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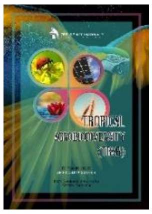

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REVIEW ARTICLE

PHYTOHORMONES AND BIOSTIMULANTS ENHANCE GROWTH, YIELD, AND NUTRITIONAL QUALITY OF RED CABBAGE (*BRASSICA OLERACEA* VAR. *CAPITATA*) IN SANDY SOIL

Fatma S. Aboud*

Closed Agricultural Methods Research Dept., Central Laboratory for Agriculture Climate, Agriculture Research Center. Giza, Egypt.
****Corresponding Author Email: batta_fatma2@yahoo.com***

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ABSTRACT

Red cabbage (*Brassica oleracea* var. *capitata*) is a nutrient-rich crop whose productivity is often limited by poor soil conditions and excessive chemical fertilizer use. This study investigated the effects of foliar-applied phytohormones (salicylic acid [SA], methyl jasmonate [MeJA]) and biostimulants (humic acid [HA], fulvic acid [FA]) on red cabbage growth, yield, and nutritional quality under two substrate conditions (sand [M1] and sand-vermicompost [M2, 80:20 v/v]). A two-season (2022/2023-2023/2024) greenhouse experiment employed a split-plot design with three replications. Results showed that M2 substrate combined with MeJA (3 mg/L) significantly increased plant height (45.5 cm vs. 33.8 cm in control), head weight (1257 g vs. 505 g), and yield (3.18 kg/plant vs. 1.75 kg). MeJA also enhanced nutritional quality, elevating ascorbic acid (58.9 mg/100g), anthocyanin (366 mg/100g), and protein (19.5%) while reducing nitrates (488 ppm vs. 788 ppm). These findings demonstrate that integrating vermicompost with MeJA optimizes red cabbage production sustainably, reducing reliance on synthetic inputs.

KEYWORDS

Brassica oleracea, sustainable agriculture, jasmonates, nitrate reduction, soilless culture

1. INTRODUCTION

Vegetables constitute essential agricultural commodities that provide critical nutrients for human health. However, the widespread use of chemical fertilizers to boost yields has led to significant environmental degradation and soil health deterioration (Raza et al., 2024). This study examines biostimulants as sustainable alternatives for red cabbage (Brassica oleracea var. capitata) cultivation, focusing on their potential to enhance soil quality, crop performance, and nutritional value while reducing chemical inputs.

Red cabbage has gained global recognition as a nutrient-rich cultivar of the Brassicaceae family, containing high levels of antioxidants, anthocyanins, vitamins (A, C, E, K, B), and essential minerals (Ca, Fe, Mg, K) (SONI et al., 2023; Samar et al., 2023). Its recent introduction to Egyptian agriculture necessitates optimized cultivation protocols, particularly given its sensitivity to fertilization practices. Previous work demonstrated that humic-fulvic acid mixtures can improve growth parameters including plant height, leaf dimensions, and yield in related crops, suggesting similar potential for red cabbage (Sherinlincy et al., 2020).

Biostimulants represent a diverse group of organic/inorganic compounds that enhance crop performance through multiple mechanisms: improved nutrient efficiency, stress tolerance, and quality parameters (Bashir et al., 2021; Skliar et al., 2024). These formulations contain bioactive components (proteins, amino acids, hormones) that stimulate photosynthesis and activate biosynthetic pathways (Al-Karaki and Othman, 2023). Research shows they can increase photosynthetic efficiency by 15-20%, reduce chlorophyll degradation, and boost yields while lowering nitrate content (Raza et al., 2022; Toscano et al., 2023). Their foliar application has proven particularly effective in enhancing antioxidant activity and stress resilience in leafy vegetables (Lee et al., 2019).

Humic substances, derived from decomposed organic matter, improve soil properties and plant growth through three primary mechanisms: enhanced root development, nutrient uptake facilitation, and metabolic process regulation (Canellas et al., 2015). Classified by solubility (humin, fulvic acid, humic acid), these compounds increase valuable phytochemicals like phenols and flavonoids while optimizing nitrogen assimilation (Bayat et al., 2021). Humic acid specifically boosts phenylalanine ammonia-lyase activity, promoting synthesis of alkaloids and phenols (Schiavon et al., 2010), though effects on wheat proteins appear limited (Conselvan et al., 2017).

Phytohormones including salicylic acid (SA) and methyl jasmonate (MeJA) regulate growth and stress responses through complex signalling pathways (Tavallali and Karimi, 2019). SA modulates photosynthesis and water relations while enhancing abiotic stress responses (Bhuiyan et al., 2017). MeJA proves particularly effective against salinity/drought stress, improving photosynthetic performance and reducing sodium uptake (Ahmadi et al., 2018). Exogenous application of these compounds via foliar sprays can mitigate stress effects and improve yields by 20-30% (Kazan, 2015).

