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Enhancing the Growth and Productivity of Chia (*Salvia hispanica* L.) Using Compost and Biostimulants

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ABSTRACT

A two-year field study (2022/2023 and 2023/2024) investigated the effects of organic manure and biostimulant foliar applications on chia (*Salvia hispanica* L.). The experimental design included four compost rates (0, 20, 30, and 40 m^3 ha^{-1}) and foliar sprays of two biostimulants: an amino acid blend (100 and 200 ppm) and seaweed extract (2 and 4 mL L^{-1}). Results indicated that compost application significantly improved growth parameters, yield (i.e., the average seed yield increased by 103.0 and 108.4% compared to the control in the respective seasons), fixed oil production, reaching 153.7 and 153.1% per plant and per ha, respectively, compared to the control during both seasons, and chemical constituents, with the highest compost rate (40 m^3 ha^{-1}) generally showing the most positive impact. Foliar treatments with both amino acids and seaweed extract further enhanced these traits, particularly with 4 mL L^{-1} seaweed extract (i.e., the average seed yield increased by 44.6 and 42.6%, and fixed oil production increased by 65.2 and 61.9% in the respective seasons). Moreover, significant interactive effects were observed between compost and biostimulant treatments. Notably, the combination of 40 m^3 ha^{-1} compost with 4 mL L^{-1} seaweed extract yielded the most substantial improvements across all measured parameters.

Abbreviations: Amino acids (AAs), Seaweed extract (SWE), Fixed oil (FO)

Introduction

The chia plant (family Lamiaceae) thrives best in fertile soils, light to medium loam or sandy, provided they are well-drained and rich in organic matter. It can tolerate slightly acidic soils. Because its leaves contain essential oils, chia exhibits natural resistance to pests, making cultivation possible without pesticides. Commercial yields typically range from 500 to 600 kg of seeds per hectare, with trade prices varying between 800 and 1200 USD per ton (Segura-Campos et al., 2014; Peperkamp, 2014).

Chia plants can grow up to 1 meter tall. Their seeds are oval-shaped, 1–2 mm in size, and occur in colors such as black, grey, black-speckled, and white. Nutritionally, chia seeds are a rich source of mucilage, protein, oil, and fiber. They contain 25–40% oil, composed largely of omega-3 α-linolenic acid (60–68%) and omega-6 γ-linoleic acid (about 20%) (Cahill and Provance, 2002; Peiretti and Meineri, 2008; Reyes-Caudillo et al., 2008; Bresson et al., 2009). In addition, chia seeds provide protein (15–25%), lipids (30–33%), carbohydrates (26–41%), dietary fiber (18–30%), ash (4–5%), minerals, and vitamins, as well as being high in antioxidants (Ixtaina et al., 2008).

Chia has a long history of use: for more than 5,500 years, its seeds have been consumed in Mexico alongside corn. In Southern California and other parts of the United States, chia has also been used in traditional medicinal preparations (Armstrong, 2004). Today, countries including Argentina, Canada, New Zealand, Chile, the USA, and Australia incorporate chia extensively into their cuisine. With no known adverse effects, chia is considered a safe food and is now widely used in baked goods, cereal bars, nutritional supplements, cakes, and snacks (Beltran-Orozco and Romero, 2003). The seeds, which may contain up to 32% oil, are especially valued for their high dietary fiber, vitamins, minerals, polyphenolic compounds, omega-3 fatty acids, and premium-quality protein (Bochicchio et al., 2015).

Soil fertility is a critical factor in maximizing chia's productivity. Compost, produced through the decomposition of organic materials by microorganisms, is a valuable soil amendment (Lazcano et al., 2009). It supplies essential organic and nutritional compounds, reduces mineral losses, and enhances soil structure (Rantala et al., 1999). Organic fertilizers also contribute to the biological control of many plant diseases (Hoitink and Grebus, 1994) and have been shown to enhance the yield of crops such as peppermint and dragonhead (O'Brien and Barker, 1996; Hussein et al., 2006).

Amino acids (AAs) play vital physiological and biochemical roles in plants, including serving as precursors for pigments, enzymes, purines, and pyrimidines, which has led to their growing use in agriculture and horticulture to improve crop yield (Kamar and Omar, 1987). They also act as phytohormone precursors or activators, functioning as plant growth regulators (Goss, 1973; Taiz and Zeiger, 2002). Each amino acid is unique due to its specific organic side chain, and plants use them in multiple processes such as hormone synthesis, stress alleviation, and nitrogen metabolism (Maeda and Dudareva, 2012).

Foliar application of amino acids has been shown to significantly improve growth traits in *Vicia faba*, including shoot length, leaf number, biomass, and photosynthetic pigment content (Sadak et al., 2015). Numerous studies confirm that amino acids enhance plant growth and yield. For example, in *Hibiscus sabdariffa* (Mahmoud et al., 2021), *Glycine max* (Saeed et al., 2005), and *Ocimum basilicum* (Talaat and Youssef, 2002), in addition to their influence on the chemical composition of these plants.

Seaweed extract (SWE) has been widely used in agriculture due to its high content of organic matter, microelements, and growth regulators such as gibberellins, auxins, and cytokinins (Crouch and Van Staden, 1994). Although the specific mechanisms of action remain unclear, the beneficial effects of SWE are thought to result from synergistic interactions that vary with application concentration (Fornes et al., 2002). Seaweed extracts are considered non-toxic, environmentally friendly, biodegradable, and safe for human use. Overall, SWE have been shown to outperform chemical fertilizers (Booth, 1969). Turan and Köse (2004) reported that SWE application enhanced yield and increased N, P, and K content in grapevine. Similarly, Zodape et al. (2009) demonstrated that SWE improved carbohydrate and protein content, pod weight, and seed production in *Abelmoschus esculentus*. In a later study, Zodape et al. (2010) found comparable benefits in *Phaseolus radiatus*. Marine macroalgae, from which SWE is derived, are increasingly used as fertilizers in modern agriculture, as SWE provides essential nutrients, hormones, and regulatory compounds that promote plant growth and optimize yield traits (Crouch and Van Staden, 1991; Crouch and Van Staden, 1993).

