

Synergistic Effects of Humic Acid, Microbial Biofertilizers, and Seaweed Extract on Growth, Yield, and Essential Oil Composition of Dill (*Anethum graveolens* L.) under Semi-Arid Conditions

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HOW TO CITE:

Hesham. M. Gebira, S. M. Abo Gharsa, E. A. Hassan (2026). Synergistic Effects of Humic Acid, Microbial Biofertilizers, and Seaweed Extract on Growth, Yield, and Essential Oil Composition of Dill (*Anethum graveolens* L.) under Semi-Arid Conditions International Journal of Special Education, 41(10s), 487-502.

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ABSTRACT:

Semi-arid agroecosystems impose multiple constraints on aromatic crops, including low soil fertility and limited water availability, ultimately reducing biomass accumulation and essential oil productivity. This study investigated the individual and combined effects of humic acid (HA), microbial biofertilizers, and seaweed extract (SE) on growth performance, yield components, and essential oil quantity and composition of dill (*Anethum graveolens* L.) under field conditions in Misurata, Libya during the 2024/2025 season. A split-plot design with four replicates was employed, where HA rates (0, 5, 10, and 20 kg ha⁻¹) were assigned to main plots and promoter treatments (microbial biofertilizers, SE, and their combination) to subplots. Results revealed a clear dose-dependent response to HA, with the highest rate (20 kg ha⁻¹) significantly improving plant height (117.38 cm), branch number (17.38 plant⁻¹), fresh biomass (216.81 g plant⁻¹), and fruit yield (2.423 t ha⁻¹). The combined application of microbial biofertilizers and SE further enhanced these parameters, demonstrating strong synergistic effects. The interaction treatment (20 kg HA ha⁻¹ + biofertilizers + SE) produced the highest essential oil content (1.578%) and yield (41.79 L ha⁻¹). GC-MS analysis identified carvone, D-limonene, dillapiole, and (+)-dihydrocarvone as major constituents, with treatment-dependent compositional shifts. These findings highlight the effectiveness of integrated biostimulant-based fertilization strategies in enhancing dill productivity and oil quality under semi-arid conditions, offering a sustainable alternative to conventional inputs.

Keywords: *Anethum graveolens*, humic acid, biofertilizers, seaweed extract, essential oil, semi-arid agriculture, GC-MS.

1. Introduction

The Apiaceae family, which includes more than 250 species of significant aromatic and medicinal crops, includes the dill plant (*Anethum graveolens* L.).

These aromatic plants have varying quantities and types of volatile oils (Stuart, 1982). The dill leaves could be used to make soup, eggs, pork, salad, and seafood. The seeds might be added to bread and

used to flavor soups and pickles. Pickles, sweets, and chewing gum all include dill essential oil that is derived from the herb and seeds (Zohary and Hopf, 2000). In addition to being utilized to treat hemorrhoids, renal colic, branchial asthma, neuralgia, dysuria, and dysmenorrhea genital ulcers, dill fruits are also used as a diuretic, carminative, sedative stimulant, and antispasmodic (Al Masoody et al., 2023).

Applying humic compounds to aromatic and therapeutic plants has become more popular especially in the last years. Humic acid is a component of humus compounds, which are crucial to the plant's nutritional balance. Globally, farmers are embracing humic acid as a crucial component of their fertilization strategy. It can be sprayed directly onto plant leaves as a foliar spray or added to the soil in granular form (Delfine et al., 2005). Humic compound affect the chemical, biological and physical characteristics of soil as well as the physiological and biochemical processes in plants both indirectly and directly (Sangeetha et al., 2006). Moreover, the greatest production in terms of vegetative growth, fruit yield and its components and the generation of essential oils were obtained when dill plants were treated with humic acid at a concentration of 8 or 4 ml/l (Ahmed et al., 2020). Likewise, in anise plant, the humic acid significant enhanced all vegetative growth traits, yield and volatile oil content (Aly et al., 2022).

The primary sources of biological fertilizers are microorganisms, primarily nitrogen fixers, mycorrhizal bacteria and phosphate as well as potassium solubilizers. Bio-fertilizers are compounds that contain microorganisms that infiltrate the plant's rhizosphere and boost the target crop's access to primary nutrients and/or growth stimulants (Almansour, 2021). Numerous kinds of soil bacteria are primarily found in the plant root zone. Together, these bacteria are referred to as rhizobacteria that promote plant growth (Ahmed, 2017). Furthermore, seaweed extract (SE) based biostimulants have become popular among these developments as efficient

and sustainable ways to enhance stress tolerance, plant growth and its productivity (Deolu-Ajayi et al., 2022). Seaweed extracts have been shown in numerous studies to improve photosynthetic activity, nitrogen absorption, and root development in addition to promoting the synthesis of secondary metabolites and antioxidant enzymes (Mughunth et al., 2024). The development and phytochemicals of basil plants have benefited from the application of seaweed extract (Lam et al., 2025). In addition, the maximum values of vegetative growth characters, total fresh leaf weight, oil yield and mineral (N%, P%, and K%) contents of celery plants were observed when algal extract was sprayed with microbein inoculation as a biofertilizer (Zaki et al., 2023).

Although individual effects of these inputs have been widely studied, their integrated application under semi-arid conditions remains insufficiently explored, particularly for dill. Therefore, this study aimed to evaluate the synergistic effects of HA, microbial biofertilizers, and SE on growth, yield, and essential oil production and composition.

2. Methodology

In order to investigate the effects of humic acid, biological fertilizer inoculation treatments, and seaweed extract applied topically on the vegetative growth, yield components, and volatile oil production of dill (*Anethum graveolens* L.) plants, a field trial was conducted in 2024 and 2025 at the Agriculture Faculty experimental farm, Misurata University, Libya.

Experimental establishment

On October 18th dill fruits were sown. Fruits were seeded in hills, 30 cm apart on one side of the ridge, and the experimental unit (plot) measured 3.50 × 3.00 meters. As a result, each plot had 21 hills, and after a month from the date of sowing, plants were reduced to two plants per hill.

