic quality traits.

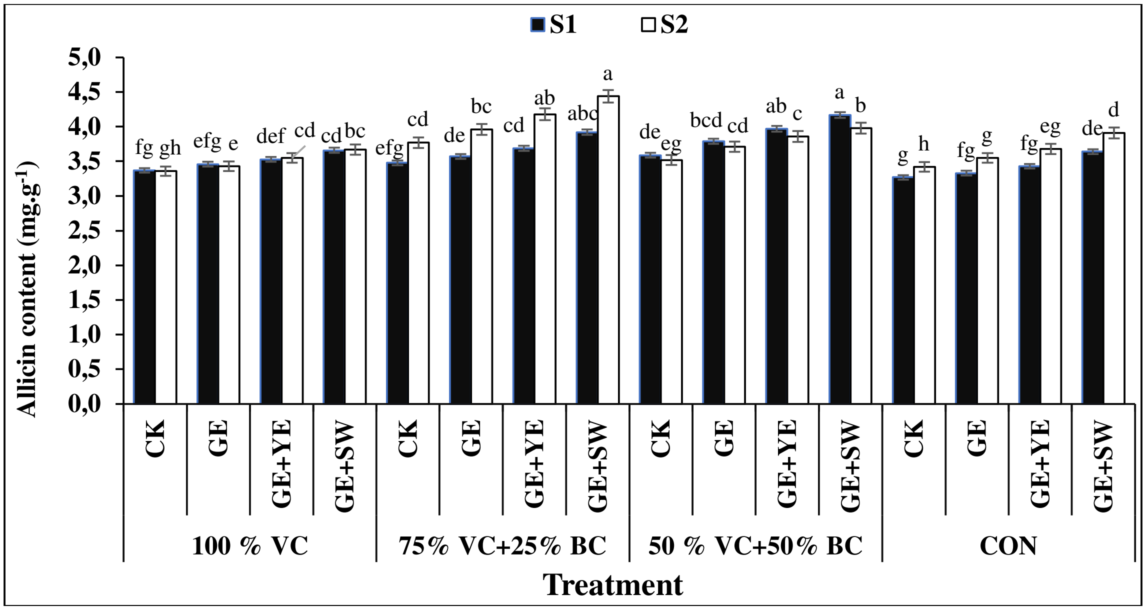

Figure 2. Effect of organic fertilizers and biostimulants on allicin content of garlic bulb over two seasons
Columns followed by different letter (s) indicate significant differences between the treatments according to Tukey's multiple range test ($p \leq 0.05$). CON=control, VC= vermicompost, CK= control, GE=garlic extract, YE= yeast extract, and SW=seaweed

Clustering heatmap

The clustering heatmap illustrates the strong influence of combined vermicompost (VC), biochar (BC), and biostimulant applications on garlic growth, yield, and biochemical attributes (Figure 3). Treatments involving GE + SW and GE + YE, particularly under 75% VC + 25% biochar and 50% VC + 50% biochar, were grouped together and showed a positive correlation with key quality traits such as allicin content, bulb fresh weight, yield, N, P, K, Mn, and Fe concentrations. These clusters (Group A) were characterized by high intensities (red zones), highlighting their superior performance. In contrast, treatments based on sole VC or control (CON) were clustered separately (Group B), showing weaker associations (blue zones) with most yield and quality traits, indicating relatively poor performance compared with the integrated treatments. Zn concentration remained less variable across treatments, whereas traits such as allicin content, macronutrient uptake (N, P, K), and bulb yield were the most positively influenced by the integration of organic fertilizers and stimulants.