The present study aimed to enhance the productivity of field-grown chia (*Salvia hispanica*) by integrating compost with biostimulant substances, namely amino acids (AAs) and SWE. Specifically, it evaluated the effects of these combined treatments on plant morphology, seed production, and fixed oil yield. The ultimate objective was to identify the most effective treatment combinations and concentrations in order to provide commercially valuable recommendations to growers in the Assiut Governorate.

Materials and Methods

A field experiment was conducted during the 2022/2023 and 2023/2024 growing seasons at the Experimental Farm of the Faculty of Agriculture, Al-Azhar University, Assiut, Egypt. The study aimed to investigate the effects of compost, foliar applications of a blend of amino acids (AAs: methionine, tryptophan, and glycine), seaweed extract (SWE), and their interactions on chia (*Salvia hispanica*) productivity and quality characteristics.

Experimental design

The experiment was arranged in a split-plot design within a randomized complete block (RCBD) structure, with three replicates. Compost was applied at four levels and assigned to the main plots, while foliar treatments (combinations of amino acids and seaweed extract, plus a control; five levels in total) were allocated to the subplots. This design resulted in 20 treatment combinations representing the interactions between compost levels and stimulant substance concentrations.

Plant material and cultivation

Chia (*Salvia hispanica*) seeds were obtained from the Department of Medicinal and Aromatic Plants, Agricultural Research Center, Dokki, Giza, Egypt. Seeds were sown directly on November 1st in both seasons (2022 and 2023) in plots measuring 2.1 × 1.8 m, which served as the experimental units. Each unit contained three rows, each 2.1 m in length, with 60 cm spacing between rows and 30 cm between hills.

Approximately 5–6 seeds were placed per hill, later thinned to one plant 45 days after sowing. Thus, each experimental unit contained 21 plants, equivalent to a planting density of 53,333 plants ha^{-1}. The chemical and physical properties of the experimental soil are presented in Table 1.

Time and fertilizer application rate

Throughout the two seasons, compost amounts of 20, 30, and 40 m^3 ha^{-1} were put into the soil before to cultivation. The fertilizer, termed compost El-Neel, came from New Minia City. Physical and chemical analyses of the compost are provided in Table 2.

Table 1. Different chemical and physical characteristics of the examined soil before the two successive growing seasons (averaged over both growing seasons).

Texture	E.C m.mohs cm^{-1})	PH (1:2.5)	O.M	$CaCo_3$	Total N	Ca^+	Mg^+	Cl^-	So_4^-	Available	
										P ppm	K Mg $100g^{-1}$ soil
Loamy	2.01	7.1	0.8%	1.98	0.15%	2.9	2.2	2.1	6.5	0.19	3.4

Table 2. Physical and chemical composition of the compost applied in this study, averaged over both growing seasons.

Parameters	%	Parameters	%	Parameters	%
pH (1-2.5)	7.4	E.C. (mm cm^{-1})	3.2	C:N Ratio	15.1
Organic matter%	39.5	Organic carbon%	21.1	Total N%	1.7
Total P%	0.8	Total K%	0.91	Fe ppm	1648
Mn ppm	96	Cu ppm	182	Zn ppm	88

Biostimulant substance treatments

Biostimulant treatments included a control (unsprayed plants, sprayed with tap water), a blend of amino acids (AAs: tryptophan, methionine, and glycine) applied at 100 and 200 ppm, and seaweed extract (SWE) applied at 2 and 4 mL L^{-1}. Foliar applications were carried out three times during each growing season, on December 30th, January 19th, and February 8th. The AAs were provided by Techno Gene Company, Dokki, Giza, Egypt, whereas SWE was applied using the Oligo X product supplied by United for Agricultural Development.

Sampling method and data collection

Three months after sowing (February 1st), five plants were randomly selected from each plot, and their height, number of branches, and herb dry weight were recorded. At the harvest stage, which occurred in the second week of April in both seasons, the number of inflorescences per plant and seed yield per plant and per hectare were measured. Fixed oil (FO) was extracted using the Soxhlet extraction method with hexane (boiling point 60–80 °C) as the solvent (A.O.A.C., 1980), and oil yield was subsequently calculated on both a per-plant (mL $plant^{-1}$) and per-hectare (L ha^{-1}) basis. Nitrogen percentage was determined using the modified Micro-Kjeldahl method (Wilde et al., 1985), phosphorus percentage was measured using the colorimetric method described by Chapman and Pratt (1975), and potassium percentage was estimated by flame photometry following Cottonie et al. (1982).

Statistical analysis

All collected data were compiled, organized, and subjected to statistical analysis according to Mead et al. (1993) using STATISTICS version 9 software (Analytical Software, 2008). Mean values of the treatment groups were compared using the Least Significant Difference (LSD) test at the 5% probability level.

Results

Vegetative growth traits

Table 3 shows that the application of compost at all levels significantly enhanced chia growth parameters during both the 2022/2023 and 2023/2024 seasons, with the exception of the 10 m^3 ha^{-1} treatment for plant height in 2023/2024. The highest values were obtained with 40 m^3 ha^{-1} of compost, which produced plant heights of 90.0 and 98.8 cm, branch counts of 17.9 and 19.5, and herb dry weights of 37.4 and 41.2 g $plant^{-1}$ in the two seasons, respectively. In comparison, the control treatment recorded plant heights of 72.5 and 78.5 cm, branch counts of 12.2 and 14.0, and herb dry weights of 19.5 and 25.7 g $plant^{-1}$ in 2022/2023 and 2023/2024, respectively.