In order to justify the effect and the suitable rate of humic acid (HA) on dill plant, four rates,

namely 0.0, 5, 10 and 20 kg/ hectare were tested of the present experiment. Also, *Glomus mosseae* NRC31 and *Glomus fasciculatum* NRC15, which were initially isolated from soil and multiplied on sterilized peat, vermicolite and perlite, made up the arbuscular mycorrhizal fungus inoculum (Badr El-Din et al., 1999). The soil surrounding the dill seeds were treated with nitrobenin (*Azospirillum lipoferum*) and potassium solubilization bacteria (*Bacillus circulans*) once prior to sowing, per the manufacturer's recommendations. Seaweed extract produced used as liquid extract at 3ml/l,

contains Zn, Fe, Cu, Mo and Mn minerals, vitamins, enzymes, sugars, plant hormones and amino acids.

Soil sample

Before humic acid and growth promoters treatment, a soil sample was collected, which was done 16th days before planting date. The soil sample was taken at a depth of 30 cm and examined using the techniques outlined by Chapman and Pratt (1978). Table 1 lists the properties of the soil sample.

Table 1. Physicochemical characteristics of the experimental soil

Physical analysis										Soil texture		
Clay (%)		Silt (%)		Fine sand (%)			Coarse sand (%)			Sandy		
5.76		3.03		78.47			12.74					
Chemical analysis												
pH	E C m.mohs /cm	Organic mater (%)	Soluble cations (meq./ L)				Soluble anions (meq. /L)			Available (ppm)		
			Mg++	Ca++	K +	Na+	Cl-	HCO3-	SO4- -	N	P	K
7.89	1.52	2.71	3.02	1.24	4.13	4.41	6.46	1.23	5.11	42.3	58.8	14.4

Experimental Design

The treatments under study were arranged in a split-plot design with four replicates. However, the main plots were filled with humic acid rates, while, the promoters types (mixture of biological fertilizers or/and seaweed extract) were occupied at sub-plots. In the location where dill plants were planted, standard agricultural practices were followed.

Data Recorded

Three plants were randomly selected from each experimental unit 100 days after the dill was sown and the following growth characters were recorded: Plant height (cm), branches number per plant as well as fresh and dry weights of dill plant (g).

The yield components were given as follows during the harvesting stage (152 days following the date of sowing): Umbels number

per dill plant, fruits yield per plant (g) and per hectare (ton) were listed.

The experiment's last stage was utilizing hydro distillation to extract the essential oils from air-dried dill fruits by separating the volatile oil (Guenther, 1961). Additionally, the plant's volatile oil yield (ml) was calculated by multiplying that quantity by the percentage of volatile oils included in the fruit output. We calculated the amount of volatile oil produced in each treatment by multiplying the volatile oil output per dill plant by the weight of fruits per hectare (l).

Gas chromatography–mass spectrometry analysis (GC-MS)

The GC-MS system (Agilent Technologies) was equipped with gas chromatograph (7890B) and mass spectrometer detector (5977A) at Central Laboratories

Network, National Research Centre, Cairo, Egypt. The GC was equipped with VF-624ms column (30 m x 250 µm internal diameter and 1.4 µm film thickness). Analysis was carried out using Hydrogen as the carrier gas at a flow rate of 1.00 ml/min at a splitless, injection volume of 1.0 µl and the following temperature program: 40 °C for 0 min; rising at 6 °C /min to 200 °C and held for 0 min; rising at 15 °C /min to 220 °C and held for 0 min; rising at 30 °C /min to 250 °C and held for 2 min. The injector and detector were held at 250 °C. Mass spectra were obtained by electron ionization (EI) at 70 eV; using a spectral range of m/z 33-600 and solvent delay 3.50 min. The mass temperature was 230°C and Quad 150 °C. Identification of different constituents was determined by comparing the spectrum fragmentation pattern with those stored in Wiley and NIST Mass Spectral Library data.

Statistical Analysis

The computer program Statistix Version 9 (Analytical Software, 2008) was used to statistically evaluate the data from the current study. Variation between the treatment means (humic acid rates and promoter types) was considered significant using Duncan's multiple range test if it was greater than the least significant differences (L.S.D.) at the 5% level (Duncan, 1955).

3. Results and Discussion

Plant growth characters

Results tabulated in Table 2 point out that fertilizing dill plants with any humic acid rate significantly increased plant height, number of branches /plant, and plant fresh and dry weights compared to the control (without humic acid application). Fertilizing with humic acid (HA) at 20 kg/hectare significantly recorded the maximum values of dill height (117.38 cm), number of branches/plant (17.38), and plant

fresh (216.81 g) and plant dry weight (53.81 g). The increases in plant fresh weight were about 31.10% for HA at 20 kg/hectare, 8.08 % for HA at 10 kg/hectare and 5.25 % for 5 kg/hectare over the control treatment, respectively.

A naturally occurring soil component created by the breakdown of organic matter, humic acid (HA) has been shown to be beneficial in encouraging the growth of a range of crops. Improved plant growth and increased absorption of macronutrients and micronutrients are among its advantages for plant development (Guo Gao et al., 2015). Moreover, Samy et al. (2025) pointed out that enrichment humic acid with 5 kg/hectare significantly improved plant height and branch number of fennel plants.

Applying dill plants with mixture of biological fertilizers or/and seaweed extract was the best treatment for improving dill height (97.7, 93.75 and 103.44 cm) and plant fresh weight (185.94, 181.25 and 190.75 g/plant) as well as plant dry weight (47.00, 45.38 and 48.50 g/plant), compared to control treatment, which produced the lowest values in these characters (89.81 cm, 177.16 g as fresh weight and 44.63 g as dry weight), respectively (Table 2). Foliar spray with some growth promoters (mixture of biological fertilizers + seaweed extract) gave the maximum values in this connection compared to control (spraying with water). In the same time, all concentrations (1, 2 and 3 ml/liter) of seaweed liquid extract treatments were found to significantly improve the dill plants' height, number of branches and dry weight (Hassan, 2015). Furthermore, by lowering the dosages of chemical fertilizers, biological fertilizers as well as seaweed extract - one of these bio-stimulants - offer an affordable and environmentally safe fertilizer. Additionally, they are essential for sustainable agriculture (Khan et al., 2009; Chatterjee et al., 2017).