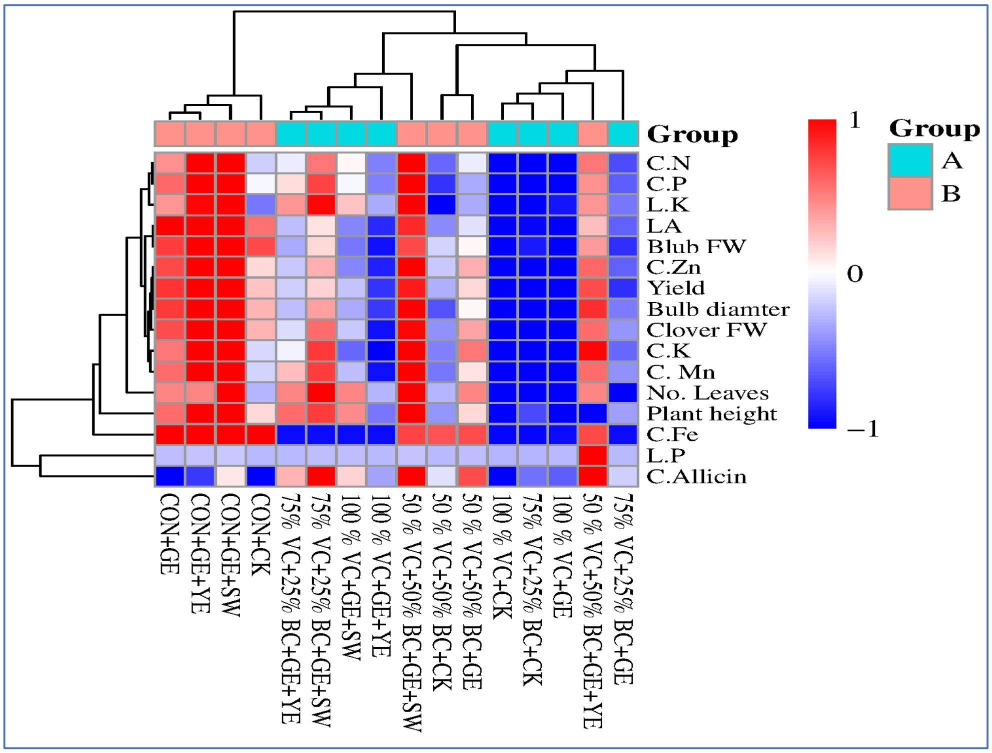

Figure 3. Clustering heatmap showed the correlation between morphological and chemical properties of garlic treated with organic fertilizers and biostimulants

Abbreviations: LA, leaf area; Bulb FW, bulb fresh weight; L., leaf; C., Cloves. CON=control, VC= vermicompost, CK= control, GE=garlic extract, YE= yeast extract, and SW=seaweed

Principal component analysis

Principal component analysis (PCA) showing the relationships among garlic growth, yield, and biochemical traits. The PCA analysis (Figure 4) revealed that the first two components (Factor 1 and Factor 2) explained 65.29% and 11.51% and 11.51% of the total variance, respectively, accounting for 76.8% of the overall variation among traits. Factor 1 was mainly associated with bulb diameter, allicin content, clove fresh weight, yield, and macronutrient concentrations (N, P, K), indicating their strong positive contribution to garlic productivity and quality. Traits such as Mn, Cu, and Zn contents also clustered closely with yield components, highlighting their positive correlation. On the other hand, leaf N (LN) and leaf P (LP) loaded more strongly on Factor 2, suggesting a different contribution pattern compared with bulb quality traits. Interestingly, plant height and Fe concentration were positioned negatively along Factor 1, indicating weak or inverse associations with yield and quality parameters. Overall, the PCA confirmed that bulb-related traits (diameter, clove FW, yield, and allicin content), along with nutrient accumulation (N, P, K, Zn, Mn, Cu), are the major discriminating factors driving garlic performance under different organic and biostimulant treatments.