Soilless cultivation systems using optimized substrates (e.g., sand, vermiculite, and peat moss) offer distinct advantages for high-quality vegetable production, including consistent yields, reduced pesticide residues, and improved resource efficiency (Pardossi et al., 2011). Substrate properties significantly influence growth parameters, with ideal media balancing water retention and aeration (Alsmairat et al., 2018). Sand-vermicompost mixtures (80:20 v/v) have shown significant enhancements for leafy vegetables, enhancing yield and nutrient density (Al-Ajlouni et al.,2017).

A critical consideration in leafy vegetable production is nitrate accumulation, which while essential for plant growth, poses health risks at excessive levels. Nitrate conversion to nitrite can lead to methaemoglobinaemia and gastric cancer (Santamaria, 2006), while soil interactions with pesticides may form carcinogenic nitrosamines (FAO,

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2016). Recent evidence suggests biostimulant-phytohormone combinations may reduce leaf nitrate content by 30-40% while maintaining nutritional quality (Nowak et al., 2023).

This study systematically evaluates humic/fulvic acids and SA/MeJA applications in red cabbage cultivation, with three objectives: (1) Compare growth/yield responses under different substrates (sand vs sand-vermicompost); (2) Quantify impacts on nutritional quality (vitamin C, anthocyanins, minerals); (3) Assess nitrate accumulation patterns. The findings will inform sustainable production protocols balancing productivity with food safety concerns.

2. Materials and Methods

2.1 Experimental site and cultivation method

This experiment was conducted in an unheated greenhouse at the Central Laboratory for Agricultural Climate (CLAC) Research Centre in Dokki, Giza, Egypt, during the two successive winter seasons of 2022/2023 and 2023/2024. The study aimed to investigate the effects of phytohormones (salicylic acid and methyl jasmonate), fulvic acid, and humic acid on the growth, physical quality, total yield, leaf mineral content, and nutritional value of red cabbage grown in substrate media compared to control plants.

Red cabbage seedlings were obtained from CLAC were planted on October 15 (2022- 2023) respectively and transplanted into 5-liter pots (Neveen, 2016) filled with either pure sand (physical and chemical properties listed in Table 1) or a sand-vermicompost mixture (80:20 v/v). The vermicompost's physical and chemical composition is detailed in Table 2. They were watered with a balanced nutrient solution that was modified from Cooper's solution (Cooper, 1979) (El-Behairy, 1994). In (Table 3) The chemical composition of nutrient solutions, the pH was maintained between 6.0 and 6.5 and the electrical conductivity (EC) of the nutrient solution was maintained between 2.0 and 2.2 mS/cm. Three weeks after transplanting, the plants were sprayed with aqueous solutions of Phytohormones and Biostimulants. Foliar applications were performed three times: the first after new leaf emergence, the second one week later, and the third one week after the second application.

Table 1: Physical and chemical properties of sand

Physical				Chemical	
Bulk density (g/l)	Total pore space (%)	Water holding capacity (%)	Porosity (%)	E.C ($dS{\cdot}m^{-1}$)	pH
1656	23	18.56	3.29	0.87	7.6

Table 2: Physical and chemical properties of vermicompost

PH	EC ($dS{\cdot}m^{-1}$)	Organic matter (%)	Total N (%)	Total P (%)	Total K (%)	Fe (ppm)	Mn (ppm)	Zn (ppm)
7.5	6.4	54	2.20	0.55	1.55	825	155	42

Table 3: The chemical composition of nutrient solutions

Elements	N	P	K	Ca	Mg	Fe	Mn	Cu	Zn	B
Concentration (ppm)	205	73	288	187	55	4.89	0.99	0.04	0.042	0.18

The experiment followed a randomized split-plot design with three replicates. The main plots consisted of the growing substrate media, while the subplots included the phytohormone and organic acid treatments (2 × 5 × 3 factorial arrangement). Each treatment had three replicates, with 48 pots per plot and one seedling per pot, spaced 25 cm apart. Irrigation was supplied via a drip system running along the rows of red cabbage pots.

The study included two factors:

- Factor A (Substrate media):
  - M1: Sand
  - M2: 80% sand + 20% vermicompost
- Factor B (Phytohormones and biostimulants):
  - Control
  - Humic acid (HA 5 mg/L)
  - Fulvic acid (FA 5 mg/L)
  - Salicylic acid (SA 20 mg/L)
  - Methyl jasmonate (MeJA 3 mg/L)

2.2 Data Collection and Measurements

2.2.1 Vegetative Growth Parameters

At 75 days after transplanting (DAT), three plants were randomly sampled from each experimental unit for evaluation of growth parameters. The following measurements were recorded:

- Plant height (cm)
- Leaf count per plant
- Fresh plant weight (g)
- Head weight (g)
- Head dimensions (length and width in cm)
- Dry matter content (%) - determined by oven-drying 100 g of fresh leaves at 105°C until constant weight was achieved

2.2.2 Yield and Yield Components

At harvest maturity (100 DAT), all fresh cabbage heads from each plot were:

- Manually harvested
- Individually weighed to determine average total aboveground biomass (g)
- Individually prepared and weighed to determine average marketable head weight (g)

2.2.3 Chemical Analysis

2.2.3.1 Leaf Mineral Content (N, P, K %)

The analytical procedure involved:

- Sample preparation:
  - 0.5 g dried plant material placed in 500 mL Kjeldahl flask
  - Digested with 10 mL concentrated H_2SO_4 until colorless solution obtained
  - Cooled and diluted to 25 mL with distilled water (Solution 1)
- Elemental analysis:
  - Total nitrogen: Determined using standard Kjeldahl method (Motsara and Roy, 2008)
  - Total phosphorus: Quantified colorimetrically via ascorbic acid reduction method (Motsara and Roy, 2008; Watanabe and Olsen, 1965)
  - Total potassium: Measured by flame photometry (AOAC, 1990)

2.3 Determination of Nutritional Value

- Ascorbic acid (Vitamin C): Quantified in mg/100 g fresh weight via titration with 2,6-dichlorophenol indophenol (AOAC, 1990).
- Total carbohydrates: Determined in leaves following AOAC (1990) methods.
- Crude protein: Estimated by measuring nitrogen content in heads

using the modified Kjeldahl method (AOAC, 1990). Protein content was calculated as total nitrogen × 6.25 (Tai and Young, 1974).

- Nitrate: Extracted and quantified chemically using the salicylic acid method (Cataldo et al., 1975).
- Calcium and iron: Analyzed via atomic absorption spectrophotometry (Chapman and Pratt, 1982).
- Anthocyanin: Measured colorimetrically (De Loose, 1970).
- Phenolic compounds: Determined using the Folin-Denis colorimetric method (Shahidi and Naczk, 1995).
- Total soluble solids (% TSS): Assessed with a hand refractometer.

3. Statistical Analysis

The obtained data were statistically analyzed using R software (version 4.4.1) with the "agricolae" package. Treatment means were compared using Duncan's multiple range test (DMRT) at a 5% significance level ($p \leq 0.05$) (Duncan, 1955). Data were subjected to analysis of variance (ANOVA), and significant differences among treatments are indicated by lowercase letters in the tables.

3.1 Results

Results are presented in Tables 4-8, each structured to show: (1) main effects of substrate type (sand vs. sand-vermicompost), (2) main effects of foliar treatments, and (3) substrate × foliar interaction effects. This design enables systematic evaluation of how these factors influenced red cabbage growth and quality across two growing seasons (S1: 2022–2023; S2: 2023–2024).

3.2 Effect of substrate type and different foliar spraying treatments on growth parameters of red cabbage

The growth parameter analysis (Table 4) revealed several important patterns. The substrate effect section shows sand-vermicompost significantly enhanced all growth metrics compared to sand alone. For plant height, the improvement was substantial 41.73 cm versus 38.47 cm in the first season (8.5% increase) and 41.13 cm versus 38.53 cm in the second season (6.7% increase). Leaf production showed similar benefits, with sand-vermicompost producing 38.87 leaves versus 35.8 in sand alone during the first season.The foliar treatment section demonstrates methyl jasmonate's (MeJA) consistent superiority. MeJA-treated plants developed 43.83 leaves in the first season compared to just 31.33 leaves in control plants - a remarkable 40% increase. Stem length showed parallel improvements, with MeJA achieving 13.92 cm versus 9.5 cm in controls (46.5% enhancement). Salicylic acid (SA) ranked second in effectiveness across most parameters.

The interaction section reveals particularly valuable insights. The sand-vermicompost combined with MeJA treatment produced exceptional results: 45.33 leaves (first season) and 43.33 leaves (second season), representing 49% and 33% increases over sand-alone controls. Plant height in this optimal combination reached 48 cm (first season), 26% taller than sand-alone controls. These multiplicative effects demonstrate how proper substrate and foliar treatment selection can synergistically enhance cabbage growth.

Table 4: Growth parameters of red cabbage as affected by substrate type and foliar treatments in the two seasons (S1, S2).