Table 2. Effects of humic acid rates, biostimulant treatments and interaction on vegetative growth parameters of dill plants

Humic acid rates (kg / hectare)	Growth promoter types				Mean (C)
	Control	MM	SE	MM + SE	
	Plant height (cm)				
Control	73.50k	77.25ij	75.00jk	79.50i	76.31D
5	83.50h	89.25g	86.25gh	93.75f	88.19C
10	96.00ef	104.00d	99.00e	112.25c	102.81B
20	106.25d	120.50b	114.50c	128.25a	117.38A
Mean (M)	89.81D	97.75B	93.69C	103.44A	
	Branch number per plant				
Control	8.75h	11.25g	9.50h	12.00g	10.38D
5	11.25g	13.50f	12.25g	14.50ef	12.88C
10	13.75f	16.00d	14.25ef	17.25bc	15.31B
20	15.25de	18.25b	16.25cd	19.75a	17.38A
Mean (M)	12.25D	14.75B	13.06C	15.88A	
	Plant fresh weight (g)				
Control	157.25i	167.50gh	162.75h	174.00f	165.38D
5	167.50gh	176.50ef	172.00fg	180.25e	174.06C
10	172.50fg	181.00e	176.25ef	190.25d	178.75B
20	208.50c	216.25b	214.00b	223.50a	216.81A
Mean (M)	177.16D	185.94B	181.25C	190.75A	
	Plant dry weight (g)				
Control	39.75k	42.50j	40.25k	45.50ef	42.00D
5	42.25ij	44.75fg	43.25hi	45.25ef	43.88C
10	44.25fg	46.25e	45.25ef	47.50d	45.81B
20	52.25c	54.50b	52.75c	55.75a	53.81A
Mean (M)	44.63D	47.00B	45.38C	48.50A	

MM= mixture of microbial fertilizers; SE= seaweed extract

Regarding the combination effect between humic acid and mixture of biological fertilizers or/ and seaweed extract, Table (2) and Figs (1 and 2) reveals that all combination treatments significantly improved plant height, branch number per dill plant and fresh and dry weights of plant compared to control (without HA application, without biological fertilizers inoculation and without seaweed spraying). The best treatment in improve dill growth traits was humic acid at 20 kg/ hectare + biological inoculation + seaweed extract compared to the

other combination treatments under study. The increases regard the best treatment in plant growth traits over control were about 74.49 % in plant height, 125.71 % in branches number per plant, 42.13 % in plant fresh weight and 40.25% in plant dry weight. Likewise, Shehata (2019) reported that the combination treatment between microbein + phosphorein and humic acid at 200 mg/l + 50 % of recommended NPK was significantly influenced parsley vegetative growth (plant height, fresh and dry weights per plant and leaves area) compared to control.

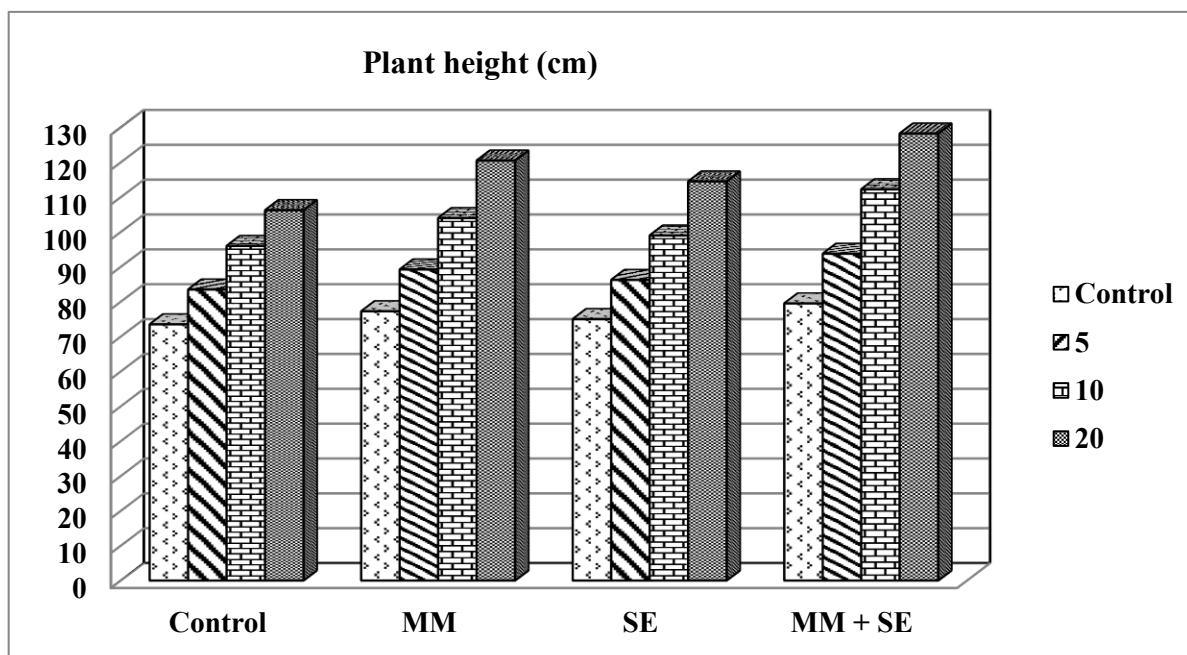


Figure 1. Effect of humic acid rates, biostimulant treatments and their interaction treatments on plant height (cm) of dill plan