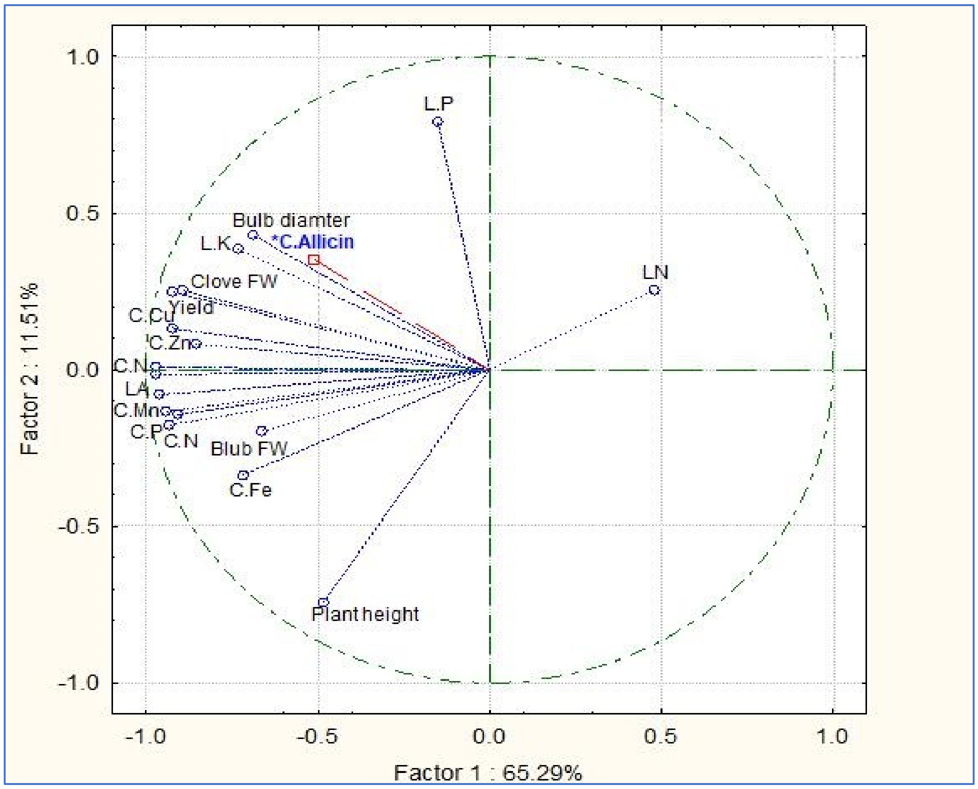

Figure 4. Principal component analysis of the main agrochemical analysis of garlic plants
Abbreviations: LA, leaf area; Bulb FW, bulb fresh weight; L., leaf; C., Cloves

Discussion

Vermicompost and biostimulants are increasingly recognition as sustainable alternatives to synthetic fertilizers due to their capacity to enhance soil fertility, promote plant growth, and increase crop productivity (El-Mogy *et al.*, 2024). The application of these bioproducts may provide complementary or synergistic effects that improve plant growth, nutrient uptake, stress tolerance, and overall crop performance (Di Sario *et al.*, 2025; Fajdetić *et al.*, 2025). The findings of current study demonstrated that the co-application of vermicompost and a seaweed biostimulant significantly improveed garlic growth, endogenous nutrient content, yield quantity, and quality. Overall, the foliar application of garlic extract (GE) and seaweed extract (SW) treatment consistently exhibited the higher vegetative performance, particularly under mixed vermicompost (VC) and biochar regimes (BC). In both seasons, the foliar application of GE + SW significantly increased plant height, leaf number, and leaf area compared to the untreated control (CON + CK). For instance, plant height increased by 14.2% in the first season and 13.8% in the second. The bioactive constituents in both garlic and seaweed extracts likely contribute to this positive effect on vegetative growth. Garlic extract contains organosulfur compounds, flavonoids, and phenolic substances, which can act as signaling molecules and enhance metabolic activity (Hayat *et al.*, 2018). The combined application of GE + SW may enhance these beneficial effects on leaf expansion, resulting in an increased photosynthetic area and greater assimilate production. The increased number of leaves observed with GE + SW supports this notion, as leaf initiation and expansion are vital for determining carbon assimilation capacity. Improved vegetative growth establishes a strong foundation for future yield formation, consistent with several studies on the effects of biostimulants (Jędrszczyk *et al.*, 2019). These improvement in vegetative growth could be related to chemical components found in seaweed extracts, such as cytokinins and auxin-like substances, as well as polysaccharides and osmoprotectants. These components have been well-documented for their ability to promote cell division, expansion, and stress resilience (Ali *et al*., 2021; Singh *et al*., 2025).

The biostimulant treatments significantly influenced the concentrations of leaf nitrogen (N), phosphorus (P), and potassium (K). The combination of GE and SW consistently produced the highest nutrient levels across different fertilizer regimes. These results support the idea that biostimulants can enhance nutrient uptake efficiency, potentially through mechanisms such as root stimulation, increased membrane transport activity, or the mobilization of soil-bound nutrients (Hassan *et al*. 2024). Specifically, seaweed extracts have been shown to promote root growth and exudation, which increases nutrient acquisition (Shang *et al*. 2023). The synergistic effects of organic amendments and biostimulants likely contribute to improved outcomes: vermicompost and biochar enhance soil's physical, chemical, and microbial properties - such as increased cation exchange capacity and improved moisture retention - while biostimulants boost root activity and nutrient transport to the plant (El-Mogy *et al*., 2024; Osman *et al*. 2025). The vermicompost treatment (100%) produced higher nitrogen levels but lower phosphorus (P) and potassium (K) levels. This suggests that relying on only one organic source without adding anything else could lead to an imbalance in nutrients (Hatwal *et al*., 2015). The incorporation of GE + SW in this regime partially addressed this imbalance, emphasizing the value of combining biostimulants with various organic inputs (Hatwal *et al*., 2015, Rana *et al*., 2020).