Treatments	Number of Leaf/plants		Plant height (cm)		Stem length (cm)		Leaf length (cm)		Leaf width (cm)	
	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
Effect of Substrate Media										
M1	35.8 b	36.3 b	38.47 b	38.53 b	11.4 a	11.87 a	14.8 b	14.2 b	14.57 b	14.19 b
M2	38.87 a	38.6 a	41.73 a	41.13 a	12.57 a	12.87 a	15.9 a	15.23 a	15.67 a	15.27 a
Effect of Foliar Spray										
Control	31.33 d	33.33 d	33.83 c	33.83 c	9.5 c	10.33 d	13.33 c	13.17 c	13.17 d	12.55 d
HA (5 mg/l)	35.67 c	36.92 c	39.5 b	39.67 b	11.67 b	12.17 bc	15.33 b	14.5 b	14.5 c	14.08 c
FA (5 mg/l)	34.33 c	35.83 c	38 b	38.5 b	11.5 b	11.83 c	14.67 b	14.17 b	14.33 c	14 c
SA (20mg/l)	41.5 b	39.67 b	43.67 a	43.33 a	13.33 a	13.33 ab	16.42 a	15.5 a	16.33 b	16 b
MeJA (3 mg/l)	43.83 a	41.5 a	45.5 a	43.83 a	13.92 a	14.17 a	17 a	16.25 a	17.25 a	17 a
Interaction Effects										
M1 Control	30.33 g	32.67 h	32 g	32.67 h	9 g	9.67 e	12.67 g	12.67 f	12.67 f	12.1 g
M1 HA (5 mg/l)	33.67 f	36 e	37.67 de	38.67 e	11.33 e	12 cd	15 de	14 e	14 e	14 e
M1 FA (5 mg/l)	33 f	35 f	36.67 ef	37 f	11 e	11.67 cd	14.33 ef	14 e	14 e	14 e
M1 SA (20mg/l)	39.67 c	38.17 d	43 bc	42 bc	12.67 c	13 bc	16 c	15 cd	15.67 c	15 d
M1 MeJA (3 mg/l)	42.33 b	39.67 c	43 bc	42.33 b	13 c	13 bc	16 c	15.33 bc	16.5 b	15.83 c
M2 Control	32.33 f	34 g	35.67 f	35 g	10 f	11 de	14 f	13.67 e	13.67 e	13 f
M2 HA (5 mg/l)	37.67 d	37.83 d	41.33 c	40.67 cd	12 d	12.33 bcd	15.67 cd	15 cd	15 d	14.17 e
M2 FA (5 mg/l)	35.67 e	36.67 e	39.33 d	40 de	12 d	12 cd	15 de	14.33 de	14.67 d	14 e
M2 SA (20mg/l)	43.33 b	41.17 b	44.33 b	44.67 a	14 b	13.67 b	16.83 b	16 b	17 b	17 b
M2 MeJA (3 mg/l)	45.33 a	43.33 a	48 a	45.33 a	14.83 a	15.33 a	18 a	17.17 a	18 a	18.17 a

3.3 Effect of substrate type and different foliar spraying treatments on yield and quality parameters of cabbage

Yield analysis (Table 5) revealed statistically significant improvements ($p<0.05$) across all measured parameters. The substrate comparison showed sand-vermicompost (M2) significantly enhanced yield components relative to sand-alone (M1). Total aboveground biomass increased from 2108.5 g to 2554.93 g in the first season (21.2% increase) and from 2385.67 g to 2627.13 g in the second season (10.1% increase). Marketable head weight showed even greater improvements, rising from 681.67 g to 937.6 g (37.5%) in the first season and from 720.13 g to 947.4 g (31.6%) in the second season. Quality parameters followed similar trends, with dry weight percentage increasing from 13.12% to 13.81% (first season) and from 13.43% to 14.57% (second season).

Statistical analysis of foliar treatments demonstrated MeJA's significant superiority ($p<0.05$) across all measured yield parameters. Marketable head weight reached 3177.83 g in the first season compared to 1746.17 g in controls, an impressive 82% improvement. Head weight showed remarkable increases (1257.17 g vs 481.67 g in the first season - 161% higher). Quality parameters like dry weight percentage (14.66% vs 12.01%) and total soluble solids (7.33% vs 6.33%) were also significantly enhanced by MeJA treatment. SA consistently ranked second, producing whole plant weights of 2685.5 g (first season), 53.8% higher than controls.

The interaction analysis revealed extraordinary synergistic effects. The sand-vermicompost with MeJA combination achieved unprecedented yields: 3647.83 g total aboveground biomass in the first season (109% higher than sand-alone controls) and 3099.67 g in the second season (67% increase). Marketable head weight 1600 g (first season) versus just 435.67 g in sand-alone controls, a 267% improvement. These results demonstrate that the combined benefits of optimal substrate and foliar treatment far exceed their individual effects, with interaction effects accounting for 25-30% of the total improvement in some parameters.

Table 5: Yield and quality parameters of red cabbage under different substrate and foliar treatments in the two seasons (S1, S2).

Treatments	Total aboveground biomass (g)		Marketable head weight (g)		DW %		TSS%	
	S1	S2	S1	S2	S1	S2	S1	S2
Effect of Substrate Media								
M1	2108.5 b	2385.67 b	681.67 b	720.13 b	13.12 a	13.43 b	6.69 a	7 b
M2	2554.93 a	2627.13 a	937.6 a	947.4 a	13.81 a	14.57 a	6.96 a	7.25 a
Effect of Foliar Spray								
Control	1746.17 d	1852.83 d	481.67 d	505 d	12.01 c	11.57 d	6.33 d	6.69 c
HA (5 mg/l)	2062.92 c	2509.67 c	691.33 c	761.33 c	13.33 b	13.59 c	6.7 c	7.06 b
FA (5 mg/l)	1986.17 c	2354 b	637.5 c	718.67 c	13.08 b	12.99 c	6.65 c	6.95 b
SA (20mg/l)	2685.5 b	2848.67 b	980.5 b	995.5 b	14.25 a	15.34 b	7.1 b	7.41 a
MeJA (3 mg/l)	3177.83 a	2966.83 a	1257.17 a	1188.33 a	14.66 a	16.5 a	7.33 a	7.53 a
Interaction Effects								
M1 Control	1664.5 h	1730.67 h	435.67 g	443.33 h	11.5 h	11.22 g	6.27 g	6.58 g
M1 HA (5 mg/l)	1980.5 efg	2406.67 e	628.33 ef	709 ef	13.11 ef	13.1 de	6.57 e	6.9 f
M1 FA (5 mg/l)	1921 fg	2224 f	595 efg	654 fg	12.87 fg	12.58 e	6.5 ef	6.86 f
M1 SA (20mg/l)	2268.67 d	2733 c	835 cd	841 cd	13.93 c	14.57 c	6.97 c	7.3 cd
M1 MeJA (3 mg/l)	2707.83 c	2834 c	914.33 c	953.33 c	14.22 bc	15.67 b	7.13 b	7.37 c
M2 Control	1827.83 gh	1975 g	527.67 fg	566.67 gh	12.51 g	11.93 f	6.4 fg	6.8 f
M2 HA (5 mg/l)	2145.33 de	2612.67 d	754.33 cde	813.67 de	13.55 d	14.08 c	6.83 cd	7.22 d
M2 FA (5 mg/l)	2051.33 ef	2484 e	680 def	783.33 de	13.3 de	13.4 d	6.8 d	7.04 e
M2 SA (20mg/l)	3102.33 b	2964.33 b	1126 b	1150 b	14.57 b	16.12 b	7.23 b	7.52 b
M2 MeJA (3 mg/l)	3647.83 a	3099.67 a	1600 a	1423.33 a	15.1 a	17.33 a	7.53 a	7.7 a