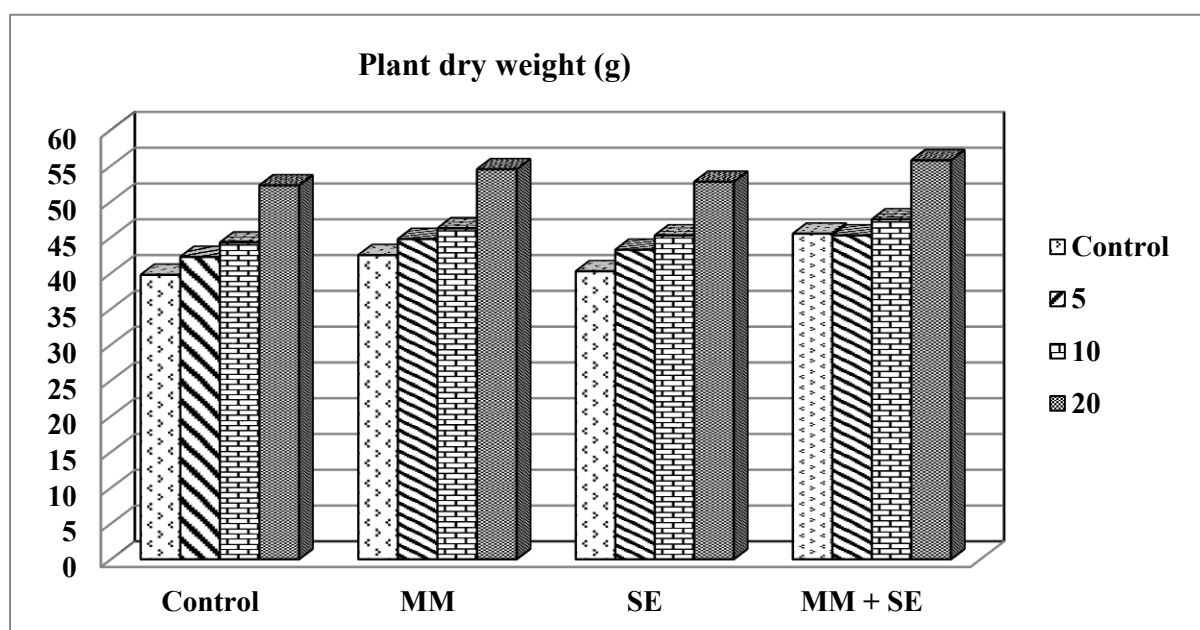


Figure 2. Interactive effects of humic acid, biostimulants and their interaction treatments on dry biomass accumulation (g) of dill plan

Yield and its components

Fertilizing dill plants with humic acid rates (mixture of biological fertilizers or/and seaweed extract) significantly increased the number of umbels, fruit weight per plant and fruit yield/hectare compared to the control treatment

(Table 3). Applying dill plants with humic acid at 20 kg/hectare enhanced the number of umbels/plant (34.81), fruit yield/plant (30.28 g) and fruit yield/hectare (2.423 ton) as listed in Table 4, followed by fertilizing dill plants with humic acid at 10 kg/hectare. Increasing humic

acid rates from 5, 10 to 20 kg/hectare gradually improved yield components. In this connection, humus compounds, particularly humic acid, are known to promote root branching and elongation, which improves yield components (Nardi et al., 2002). Likewise, Abdul-Hafeez et al. (2020) reported that humic acid application at 4.5 g/l (a high concentration) had a significant influence on the umbels number per fennel plant, yield of fruit per plant and total fruit yield.

The simulative influence of biological fertilizers (nitrobenin, mycorrhizae and *Bacillus circulans*) or / and seaweed extract on number of umbels per plant, fruit yield per plant and per

hectare were recorded in Table (3). The increases in total fruit yield per hectare were about 13.43 for biological fertilizers, 7.04 for seaweed extract and 20.20 % for mixture of biological fertilizers + seaweed extract over the control plot. In general, spraying dill plants with any growth promoters under study significantly improved fruit yield components compared to untreated plants (control). In the same line, Aly et al. (2021) found that in comparison to the control, the use of biological fertilizers + seaweed extract produced the greatest results for the number of umbels per parsley plant, fruit yield per plant, and overall fruit production.

Table 3. Influence of humic acid, microbial biofertilizer and seaweed extract on yield components of dill plant

Humic acid rates (kg / hectare)	Growth promoter types				Mean (C)
	Control	MM	SE	MM + SE	
	Umbels number per plant				
Control	21.75j	24.50h	22.50i	25.50g	23.56D
5	23.00i	27.00f	25.00gh	28.50e	25.88C
10	27.50f	31.50d	28.75e	33.00c	30.19B
20	31.75d	36.25b	33.50c	37.75a	34.81A
Mean (M)	26.00D	29.81B	27.44C	31.19A	
	Fruit yield per plant (g)				
Control	19.375k	21.500i	20.313j	22.625h	20.95D
5	22.938h	26.125e	25.187ef	28.062d	25.58C
10	24.125f	27.437d	25.503	29.000c	26.52B
20	27.375d	31.313b	29.375c	33.063a	30.28A
Mean (M)	23.45D	26.59B	25.09C	28.19A	
	Fruit yield per hectare (kg)				
Control	1.550k	1.720i	1.625j	1.810h	1.676D
5	1.835h	2.090e	2.015f	2.245d	2.046C
10	1.930g	2.195d	2.040ef	2.320c	2.121B
20	2.190d	2.505b	2.350c	2.645a	2.423A
Mean (M)	1.876D	2.128B	2.008C	2.255A	

