

Research Article

Impact of Integrated Application of Potassium Fertilization and Several Biostimulants on Morphological Traits, Yield and Essential Oil Content of Caraway

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Abstract:

Chemical-free production of medicinal and aromatic plants is of great interest to guarantee their quality and safety. Biostimulants are products derived from organic material that, applied in small quantities, are able to stimulate the growth and productivity of several species. Caraway (*Carum carvi* L.) is an important aromatic plant and its economic value is related mainly to the fruits which contain essential oil. Improving the growth and productivity of aromatic plants via biostimulants is a very imperative theme and it has attracted the attention of many researchers worldwide. The aim of this study therefore was to evaluate the impact of potassium (K) fertilization and/or moringa leaf extract (MLE), seaweed extract (SWE) and yeast extract (YE) on the growth, fruit yield, volatile oil content, oil components and chemical composition of *Carum carvi* L. plant. K fertilizer was applied at rates of 0 (K0), 50 (K1), and 100 kg/fed (K2) as potassium sulfate. Biostimulants were applied at 1:30 v:v, 5 g/L and 10 mL/L for MLE, YE and SWE, respectively. The results revealed that the growth traits and fruit yield components were significantly enhanced due to K fertilization or biostimulants, more so with the interaction between K2 and SWE in both seasons. Moreover, K fertilization and/or biostimulants markedly improved the essential oil content since considerable increases in essential oil percentage and yield were observed in treated plants compared to the control. Specifically, SWE treatment increased essential oil yield/feddan by 80.76 and 80.58% compared to the control in both seasons, respectively. Interestingly, essential oil composition was also affected by these treatments and GC-MS analysis showed that the main components of caraway essential oil are β -Myrcene, D-Limonene, trans-Dihydrocarvone and Carvone. Furthermore, K fertilization and/or biostimulants (MLE, YE or SWE) considerably enhanced total chlorophyll, carotenoids, and N, P and K elements in caraway compared to the control. Collectively, K fertilizer combined with biostimulants, particularly SWE as promise and ecofriendly bio-stimulant may be used to improve the growth, productivity and essential oil content in caraway.

1. Introduction

Caraway (*Carum carvi* L.) is an important annual aromatic herb, belonging to Apiaceae family and its economic value is related mainly to the fruits which contain essential oil. Caraway fruits and their essential oil are widely used in several pharmaceutical and food industries (Ibrahim et al., 2006; Hassan et al., 2024). Chemical fertilization is the primary growth-limiting factor and efficiently enhances the productivity of aromatic plants (El Gendy et al., 2015). One of the most important macro elements that affect plant growth and development is potassium (K). It affects water status, meristem development, long-distance assimilation of nutrients, photosynthesis, aid translocate sugars, raise protein content, boost several enzyme functions, and regulate ionic equilibrium (Mengel and Kirkby, 2001). K also involves in production of secondary metabolites, regulation of osmotic potential, and serving as a counter ion to both inorganic ions and organic biopolymers (Britto and Kronzucker, 2008). Therefore, it participates in several physiological and biochemical processes participated in plant growth and productivity. Several reports revealed the positive impact of K fertilization on improving the growth and essential oil content in aromatic plants such as Lothe et al. (2021) and Abdou et al. (2024) in *Mentha spicata* and *Mentha piperita*.

Unfortunately, the excessive use of such chemical fertilizers causes serious impacts such as deterioration of soil fertility, agro-ecosystem pollution and higher production costs (Kahil et al. 2017; Alshallash et al. 2022). Importantly, chemical-free production of medicinal and aromatic plants is of great interest to guarantee their quality and safety. Therefore, several strategies such as non-traditional fertilizers and biostimulants have been developed to achieve those goals (Ali et al., 2022; Moussa et al., 2024, El-Nagar et al., 2025). Biostimulants are products derived from organic material that, applied in small quantities, are able to stimulate the growth and development of several crops under both optimal and stressful conditions. These products can be used as a complement to fertilizers because they strengthen the immune system and improve the plant's growth and productivity (Tolisano and Del Buono et al., 2023). It is worth noting that, biostimulants are beneficial for plants, because they are currently considered complements or substitutes for chemical fertilizers (Drobek et al., 2019).

Moringa leaf extract (MLE) is an effective biostimulant due to its content of phenols, vitamins, hormones such as gibberellic acid and cytokines, essential elements, sterols, sugars, amino acids, flavonoid, carotenoids, vitamins and antioxidants that make it beneficial for plant growth and productivity (Arif et al., 2022).