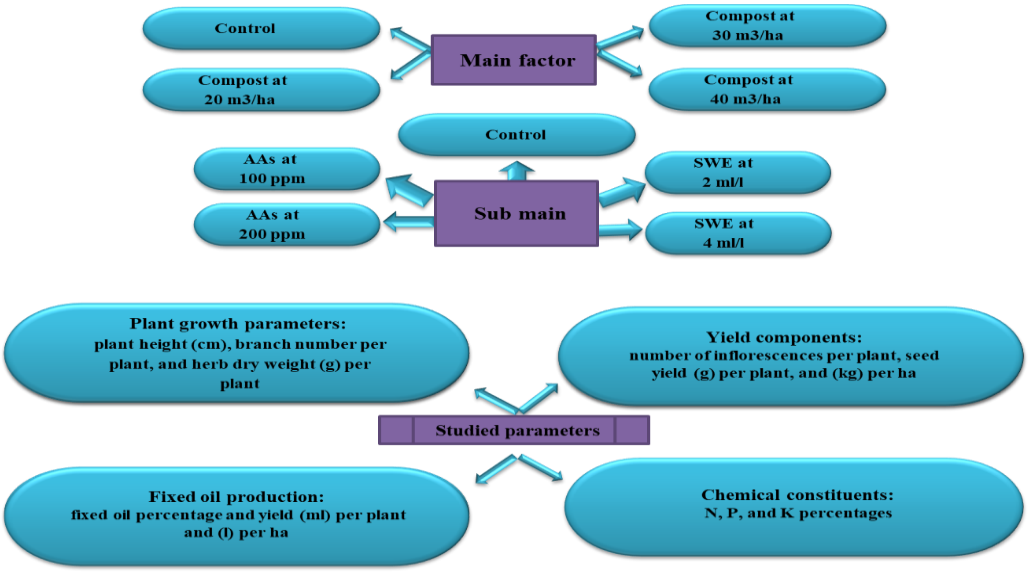

Fig. 1. A flowchart that illustrates the treatments applied and the parameters measured in the study on *Salvia hispanica*, conducted over two growing seasons (2022/2023 and 2023/2024).

Table 3. Plant height, number of branches, and herb dry weight (g)/plant as affected by compost and biostimulants during 2022/2023 and 2023/2024 seasons.

Parameters		Plant height (cm)		Branch number/plant		Herb dry weight g/plant	
Compost levels (A)		Year1	Year2	Year1	Year2	Year1	Year2
Control		72.5^{d}	78.5^{c}	12.2^{d}	14.0^{d}	19.5^{d}	25.7^{d}
20 m^3 ha^{-1}		77.5^{c}	84.8^{bc}	14.1^{c}	16.1^{c}	25.5^{c}	30.7^{c}
30 m^3 ha^{-1}		81.4^{b}	90.9^{b}	15.7^{b}	17.8^{b}	32.4^{b}	34.0^{b}
40 m^3 ha^{-1}		90.0^{a}	98.8^{a}	17.9^{a}	19.5^{a}	37.4^{a}	41.2^{a}
Biostimulants (B)							
Control		75.2^{d}	81.1^{c}	13.2^{c}	15.0^{c}	24.8^{e}	29.1^{d}
AAs1		78.6^{c}	85.7^{bc}	14.2^{bc}	16.5^{b}	26.9^{d}	32.2^{c}
AAs2		82.9^{ab}	91.9^{ab}	16.2^{a}	17.9^{a}	31.2^{b}	34.3^{b}
SWE1		80.6^{bc}	87.7^{bc}	14.8^{b}	16.9^{ab}	28.2^{c}	32.7^{c}
SWE2		84.4^{a}	94.9^{a}	16.5^{a}	18.1^{a}	32.5^{a}	36.2^{a}
(A)	(B)						
Control	Control	66.9^{k}	73.8^{h}	9.9^{k}	11.3^{i}	17.4^{l}	23.9^{j}
	AAs1	71.5^{jk}	76.9^{gh}	11.6^{jk}	13.8^{h}	18.1^{l}	25.0^{i}
	AAs2	75.1^{hij}	81.4^{efgh}	13.5^{ghij}	16.0^{efgh}	21.4^{jk}	26.2^{i}
	SWE1	73.0^{ijk}	77.4^{gh}	12.1^{ij}	13.9^{gh}	18.7^{l}	25.3^{i}
	SWE2	75.8^{ghij}	82.9^{efgh}	13.8^{fghi}	15.2^{fgh}	22.1^{ijk}	28.1^{fgh}
20 m^3 ha^{-1}	Control	74.6^{hij}	78.2^{fgh}	12.1^{ijk}	14.0^{gh}	21.0^{kl}	25.6^{i}
	AAs1	75.9^{ghij}	83.3^{defgh}	13.0^{hij}	15.6^{efgh}	23.7^{hij}	30.1^{gh}
	AAs2	79.6^{efgh}	87.8^{cdefg}	15.7^{cdefg}	17.2^{cdef}	28.3^{fg}	33.0^{fg}
	SWE1	77.3^{fghij}	85.0^{cdefgh}	14.1^{fghi}	16.2^{defg}	25.3^{hi}	31.0^{gh}
	SWE2	80.4^{efgh}	89.6^{cdefg}	15.9^{cdef}	17.7^{bcde}	29.1^{fg}	33.5^{fg}
30 m^3 ha^{-1}	Control	77.8^{fghi}	82.9^{efgh}	14.2^{fghi}	16.2^{defg}	27.2^{gh}	28.9^{fgh}
	AAs1	79.0^{efghi}	87.8^{cdefg}	14.9^{efgh}	17.3^{cdef}	30.4^{ef}	33.5^{fg}
	AAs2	83.2^{def}	94.0^{bcde}	17.0^{abcd}	18.8^{abc}	36.4^{bcd}	36.2^{de}
	SWE1	82.5^{def}	91.5^{bcdef}	15.1^{defgh}	17.9^{bcde}	31.4^{ef}	34.2^{fg}
	SWE2	84.5^{cde}	98.2^{abc}	17.3^{abc}	19.0^{abc}	36.7^{bcd}	37.2^{de}
40 m^3 ha^{-1}	Control	81.6^{efg}	89.4^{cdefg}	16.7^{bcde}	18.5^{abcd}	33.7^{de}	37.8^{de}
	AAs1	88.0^{bcd}	95.0^{bcde}	17.3^{abcd}	19.2^{abc}	35.6^{cd}	40.0^{bc}
	AAs2	93.9^{ab}	104.2^{ab}	18.6^{ab}	19.7^{ab}	38.7^{b}	41.9^{bc}
	SWE1	89.6^{bc}	96.7^{abcd}	17.8^{abc}	19.6^{abc}	37.2^{bc}	40.2^{bc}
	SWE2	97.0^{a}	108.7^{a}	19.0^{a}	20.4^{a}	42.0^{a}	45.8^{a}

