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Agronomic and Phytochemical Enhancement of Ajwain (*Trachyspermum ammi* L.) using Compost and Foliar Application of Garlic and Moringa Extracts

El-Sayed Mohamed Mahmoud[1]*, Ahmed Fouad Ali[1], Abeer Mohamed Shehata[2]

1 Horticulture Department, Faculty of Agriculture, Al-Azhar University, Assiut, Egypt
2 Medicinal and Aromatic Plants Department, Institute of Horticulture Research, Agriculture Research Centre, Cairo, Egypt

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*Corresponding author's email: ahmadfouad@agricuta.edu.eg

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ABSTRACT

A field experiment was conducted during the 2022-2023 and 2023-2024 growing seasons at the Almonsha Center in Sohag Governorate, Egypt. The study employed a split-plot design with three replicates to investigate the effects of organic fertilizers and some plant extracts as foliar applications on ajwain (*Trachyspermum ammi*) plants. The experiment employed four levels of compost (0, 20, 30, and 40 m^3 per ha) and foliar applications utilizing two plant extracts: garlic extract (GE) at concentrations of 0, 10, and 20 mL L^{-1}, and moringa extract (ME) at 10 and 20 g L^{-1}. The effects of these treatments and their interactions were evaluated in terms of ajwain vegetative growth (weight of herb as dry plant matter^{-1}), yield (fruit (g) per plant and (kg) per ha), essential oil yield and percentage, and some chemical constituents (N, P and K%). The highest compost application (40 m^3 ha^{-1}) significantly improved all parameters, increasing dry herb weight by 64.3 and 40.7%, fruit yield by 87.6 and 79.4%, and essential oil yield by 98.3 and 88.0%, compared to the control in the two seasons, respectively. Garlic extract at 20 mL L^{-1} was the most effective foliar treatment, enhancing dry herb weight by 20.2 and 16.7%, fruit yield by 48.1 and 38.1%, and essential oil yield by 54.5 and 43.1%, compared to the control in the first and second seasons, respectively. The combination of 40 m^3 ha^{-1} compost with 20 mL L^{-1} garlic extract produced the greatest overall improvements.

Introduction

Ajwain (*Trachyspermum ammi* L.) is a perennial herb belonging to the Apiaceae family, native to the Mediterranean and Southwest Asia. It is widely cultivated for its aromatic, grayish-brown seeds on black alluvial soils in regions such as Egypt, India (notably Rajasthan and Gujarat), Iran, and Iraq (Thomas et al., 2020; Fathi and Najafian, 2020). The branched plants (≤90 cm tall) bear pinnate leaves and small white flowers; their seeds contain 2–5% essential oil, 35–60% thymol, as well as α-pinene, p-cymene, γ-terpinene, and limonene. These features underpin uses in spice blends, perfumery, pharmaceuticals, and as germicidal, antispasmodic, and fungicidal agents (Mohagheghzadeh et al., 2007; Nath et al., 2008; Yadav et al., 2011). Traditionally, ajwain serves as a stimulant, laxative, and stomachic, with thymol extracts employed in cholera treatment and explored against COVID-19 (Lawless, 1992; Gaddamwar et al., 2020).

Sustainable agriculture aims to enhance crop productivity while reducing adverse environmental impacts, a challenge that is particularly pronounced in semi-arid regions where low soil organic matter undermines soil fertility and agricultural performance (Al-Sayed et al., 2024). In Egypt's Northwestern Coastal region, calcareous soils characterized by high pH and elevated calcium carbonate levels occupy nearly 8% of the country's land area. These soil conditions frequently limit nutrient availability, compelling farmers to apply higher rates of fertilizers to alleviate nutrient deficiencies and achieve satisfactory crop yields (Rasha, 2005; Ali et al., 2020). Composting transforms plant and animal residues into humus-rich, pathogen-free soil amendments that recycle organic waste, degrade toxins (such as pesticides and petroleum), eliminate weed seeds, enhance soil structure, improve water retention capacity, facilitate nutrient cycling, and regulate cation–anion exchange capacity, thereby stabilizing yields and reducing reliance on synthetic fertilizers (Madeleine et al., 2005; Paulin and Peter, 2008; Edwards and Hailu, 2011; Zheljazkov and Warman, 2004). In medicinal and aromatic crops, such as *Ocimum sanctum*, *Rosmarinus officinalis*, *Tagetes erecta*, *Mentha spp.*, and *Hyoscyamus muticus*, the use of compost can increase plant growth, biomass, and essential-oil yield and composition (Khalil, 2002; Khalil and El-Sherbeny, 2003; Naguib and Aziz, 2004).