MLE as a natural and ecofriendly biostimulant has been found to improve the growth, productivity and essential oil content in *Pelargonium graveolens* (Ali et al., 2018), *Foeniculum vulgare* (Abdel-Rahman and Abdel-Kader, 2020) and *Coriandrum sativum* (Mazrou, 2019a). Therefore, it is suggested to be an ecofriendly biostimulant to enhance caraway productivity in this study.

Yeast extract (YE) is considered a plant growth enhancer as a natural cytokinins source that simulates cell division and enlargement as well as the synthesis of protein, nucleic acid and vitamin B (Amer, 2004) and releases CO₂ which resulted in enhancing net photosynthesis (Kurtzman and Fell, 2005). Furthermore, Khedr and Farid (2000) ascribed the promotion effect of YE to its stimulation effect of endogenous hormones such as GA₃ and IAA. It also enhances synthesis of chlorophyll, protein, and nucleic acids (Ahmed et al., 2021). Researchers have revealed that YE is among the most commonly elicitors which used for improving the plant growth and productivity as well as secondary metabolites accumulation (Kassem, 2013). In this context, the positive effects of dry yeast on growth, productivity and volatile oil content have been observed in several medicinal and aromatic plants such as *Pimpinella anisum* (Mazrou, 2019b), *Foeniculum vulgare* (El-Serafy et al., 2021) and *Carum carvi* (Hassan et al., 2025).

Seaweed extract (SWE) as biostimulants offer a natural substitute for synthetic fertilizers in promoting plant growth and yield (Ali et al. 2023; Mazrou et al., 2025). Important growth-promoting compounds, such as auxins, cytokinins, gibberellins, and several nutrients essential for plant development, are found in seaweed extracts (Mughunth et al., 2024). Plant growth, yield, and essential oil content were improved in several aromatic species by foliar spray with SWE (Tursun, 2022; Ali et al., 2023; El-Nagar et al., 2025).

Despite the several published reports on the impact of the aforementioned biostimulants on medicinal and aromatic plants, little information is available on caraway species. To our knowledge, this is the first report that compare the efficacy of MLE, SWE and YE in combination with potassium fertilization on the growth performance, fruit yield and essential oil content of caraway. The aim of this study therefore was to evaluate the impact of potassium fertilization and/or MLE, SWE and YE on the growth, fruit yield, volatile oil content, oil components and chemical composition of *Carum carvi* L. plant.

2. Materials and Methods

2.1. Experimental site and setup

A field experiment was carried out at the Experimental Farm of the Faculty of Agriculture, Menoufia University, Egypt, during the winter seasons of 2021 and 2022. The study aimed to assess the impact of various potassium fertilization and biostimulants treatments on the growth, yield, and volatile oil content of caraway (*Carum carvi* L.) plants. The seeds used for the

experiment were sourced from the Medicinal and Aromatic Plants Department at the Horticulture Research Institute, affiliated with the Ministry of Agriculture in Egypt. The experimental soil was a clay loamy one. The physical properties of soil were 44.23% silt, 31.24% sand and 24.53% clay. The chemical properties were: pH, 7.9; EC, 0.4 mmhos/cm; N, 0.12%; P₂O₅, 0.26%; K, 0.12%; Ca, 0.42%; Mg, 0.68% and Na, 0.62%. During soil preparation, a standardized dose of 150 kg/fed of calcium superphosphate (15.5% P₂O₅) was applied during each growing season, as recommended by the Ministry of Agriculture. Seeds were planted on October 28th in each season, with hills spaced 25 cm apart. Each experimental unit measured 2 x 2 meters and consisted of three rows, spaced 50 cm apart. Three weeks after sowing, the plants were thinned out, leaving one plant per hill.

2.2. Treatments and Experimental design

2.2.1. Potassium treatment

Potassium (K) fertilizer, in the form of potassium sulfate containing 48% K₂O, was applied at rates of 0 kg/fed (K0), 50 kg/fed (K1), and 100 kg/fed (K2). These potassium doses were distributed across two basal applications. The first dose was administered immediately after thinning the plants, while the second dose followed one month after the initial application during both experimental seasons.

2.2.2. Biostimulants treatment

Fresh, young leaves from Moringa trees were collected and blended thoroughly with distilled water at a 1:10 weight-to-volume ratio using a household blender. The resulting mixture was filtered through gauze cloth and further diluted at a 1:30 volume-to-volume ratio with distilled water to produce the MLE. Spraying was carried out three times at one-month intervals. For comparison, control plants were sprayed with tap water following the same schedule as the seaweed spray application.