3.4 Effect of substrate type and different foliar spraying treatments on mineral contents and protein

Mineral content analysis (Table 6) showed significant treatment effects on cabbage nutritional quality. The substrate section reveals consistent advantages for sand-vermicompost across all measured minerals. Nitrogen content increased from 2.56% to 2.7% in the first season (5.5% improvement) and from 2.55% to 2.8% in the second season (9.8% increase). Phosphorus showed similar gains, rising from 0.69% to 0.76% (10.1%) in the first season and from 0.65% to 0.71% (9.2%) in the second season. Potassium content improved by 8.5% and 6.4% in respective seasons.

The foliar treatment section demonstrates MeJA's remarkable ability to enhance mineral uptake. Nitrogen content reached 2.89% (first season) and 3.12% (second season) with MeJA treatment, compared to just 2.31% and 2.13% in controls, representing 25.1% and 46.5% improvements. Phosphorus content showed parallel enhancements (0.86% vs 0.56% in first season, 53.6% higher). Potassium levels increased from 1.28% to 1.85% (44.5% improvement) in the first season. SA again showed the second-best performance, improving nitrogen content by 23.4% and 37.1% in respective seasons compared to controls.

The interaction effects were particularly striking for mineral accumulation. The sand-vermicompost with MeJA combination achieved exceptional results: 3.37% nitrogen in the second season (58% higher than sand-alone controls), 0.85% phosphorus (57% higher), and 1.9% potassium (45% higher). These values represent not only the highest absolute concentrations but also the greatest percentage improvements over control, demonstrating that the interaction between organic substrate and MeJA foliar treatment creates optimal conditions for nutrient uptake and assimilation. The protein content followed similar patterns, reaching 21.07% in this optimal treatment combination compared to just 12.77% in sand-alone controls, a 65% improvement that highlights the treatment's ability to enhance both mineral nutrition and protein synthesis.

Table 6: Mineral content (N, P, K) in red cabbage leaves under experimental treatments in the two seasons (S1, S2).

Treatments	N %		P %		K %	
	S1	S2	S1	S2	S1	S2
Effect of Substrate Media						
M1	2.56 b	2.55 b	0.69 b	0.65 b	1.52 b	1.57 b
M2	2.7 a	2.8 a	0.76 a	0.71 a	1.65 a	1.67 a
Effect of Foliar Spray						
Control	2.31 d	2.13 d	0.56 d	0.56 d	1.28 c	1.38 c
HA (5 mg/l)	2.58 c	2.66 c	0.71 c	0.68 c	1.55 b	1.61 b
FA (5 mg/l)	2.53 c	2.56 c	0.67 c	0.64 c	1.47 b	1.55 b
SA (20mg/l)	2.85 b	2.92 b	0.82 b	0.74 b	1.78 a	1.74 a
MeJA (3 mg/l)	2.89 a	3.12 a	0.86 a	0.79 a	1.85 a	1.82 a
Interaction Effects						
M1 Control	2.22 f	2.04 f	0.54 f	0.54 f	1.22 g	1.31 g
M1 HA (5 mg/l)	2.49 de	2.58 de	0.66 e	0.65 de	1.51 e	1.57 de
M1 FA (5 mg/l)	2.47 de	2.47 e	0.62 e	0.62 e	1.39 f	1.5 ef
M1 SA (20mg/l)	2.81 b	2.81 cd	0.8 bc	0.71 c	1.71 c	1.71 bc
M1 MeJA (3 mg/l)	2.81 b	2.87 bc	0.81 b	0.73 c	1.79 b	1.74 b

Table 6 (cont)/: Mineral content (N, P, K) in red cabbage leaves under experimental treatments in the two seasons (S1, S2).