Garlic extract from *Allium sativum* L. is rich in sulfur-amino acids (cysteine and methionine), volatile oils (allicin, alliin), sugars, iodine, and vitamins. It exhibits auxin-like activity that promotes lateral extension, cell elongation, and biomass accumulation in bulbous ornamentals (*Narcissus tazetta*, *Polianthes tuberosa*) and *Freesia refracta*. It enhanced growth in *Schefflera arboricola* (Gommaa et al., 2005; Emam, 2010; Atowa, 2012; Hanafy et al., 2012). Its organosulfur compounds function as natural insect repellents/insecticides, and aqueous extracts trigger defense responses against *Phytophthora capsici* in pepper (Desvani et al., 2015; Sikandar et al., 2018).

Moringa leaf extract (MLE) is a versatile biostimulant replete with phytohormones (zeatin, indole-3-acetic acid, cytokinins, and gibberellins) along with an array of macro- and micronutrients (nitrogen, phosphorus, potassium, calcium, magnesium, iron, zinc, manganese, copper, and selenium), vitamins (ascorbic acid), amino acids, phenolics, flavonoids, and saponins, conferring antioxidant capacity and stress resilience (Barciszweski et al., 2000; Arif et al., 2019; García-Beltrán et al., 2020). Foliar/soil applications of MLE enhance nutrient uptake, photosynthesis, and dry-matter accumulation, yielding 20-45% increases in vegetative growth, fruit set, seed count, and essential-oil content across vegetables, fruits, ornamentals (Foidle et al., 2001; Culver et al., 2012; Yameogo et al., 2011; Latif and Mohamed, 2016). Collectively, these organic inputs and biostimulants, compost, garlic extract, and MLE, offer sustainable, eco-friendly strategies to enhance soil fertility, plant growth, yield, and product quality in ajwain and a wide array of horticultural and medicinal crops.

The principal objectives of this study were to explore the ramifications of applying organic fertilizers using compost and foliar application of garlic and moringa extracts as biostimulants on ajwain (*Trachyspermum ammi*) plants. In particular, the research evaluated the individual and combined effects of these treatments on ajwain vegetative growth, fruit yield, the production of essential oils, along with various chemical constituents.

Materials and Methods

A two-season field trial (2022/23–2023/24) was conducted in Almonsha Center, Sohag Governorate, Egypt (26°22′45.5″N, 31°46′06.1″E), to assess the impact of compost-based organic fertilization and foliar sprays (garlic and moringa extracts) on ajwain (*Trachyspermum ammi* L.). Ajwain seeds, sourced from Cairo University’s Experimental Farm, were sown directly on November 2 each season at 64000 plants per ha (five seeds per hill, thinned to one plant) in 3.60 m^2 plots (1.8 × 2.0 m), arranged in three 60 cm–spaced rows with 25 cm between plants. Basal compost treatments (0, 20, 30, and 40 m^3 ha^{-1}) formed the main-plot factor, while foliar sprays of garlic extract (0, 10, and 20 mL L^{-1}) and moringa leaf extract (10 and 20 g L^{-1}) constituted the subplot factor within a split-plot design featuring three replications (20 treatments total). Irrigation was applied immediately after sowing (Irrigation was carried out using flood irrigation every 3 weeks), and soil physico-chemical properties (0-30 cm depth) were characterized before planting (Table 1). Key response variables included vegetative growth parameters, fruit yield, essential oil content, and selected chemical constituents.

Table 1. Mechanical and chemical properties of the soil.

Mechanical analysis				Texture
Clay (%)	Silt (%)	Fine sand (%)	Coarse sand (%)	Loamy
34.45	39.10	13.48	12.97	

Chemical analysis												
pH	E C (m mohs cm^{-1})	Organic matter (%)	Soluble cations (meq L^{-1})				Soluble anions (meq L^{-1})			Available (ppm)		
			Mg^{++}	Ca^{++}	K^{+}	Na^{+}	Cl^{-}	HCO_3^{-}	SO_4^{--}	N	P	K
7.7	1.28	1.24	2.7	1.5	1.5	4.0	5.4	1.6	2.7	18.1	8.39	72.1

All compost treatments were meticulously applied during the soil preparation phase prior to cultivation in both growing seasons. The physical and chemical properties of the compost were assessed in accordance with the methodologies established by Black et al. (1965) and are delineated in Table 2. Foliar applications of garlic and moringa extracts were conducted thrice at three-week intervals, commencing two months post-planting, with treatments administered during the early morning hours [Average high temperature (18-23 °C) and low (7-10 °C) and humidity (49-51%)]. A biofilm at a concentration of 1 g L^{-1} and Tween 20 at 0.1% (1 mL L^{-1}) were incorporated into all spray solutions, including the control, to function as a wetting agent. The plants were misted to the point of runoff utilizing a hand pump mister, and all other agronomic practices were executed as per standard protocols.