Active dry yeast was sourced in powdered form from a local market. To prepare for foliar application, an aqueous solution of the yeast was activated overnight. The plants were treated monthly with a yeast extract solution at a concentration of 5 g/L, applied three times at one-month intervals, with the first application occurring one month after thinning. Meanwhile, control plants were sprayed with tap water at the same intervals as the yeast extract treatments.

A commercial liquid product derived from marine algae extract served as the source of seaweed in the study. The seaweed extract was applied at a concentration of 10 mL/L, with spraying carried out three times at monthly intervals. Meanwhile, control plants were sprayed using tap water during the same periods as the seaweed applications.

Potassium fertilization was implemented either individually or in combination with one of three biostimulants: MLE (moringa leaf extract), yeast extract, or

seaweed extract. The experimental setup followed a split-plot design, including three replicates. All essential farming practices were carried out in accordance with the recommendations provided by Egypt's Ministry of Agriculture.

2.3. Investigated traits

2.3.1. Growth and yield characters

During the harvesting phase, typically in mid-May of each growing season, random plant samples were selected from each treatment. These samples were harvested by cutting the plants just above the soil surface, and plant height (cm), number of branches per plant, and fresh and dry weight of herb / plant (g) were subsequently recorded. After that, the plants were translocated to a shade and well-ventilated place for drying for 15 days, then hammered for fruits separation and fruit yield/ plant (g) and per feddan (kg) were recorded.

2.3.2. Essential oil attributes

2.3.2.1. Essential oil percentage

Dry caraway fruit samples, weighing 50 g each, were utilized to determine the essential oil percentage. Prior to distillation, the fruits were milled. Essential oil extraction was carried out using hydro-distillation in a Clevenger apparatus for a duration of three hours. The process was performed on three separate samples, and the reported oil content represents the average of these measurements. The percentage of essential oil was calculated following the methodology outlined in the British Pharmacopoeia (1963), applying the specified equation:

Volatile oil percentage = oil volume in the graduated tube/weight of sample x 100.

The oil yield per plant (mL) and per feddan (L) was calculated. Anhydrous sodium sulfate was used for volatile oil drying then the oil was stored in dark and cool conditions till GC-MS analysis.

GC-MS analysis was utilized to identify the components of essential oils. The analysis was conducted on a HP 6890 series gas chromatograph system equipped with an HP 5973 mass selective detector. A TR-FAME capillary column (Thermo 260 M 142 P) was employed, with dimensions of 30 m × 0.25 mm ID and a film thickness of 0.25 µm, composed of 70% cyanopropyl-polysilphenylene siloxane. Helium served as the carrier gas, flowing at a rate of 1.5 mL/min. The solvent delay was set at 3 minutes. The mass spectrometer operated in electron impact ionization mode at 70 eV, scanning within the m/z range of 50 to 600 Da. Temperature settings included a source temperature of 200°C and an MS transfer line temperature of 280°C for the injector. The column's initial temperature was maintained at 50°C for 1 minute before being ramped to 230°C at a rate of 3°C/min, held for 1 minute, and further maintained at 230°C for an additional hold of 2 minutes with a ramp rate of 9°C/min. A manual injection of a 1 µL sample of the essential oil was performed

using a split ratio of 1:20. Components of the essential oil were identified by comparing retention times and mass spectra with reference standards, the NIST library integrated into the GC-MS system, as well as data sourced from existing literature.

2.3.3. Chemical analysis

2.3.3.1. Photosynthetic pigments

The analysis of chlorophyll a, chlorophyll b, and total chlorophyll was conducted following the method outlined by Metzner et al. (1965) during the flowering stage. Fresh leaf samples weighing 0.1 g were finely cut into fragments of 1 mm x 1 mm and soaked for 24 hours at 4°C in 20 ml of 96% methanol. The mixture was subsequently filtered using Whatman GF/C filter paper with a diameter of 47 mm. Absorbance readings for each filtrate were taken against a blank solution of 96% methanol at wavelengths of 666 nm and 653 nm, corresponding to chlorophyll a and b, respectively. Pigments content was expressed as mg g⁻¹ fresh weight (FW).

2.3.3.2. Mineral content

Herb samples collected at the flowering stage were desiccated, ground into a fine powder, and digested using a mixture of perchloric acid and sulfuric acid in a 1:5 ratio (v/v). The percentages of nitrogen (N), phosphorus (P), and potassium (K) in caraway herb tissues were analyzed using this digestion solution. Nitrogen levels were determined with a micro-Kjeldahl apparatus, following Black's method from Black (1965). Phosphorus content was assessed spectrophotometrically using a Pharmacia LKB-Novaspec II, based on the blue coloration according to the method of Jackson (1978). Potassium concentration was measured by flame emission photometry using Corning equipment (Tewksbury, MA, USA) as explained by Jackson (1978).