The application of GE + SW treatments along with vermicompost significantly improved garlic productivity traits such as bulb weight, clove fresh weight, bulb diameter, and total yield compared the untreated plants (Table 6). A similar result were observed by Zhang *et al* (2025), who reported that the co-application of biostimulant with organic fertilizers increased the yield quantity and quality of onion plants. The observed increases in bulb yield are logically linked to the earlier improvements in vegetative growth and nutrient uptake (Mubarak *et al*., 2025; Zhang *et al*., 2025; El-Mogy *et al*., 2025). An increase in leaf area, enhanced photosynthetic capacity, and improved nutrient status contribute to a greater supply and allocation of assimilates to the bulbs. The strong positive correlations observed ($r = 0.79 - 0.96$) between vegetative traits and yield components further confirm that the capacity to accumulate biomass in the vegetative stage is a key driver of final yield (Figure 1).

The PCA analysis (explaining ~76.8 % of variance in first two axes) identified bulb diameter, allicin content, clove fresh weight, yield, and macronutrient concentrations (N, P, K) as the primary discriminators among treatments, consistent with these being the most responsive and impactful traits (Figure 4). Bulb quality parameters and nutrient content were closely clustered with yield, highlighting their integrated role in productivity (Figures 1, 3, and 4). These findings are consistent with meta-analytical evidence indicating that biostimulants typically enhance crop yield by approximately 17.9% (Parađiković *et al*., 2019; Li *et al*., 2022; Verma *et al*., 2025). The observed increase in bulb yield and quality, particularly in allicin concentration, may be attributed to the simultaneous application of biostimulants (GE + SW) along with organic amendments. The concentrations of N, P, and K in garlic cloves were significantly enhanced by GE + SW application alone or in the combination with organic fertilizers (vermicompost and bichar) at different regimes. These enhanced nutrient levels reflect increased translocation of assimilates and nutrients into storage organs such as bulb (Thirumalesh *et al*., 2025).

Micronutrient accumulation (Mn, Cu, and Fe) in cloves showed significant improvement under the GE + SW treatment, while Zn exhibited less variability across treatments. These enhancements in micronutrients may be attributed to improved root length, root uptake or mobilization resulting from biostimulant activity, which aligns with previous studies indicating that seaweed extracts can facilitate the use of micronutrients and reduce antagonistic interactions (Manoj Kumar *et al*., 2018; Szczepanek *et al*., 2019; Di Sario *et al*., 2025). These micronutrients are crucial for enzymatic processes; their increased levels contribute not only to yield but also to the quality of bulbs and cloves. The results of the current study aligned with previous researches indicating that the foliar application of microelements (Cu, Mn, Zn, and Fe) or the soil application of vermicompost containing these microelements significantly enhanced various growth parameters. These include the fresh weight of the bulb, bulb diameter, length of cloves, number of cloves, bulb yield, total soluble solids, cured protein, and allicin content (Ballabh *et al.*, 2013; Hatwal *et al.*, 2015; Wang *et al.*, 2020).