Table 2. The comprehensive physical and chemical analysis of the applied compost.

Properties	Value	Properties	Value	Properties	Value
Dry weight of 1 m^3	450 kg	Organic carbon%	20.2	Fe (ppm)	295
Moisture (%)	27-31	C/N ratio	14.4	Mn (ppm)	29.7
pH (1:10)	7.5	Total N (%)	1.4	Cu (ppm)	160
E.C. (m mhose cm^{-1})	2-3.1	Total P (%)	0.8	Zn (ppm)	158
Organic matter%	38	Total K (%)	1.5		

Preparation of extracts

Garlic (Allium sativum) extract

The aqueous garlic extract was prepared according to Bhatti (1988) as follows. A 100 g portion of fresh *Allium sativum* L. cloves was thoroughly washed with sterile distilled water and ground in 100 mL of the same using a sterile pestle and mortar. The homogenate was initially filtered through a double-layered sterile muslin cloth to remove coarse debris, then through Whatman No. 1 filter paper. The filtrate was centrifuged at 4,000 rpm for 5 min to clarify the solution, and the supernatant was collected. To ensure sterility, this supernatant was passed through a sintered glass filter, yielding the final 100% (w/v) garlic extract. The garlic extract was analyzed in vitro to determine its chemical constituents. The primary chemical constituents of the garlic extract are detailed in Table 3.

Table 3. Important chemicals and minerals in 100 g^{-1} of garlic.

Chemical composition	Concentrations	Chemical composition	Concentrations
Lysine (g)	0.273	Aspartic acid (g)	0.489
Carbohydrates (g)	33.07	Leucine (g)	0.308
Lipids (g)	0.50	Manganese (mg)	1672.0
Sodium (mg)	17.0	Calcium (mg)	181.00
Magnesium (mg)	32.0	Phosphorus (mg)	153.00
Calories Kcal	149.0	Potassium (mg)	401.00
Glutamic acid (g)	0.805	Vit. B 6 (mg)	1235.0
Argenine (g)	0.634	Vitamin C (mg)	31.0
Water (g)	59.0	Fiber (g)	2.10
Sulphur (mg)	70.0		

Moringa (Moringa oleifera) leaf extract

Fresh, mature foliage of *Moringa oleifera* was meticulously harvested from well-established moringa trees situated within the Faculty of Agriculture at Al-Azhar University, Assiut, Egypt. These leaves were then arranged on dry blotters and allowed to air dry for 3 d. After drying, samples weighing 10 and 20 g were ground in a mechanical blender for 3 min, and the resulting powder was soaked in 1 L of distilled water for 24 h. The mixture was subsequently filtered through cotton cloth to obtain the extract then the moringa extract was analyzed *in vitro* to determine its chemical constituents. The chemical analysis of the resulting moringa extract, as elucidated by Ali et al. (2018), is delineated in Table 4.

Table 4. Chemical composition of moringa leaf extract (Values expressed in mg g^{-1} DW).

		Nutrient profile		Phytohormonal profile	
Total phenols	1.635	Potassium	13.78	Gibberellins	0.65
Total chlorophyll (Chl)	4.378	Phosphorus	3.82	Cytokinins	0.63
Ascorbic acid (mg g-1 FW)	8.47	Nitrogen	12.36	IAA	0.72
Total carotenoids	1.72	Calcium	15.92	Abscisic acid	0.13
Amino acids	387.72	Magnesium	3.96	Salicylic acid	1.87
Proline	33.65	Zinc	0.051		
		Iron	0.379		
		Manganese	0.081		
		Copper	0.038		

Data analysis

Vegetative growth was assessed at the onset of flowering by determining the dry weight of aerial biomass (g $plant^{-1}$), while fruit yield was quantified at harvest both per plant (g $plant^{-1}$) and extrapolated to a per-fed basis (kg ha^{-1}). Essential oil content and yield were determined following the Egyptian Pharmacopoeia (1984) via hydro-distillation, whereby 100 g of air-dried ajwain fruit was distilled in a 1,000 mL flask for 4 h. Subsequently, the percentage of oil was meticulously calculated. Concurrently, chemical analyses of the dry herb sampled at flowering included total nitrogen, measured by a modified micro-Kjeldahl procedure (AOAC, 1990); phosphorus, determined colorimetrically at 882 nm following Murphy and Riley (1962); and potassium, quantified by flame photometry as per Cottenie et al. (1982). All experimental data were subjected to analysis of variance using MSTAT-C (1986) based on the principles outlined by Mead et al. (1993), with treatment means compared at the 5% significance level.