2.4. Statistical analysis

Data from each season were statistically analyzed separately using analysis of variance (ANOVA) with CoStat software (Version 6.303, CoHort Software, Monterey, CA, USA). Treatment means were compared using LSD Test at a significance level of $p \leq 0.05$.

3. Results

3.1. Growth characters

Data presented in Table 1 clearly show that plant height, branch number as well as fresh and dry weights per plant of caraway were markedly increased as a result of K application compared to the control in both seasons. These attributes were gradually increased with increasing K level and the highest plants were obtained by applying K2 level in both seasons. Similarly, all used biostimulants significantly increased plant height, branch number as well as fresh and dry weights per plant relative to the control in both experimental seasons. In this context, SWE resulted in the tallest plants compared to MLE or YE; while there were no signifi-

cant differences between MLE and YE in this respect in both seasons. Concerning the interaction between K and biostimulants, data revealed that plant height, branch number as well as fresh and dry weights per plant were markedly enhanced due to the combinations compared to the control in both seasons. The tallest plants were recorded when K2 was interacted with MLE, YE or SWE treatments without difference in between. For example, the plant height was increased by 19.18 and 17.06% in both seasons, respectively.

The increase in growth characters of *carum carvi* L. plant as a result of application of potassium could be explained through the important of nutrient in plant metabolism, enhancing carbohydrates synthetic, positively affecting water transport in the xylem and cell elongations. Potassium activates many enzymes in

plants and accelerates secondary metabolite production. These results are in accordance with those obtained by Khashaba et al. (2023) on caraway, Mohammadi et al. (2024) on *Cichorium intybus* L. and Elsayed et al. (2023) on *Prunella* plant. Additionally, the growth promotion as a result of using all biostimulants (MLE, YE and SWE) reflected the effective role of these bio-stimulant function known as metabolic enhancers because they contained constituents such as macro- and microelement nutrients, amino acids, vitamins, cytokinins and auxins which affect cellular increase of crop yield metabolism in explicated plants leading to improve growth treats (Hassan et al., 2021). In accordance with current results, Alkuwayti et al. (2020) on *Ocimum basilicum*, Al-Khamas and Al-Rubaie (2023) on *Rosmarinus officinalis* L. and Khashaba et al. (2023) on caraway reported who reported similar trend.

Table 1. Impact of potassium fertilization, bio stimulants and their interaction on growth attributes of caraway plants at 2022/2023 and 2023/2024 seasons.

Treatments	First Season				Second Season			
	Plant height (cm)	Branch Number	Fresh weight (g/plant)	Dry weight (g/plant)	Plant height (cm)	Branch Number	Fresh weight (g/plant)	Dry weight (g/plant)
K0	126.08	10.66	174.55	34.37	135.75	13.66	181.91	35.69
K1	129.66	11.66	223.2	43.75	139.75	14.41	224.5	44.34
K2	132.75	12.25	249.93	46.26	142.5	15.25	252.41	46.63
LSD (K) 5%	0.65	0.82	2.72	0.44	2.58	1.28	1.05	1.49
Bio0	117.66	9.00	151.91	28.53	128.11	12.11	162.22	30.36
MLE	132.11	12.22	225.96	43.87	141.66	15.22	226.11	44.07
YE	133.00	12.11	224.82	42.9	142.44	14.66	225.22	42.9
SWE	135.22	12.77	260.88	50.55	145.11	15.77	264.88	51.54
LSD (Bio) 5%	1.19	0.62	3.49	0.40	1.22	0.91	2.27	1.93
K0 X Bio0	114.67	7.33	123.10	21.98	125.00	10.67	145.33	25.63
K0 X MLE	127.67	11.67	182.33	37.07	137.00	14.67	187.00	38.00
K0 X YE	128.67	11.33	188.80	37.37	137.67	14.00	190.33	37.70
K0 X SWE	133.33	12.33	204.00	41.10	143.33	15.33	205.00	41.43
K1 X Bio0	117.00	9.33	162.17	30.80	127.33	12.33	165.67	31.70
K1 X MLE	132.33	12.33	231.30	45.93	142.33	15.33	232.33	46.53
K1 X YE	133.67	12.33	225.67	44.60	143.67	14.33	220.00	43.13
K1X SWE	135.67	12.67	273.67	53.70	145.67	15.67	280.00	56.00
K2 X Bio0	121.33	10.33	170.47	32.83	132.00	13.33	175.67	33.77
K2 X MLE	136.33	12.67	264.27	48.63	145.67	15.67	259.00	47.70
K2 X YE	136.67	12.67	260.00	46.73	146.00	15.67	265.33	47.87
K2X SWE	136.67	13.33	305.00	56.87	146.33	16.33	309.67	57.20
LSD (K X Bio) 5%	2.06	1.073	6.04	0.69	2.11	1.57	3.93	3.34