MM= mixture of microbial fertilizers; SE= seaweed extract

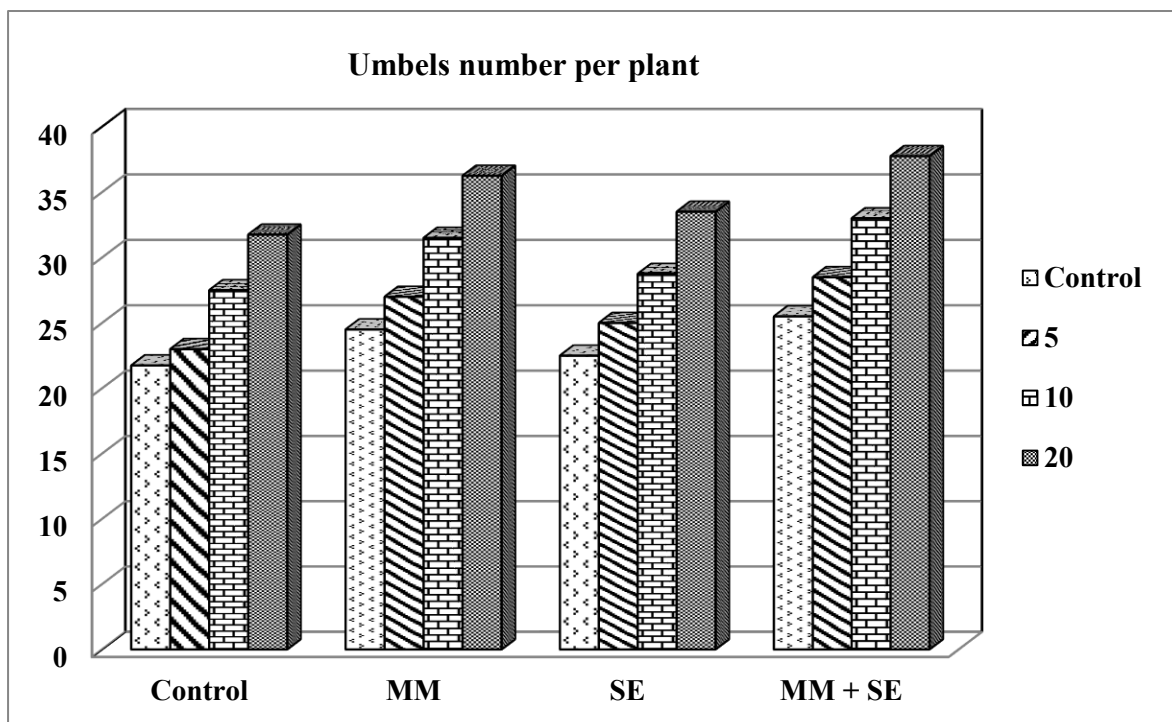


Figure 3. Influence of humic acid and biostimulants and their interaction treatments on umbels number per plant of dill

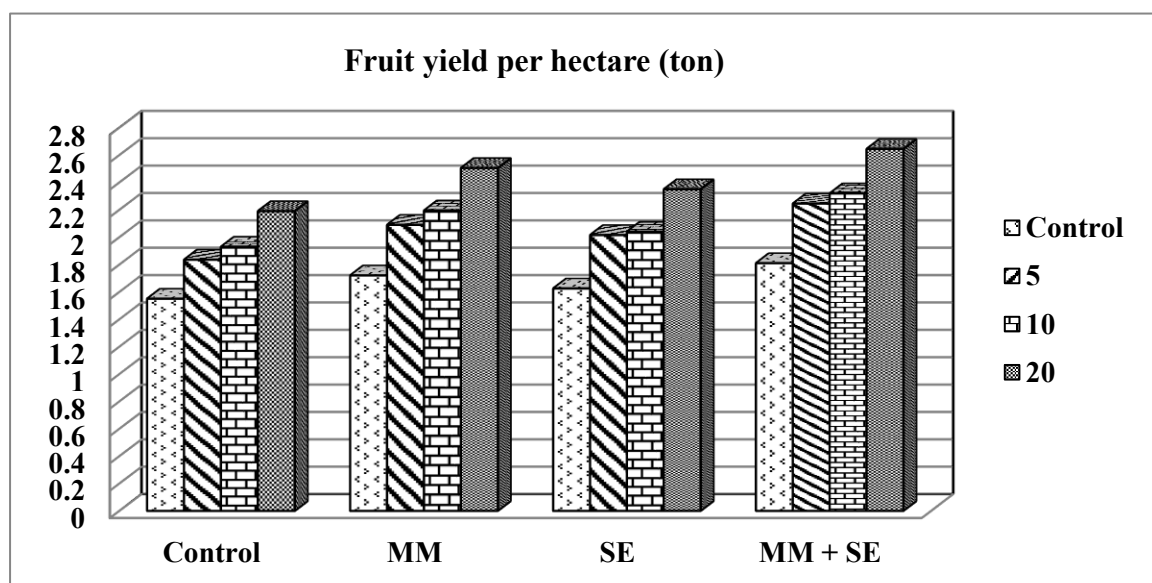


Figure 4. Effect of treatment combinations on fruit yield per hectare of dill plant

The maximum values in umbels number per dill plant (37.75 umbels), fruit yield per plant (33.063 g fruit/ plant) and fruit yield per hectare (2.645 tons /hectare) were noticed when dill plants fertilized with 20 kg/ hectare of HA + mixture of biological fertilization + seaweed extract (Table 3 as well as Figs 3 and 4). In

general, all combination treatments between main factor (humic acid) and growth promoters (biological fertilization or / and seaweed extract) significantly improved fruit yield components compared to control treatment. Moreover, increasing humic acid rates under any growth promoters under study gradually improved

number of umbels, fruit yield per plant and hectare. Moreover, Abdul-Hafeez et al. (2020) on fennel regard humic acid effect as well as Aly et al. (2021) on parsely regard biological fertilizers + seaweed extract effect reported similar results. In addition, Kisvarga et al. (2024) revealed that applied sweet basil plants with humic acids combined with seaweed extract significantly enhanced herb yield as fresh green mass compared to untreated plants.

Volatile oil production

The highest values of volatile oil %, volatile oil yield per plant and per hectare in dill fruits were obtained from fertilizing with 20 kg humic acid/hectare (Table 4). Fertilizing dill

plants with different rates significantly enhanced dill oil production compared to the control treatment (without humic acid addition). Humic acid at 20 kg /hectare recorded maximum values of volatile oil % (1.479), yield of oil per plant (0.450 ml) and volatile oil yield per hectare (36.013 l), followed by humic acid at 10 kg /hectare. In this regard, Said-Al Ahl et al. (2016) showed that humic acid recorded the highest values of dill volatile oil production (percentage or yield). Also, Alizadeh et al. (2022) revealed that fennel treated with humic acid showed a 20% increase in essential oil yield when compared to untreated plants. Increased plant volatile oil production, greater nutrient uptake and better root development are all associated with this improvement.