Results

Growth and yield parameters

Herb dry weight/plant

Data in Table 5 reveal that compost incorporation at each tested rate markedly increased the dry biomass of ajwain per plant during both seasons. A clear dose–response was observed: the 40 m^3 ha^{-1} compost treatment yielded the largest increases, elevating dry weight by 64.3% compared to the control in year one and by 40.7% in year two. In parallel, foliar sprays of all extract concentrations significantly boosted herb dry weight compared to non-sprayed plants. Notably, foliar application of garlic extract at 20 mL L^{-1} caused the greatest enhancement, with increases of 20.2 and 16.7% compared to the control in the first and second seasons, respectively.

The interaction between experimental factors demonstrated a statistically significant influence ($P \leq 0.05$) on the dry weight of herb biomass per plant across both growing seasons. Specifically, the application of nearly all integrated treatments resulted in a significant increase in this parameter, with the exception of the treatment involving zero compost combined with moringa extract at the lower concentration (10 g L^{-1}) during the first season. Notably, the highest dry herb weight was achieved through the combined application of the higher level of compost (40 m^3 ha^{-1}) and garlic extract at a concentration of 20 mL L^{-1}, significantly exceeding the outcomes observed from other treatment combinations (Table 5).

I.2. Fruit yield/plant (g plant–1) and fruit yield (kg ha^{-1})

Data in Table 5 show a statistically significant positive correlation between ajwain compost application rates and fruit yield (per plant and per ha) across two seasons. Higher compost rates progressively increased yields, with the maximum rate (40 m^3 ha^{-1}) achieving 87.6 and 79.4% improvements compared to the control in seasons one and two, respectively. Absolute yields reached 625.92 and 744.06 kg ha^{-1} under this treatment, compared to control yields of 333.65 and 414.76 kg ha^{-1}. Foliar sprays of garlic and moringa extracts significantly boosted fruit yields, with 20 mL L^{-1} garlic extract being most effective (48.1 and 38.1% increases compared to the control in seasons one and two). This treatment yielded 574.40 and 675.47 kg ha^{-1}, versus control values of 387.73 and 489.01 kg ha^{-1} (Table 5).

The interaction between compost and foliar treatments significantly influenced yields ($P \leq 0.05$). All combined treatments increased yields except zero compost paired with 10 mL L^{-1} garlic extract or 10 g L^{-1} moringa extract in season one. The optimal treatment 40 m^3 ha^{-1} compost + 20 mL L^{-1} garlic extract produced the highest yields (746.67 and 877.01 kg ha^{-1}), significantly exceeding the control (270.93 and 328.96 kg ha^{-1}) (Table 5).

Table 5. Effect of compost rates and foliar applications of garlic and moringa extracts on ajwain herb dry weight (g plant^{-1}), fruit yield/plant (g plant^{-1}) and fruit yield (kg ha^{-1}) during the 2022/2023 and 2023/2024 growing seasons.

Plant extracts (Ex)	Compost levels (CM) (m^3 ha^{-1})									
	Herb dry weight (g plant^{-1})									
	Control	20	30	40	Mean (Ex)	Control	20	30	40	Mean (Ex)
	First season					Second season				
Control	31.7	39.0	45.3	52.2	42.1	33.9	36.6	40.3	49.5	40.1
GE 10 mL L^{-1}	34.0	43.8	49.8	56.5	46.0	36.8	42.1	45.5	52.1	44.1
GE 20 mL L^{-1}	37.1	48.1	55.8	61.4	50.6	39.5	45.2	48.1	54.4	46.8
ME 10 g L^{-1}	33.2	43.3	48.4	54.5	44.8	36.2	40.4	44.2	50.8	42.9
ME 20 g L^{-1}	36.4	47.0	54.0	58.6	49.0	38.0	44.5	47.5	52.9	45.7
Mean (CM)	34.5	44.3	50.7	56.7		36.9	41.8	45.2	51.9	
L.S.D. for 5%	CM: 1.9	Ex: 1.1	CMxEx: 2.1			CM: 1.5	Ex: 1.0	CMxEx: 2.1		
	Fruit yield/plant (g plant^{-1})									
Control	4.23	5.10	6.87	8.03	6.06	5.14	7.00	8.44	9.98	7.64
GE 10 mL L^{-1}	5.07	5.87	7.63	9.77	7.08	6.68	7.88	9.01	11.78	8.84
GE 20 mL L^{-1}	6.07	7.50	10.67	11.67	8.98	7.31	9.17	12.03	13.70	10.55
ME 10 g L^{-1}	5.00	5.70	7.50	9.43	6.91	6.47	7.57	8.64	11.04	8.43
ME 20 g L^{-1}	5.70	7.27	9.33	10.00	8.08	6.80	8.00	10.37	11.63	9.20
Mean (CM)	5.21	6.29	8.40	9.78		6.48	7.93	9.70	11.63	
L.S.D. for 5%	CM: 0.31	Ex: 0.43	CMxEx: 0.86			CM: 0.32	Ex: 0.58	CMxEx: 1.16		
	Fruit yield (kg ha^{-1})									
Control	270.93	326.40	439.47	514.13	387.73	328.96	448.21	540.37	638.51	489.01
GE 10 mL L^{-1}	324.27	375.47	488.53	625.07	453.33	427.31	504.11	576.64	753.71	565.44
GE 20 mL L^{-1}	388.27	480.00	682.67	746.67	574.40	467.84	586.88	770.13	877.01	675.47
ME 10 g L^{-1}	320.00	364.80	480.00	603.73	442.13	414.29	484.69	552.96	706.56	539.63
ME 20 g L^{-1}	364.80	465.07	597.33	640.00	516.80	435.41	512.21	663.89	744.53	589.01
Mean (CM)	333.65	402.35	537.60	625.92		414.76	507.22	620.80	744.06	
L.S.D. for 5%	CM: 19.67	Ex: 27.56	CMxEx: 55.12			CM: 20.41	Ex: 37.05	CMxEx: 74.10		