AAs1= 100 ppm, AAs2= 200 ppm, SWE1= 2 mL L^{-1} and SWE2= 4 mL L^{-1}

In terms of biostimulant treatments, Table 3 shows that, compared to untreated plants, the application of biostimulant substances (amino acids and seaweed extract) at all concentrations, with the exception of amino acids at 100 ppm for plant height in 2023/2024, significantly improved chia growth parameters. The most pronounced effect was observed with seaweed extract at 4 mL L^{-1}, which increased plant height by 12.2 and 17.0%, branch number per plant by 25.0 and 20.7%, and herb dry weight per plant by 31.0 and 24.4% in the two seasons, respectively, compared with the control.

Table 3 also reveals a significant interactive effect between compost and biostimulant treatments on the vegetative growth of chia plants in both experimental seasons. Relative to untreated plants, all treatment combinations enhanced growth traits, with the highest values consistently recorded when the highest compost level (40 m^3 ha^{-1}) was combined with SWE at 4 mL L^{-1}, followed by AAs at 200 ppm. These combinations markedly improved vegetative growth parameters compared to all other treatment combinations.

Yield characteristics

Table 4 shows that fertilizing chia plants with compost at all levels significantly increased yield traits (number of inflorescences and seed output) during both growing seasons compared with the control. The highest compost level (40 m^3 ha^{-1}) was the most effective in enhancing yield traits in 2022/2023 and 2023/2024. This treatment produced the greatest number of inflorescences (22.6 and 23.8 per plant) and the highest seed output (9.8 and 10.9 g $plant^{-1}$), corresponding to seed yields of 520.5 and 583.8 kg ha^{-1} in the two seasons, respectively.

Table 4. Inflorescence count, seed yield (g)/plant in addition to seed yield (kg ha^{-1}) as affected by compost and biostimulants during 2022/2023 and 2023/2024 seasons.