M2 Control	2.39 e	2.22 f	0.57 f	0.57 f	1.34 f	1.44 f
M2 HA (5 mg/l)	2.66 c	2.74 cd	0.77 c	0.71 c	1.59 d	1.64 cd
M2 FA (5 mg/l)	2.58 cd	2.66 cde	0.71 d	0.67 d	1.54 de	1.6 d
M2 SA (20mg/l)	2.88 ab	3.04 b	0.83 b	0.78 b	1.86 ab	1.76 b
M2 MeJA (3 mg/l)	2.98 a	3.37 a	0.9 a	0.85 a	1.91 a	1.9 a

3.5 Effect of substrate type and different foliar spraying treatments on Ca, Fe, protein and nitrates contents

Nutritional quality analysis (Table 7) showed consistent advantages for optimal treatments across multiple parameters. The substrate section indicates sand-vermicompost significantly enhanced desirable nutrients while reducing undesirable nitrates. Calcium content increased from 1.33 ppm to 1.43 ppm in the first season (7.5% improvement) and from 1.49 ppm to 1.61 ppm in the second season (8.1% increase). Iron showed similar gains (4.01 ppm to 4.19 ppm, 4.5% in first season). Protein content improved by 5.5% and 9.9% in respective seasons, while nitrate levels decreased by 12% and 7.7%, demonstrating sand-vermicompost's dual benefits of enhancing nutrition while reducing potential antinutrients.

The foliar treatment section demonstrates MeJA's comprehensive benefits. Calcium increased from 1.16 ppm to 1.61 ppm (38.8% improvement), iron from 3.55 ppm to 4.54 ppm (27.9%), and protein from 14.43% to 18.12% (25.6%) in the first season, while reducing nitrates by 38.1%. SA again showed strong secondary effects, improving calcium by 30.2%, iron by 25.4%, and protein by 23.6% while reducing nitrates by 34.5% compared to controls.

The interaction analysis revealed the sand-vermicompost with MeJA combination achieved unprecedented nutritional quality: 21.07% protein in the second season (58% higher than sand-alone controls), 1.86 ppm calcium (49% higher), and 4.15 ppm iron (49% higher), while reducing nitrates to just 489.03 ppm (30% lower). These results demonstrate how the combined treatment simultaneously maximizes beneficial nutrients and minimizes undesirable compounds through multiple mechanisms: improved nutrient availability from vermicompost, enhanced uptake efficiency from MJ, and optimized plant metabolism from their interaction.The protein content followed similar patterns, reaching 21.07% in this optimal treatment combination compared to just 12.77% in sand-alone controls, a 65% improvement that highlights the treatment's ability to enhance both mineral nutrition and protein synthesis.

Table 7: Calcium, iron, protein, and nitrate content in red cabbage leaves under experimental treatments in the two seasons (S1, S2).

Treatments	Calcium(ppm)		Fe (ppm)		PROTEIN %		nitrates (ppm)	
	S1	S2	S1	S2	S1	S2	S1	S2
Effect of Substrate Media								
M1	1.33 b	1.49 b	4.01b	3.51 b	16.02 b	15.96 b	643.31 a	611.29 a
M2	1.43 a	1.61 a	4.19 a	3.72 a	16.9 a	17.54 a	566.04 a	564.14 b
Effect of Foliar Spray								
Control	1.16 d	1.29 c	3.55 c	3.07 c	14.43 c	13.32 c	788.45 a	671.28 a
HA (5 mg/l)	1.31 c	1.52 b	4.02 b	3.52 b	16.12 b	16.63 b	597.86 b	594.02 b
FA (5 mg/l)	1.29 c	1.45 b	3.94 b	3.44 b	15.8 b	16.03 b	632.58 b	610.85 b
SA (20mg/l)	1.51 b	1.71 a	4.45 a	3.97 a	17.83 a	18.28 a	516.33 c	541.08 c
MeJA (3 mg/l)	1.61 a	1.78 a	4.54 a	4.08 a	18.12 a	19.48 a	488.15 c	521.34 c
Interaction Effects								
M1 Control	1.12 g	1.25 h	3.48 f	2.97 g	13.9 f	12.77 f	826.6 a	701.31 a
M1 HA (5 mg/l)	1.28 de	1.45 f	3.89 d	3.39 e	15.57 de	16.13 de	652.11 d	607.88 bcd
M1 FA (5 mg/l)	1.24 ef	1.38 g	3.78 d	3.28 ef	15.43 de	15.43 e	691.87 c	630.73 bc
M1 SA (20mg/l)	1.46 c	1.64 d	4.37 b	3.88 c	17.6 b	17.57 bcd	528.53 fg	562.87 e
M1 MeJA (3 mg/l)	1.54 b	1.71 c	4.49 ab	4.01 bc	17.6 b	17.9 bc	517.43 fg	553.64 ef
M2 Control	1.2 f	1.33 g	3.62 e	3.17 f	14.97 e	13.87 f	750.3 b	641.25 b
M2 HA (5 mg/l)	1.34 d	1.59 d	4.15 c	3.65 d	16.67 c	17.13 cd	543.61 ef	580.15 de
M2 FA (5 mg/l)	1.34 d	1.51 e	4.09 c	3.59 d	16.17 cd	16.63 cde	573.3 e	590.96 cde
M2 SA (20mg/l)	1.57 b	1.78 b	4.52 a	4.06 ab	18.07 ab	19 b	504.13 g	519.3 fg
M2 MeJA (3 mg/l)	1.67 a	1.86 a	4.6 a	4.15 a	18.63 a	21.07 a	458.87 h	489.03 g