Table 4. Effect of humic acid, biostimulant treatments and their interaction treatments on volatile oil yield of dill plants

Humic acid rates (kg / hectare)	Growth promoter types				Mean (C)
	Control	MM	SE	MM + SE	
	Volatile oil percentage				
Control	1.185l	1.270j	1.223k	1.308h	1.246D
5	1.263j	1.323g	1.285i	1.388e	1.314C
10	1.310gh	1.403d	1.358f	1.460c	1.386B
20	1.388e	1.495b	1.458c	1.578a	1.479A
Mean (M)	1.286D	1.373B	1.331C	1.433A	
	Volatile oil yield per plant (ml)				
Control	0.230j	0.274h	0.249i	0.297g	0.262D
5	0.290g	0.346e	0.325f	0.390d	0.338C
10	0.317f	0.386d	0.347e	0.424c	0.368B
20	0.381d	0.469b	0.429c	0.523a	0.450A
Mean (M)	0.304D	0.369B	0.337C	0.408A	
	Volatile oil yield per hectare (l)				
Control	18.392j	21.890h	19.915i	23.728g	20.981D
5	23.205g	27.687e	25.965f	31.200d	27.014C
10	25.312f	30.830d	27.750e	33.912c	29.451B
20	30.422d	37.525b	34.315c	41.790a	36.013A
Mean (M)	24.333D	28.483B	26.986C	32.658A	

MM= mixture of microbial fertilizers; SE= seaweed extract

As shown in Table 4 in it is clear that using the combination treatment between mixture of biological fertilizers + seaweed extract produced the maximum values of volatile oil percentage (1.433 %), yield of volatile oil per plant (0.408 ml/plant) and yield of volatile oil per hectare (32.658

l/ hectare) compared to the other treatments and control. Utilizing biological fertilizers mixture (nitroben, mycorrhizae and *Bacillus circulans*) significantly enhanced volatile oil production compared to seaweed extract and control. Spraying dill plants with any growth promoters

significantly improved oil yield per plant and per hectare compared to control. In the same line, with increases of 118.18 and 116.25 percent, respectively, over the control, the combination treatment of seaweed extract with phosphate-

solubilizing bacteria at 100 and 70 percent field capacity demonstrated the greatest gain in essential oil content of *Calendula officinalis* plant (Azizi et al., 2024).

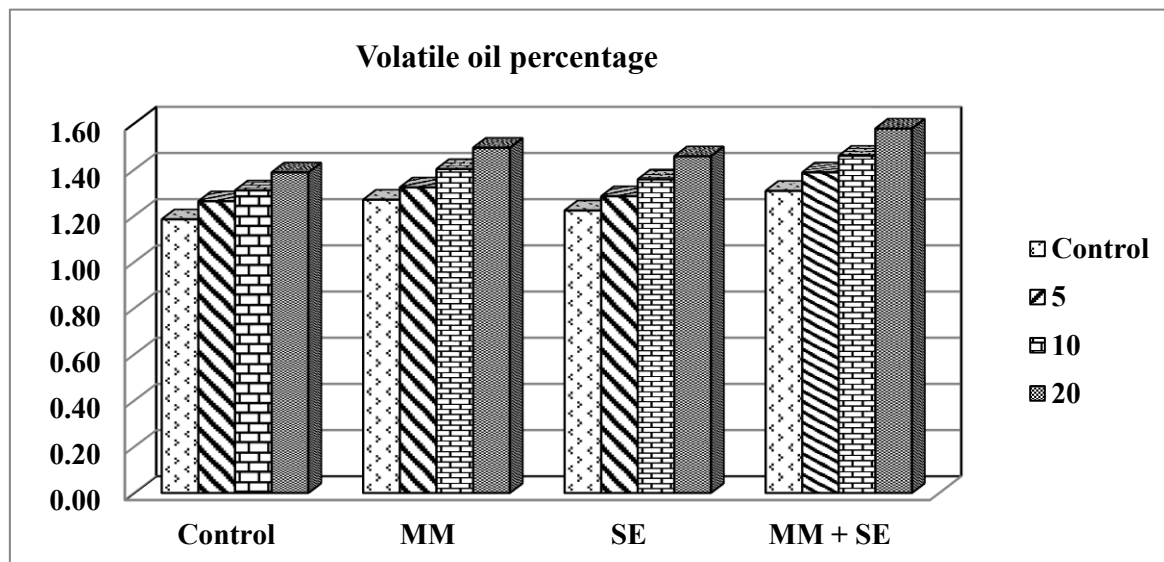


Figure 5. Effect of humic acid rate, biostimulant treatments and their interaction treatments on volatile oil percentage of dill plant