Essential oil production

Essential oil percentage

Data in Table 6 show that ajwain plants grown with organic compost (excluding the lowest rate of 10 m^3 fed^{-1}) significantly increased essential oil percentage compared to the control in both seasons. The highest compost rate (40 m^3 ha^{-1}) achieved maximal oil percentage, improving by 5.7% (in the first season) and 4.9% (in the second season) compared to the control. No significant differences existed among compost rates except between 30 and 40 m^3 ha^{-1} in the second season.

Foliar sprays with garlic and moringa extracts (all concentrations) enhanced essential oil percentage, except for 20 mL L^{-1} garlic extract and 10 g L^{-1} moringa extract in season one. The highest oil percentages occurred with 20 mL L^{-1} garlic extract (4.7 and 3.6% increase compared to the control) and 20 g L^{-1} moringa extract (3.4 and 3.0% increase), with no statistical difference between these treatments (Table 6).

Interaction treatments positively influenced the oil percentage in both seasons. Most combined treatments significantly increased oil levels, except for 0 compost + 10 mL L^{-1} garlic extract or 10 g L^{-1} moringa extract (season one), 20 m^3 ha^{-1} compost + no foliar spray (season one), and 0 compost + 10 mL L^{-1} garlic extract (season two). The highest oil percentages resulted from 40 m^3 ha^{-1} compost combined with higher foliar concentrations (e.g., 20 mL L^{-1} garlic extract or 20 g L^{-1} moringa extract), outperforming other treatments (Table 6).

Essential oil yield (ml plant^{-1}) and essential oil yield (L ha^{-1})

Data in Table 6 reveal that organic cultivation with compost significantly increased ajwain essential oil yield (per plant and per ha) in both seasons. Higher compost rates progressively enhanced yields, with the maximum rate (40 m^3 ha^{-1}) achieving 98.3 and 88% improvements compared to the control, yielding 19.68 and 23.75 L ha^{-1} versus the control's 9.93 and 12.63 L ha^{-1}.

Foliar sprays (all concentrations) boosted oil yields, with 20 mL L^{-1} garlic extract being most effective (54.5 and 43.1% increases compared to the control). This treatment produced 17.97 and 21.42 L ha^{-1}, compared to the control's 11.63 and 14.97 L ha^{-1} (Table 6).

The interaction of compost and foliar treatments significantly influenced yields. All combined treatments increased yields, but the integration of 40 m^3 ha^{-1} compost + 20 mL L^{-1} garlic extract outperformed others, yielding 23.85 and 28.45 L ha^{-1}, significantly exceeding the control's 7.75 and 9.70 L ha^{-1} (Table 6).

Table 6. Effect of compost rates and foliar applications of garlic and moringa extracts on ajwain essential oil%, essential oil yield (mL plant^{-1}) and essential oil yield (L fed^{-1}) during the 2022/2023 and 2023/2024 growing seasons.