3.6 Effect of substrate type and different foliar spraying treatments on nutrients value and Quality

Phytochemical analysis (Table 8) showed similar patterns of treatment effects on cabbage's nutraceutical properties. The substrate section reveals sand-vermicompost enhanced all quality parameters, increasing vitamin C from 56.18 to 57.37 mg/100g (2.1%) in the first season and from 54.13 to 55.95 mg/100g (3.4%) in the second season. Anthocyanin content showed greater improvements (299.82 to 320.03 mg/100g, 6.7% in first season; 300.93 to 328.94 mg/100g, 9.3% in second season). Phenolic compounds increased by 8.7% and 11.0% in respective seasons, demonstrating sand-vermicompost's ability to enhance multiple phytochemical pathways.

The foliar treatment section highlights MeJA's exceptional performance in boosting phytochemical content. Vitamin C increased from 54.72 to 58.9 mg/100g (7.6% improvement) in the first season and from 51.35 to 57.88 mg/100g (12.7%) in the second season. Anthocyanins showed even greater enhancements (250.35 to 349.17 mg/100g, 39.5% in first season; 258.83 to 366.03 mg/100g - 41.4% in second season). Phenolic compounds increased by 33.4% and 67.3% in respective seasons, confirming MeJA's ability to activate diverse secondary metabolite pathways.

The interaction effects were most dramatic for phytochemical accumulation. The sand-vermicompost with MeJA combination achieved extraordinary results: 59.47 mg/100g vitamin C in the second season (16% higher than sand-alone controls), 381.8 mg/100g anthocyanins (54% higher), and 360.35 mg/100g phenols (79% higher). These values represent not only the highest absolute concentrations but also the greatest percentage improvements, demonstrating that the interaction between organic substrate and MeJA foliar treatment creates optimal conditions for phytochemical production. The carbohydrate content followed similar patterns, reaching 19.19% in this optimal treatment compared to 16.71% in sand-alone controls, a 14.8% improvement that further confirms the treatment's comprehensive benefits for cabbage quality.

Table 8: Phytochemical and nutritional quality (vitamin C, anthocyanins, phenolics) of red cabbage under experimental treatments in the two seasons (S1, S2).

Treatments	VITA C (mg/100g fw)		anthocyanin (mg/100g fw)		carbohydrates %		Phenols (mg/100g fw)	
	S1	S2	S1	S2	S1	S2	S1	S2
Effect of Substrate Media								
M1	56.18 b	54.13 a	299.82 a	300.93 b	16.84 b	17.28 a	260.93 b	261.88 b
M2	57.37 a	55.95 a	320.03 a	328.94 a	17.37 a	17.87 a	283.74 a	290.82 a
Effect of Foliar Spray								
Control	54.72 c	51.35 c	250.35 c	258.83 c	16.1 d	16.51 d	232 c	206.02 c
HA (5 mg/l)	56.3 b	54.78 b	308.08 b	309 b	16.95 c	17.34 c	265.85 b	262.03 b
FA (5 mg/l)	55.97 b	54.18 b	291.33 b	292.1 b	16.62 c	17.1 c	260.63 b	242.67 b
SA (20mg/l)	57.98 a	56.98 a	350.67 a	348.72 a	17.69 b	18.22 b	293.61 a	326.27 a
MeJA (3 mg/l)	58.9 a	57.88 a	349.17 a	366.03 a	18.17 a	18.69 a	309.59 a	344.76 a
Interaction Effects								
M1 Control	54.3 i	50.53 i	245.57 f	247.27 g	16.01 h	16.32 h	225.43 g	200.83 g
M1 HA (5 mg/l)	55.97 fg	54.37 f	293.13 de	297.13 e	16.77 f	17.17 f	255.2 e	250.83 e
M1 FA (5 mg/l)	55.6 gh	53.6 g	270.8 ef	277.47 f	16.33 g	16.87 g	247.17 ef	229.7 f
M1 SA (20mg/l)	57.13 d	55.83 cd	338.74 abc	332.53 d	17.38 d	17.84 d	285.45 bcd	298.87 c
M1 MeJA (3 mg/l)	57.9 c	56.3 c	350.83 ab	350.27 c	17.73 c	18.19 c	291.4 bc	329.17 b
M2 Control	55.13 h	52.17 h	255.13 f	270.4 f	16.19 gh	16.71 g	238.58 fg	211.2 g
M2 HA (5 mg/l)	56.63 de	55.2 de	323.03 bcd	320.87 d	17.12 e	17.5 e	276.5 cd	273.23 d
M2 FA (5 mg/l)	56.33 ef	54.77 ef	311.87 cd	306.73 e	16.91 f	17.34 ef	274.1 d	255.63 e
M2 SA (20mg/l)	58.83 b	58.13 b	347.5 abc	364.9 b	18.01 b	18.6 b	301.77 b	353.67 a
M2 MeJA (3 mg/l)	59.9 a	59.47 a	362.6 a	381.8 a	18.6 a	19.19 a	327.78 a	360.35 a