Parameters		Inflorescence count/plant		Seed yield (g)/plant		Seed yield (kg ha^{-1})	
Compost levels (A)		Year1	Year2	Year1	Year1	Year2	Year1
Control		13.2^{d}	15.6^{d}	4.8^{d}	5.3^{d}	256.4^{d}	280.2^{d}
20 m^3 ha^{-1}		15.2^{c}	17.4^{c}	5.8^{c}	6.4^{c}	308.3^{c}	340.3^{c}
30 m^3 ha^{-1}		17.8^{b}	19.2^{b}	7.5^{b}	8.1^{b}	399.6^{d}	429.5^{b}
40 m^3 ha^{-1}		22.6^{a}	23.8^{a}	9.8^{a}	10.9^{a}	520.5^{a}	583.8^{a}
Biostimulants (B)							
Control		15.0^{d}	16.5^{d}	5.8^{c}	6.4^{d}	309.3^{c}	338.7^{d}
AAs1		16.3^{c}	18.3^{c}	6.3^{c}	7.0^{c}	336.0^{c}	374.7^{c}
AAs2		18.0^{b}	20.0^{ab}	7.4^{b}	8.1^{b}	392.0^{b}	433.8^{b}
SWE1		17.5^{b}	19.5^{b}	7.0^{b}	7.7^{b}	371.6^{b}	412.0^{b}
SWE2		19.3^{a}	21.0^{a}	8.4^{a}	9.1^{a}	447.1^{a}	483.1^{a}
(A)	(B)						
Control	Control	11.0^{k}	12.7^{i}	3.7^{l}	3.9^{l}	195.6^{l}	209.8^{l}
	AAs1	12.5^{jk}	14.9^{h}	4.1^{kl}	4.4^{kl}	216.9^{kl}	236.4^{kl}
	AAs2	14.6^{hi}	17.1^{efgh}	5.5^{hij}	6.1^{ghij}	291.6^{hij}	327.1^{ghij}
	SWE1	13.3^{ij}	15.8^{gh}	5.1^{ijk}	5.6^{ijk}	273.8^{ijk}	296.9^{ijk}
	SWE2	14.8^{hi}	17.6^{fgh}	5.7^{ghij}	6.2^{ghij}	304.0^{ghij}	330.7^{ghij}
20 m^3 ha^{-1}	Control	13.1^{ijk}	15.8^{gh}	4.6^{jkl}	5.3^{jk}	247.1^{jkl}	280.9^{jk}
	AAs1	14.0^{ij}	16.7^{efgh}	5.1^{ijk}	5.8^{hij}	270.2^{ijk}	309.3^{hij}
	AAs2	16.6^{fgh}	18.2^{cdef}	6.4^{efgh}	7.0^{fgh}	339.6^{efgh}	371.6^{fgh}
	SWE1	15.1^{ghi}	17.5^{fgh}	6.1^{fghi}	6.8^{fghi}	327.1^{fghi}	360.9^{fghi}
	SWE2	17.0^{defgh}	18.8^{bcde}	6.7^{efg}	7.1^{fg}	357.3^{efg}	378.7^{fg}
30 m^3 ha^{-1}	Control	16.5^{gh}	17.8^{fgh}	6.9^{ef}	7.3^{fg}	366.2^{ef}	391.1^{ef}
	AAs1	17.0^{efgh}	18.4^{cdef}	7.1^{def}	7.7^{ef}	376.9^{def}	410.7^{ef}
	AAs2	18.7^{def}	19.8^{bcde}	7.5^{de}	8.0^{def}	398.2^{de}	428.4^{def}
	SWE1	17.5^{defg}	19.9^{bcde}	7.4^{de}	7.9^{ef}	392.9^{de}	421.3^{ef}
	SWE2	19.3^{d}	20.9^{cd}	8.7^{c}	9.3^{cd}	464.0^{c}	496.0^{cd}
40 m^3 ha^{-1}	Control	19.2^{de}	19.8^{bcde}	8.0^{cd}	8.9^{de}	428.4^{cd}	472.9^{de}
	AAs1	21.8^{c}	23.0^{c}	9.0^{bc}	10.2^{bc}	480.0^{bc}	542.2^{bc}
	AAs2	22.3^{bc}	24.8^{ab}	10.1^{b}	11.4^{b}	538.7^{b}	608.0^{b}
	SWE1	23.9^{ab}	24.9^{ab}	9.2^{bc}	10.7^{b}	492.4^{bc}	568.9^{b}
	SWE2	25.9^{a}	26.6^{a}	12.4^{a}	13.6^{a}	663.1^{a}	727.1^{a}

AAs1= 100 ppm, AAs2= 200 ppm, SWE1= 2 mL L^{-1} and SWE2= 4 mL L^{-1}

Regarding biostimulant substance treatments, the findings in Table 4 demonstrate that chia plants sprayed with biostimulants exhibited significantly higher yields and yield components in both seasons compared with unsprayed plants. The application of SWE at 4 mL L^{-1} resulted in the greatest improvements, with the number of inflorescences per plant increasing by 28.7 and 27.3% in the 2022/2023 and 2023/2024 seasons, respectively, and seed yield increasing by 44.6 and 42.6% in the corresponding seasons, compared to the control. Table 4 further indicates that yield traits were significantly influenced by the interaction between compost and biostimulant treatments across both seasons. Almost all treatment combinations resulted in significant increases in yield traits compared to untreated plants, with the exception of 0 compost combined with 100 ppm AAs for inflorescence count, the same treatments for seed output in both seasons, and 20 m^3 ha^{-1} compost with no biostimulant treatment for seed output in 2022/2023. Moreover, the highest values for yield traits were consistently obtained from the combination of 40 m^3 ha^{-1} compost with SWE at 4 mL L^{-1}, which outperformed all other combinations in both the 2022/2023 and 2023/2024 growing seasons.

Fixed oil productivity

Table 5 shows that compost application markedly improved fixed oil (FO) production in chia plants compared with untreated controls. All compost levels significantly increased FO percentage, FO per plant (mL $plant^{-1}$), and FO per hectare (L ha^{-1}) during both seasons. The highest values were consistently obtained with the application of 40 m^3 ha^{-1} compost, which recorded increases of 25.9 and 22.9% in FO%, and 153.7 and 153.1% in FO yield per plant and per hectare, respectively, over the control in the 2022/2023 and 2023/2024 seasons. In absolute terms, this superior treatment produced 144.93 and 165.62 L ha^{-1} FO, compared with 57.12 and 65.42 L ha^{-1} in the control plots during the first and second seasons, respectively.

Table 5. FO%, FO yield (mL)/plant in addition to FO yield (L ha^{-1}) as affected by compost and biostimulants during 2022/2023 and 2023/2024 seasons.