Plant extracts (Ex)	Compost levels (CM) (m^3 ha^{-1})									
	Essential oil%									
	Control	20	30	40	Mean (Ex)	Control	20	30	40	Mean (Ex)
	First season					Second season				
Control	2.86	2.97	3.01	3.09	2.98	2.95	3.05	3.07	3.12	3.05
GE 10 mL L^{-1}	2.94	3.01	3.06	3.12	3.03	3.02	3.07	3.11	3.19	3.10
GE 20 mL L^{-1}	3.05	3.10	3.13	3.20	3.12	3.09	3.14	3.17	3.24	3.16
ME 10 g L^{-1}	2.97	2.99	3.04	3.14	3.03	3.06	3.08	3.09	3.17	3.10
ME 20 g L^{-1}	3.03	3.02	3.11	3.16	3.08	3.08	3.11	3.15	3.21	3.14
Mean (CM)	2.97	3.02	3.07	3.14		3.04	3.09	3.12	3.19	
L.S.D. for 5%	CM: 0.10		Ex: 0.06		CMxEx: 0.12	CM: 0.06		Ex: 0.04		CMxEx: 0.09
	Essential oil yield (mL plant^{-1})									
Control	0.121	0.151	0.207	0.248	0.182	0.152	0.214	0.259	0.311	0.234
GE 10 mL L^{-1}	0.149	0.176	0.234	0.304	0.216	0.201	0.242	0.280	0.376	0.275
GE 20 mL L^{-1}	0.185	0.232	0.333	0.373	0.281	0.226	0.288	0.381	0.445	0.335
ME 10 g L^{-1}	0.149	0.170	0.228	0.296	0.211	0.198	0.233	0.267	0.350	0.262
ME 20 g L^{-1}	0.173	0.219	0.290	0.316	0.250	0.210	0.249	0.327	0.373	0.290
Mean (CM)	0.155	0.190	0.258	0.307		0.197	0.245	0.303	0.371	
L.S.D. for 5%	CM: 0.010		Ex: 0.013		CMxEx: 0.026	CM: 0.008		Ex: 0.019		CMxEx: 0.038
	Essential oil yield (L ha^{-1})									
Control	7.75	9.69	13.24	15.86	11.63	9.70	13.67	16.60	19.93	14.97
GE 10 mL L^{-1}	9.53	11.29	14.96	19.48	13.82	12.89	15.47	17.95	24.04	17.59
GE 20 mL L^{-1}	11.84	14.87	21.33	23.85	17.97	14.44	18.41	24.39	28.45	21.42
ME 10 g L^{-1}	9.51	10.90	14.59	18.95	13.48	12.67	14.93	17.09	22.42	16.78
ME 20 g L^{-1}	11.05	14.03	18.56	20.24	15.97	13.42	15.91	20.90	23.88	18.53
Mean (CM)	9.93	12.16	16.54	19.68		12.63	15.68	19.39	23.75	
L.S.D. for 5%	CM: 0.62		Ex: 0.82		CMxEx: 1.63	CM: 0.52		Ex: 1.20		CMxEx: 2.40

Nitrogen, phosphorus, and potassium percentages

The data from Table 7 showed a significant increase in nitrogen (N), phosphorus (P), and potassium (K) percentages in ajwain plants with compost application at all rates except the lowest (20 m^3 ha^{-1}) for P and K, compared to the control across both seasons. Nitrogen percentage increased gradually with higher compost rates. Phosphorus showed no significant differences between low and moderate compost rates, while potassium showed no differences among rates except between low and moderate in the first season. The highest compost rate (40 m^3 ha^{-1}) yielded the greatest increases: 19.3 and 18.3% for N, 23.7 and 25.2% for P, and 30.1 and 27.7% for K compared to the control in the two seasons, respectively.

Foliar spraying with garlic extract and moringa extract at all concentrations generally increased N, P, and K percentages, except for 10 mL L^{-1} garlic extract (N in both seasons, K in the second season) and 10 g L^{-1} moringa extract (N, P, and K in both seasons). The highest nutrient percentages were observed from the 20 mL L^{-1} garlic extract and the 20 g L^{-1} moringa extract, with no significant differences between them in most cases. These treatments increased the N content by 4.9 and 4.6% (garlic), 3.6 and 3.3% (moringa), P by 10.8 and 9.4% (garlic), 9.5 and 7.9% (moringa), and K by 12.7 and 12.7% (garlic), 7.4 and 9.3% (moringa), compared to the unsprayed control in the two seasons, respectively.

The interaction of compost and foliar treatments significantly enhanced N, P, and K percentages in ajwain plants across both seasons. Most combined treatments increased N%, except the control (0 compost, no spray). For P%, significant increases occurred with most combinations, except 0 compost with 10 g L^{-1} moringa extract (both seasons), 20 m^3 ha^{-1} compost with 10 g L^{-1} moringa extract (first season), and 0 compost with 10 mL L^{-1} garlic extract or 10 or 20 g L^{-1} moringa extract (second season). For K%, significant increases were observed except for 0 compost alone or with 10 mL L^{-1} garlic extract or 10 g L^{-1} moringa extract (both seasons) and 20 g L^{-1} moringa extract (first season) and 20 m^3 ha^{-1} compost with no spray (both seasons). The combination of 40 m^3 ha^{-1} of compost with foliar spray of 20 mL L^{-1} of garlic extract proved to be the most effective treatment in increasing the values of these elements.

Table 7. Effect of compost rates and foliar applications of garlic and moringa extracts on ajwain N, P and K% of dry herb during the 2022/2023 and 2023/2024 growing seasons.