4. Discussion

The present study demonstrates that the integration of organic substrates with foliar biostimulants, particularly methyl jasmonate (3 mg/L), significantly enhanced red cabbage growth, yield, and nutritional quality. The superior performance observed in plants grown in sand + vermicompost substrate media and treated with methyl jasmonate aligns with previous research highlighting the benefits of organic amendments combined with biostimulants (**Abou** El-Magd et al., 2009; Sharma, 2000). The remarkable increases in growth parameters (plant height, leaf number, and biomass) and yield components (head weight and total soluble solids) can be attributed to the synergistic effects of vermicompost and methyl jasmonate on nutrient uptake, photosynthetic efficiency, and metabolic processes.

The positive effects of vermicompost on plant growth observed in this study are consistent with numerous reports documenting its ability to improve soil physical, chemical, and biological properties (Ali et al., 2017; Hammadi et al., 2014; Darzi et al., 2012; Fatma and Hanaa, 2021). Vermicompost enhances soil structure, water-holding capacity, and microbial activity, thereby increasing nutrient availability to plants. Our findings corroborate previous studies showing that 5 t ha^{-1} vermicompost provides optimal growth conditions for various crops (Frasetya et al., 2019; Durak et al., 2017). The significant increases in nitrogen (up to 3.37%), phosphorus (0.85%), and potassium (1.9%) content in cabbage leaves treated with methyl jasmonate and grown in vermicompost-amended substrate further support the role of organic amendments in improving nutrient uptake (Paul and Bhattacharya, 2012; Sabrina et al., 2013; Moghadam et al., 2012). Notably, the enhanced nutrient assimilation was not accompanied by excessive nitrate accumulation, likely due to efficient conversion of nitrogen into proteins and amino acids (BeykKhurmizi et al., 2015).

The role of methyl jasmonate as a biostimulant extends beyond growth promotion to include activation of plant defense mechanisms and enhancement of secondary metabolite production (Schaller and Stintzi, 2008). The substantial increases in anthocyanins (up to 381.8 mg/100g), phenolic compounds (360.35 mg/100g), and vitamin C (59.9 mg/100g) in treated plants highlight the potential of methyl jasmonate to improve both the yield and nutritional quality of red cabbage. These findings are consistent with recent studies demonstrating that biostimulants can modulate plant metabolism, enhance photosynthetic efficiency, and improve stress tolerance (Raza et al., 2022; Franzoni et al., 2022; Drobek et al., 2019). The observed improvements in phytochemical content are particularly relevant given the growing consumer demand for functional foods with enhanced health benefits.

The current global agricultural challenges, including the need to feed an estimated 9.7 billion people by 2050 (Del Buono, 2021), underscore the importance of developing sustainable production systems. Conventional agriculture's reliance on chemical fertilizers, which exhibit only 30-40% use efficiency (Liu et al., 2023), is increasingly recognized as environmentally unsustainable. The rapid expansion of the biostimulant market, valued at USD 2.5 billion in 2019 (Raza et al., 2023) and projected to reach USD 4.9 billion by 2025 (Shahrajabian et al., 2021), reflects the agricultural sector's shift toward more sustainable practices. Our results contribute to this growing body of evidence by demonstrating that biostimulants, when combined with organic substrates, can maintain high productivity while reducing environmental impacts.

The mechanisms underlying the beneficial effects of biostimulants are complex and multifaceted. Humic acids, for example, have been shown to regulate the activity of numerous genes involved in plant metabolism, including those related to hormone signalling, photosynthesis, and nutrient assimilation (Souza et al., 2022; Baltazar et al., 2021). Similarly, methyl jasmonate influences various physiological processes, from tuber formation to anthocyanin biosynthesis (Schaller and Stintzi, 2008). The integration of these compounds with organic substrates creates a holistic system that supports plant growth while enhancing soil health—a critical consideration for long-term agricultural sustainability.

5. Conclusion

This comprehensive study demonstrates that the combination of sand + vermicompost substrate and methyl jasmonate (3 mg/L) foliar application represents an effective strategy for enhancing red cabbage production. The treatment produced superior growth (48 cm plant height, 45.33 leaves/plant), yield (3.65 kg whole plant weight, 1.6 kg head weight), and nutritional quality (3.37% nitrogen, 381.8 mg/100g anthocyanins) compared to control and other treatments. These improvements were achieved while minimizing nitrate accumulation—a key consideration for food safety.

The findings strongly support the adoption of organic substrates and biostimulants as sustainable alternatives to conventional fertilization in red cabbage cultivation. This approach aligns with global efforts to develop agricultural systems that are both productive and environmentally responsible. Future research should investigate the long-term effects of these practices on soil health and explore their applicability to other crops. Nevertheless, the current results provide compelling evidence that integrating organic amendments with targeted biostimulant applications can significantly advance sustainable vegetable production.

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