Allicin, a key bioactive compound in garlic, is essential for both the quality and medicinal properties of the plant. The current findings indicate that the GE + SW treatment maximized allicin concentration, achieving 4.2 mg g^{-1} FW in the first season and 4.6 mg g^{-1} FW in the second season under the 75% VC + 25% biochar treatment (Figure 2). This improvement suggests that biostimulants enhance not only yield but also secondary metabolism and phytochemical synthesis. The increase in allicin may be attributed to the elicitor-like behavior of garlic extract components and bioactive molecules from seaweed, which could activate defense pathways and stimulate the biosynthesis of secondary metabolites (Hayat *et al.*, 2018; Di Sario *et al.*, 2025).Previous studies have demonstrated that aqueous garlic extracts can modulate antioxidant enzyme activity and reactive oxygen species (ROS) signaling in treated plants potentially upregulating sulfur metabolism pathways involved in allicin synthesis (Hayat *et al.* 2018). Thus, GE + SW may function as both growth promoters and mild elicitors, driving enhancements in both quality and quantity. The correlation heatmap analysis illustrates the interconnectedness of growth, nutrient uptake, yield, and quality traits (Figure 3). The strong positive correlations among nitrogen (N), phosphorus (P), potassium (K), and yield components indicate that efficient nutrient assimilation is crucial for productivity. The negative correlations observed between leaf nitrogen (LN) and certain micronutrients (manganese and iron), as well as the negative association between leaf phosphorus (LP) and plant height, may reflect nutrient allocation trade-offs or antagonistic interactions that could arise under specific fertilization regimes. These patterns underscore the importance of balanced nutrition and caution against an overemphasis on a single nutrient. Additionally, the cluster heatmap analysis grouped treatments with GE + SW - particularly under mixed VC-biochar regimes - into a high-performance cluster, distinctly separating them from treatments lacking stimulants or using only vermicompost. This highlights the positive benefits of combining biostimulants and organic amendments.Additionally, the results of this study affirm that the integration of biostimulants with organic fertilizers improves growth performance, total yield, and bulb quality in garlic plants (Figure 5).

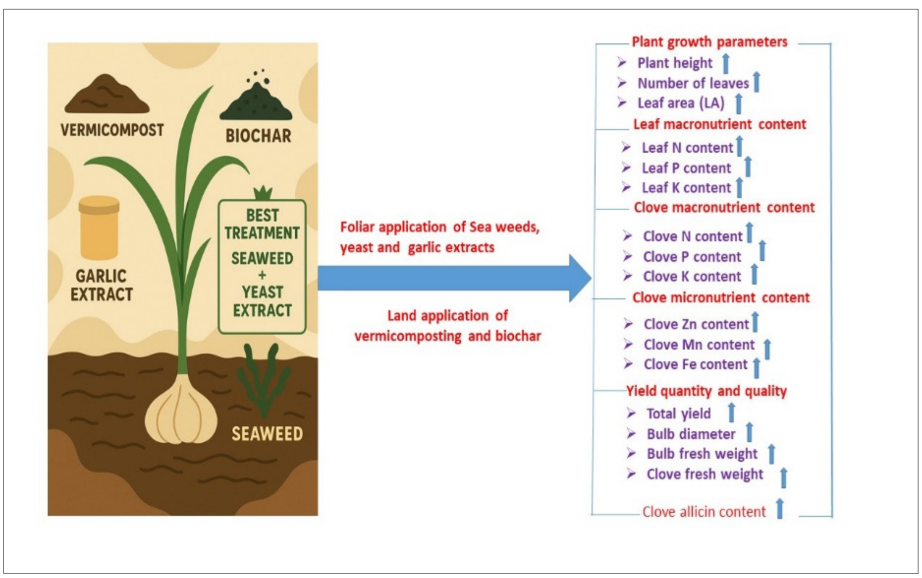

Figure 5. Schematic illustration clarifies the effect of vermicompost and biostimulants on growth performance, nutrient content, total yield, and bulb quality

Conclusions

The present study demonstrated that the co-application of organic amendments, specifically vermicompost and biochar, with biostimulants such as garlic extract (GE) or seaweed extract (SW), was beneficial for improving growth performance, crop yield, and bulb quality of garlic plants cultivated under open field conditions. This combination resulted in increased plant height, number of leaves, leaf area, total yield, bulb weight, bulb diameters, and bulb nutrient composition. Additionally, the integration of organic fertilizers (VC + BC) with biostimulants (GE + SW) led to a significant rise in bulb allicin concentration. Overall, the findings suggest that the combination of organic fertilizers with natural biostimulants represents a promising strategy for sustainable garlic production. This integrated approach not only enhances soil fertility and improves plant performance but also contributes to higher yield and quality without relying on synthetic inputs. Future research should focus on optimizing application rates and evaluating economic feasibility across various environmental conditions.

Authors' Contributions

Conceptualization: HAH, MMS and OSD; Data curation AMA, SMA, and OSD; Formal analysis MME and SMA; Funding acquisition; MME Investigation; AMA Methodology; SMA, AMA, and OSD Project administration; MME, Resources; MME, SMA, and OSD Software; SMA, and OSD Supervision HAH, MMS, OSD; Validation; SMA, and OSD Visualization MME; Writing - original draft MME, SMA, and OSD; Writing - review and editing HAH, MMS, OSD.

All authors read and approved the final manuscript.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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