Plant extracts (Ex)	Compost levels (CM) (m^3 ha^{-1})									
	N%									
	Control	20	30	40	Mean (Ex)	Control	20	30	40	Mean (Ex)
	First season					Second season				
Control	2.03	2.26	2.29	2.39	2.24	2.19	2.42	2.45	2.56	2.41
GE 10 mL L^{-1}	2.08	2.28	2.35	2.48	2.30	2.23	2.44	2.52	2.66	2.46
GE 20 mL L^{-1}	2.12	2.33	2.41	2.55	2.35	2.27	2.49	2.58	2.73	2.52
ME 10 g L^{-1}	2.09	2.19	2.33	2.46	2.27	2.25	2.35	2.50	2.63	2.43
ME 20 g L^{-1}	2.10	2.28	2.40	2.50	2.32	2.27	2.44	2.57	2.67	2.49
Mean (CM)	2.08	2.27	2.36	2.48		2.24	2.43	2.52	2.65	
L.S.D. for 5%	CM: 0.08		Ex: 0.07		CMxEx: 0.13	CM: 0.09		Ex: 0.05		CMxEx: 0.10
	P%									
Control	0.262	0.307	0.313	0.339	0.305	0.296	0.335	0.352	0.377	0.340
GE 10 mL L^{-1}	0.301	0.323	0.325	0.362	0.328	0.324	0.343	0.363	0.401	0.357
GE 20 mL L^{-1}	0.307	0.324	0.344	0.376	0.338	0.332	0.362	0.382	0.414	0.372
ME 10 g L^{-1}	0.282	0.293	0.321	0.351	0.312	0.320	0.331	0.359	0.389	0.350
ME 20 g L^{-1}	0.303	0.319	0.342	0.371	0.334	0.321	0.357	0.380	0.409	0.367
Mean (CM)	0.291	0.313	0.329	0.360		0.318	0.346	0.367	0.398	
L.S.D. for 5%	CM: 0.029		Ex: 0.016		CMxEx: 0.032	CM: 0.031		Ex: 0.015		CMxEx: 0.031
	K%									
Control	1.64	1.70	2.02	2.19	1.89	1.71	1.94	2.21	2.34	2.05
GE 10 mL L^{-1}	1.72	1.88	2.08	2.21	1.97	1.89	2.04	2.28	2.43	2.16
GE 20 mL L^{-1}	1.98	2.02	2.18	2.34	2.13	2.11	2.22	2.37	2.52	2.31
ME 10 g L^{-1}	1.67	1.78	2.06	2.21	1.93	1.81	2.05	2.27	2.39	2.13
ME 20 g L^{-1}	1.73	1.98	2.10	2.30	2.03	2.02	2.17	2.30	2.48	2.24
Mean (CM)	1.75	1.87	2.09	2.25		1.91	2.08	2.29	2.44	
L.S.D. for 5%	CM: 0.17		Ex: 0.07		CMxEx: 0.13	CM: 0.23		Ex: 0.15		CMxEx: 0.30

Discussion

Organic manure application enhances soil properties by increasing organic matter, carbon content, cation–anion exchange capacity, microbial activity, and water retention, leading to higher crop yields (Aziz et al., 2010; Pandey et al., 2016; Sharma and Chetani, 2017). Studies on sweet marjoram show compost boosts biomass across harvests, with larger doses more effective in later cuts (Gharib et al., 2008). Organic amendments improve soil structure, fertility, and rhizosphere microorganism activity, promoting growth hormones like auxins (Glick, 2003; Kadoglidou et al., 2014; Balaguer et al., 2015; Yaldiz et al., 2019). These benefits extend to medicinal, aromatic and vegetable plants (e.g., sweet basil, black cumin, garlic, tomato, roselle, and guar), enhancing biomass, yield, and essential oil production (Zheljazkov and Warman, 2004; Ariafar et al., 2013; El-Naggar et al., 2015; Shaheen and Al-Hamdany, 2018; Al-Shammari, 2018; El-Sheref et al., 2019; Mahmoud et al., 2021; Abd El-Aal et al., 2022; Mahmoud et al., 2025). Compost improves soil structure and nutrient retention and reduces nitrogen loss, fostering vegetative growth and secondary metabolite synthesis, thereby increasing essential oil yield (Taiwo et al., 2002; Omar et al., 2016). Higher compost rates correlate with elevated essential oil percentages due to improved soil health and nutrient availability (Judais and Rinaldi, 2001; Taiwo et al., 2002). Similar benefits are seen in caraway and coriander (Omer et al., 2020; Hamza et al., 2021; Rasouli et al., 2022). Organic manure stimulates soil microbes, enhancing auxin production and nutrient uptake (El-Merich et al., 1997). These findings align with studies on anise, roselle, guar and khella, highlighting organic amendments' role in nutrient accumulation via microbial regulation (Hemdan, 2008; Hamed, 2017; Mahmoud et al., 2021; Abd El-Aal et al., 2022; Mohamed et al., 2023).