Parameters		**FO%**		**FO yield (mL)/plant**		**FO yield (L ha^{-1})**	
Compost levels (A)		Year1	Year2	Year1	Year2	Year1	Year2
Control		22.02^{d}	23.00^{d}	1.071^{d}	1.227^{d}	57.12^{d}	65.42^{d}
20 m^3 ha^{-1}		23.88^{c}	24.09^{c}	1.392^{c}	1.547^{c}	74.26^{c}	82.49^{c}
30 m^3 ha^{-1}		26.32^{b}	26.85^{b}	1.978^{b}	2.167^{b}	105.47^{b}	115.58^{b}
40 m^3 ha^{-1}		27.72^{a}	28.26^{a}	2.718^{a}	3.105^{a}	144.93^{a}	165.62^{a}
Biostimulants (B)							
Control		22.82^{d}	23.58^{d}	1.373^{d}	1.548^{d}	73.22^{d}	82.55^{d}
AAs1		24.60^{c}	25.03^{c}	1.594^{c}	1.808^{c}	84.99^{c}	96.45^{c}
AAs2		25.79^{ab}	26.37^{b}	1.928^{b}	2.181^{b}	102.85^{b}	116.31^{b}
SWE1		25.20^{bc}	25.65^{c}	1.785^{b}	2.014^{b}	95.19^{b}	107.44^{b}
SWE2		26.52^{a}	27.13^{a}	2.268^{a}	2.506^{a}	120.97^{a}	133.65^{a}
(A)	(B)						
Control	Control	19.07^{h}	20.10^{h}	0.699^{p}	0.791^{o}	37.30^{p}	42.19^{o}
	AAs1	21.32^{g}	21.90^{g}	0.868^{op}	0.971^{no}	46.30^{op}	51.76^{no}
	AAs2	23.05^{e}	24.15^{ef}	1.260^{lmn}	1.480^{klm}	67.18^{lmn}	78.94^{klm}
	SWE1	22.97^{g}	24.05^{ef}	1.178^{mno}	1.347^{lm}	62.85^{mno}	71.86^{lm}
	SWE2	23.68^{e}	24.82^{e}	1.349^{klm}	1.544^{jkl}	71.96^{klm}	82.33^{jkl}
20 m^3 ha^{-1}	Control	21.53^{g}	22.20^{g}	0.996^{nop}	1.170^{mn}	53.14^{nop}	62.39^{mn}
	AAs1	23.60^{e}	23.27^{fg}	1.201^{mno}	1.353^{lm}	64.07^{mno}	72.18^{lm}
	AAs2	24.53^{ef}	24.73^{e}	1.566^{ijkl}	1.724^{ijk}	83.53^{ijkl}	91.94^{ijk}
	SWE1	23.63^{e}	23.83^{ef}	1.452^{jklm}	1.615^{jkl}	77.45^{jklm}	86.15^{jkl}
	SWE2	26.08^{d}	26.40^{d}	1.746^{ghij}	1.872^{ghij}	93.09^{ghij}	99.82^{ghij}
30 m^3 ha^{-1}	Control	24.30^{ef}	24.93^{e}	1.669^{hijk}	1.830^{hijk}	88.99^{hijk}	97.59^{hijk}
	AAs1	26.13^{cd}	26.83^{cd}	1.848^{fghi}	2.062^{fghi}	98.56^{fghi}	109.95^{fghi}
	AAs2	27.27^{bc}	27.90^{bc}	2.037^{efg}	2.241^{efg}	108.61^{efg}	119.54^{efg}
	SWE1	26.57^{cd}	26.80^{cd}	1.959^{fgh}	2.117^{fgh}	104.48^{fgh}	112.92^{fgh}
	SWE2	27.35^{bc}	27.78^{bc}	2.376^{cde}	2.585^{de}	126.71^{cde}	137.89^{de}
40 m^3 ha^{-1}	Control	26.37^{cd}	27.07^{cd}	2.127^{def}	2.400^{ef}	113.46^{def}	128.02^{ef}
	AAs1	27.33^{bc}	28.10^{bc}	2.457^{cd}	2.848^{cd}	131.02^{cd}	151.91^{cd}
	AAs2	28.32^{b}	28.70^{ab}	2.851^{b}	3.278^{b}	152.06^{b}	174.81^{b}
	SWE1	27.62^{bc}	27.93^{bc}	2.550^{bc}	2.978^{bc}	136.00^{bc}	158.82^{bc}
	SWE2	28.97^{a}	29.50^{a}	3.602^{a}	4.023^{a}	192.13^{a}	214.56^{a}

AAs1= 100 ppm, AAs2= 200 ppm, SWE1= 2 mL L^{-1} and SWE2= 4 mL L^{-1}

The findings in Table 5 showed that treating chia plants with amino acids (AAs) and seaweed extract (SWE) considerably enhanced fixed oil (FO) production in the seeds compared with untreated plants during both growing seasons. Foliar spraying with SWE at 4 mL L^{-1} produced the greatest improvements, increasing FO% by 16.2 and 15.1% and FO yield (L ha^{-1}) by 65.2 and 61.9% over the control in the 2022/2023 and 2023/2024 seasons, respectively. In absolute terms, this superior treatment resulted in FO yields of 120.97 and 133.65 L ha^{-1}, whereas the control plots produced 73.22 and 82.55 L ha^{-1} in the corresponding seasons. Moreover, all combined treatments significantly enhanced FO production traits, except for the combination of 0 compost with 100 ppm AAs, which showed no significant effect in either season, and 20 m^3 ha^{-1} compost without biostimulants, which showed no significant difference from the control in the first season. The highest productivity was achieved with the application of 40 m^3 ha^{-1} compost in combination with SWE (4 mL L^{-1}), followed by the same compost level with 200 ppm AAs. These superior treatments yielded 192.13 and 214.56 L ha^{-1} FO with compost plus SWE, and 152.06 and 174.81 L ha^{-1} FO with compost plus AAs, compared with only 37.30 and 42.19 L ha^{-1} in the controls during the 2022/2023 and 2023/2024 seasons, respectively.

Chemical constituents

Table 6 reveals that compost application had a substantial influence on the percentages of nitrogen, phosphorus, and potassium in chia plants during the 2022/2023 and 2023/2024 seasons. All compost levels generally enhanced the concentrations of these nutrients compared with the control, except for the low rate (20 m^3 ha^{-1}), which showed no significant effect on P%. The highest percentages of N, P, and K were obtained with 40 m^3 ha^{-1} compost, following a consistent trend of gradual improvement in nutrient accumulation as compost levels increased across both seasons. Relative to the control, the 40 m^3 ha^{-1} compost treatment resulted in significant increases in N% (39.2% in 2022/2023 and 26.4% in 2023/2024), P% (18.2% and 17.5%), and K% (21.9% and 16.3%).