K0, K1 and K2 means potassium levels at 0, 50, 100 kg/fed., respectively. Bio0, MLE, Ye and SWE means without bio stimulants, moring leaf extract, yeast extract and seaweed extract, respectively.

3.2. Fruit yield

The data in Table 2 clearly show that fruit yield per plant and feddan increased with increasing K fertilization levels in the two experimental seasons. Meanwhile, the significantly least values in this respect were obtained by control without k fertilization. The differences in this concern between the different K fertilization levels were significant in both experimental seasons. Also, all biostimulants treatments significantly affected the produced fruit yield per plant and feddan compared with the control in the two experimental seasons. The

treatment of SWE resulted in mostly significant higher fruit yield per plant and feddan than those produced by the other biostimulant treatments and the control in the two growing seasons. When is assumed that the obtained fruit yield by control is equal 100% the improvement in this respect as a result of using the different biostimulant treatments as follows 120%, 132.6% and 138.8% in the first season, whereas in the second season it was 112.1%, 119.56% and 126.53% for MLE, YE and SWE, respectively. The obtained fruit yield per plant and feddan were considerably improved as a result of the interaction between the different kinds of biostimulants and the K

fertilization levels in comparison with the control plants grown without bio- or K fertilization addition in the two growing seasons as shown in Table (4). The best results in this respect were obtained by the interaction treatment of K2X SWE. The improvement in the produced fruit yield as a result of using K fertilization level and biostimulants could be attributed to its effect in stimulating plant growth in terms of increasing the mean number of branches / plant (Table 1) and consequently producing a greater number of umbels. These results are in accordance with those obtained by Hassan et al. (2022) on *Foeniculum vulgare*, Ali et al. (2023) on *Foeniculum vulgare* and Khashaba et al. (2023) on caraway plants.

Table 2. Impact of potassium fertilization, bio stimulants and their interaction on fruit yield of caraway plants at 2022/2023 and 2023/2024 seasons.

Treatments	First Season		Second Season	
	Seed yield (g/ plant)	Seed yield (kg/ fed)	Seed yield (g/ plant)	Seed yield (kg/ fed)
K0	24.91	598.00	27.66	664.00
K1	26.83	644.00	29.50	708.00
K2	28.58	686.00	30.66	736.00
LSD (K) 5%	0.97	23.33	1.63	39.13
Bio0	21.77	522.66	25.55	613.33
MLE	26.22	629.33	28.66	688.00
YE	28.88	693.33	30.55	733.33
SWE	30.22	725.33	32.33	776.00
LSD (Bio) 5%	0.85	20.58	1.29	31.10
K0 X Bio0	20.33	488.00	24.67	488.00
K0 X MLE	25.33	608.00	28.00	608.00
K0 X YE	26.00	624.00	27.33	624.00
K0 X SWE	28.00	672.00	30.67	672.00
K1 X Bio0	22.00	528.00	25.00	528.00
K1 X MLE	26.00	624.00	29.33	624.00
K1 X YE	29.00	696.00	31.33	696.00
K1X SWE	30.33	728.00	32.33	728.00
K2 X Bio0	23.00	552.00	27.00	552.00
K2 X MLE	27.33	656.00	28.67	656.00
K2 X YE	31.67	760.00	33.00	760.00
K2X SWE	32.33	776.00	34.00	776.00
LSD (K X Bio) 5%	1.47	35.64	2.23	53.86

K0, K1 and K2 means potassium levels at 0, 50, 100 kg/fed., respectively. Bio0, MLE, Ye and SWE means without bio stimulants, moring leaf extract, yeast extract and seaweed extract, respectively.