Garlic extract (GE) exhibits biphasic effects in ajwain: low doses stimulate germination and seedling growth, while high doses inhibit them (Yanli et al., 2007; Xiao et al., 2012). Its growth-promoting properties stem from bioactive compounds, including B and C vitamins, minerals (Na, K, Zn, P, Mn, Mg, Ca, Fe), carbohydrates, organosulfur compounds (allicin, diallyl disulfide), enzymes, saponins, alkaloids, flavonoids, and sugars, which collectively enhance photosynthesis, cell division, and nutrient absorption (Bhandari et al., 2014; Abd El–Hamied et al., 2015; Martins et al., 2016). GE-induced biomass increases correlate with elevated Chl and indole-3-acetic acid levels, suggesting hormonal and chloroplast activity modulation (Mady, 2009). Similar growth improvements (stem diameter, leaf area, N, and carbohydrate content) are documented in sweet marjoram, sage, and *Schefflera arboricola* (Hanafy et al., 2012). Foliar GE application (50 ppm) enhances herb dry weight and seed yield in guar, underscoring its potential as a natural biostimulant (Abd El-Aal et al., 2022). GE also boosts essential oil production in medicinal plants. Studies show increased oil content in Majorana hortensis (Mady, 2009), *Ocimum basilicum* (Ahmed et al., 2014), *Salvia officinalis* (Abdel-Kader et al., 2014; Nour Eldeen, 2014), and *Schefflera arboricola* (Hanafy et al., 2012). The improved N, P, and K uptake post-GE treatment may arise from its antimicrobial activity, which safeguards plants against pathogens, enhancing nutrient efficiency and health, consistent with findings in squash (Tartoura et al., 2013).

Moringa leaf extract (MLE) enhances crop growth, stress tolerance, and yield via antioxidants, phytohormones (zeatin, IAA, cytokinins, gibberellins), and minerals (P, Ca, K, Mg, Fe, Cu, Zn, Mn) (Yasmeen et al., 2012; Howladar, 2014; Rady et al., 2015). Foliar applications improve vegetative growth, seed yield, and fruit production in fennel (Abdel-Rahman and Abdel-Kader, 2020), ajwain (Abou El-Ghait et al., 2021), guar (Abdou et al., 2017), fennel (El-Serafy and El-Sheshtawy, 2020), and dill (El-Gamal and Ahmed, 2016). MLE also boosts volatile oil accumulation in ajwain by enhancing photosynthetic efficiency (elevated Chl/carotenoid levels), increasing sugar reserves for secondary metabolites, and stimulating cell division in oil-producing tissues, leading to higher biomass and oil gland formation (Taiz and Zeiger, 2010; Yameogo et al., 2011; Latif and Mohamed, 2016). In geranium, MLE (10 g L^{-1}) significantly increased essential oil yield (Ali et al., 2018). MLE foliar sprays elevate macronutrient (N, P, K, Ca, Mg) and micronutrient (Fe, Zn, Cu, Mn, S) levels across crops. Examples include increased N, K, and Ca in greenhouse plants (Jain et al., 2020), higher N, P, and K in snap bean foliage (Elzaawely et al., 2017), elevated N, P, K, and S in eggplant fruits (Hoque et al., 2020), maximal K and C in sweet pepper (Hala and Nabila, 2017), improved N, P, and K in sweet basil (Alkuwayti et al., 2020), enriched N, P, K, Ca, Mg, and Fe in pea seeds (Merwad et al., 2017), and enhanced nutrient uptake in tomato (Hoque et al., 2021). These findings align with garlic extract’s nutrient-boosting effects in *Polianthes tuberosa* (Emam, 2010) and *Schefflera arboricola* (Hanafy et al., 2012) and mirror MLE’s efficacy in ajwain (Abou El-Ghait et al., 2021), guar (Abdou et al., 2017), and freesia (Ahmad et al., 2019).

Conclusion

The current study illustrates that combining a high compost application (20 m^3 per fed) with a 20 mL L^{-1} garlic extract foliar spray produces synergistic effects that significantly enhance vegetative growth, fruit yield, and essential oil output in ajwain. This dual approach offers a promising, eco-friendly framework for improving both the quantity and quality of aromatic crop yields under practical field conditions. These results underscore the potential of integrating organic amendments with plant extracts as a sustainable approach to improve crop productivity in semi-arid soils. Future studies should focus on elucidating the underlying biochemical mechanisms and refining application strategies to facilitate wider adoption in agricultural systems.

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Conflict of Interest
The authors indicate no conflict of interest in this work.

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