Table 6. N and P in addition to K% as affected by compost and biostimulants during 2022/2023 and 2023/2024 seasons.

Parameters		N%		P%		K%	
Compost levels (A)		Year1	Year2	Year1	Year2	Year1	Year2
Control		2.17^{d}	2.31^{d}	0.418^{c}	0.429^{c}	2.37^{d}	2.52^{c}
20 m^3 ha^{-1}		2.47^{c}	2.53^{c}	0.430^{c}	0.438^{c}	2.52^{c}	2.65^{b}
30 m^3 ha^{-1}		2.68^{d}	2.61^{b}	0.452^{b}	0.459^{b}	2.65^{b}	2.71^{b}
40 m^3 ha^{-1}		3.02^{a}	2.92^{a}	0.494^{a}	0.504^{a}	2.89^{a}	2.93^{a}
Biostimulants (B)							
Control		2.39^{d}	2.43^{d}	0.430^{d}	0.439^{d}	2.47^{d}	2.56^{d}
AAs1		2.51^{c}	2.51^{c}	0.442^{c}	0.450^{c}	2.56^{c}	2.64^{c}
AAs2		2.66^{b}	2.65^{b}	0.455^{b}	0.463^{b}	2.67^{ab}	2.75^{b}
SWE1		2.58^{bc}	2.62^{b}	0.445^{c}	0.458^{bc}	2.61^{bc}	2.72^{b}
SWE2		2.78^{a}	2.75^{a}	0.471^{a}	0.477^{a}	2.72^{a}	2.85^{a}
(A)	(B)						
Control	Control	1.96^{j}	2.08^{n}	0.388^{g}	0.400^{g}	2.31^{h}	2.42^{f}
	AAs1	2.10^{ij}	2.19^{n}	0.412^{fg}	0.418^{fg}	2.36^{gh}	2.47^{ef}
	AAs2	2.25^{hi}	2.41^{lm}	0.430^{bcd}	0.440^{cde}	2.39^{gh}	2.52^{ef}
	SWE1	2.16^{i}	2.39^{lm}	0.418^{fg}	0.439^{cde}	2.37^{gh}	2.55^{ef}
	SWE2	2.38^{gh}	2.47^{jklm}	0.441^{bc}	0.446^{bcd}	2.43^{gh}	2.62^{ef}
20 m^3 ha^{-1}	Control	2.22^{hi}	2.37^{m}	0.415^{fg}	0.421^{ef}	2.37^{gh}	2.50^{ef}
	AAs1	2.35^{h}	2.45^{klm}	0.425^{def}	0.433^{def}	2.48^{fg}	2.58^{ef}
	AAs2	2.60^{ef}	2.57^{ghij}	0.437^{bcd}	0.446^{bcd}	2.58^{ef}	2.70^{gh}
	SWE1	2.51^{fg}	2.57^{ghij}	0.428^{def}	0.436^{cdef}	2.56^{ef}	2.71^{gh}
	SWE2	2.65^{def}	2.68^{efg}	0.447^{bc}	0.453^{bc}	2.61^{def}	2.78^{gh}
30 m^3 ha^{-1}	Control	2.57^{ef}	2.49^{ijkl}	0.431^{def}	0.440^{cd}	2.42^{gh}	2.52^{ef}
	AAs1	2.63^{ef}	2.55^{hijk}	0.440^{bc}	0.447^{bcd}	2.61^{def}	2.62^{ef}
	AAs2	2.73^{de}	2.66^{fgh}	0.453^{b}	0.459^{b}	2.73^{cd}	2.78^{gh}
	SWE1	2.66^{def}	2.58^{ghi}	0.443^{bc}	0.454^{bc}	2.64^{de}	2.75^{gh}
	SWE2	2.82^{cd}	2.77^{de}	0.493^{a}	0.498^{a}	2.84^{bc}	2.90^{b}
40 m^3 ha^{-1}	Control	2.81^{d}	2.76^{def}	0.483^{a}	0.495^{a}	2.79^{bc}	2.82^{bc}
	AAs1	2.98^{bc}	2.85^{cd}	0.492^{a}	0.502^{a}	2.80^{bc}	2.89^{b}
	AAs2	3.04^{b}	2.97^{ab}	0.498^{a}	0.508^{a}	2.97^{a}	3.02^{ab}
	SWE1	3.00^{b}	2.93^{bc}	0.493^{a}	0.503^{a}	2.89^{ab}	2.87^{b}
	SWE2	3.26^{a}	3.07^{a}	0.504^{a}	0.512^{a}	3.01^{a}	3.08^{a}

AAs1= 100 ppm, AAs2= 200 ppm, SWE1= 2 mL L^{-1} and SWE2= 4 mL L^{-1}

Table 6 demonstrates that chia plants treated with amino acids (AAs) and seaweed extract (SWE) exhibited significantly higher percentages of nitrogen, phosphorus, and potassium compared with the control during the 2022/2023 and 2023/2024 growing seasons. Foliar application of SWE at 4 mL L^{-1} produced the highest percentages of these elements, improving N% by 16.3 and 13.2%, P% by 9.5 and 8.7%, and K% by 10.1 and 11.3%, compared to unsprayed plants in the respective seasons. Moreover, Table 6 indicates a significant interaction effect between compost and biostimulant treatments on nutrient accumulation in the dried herb across both seasons. Exceptions were observed for N% with 0 compost combined with 100 ppm AAs in both seasons; for P% with 0 compost combined with 100 or 200 ppm AAs in both seasons and the same compost level combined with SWE at 2 mL L^{-1} in the first season; and for K% with 20 m^3 ha^{-1} compost plus control biostimulant substances in both seasons, as well as 30 m^3 ha^{-1} compost plus control biostimulants in 2023/2024. Among all combinations, 40 m^3 ha^{-1} compost together with SWE at 4 mL L^{-1} was the most effective in enhancing the percentages of nitrogen, phosphorus, and potassium.