3.3. Essential oil content

The essential oil yield (per plant or feddan) was considerably improved as a result of K fertilization compared to the control in both experimental seasons (Table 3). Increasing K level from K1 to K2 resulted in a significant increase in essential oil yield (per plant or feddan) since K2 level recorded the highest essential oil yield in both seasons. In this context, plants treated with K2 level resulted in 26.08 and 21.56% higher essential oil yield per plant and 26.56 and 20.16% per feddan compared to untreated plants in both seasons, respectively. The application of MLE, YE or SWE was

markedly enhanced essential oil yield (per plant or feddan) in comparison with untreated plants in both experimental seasons (Table 3). The highest essential oil yield (per plant or feddan) was recorded by applying SWE treatment which increased essential oil yield/plant by 81.08 and 80.48 % and per feddan by 80.76 and 80.58% compared to the control in both seasons, respectively. Additionally, plants sprayed with YE or MLE came in the second rank in this respect without significant difference between both biostimulants in case of essential oil yield per plant. However, concerning essential oil yield per feddan, YE application was superior than MLE in both seasons. The combination between K and biostimulants enhanced the efficacy of both treatments and recorded higher essential oil yield compared to a sole application in both seasons. The highest essential oil yield per plant or feddan was obtained from plants fertilized with K2 level and sprayed with SWE compared to the other interaction treatments in both experimental seasons.

GC-MS analysis of caraway essential oil showed that four components of essential oil in the first season were identified (i.e. β -Myrcene, D-Limonene, trans-Dihydrocarvone and Carvone). However, in the second season five components were detected (i.e. β -Myrcene, D-Limonene, trans-Dihydrocarvone, Carvone and Perillaldehyde). The main components of essential oil were Limonene and Carvone which recorded in general about 99.5 % of essential oil composition during both seasons (Table 4). The highest Limonene percentage was recorded by the combined treatment of K2 X SWE and K2 X YE in the first and second seasons, respectively. Furthermore, the highest Carvone percentage was obtained by the combined treatment of K2 X MLE and K2 X SWE in the first and second seasons, respectively.

The result of current study showed the importance of K fertilizer in improving the essential oil content in caraway. It has been reported that K element affects assimilation of nutrients, photosynthesis, and aid translocate sugars (Mengel and Kirkby, 2001) and involves in production of secondary metabolites (Britto and Kronzucker, 2008). Therefore, it participates in several physiological and biochemical processes participated in essential oil synthesis. These results are in agreement with the findings of Lothe et al. (2021) in *Mentha arvensis* and Abdou et al. (2024) in *Mentha spicata* and *Mentha piperita* who revealed the important role of K fertilization in the essential oil content in aromatic plants.

Increasing the essential oil content in this study due to MLE treatment could be explained through the fact that MLE is rich in macro and micro nutrients, antioxidants, amino acids, and phytohormones which altogether can enhance the synthesis of essential oil (Hassan et al., 2021). In accordance with current results, Ali et al. (2018) in *Pelargonium graveolens*, Mazrou (2019a) in *Coriandrum sativum* and Abdel-Rahman and Abdel-Kader (2020) in *Foeniculum vulgare* found similar

trends which support the current results. Similarly, in ajwain, the essential oil yield was enhanced due to applying MLE (Abou El-Ghait et al., 2021) which in agreement with current results.

The promotion effect of YE on essential oil content observed in current experiment may be ascribed to its role in enhancing net photosynthesis (Kurtzman and Fell, 2005) and stimulating endogenous hormones such as GA₃ and IAA (Khedr and Farid, 2000) which directly or indirectly improved the synthesis of essential oil. Several reports have been proved the impact of YE on

enhancing the essential oil content in several aromatic species. In this context, the positive effects of dry yeast on growth, productivity and volatile oil content have been observed in several medicinal and aromatic plants such as Mazrou (2019b) on *Pimpinella anisum*, El-Serafy et al. (2021) *Foeniculum vulgare* and Hassan et al. (2025) on *Carum carvi* found similar findings which support the current data.

Table 3. Impact of potassium fertilization, bio stimulants and their interaction on essential oil percentage and yield of caraway plants at 2022/2023 and 2023/2024 seasons.