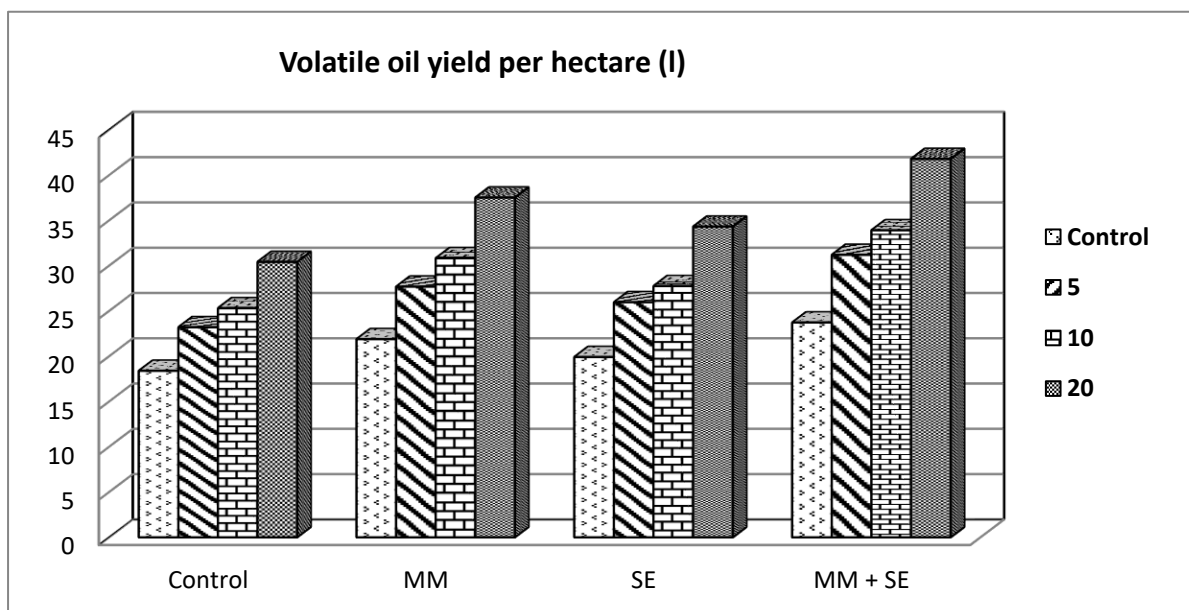


Figure 6. Effect of humic acid rate, biostimulant treatments and their interaction treatments on volatile oil yield per hectare (l) of dill plant

Fertilizing dill plants with humic acid at 20 kg/hectare combined with biological sources + seaweed extract significantly recorded the better values in volatile oil % (1.578 %), volatile oil yield

per plant (0.523 ml) and volatile oil yield per hectare (41.790 l/hectare) compared to the other combinations under study (Table 4 as well as Figs 5 and 6). While, the lowest values (1.185 %, 0.230

ml/ plant and 18.392 l/ hectare) in this concern were noticed under control plants. All combination treatments significantly improved production of volatile oil compared to control (without HA application, without biological fertilizers inoculation and without seaweed spraying). However, Alizadeh et al. (2022) pointed out that fennel treated with humic acid showed a significant increase in essential oil production compared to control. Also, Azizi et al. (2024) referred to that utilizing seaweed extract with phosphate-solubilizing bacteria significantly improved calendula officinalis oil content.

GC/MS analysis of volatile oil

Volatile oil Analysis extracted from fruits of dill detected from control treatment and the other best treatment for volatile oil production is presented in Table 5. Twelve compounds were noticed in volatile oil of dill, furthermore, eleven compounds were detected in volatile oil when dill plants treated with 10 kg humic acid /hectare +

seaweed extract (SE) as well as 10 kg humic acid + mixture of biological fertilizers (MM) + seaweed extract treatment. Also, there are eight compounds were detected in volatile oil when dill plants treated with 20 kg HA/ hectare as well as seven compounds were detected with 20 kg HA/ hectare combined with seaweed extract. Whereas, the lowest compounds number were four compounds which noticed in 20 kg HA/ hectare + MM + SE treatment. The major compound detected by GC-MS in dill volatile oil were D-Limonene, carvone followed by Dillapiole and (+)-Dihydrocarvone. Whenever, the lowest values were noticed concern Alpha-Pinene, Beta-Myrcene, Alpha-Phellandrene, Nonanal, Artemiseole, Phenol 2-methyl-5-(1-methylethyl) and 1,3-Benzodioxole, 4-methoxy-6-(2-propenyl). However, 1,3-Benzodioxole, 4-methoxy-6-(2-propenyl)- compound detected only in volatile oil of 10 kg humic acid /hectare + seaweed extract (SE) as well as 10 kg humic acid + mixture of biological fertilizers (MM) + seaweed extract treatments.

Table 5. GC-MS profiling of volatile oil composition of dill as affected by control treatment and best treatments regard yield and volatile oil production under study

Identified compounds	Treatments					
	Control	10 kg humic acid + SE	10 kg humic acid +MM + SE	20 kg humic acid + MM	20 kg humic acid + SE	20 kg humic acid +MM + SE
Alpha-Pinene	0.25	0.64	0.62	0.25	0.17	-
Beta-Myrcene	-	0.15	0.17	-	-	0.1
Alpha-Phellandrene	1.16	5.56	2.34	1.91	0.73	-
D-Limonene	21.63	36.97	24.75	27.71	28.85	23.86
Nonanal	-	0.2	0.24	0.23	-	-
Artemiseole	0.13	11.88	0.22	-	-	-
(+)-Dihydrocarvone	34.61	16.74	9.01	22.17	19.52	-
Carvone	23.44	27.72	25.2	23.1	11.96	75.84
Phenol 2-methyl-5-(1-methylethyl)-	-	0.12	0.16	0.11	0.12	-
1,3-Benzodioxole, 4-methoxy-6-(2-propenyl)-	-	0.64	0.14	-	-	-
Dillapiole	18.77	0.15	37.13	24.51	38.66	-

cis-Dihydrocarvone	-	-	-	-	-	0.21
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MM= mixture of microbial fertilizers; SE= seaweed extract

The present study demonstrates that the integrated application of humic acid (HA), microbial biofertilizers, and seaweed extract (SE) exerts a significant synergistic effect on the growth, yield, and essential oil productivity of dill under semi-arid conditions. This synergistic response is consistent with recent findings highlighting the effectiveness of combined biostimulant strategies in enhancing crop performance and resilience under stress conditions Kisvarga et al. (2024); Bulgari et al. (2023).

Growth Enhancement under Semi-Arid Conditions

The progressive improvement in vegetative growth with increasing HA rates can be attributed to its role in improving soil physicochemical properties and plant physiological processes. Humic substances enhance nutrient availability, root development, and membrane permeability, thereby promoting plant growth Canellas et al., (2023); Olaetxea et al., (2023). Additionally, HA has been shown to influence soil microbial activity and nutrient cycling, which is particularly important in sandy soils with low fertility Thilakarathna et al. (2022).