Discussion

The present study demonstrated that the application of organic manure (compost) significantly enhances vegetative growth, yield components, fixed oil productivity, and chemical composition in chia plants. These positive effects are largely attributed to improvements in soil characteristics, including increased organic matter, humus content, and total nitrogen, as well as enhanced water-holding capacity and nutrient availability across a broad pH range (Follet et al., 1981; Varanini and Pinton, 1995). The gradual release of nutrients through microbial decomposition not only minimizes nitrogen losses but also sustains soil fertility, while humic compounds may further influence plant growth through hormone-like activities.

In addition, organic manure stimulates beneficial microorganisms such as *Azotobacter* and *Azospirillum*, which improve nitrogen fixation and secrete phytohormones including IAA, GA, and cytokinins (Reynders and Vlassak, 1982; Lu et al., 2002). These findings are consistent with previous research on other crops. For example, compost application in Alexandrian senna increased plant height, leaf dry yield, and total dry biomass (Hemdan et al., 2023), while guar plants exhibited higher pod numbers and seed yield following compost treatments (Abdou et al., 2017). Beyond nitrogen, organic fertilizers also supply essential nutrients such as phosphorus, sulfur, boron, and molybdenum, while promoting microbial biomass and sustaining the availability of soluble nutrients (Bohn et al., 1985; Suresh et al., 2004; Kumar et al., 2017). Taken together, these results underscore the critical role of organic amendments in enhancing crop performance and maintaining long-term soil health (Aboudrare, 2009).

The study further reveals the importance of amino acids (AAs) in regulating plant growth and productivity through both direct and indirect mechanisms. Foliar application of AAs has been reported to enhance growth attributes such as plant height, branch number, and biomass accumulation in various crops, including potato, chamomile, and roselle (Awad et al., 2007; Omer et al., 2013; Sadak et al., 2015; Gendy and Nosir, 2016). AAs stimulate growth by promoting phytohormone synthesis (e.g., gibberellins and auxins), accelerating metabolic processes, and providing readily available nitrogen to support protein biosynthesis and cell expansion (Phillips, 1971; Walter and Nawacki, 1987; Thon et al., 1981; Smith, 1982; Pareek et al., 2000).

Moreover, amino acids are vital for the biosynthesis of pigments, enzymes, vitamins, and secondary metabolites such as alkaloids and glucosinolates (Kamar and Omar, 1987; Wink, 2010). Their buffering capacity helps maintain intracellular pH stability and reduces ammonia toxicity, while specific amino acids like tryptophan serve as precursors of auxin, thereby influencing processes such as stomatal regulation and ion transport (El-Badawy et al., 1989; Goss, 1973; Taiz and Zeiger, 2002; Zahir et al., 1999; Rai, 2002). Recent findings confirm that foliar application of AAs at concentrations of 100–300 ppm significantly improves yield and growth in crops such as *Cassia acutifolia* and roselle (Hemdan et al., 2023; Mahmoud et al., 2021). Overall, amino acids enhance photosynthetic efficiency, dry matter accumulation, and the uptake of both nutrients and water, ultimately contributing to higher crop productivity (El-Shabasi et al., 2005; Shaheen et al., 2010; Sarojnee et al., 2009; Papenfus et al., 2013).

The beneficial effects of seaweed extract (SWE) on the evaluated parameters in this study can be attributed to its diverse functional properties. SWE enhances plant growth and productivity through multiple mechanisms, functioning as a potent growth stimulant by sustaining photosynthesis and increasing chlorophyll production (Aitken and Senn, 1965). As a liquid fertilizer, it provides a comprehensive blend of vitamins, amino acids, fatty acids, macronutrients, micronutrients, and phytohormones such as auxins, cytokinins, and gibberellins (Chapman and Chapman, 1981), which collectively promote cell division, nutrient uptake, and both shoot and root development (James, 1994). Beyond its nutritional role, SWE contributes to crop quality improvement and enhances resistance against both biotic stresses, such as fungal incidence and insect damage, and abiotic stresses, including sodium chloride uptake. It also facilitates seed germination and delays senescence by stimulating endogenous cytokinin production, boosting antioxidant enzyme activity, and stabilizing cell membranes (Berlyn and Russo, 1990; Verkleij, 1992; Schmidt, 2005). In addition, SWE fosters the proliferation of beneficial soil microorganisms and increases the accumulation of osmolytes and reducing sugars, which collectively improve water status and overall plant vigor (Khan et al., 2009; O'Donnell, 1973). These integrated effects contribute to improved chloroplast development, enhanced phloem loading, and delayed leaf senescence, ultimately resulting in stronger plant growth, higher resilience, and superior crop performance (Osman and Salem, 2011; Pramanick et al., 2013).

Conclusion

Based on the findings of this research conducted in Assiut Governorate, it is recommended to apply compost at a rate of 40 m^3 ha^{-1} in combination with foliar spraying of seaweed extract at a concentration of 4 mL L^{-1}. This integrated approach is effective in enhancing vegetative growth, increasing yield, improving fixed oil production, and enriching the chemical constituents of chia plants. The combined use of organic compost and foliar application of SWE therefore represents a practical and sustainable strategy for improving both the quality and quantity of chia production under agricultural conditions in Assiut Governorate and possibly other regions with similar situations.

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Author Contributions

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Conflict of Interest

The authors indicate no conflict of interest in this work.

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