Treatments	First Season			Second Season		
	Essential oil (%)	Essential oil yield (mL/plant)	Essential oil yield (L/fed.)	Essential oil (%)	Essential oil yield (mL/plant)	Essential oil yield (L/fed.)
K0	1.85	0.46	11.18	1.84	0.51	12.40
K1	1.96	0.53	12.77	1.94	0.57	13.89
K2	2.04	0.58	14.15	2.00	0.62	14.90
LSD (K) 5%	0.01	0.01	0.43	0.04	0.03	0.76
Bio0	1.70	0.37	8.94	1.61	0.41	9.94
MLE	1.98	0.52	12.51	1.94	0.55	13.37
YE	1.90	0.55	13.19	1.86	0.56	13.65
SWE	2.22	0.67	16.16	2.31	0.74	17.95
LSD (Bio) 5%	0.01	0.01	0.41	0.02	0.02	0.61
K0 X Bio0	1.54	0.31	7.50	1.45	0.36	8.61
K0 X MLE	1.95	0.49	11.84	1.92	0.54	12.93
K0 X YE	1.86	0.48	11.63	1.82	0.50	11.94
K0 X SWE	2.05	0.58	13.80	2.19	0.67	16.15
K1 X Bio0	1.73	0.38	9.14	1.65	0.41	9.88
K1 X MLE	1.98	0.51	12.34	1.93	0.57	13.59
K1 X YE	1.89	0.55	13.13	1.86	0.58	13.96
K1X SWE	2.27	0.69	16.50	2.34	0.76	18.13
K2 X Bio0	1.85	0.42	10.20	1.75	0.47	11.34
K2 X MLE	2.04	0.56	13.38	1.98	0.57	13.62
K2 X YE	1.95	0.62	14.84	1.90	0.63	15.08
K2X SWE	2.34	0.76	18.19	2.40	0.82	19.58
LSD (K X Bio) 5%	0.01	0.01	0.71	0.03	0.03	1.05

K0, K1 and K2 means potassium levels at 0, 50, 100 kg/fed., respectively. Bio0, MLE, Ye and SWE means without bio stimulants, moringa leaf extract, yeast extract and seaweed extract, respectively.

Table 4. GC-MS analysis of essential oil of caraway fruits in response to potassium fertilization and some biostimulants during the winter seasons of 2021 and 2022.

First season			Treatments		
RT	Components (%)		MLE X K2	YE X K2	SWE X K2
1	7.714	β-Myrcene	0.23	0.18	0.26
2	8.754	D-Limonene	29.29	32.06	40.32
3	13.668	trans-Dihydrocarvone	0.19	0.24	-
4	14.841	(-)-Carvone	69.97	67.51	59.42
Total identified %			100	99.99	100
Second season			Treatments		
RT	Components (%)		MLE X K2	YE X K2	SWE X K2
1		β-Myrcene	0.36	0.29	0.17
2		D-Limonene	35.95	38.98	30.85
3		trans-Dihydrocarvone	0.28	-	0.25
4		(-)-Carvone	63.11	60.73	68.73
5		Perillaldehyde	0.3	-	-
Total identified %			100	100	100

MLE, YE and SWE means moringa leaf extract, yeast extract and seaweed extract, respectively. K2 means potassium level at 100 kg/fed.

Similarly, SWE application enhanced the essential oil content of caraway fruits in current study. Enhancing oil yield of caraway fruits due to SWE application could be explained by the presence of a considerable amount of carbohydrates in SWE which directly participated in the synthesis of plant secondary metabolites, including essential oils (ELansary et al., 2016). Furthermore, SWE contains growth-promoting compounds, such as auxins, cytokinins, gibberellins, and several nutrients (Mughunth et al., 2024) that altogether enhance the production of secondary metabolites including essential oil which in agreement with the report of Tursun (2022) on coriander. Our results are in accordance with the reports of Ali et al. (2023) on fennel and El-Nagar et al. (2025) on *Trachyspermum ammi* L. who found the SWE enhanced the essential oil content and also affected the main constituents detected in essential oil which support the current results. It is very interesting here to refer that essential oil composition was also affected by K fertilizer and all biostimulants investigated in this study (MLE, YE and SWE). In agreement with our results, the main components of essential oil have been affected by K fertilizer and biostimulants applications (Abdel-Rahman and Abdel-Kader, 2020; Abdou et al., 2024; El-Nagar et al., 2025; Hassan et al., 2025).

3.4. Photosynthetic pigments

The impact of K fertilization, biostimulants and their interaction on photosynthetic pigments of caraway leaves during both experimental seasons were presented in Table (5). The results show that total chlorophyll and carotenoids content was significantly increased as a result of K fertilization compared to the control. The highest total chlorophyll and carotenoids were obtained by applying K2 level in both seasons, respectively. Similarly, foliar application of investigated biostimulants (MLE, YE or SWE) considerably enhanced the total chlorophyll and carotenoids content in comparison with the control in both seasons. SWE application recorded significantly higher photosynthetic pigment values compared to MLE or YE treatments in both seasons. Concerning the interaction between K fertilization and biostimulants, data revealed that the photosynthetic pigments were improved due to this combination. The highest values in this respect were recorded by applying the interaction between the highest K level and SWE biostimulant in both seasons. In this context, the interacted treatment of K2 X SWE resulted in the highest photosynthetic pigments in both seasons.