The superior performance observed under combined biofertilizer and SE treatments reflects a multi-functional mode of action. Biofertilizers improve nutrient acquisition through nitrogen fixation and phosphorus solubilization, while seaweed extracts act as biostimulants by supplying phytohormones and bioactive compounds Shukla et al., (2024); Deolu-Ajayi et al., (2022). These combined effects enhance photosynthesis, enzymatic activity, and overall plant vigor, leading to improved biomass accumulation.

Yield Formation and Resource-Use Efficiency

The significant increase in yield components observed in this study is closely linked to enhanced vegetative growth and

improved assimilate partitioning. Integrated treatments likely enhanced source-sink relationships, ensuring efficient translocation of photosynthates to reproductive organs. Similar improvements in yield under combined biostimulant applications have been reported in medicinal and aromatic crops Zaki et al. (2023); Ahmed (2024).

Furthermore, the interaction between HA and biofertilizers likely improved nutrient-use efficiency, particularly under semi-arid conditions where nutrient losses are high. The improved availability and uptake of essential nutrients support reproductive development and yield formation, consistent with findings reported by Roupahel and Colla (2022).

Enhancement of Essential Oil Yield

The increase in essential oil content and yield reflects the stimulation of both primary and secondary metabolisms. Enhanced vegetative growth provides the necessary carbon skeletons, while biostimulants activate enzymatic pathways involved in secondary metabolite synthesis. Seaweed extracts, in particular, have been shown to regulate phytohormonal balance and metabolic pathways associated with oil biosynthesis Shukla et al. (2024).

The observed increase in oil yield is also consistent with previous studies on aromatic plants, where integrated fertilization strategies improved both biomass and oil accumulation Aly et al. (2023); El-Gohary et al. (2023). These findings confirm that biostimulant combinations can significantly enhance essential oil productivity under stress-prone environments.

Modulation of Essential Oil Composition

One of the most significant findings of this study is the alteration in essential oil composition in response to treatment combinations. The increased dominance of carvone under optimal treatments suggests a shift toward selective metabolic pathways within the terpenoid biosynthesis network. This is

supported by recent studies indicating that environmental and nutritional factors regulate terpene synthase activity and metabolic flux Tholl (2022); Nagegowda (2022).

The consistent presence of D-limonene across treatments indicates its role as a key intermediate, while variations in other compounds reflect treatment-dependent metabolic regulation. Stress and nutrient availability are known to influence secondary metabolite pathways, leading to compositional changes in essential oils Isah (2023). These compositional shifts are highly relevant for industrial applications, as they allow for targeted enhancement of valuable compounds, improving oil quality and market value.

Synergistic Interaction and Agronomic Implications

The superiority of the combined treatment (HA + microbial biofertilizers + SE) across all parameters confirms a true synergistic interaction, rather than additive effects. This synergy results from the integration of:

Soil improvement (humic acid)

Biological nutrient mobilization (biofertilizers)

Physiological stimulation (seaweed extract)

Such integrated approaches are increasingly recognized as key components of sustainable agriculture, particularly in semi-arid regions where soil fertility and water availability are limiting factors Meena et al. (2022); FAO (2023).

Table 5 demonstrates that humic acid and biostimulant treatments induced pronounced qualitative and quantitative shifts in the essential oil profile of dill, indicating strong regulation of secondary metabolism. In the control treatment, the oil exhibited a relatively complex composition with a higher number of detected compounds, dominated by (+)-dihydrocarvone, carvone, D-limonene, and dillapiole. This diversity reflects a baseline metabolic state in which carbon flux is distributed across multiple branches of the terpenoid biosynthesis pathway.

In contrast, the application of humic acid—particularly at higher rates combined with microbial biofertilizers and seaweed extract led to a progressive simplification of the oil profile, characterized by a reduction in the number of compounds and a marked increase in the relative abundance of specific constituents. Notably, under the optimal integrated treatment (20 kg HA ha⁻¹+MM+SE), carvone became the predominant compound, reaching a substantially higher proportion compared to other treatments. This shift suggests the occurrence of metabolic channeling, where biosynthetic intermediates are preferentially directed toward the formation of key monoterpenes at the expense of minor constituents.

D-limonene remained consistently present across all treatments, supporting its role as a central precursor in the monoterpene biosynthetic pathway, while the variability observed in dillapiole and (+)-dihydrocarvone indicates that these compounds are more sensitive to changes in nutrient availability and biostimulant-induced physiological conditions. Additionally, the appearance or disappearance of certain minor compounds under specific treatments reflects treatment-dependent modulation of enzymatic activities, likely influenced by improved nutrient status, hormonal signaling, and enhanced metabolic efficiency.

Overall, Table 5 provides compelling evidence that integrated application of humic acid, microbial biofertilizers, and seaweed extract does not merely increase essential oil yield but actively reprograms the biochemical pathways governing oil composition. This capacity to shift the oil profile toward a higher concentration of economically valuable compounds, such as carvone, underscores the potential of these treatments as tools for targeted quality enhancement in aromatic crops, particularly under semi-arid conditions.

4. Conclusion

The results of this study clearly demonstrate that the integrated application of humic acid, microbial biofertilizers, and seaweed extract significantly enhances the growth, yield, and essential oil production of dill under semi-arid conditions. Among the tested treatments, the combination of 20 kg ha⁻¹ humic acid with microbial biofertilizers and seaweed extract proved to be the most effective, resulting in maximum vegetative growth, fruit yield, essential oil content, and oil yield.

In addition to quantitative improvements, this treatment also induced favorable changes in essential oil composition, particularly increasing the proportion of carvone, a key economically

valuable compound. These findings highlight the potential of integrated biostimulant-based fertilization strategies as a sustainable and efficient approach for improving both productivity and quality of aromatic crops in stress-prone environments. The ability to simultaneously enhance yield and tailor essential oil composition provides a valuable tool for meeting both agricultural and industrial demands.

Future research should focus on elucidating the molecular and biochemical mechanisms underlying these responses, as well as evaluating the long-term impacts on soil health and economic feasibility under different agroecological conditions.

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