Improving the photosynthetic pigments observed in this study as a result of K fertilization may be attributed to the role of K as essential element in enhancing nutrient assimilation as well as photosynthesis (Mengel and Kirkby, 2001) and hence improving the photosynthetic pigments. These results are in agreement with the results of Abdou et al. (2024) who reported that K fertilization markedly enhanced the photosynthetic pigments in *Mentha spicata* and *Mentha piperita*. Similarly, enhancing the total chlorophyll and carotenoids contents

due to K fertilization was also reported in *Prunella* (Elsayed et al., 2023).

MLE treatment also enhanced the photosynthetic pigments in caraway leaves. This result may be ascribed to the enrichment of MLE with macro and micro nutrients, amino acids, and phytohormones which altogether can enhance the photosynthetic pigments (Ali et al., 2018). In this context, MLE contains Mg which is a chlorophyll constituent and also contains cytokinins that play a vital role in chlorophyll biosynthesis (Taiz and Zeiger 2010), hence an increase in photosynthetic pigments were observed. These results support the previous reports of Mazrou (2019a) on coriander and Abou El-Ghait et al. (2021) on ajwain plants who revealed increased photosynthetic pigments due to MLE application. Furthermore, Abdel-Rahman and Abdel-Kader (2020) revealed that MLE foliar spray significantly enhanced the photosynthetic pigments of *Foeniculum vulgare* compared to unsprayed plants.

The promotion effect of YE on photosynthetic pigments observed in current experiment may be ascribed to its role in enhancing net photosynthesis (Kurtzman and Fell, 2005) and promoting some endogenous hormones such as GA₃ and IAA (Khedr and Farid, 2000) which improves the metabolism processes. Several reports have been proved the impact of YE on improving the photosynthetic pigments in several aromatic species. In this context, the positive effects of dry yeast on total chlorophyll and carotenoids have been observed in *Pimpinella anisum* (Mazrou 2019b), and *Coriandrum sativum* (Mahmoud et al., 2025). Additionally, Hassan et al. (2025) revealed that yeast extract treatment resulted in a significant increase in chlorophyll and carotenoids contents of *Carum carvi* compared to the control. Similarly, SWE application enhanced the photosynthetic pigments of caraway leaves in current study. This enhancement may be due to the presence of a considerable amount of carbohydrates, growth-promoting compounds such as auxins, cytokinins and gibberellins, and several nutrients (Mughunth et al., 2024) in SWE which encourage the photosynthesis and therefore improving the photosynthetic pigments. These results are in agreement with the findings of Ali et al. (2023) on fennel and El-Nagar et al. (2025) on *Trachyspermum ammi* L. who found the SWE enhanced the chlorophyll and carotenoids contents which support the current results.

Table 5. Impact of potassium fertilization, bio stimulants and their interaction on photosynthetic pigments of caraway plants at 2022/2023 and 2023/2024 seasons.

Treatments	First Season		Second Season	
	Total chlorophyll mg/g FW	Total carotenoids mg/g FW	Total chlorophyll mg/g FW	Total carotenoids mg/g FW
K0	1.66	0.35	1.75	0.38
K1	1.78	0.41	1.89	0.43
K2	1.84	0.44	1.89	0.45
Bio0	1.65	0.35	1.72	0.38
MLE	1.89	0.46	1.91	0.49
YE	1.89	0.48	2.04	0.50
SWE	1.98	0.54	2.18	0.56
K0 X Bio0	1.61	0.33	1.69	0.36
K0 X MLE	1.83	0.45	1.88	0.48
K0 X YE	1.80	0.47	2.01	0.49
K0 X SWE	1.91	0.53	2.14	0.55
K1 X Bio0	1.76	0.39	1.86	0.41
K1 X MLE	1.86	0.48	1.93	0.50
K1 X YE	1.84	0.49	2.06	0.50
K1X SWE	1.94	0.56	2.20	0.58
K2 X Bio0	1.78	0.42	1.87	0.43
K2 X MLE	1.89	0.49	1.97	0.53
K2 X YE	1.87	0.50	2.11	0.51
K2X SWE	1.99	0.61	2.27	0.63

K0, K1 and K2 means potassium levels at 0, 50, 100 kg/fed., respectively. Bio0, MLE, Ye and SWE means without bio stimulants, moring leaf extract, yeast extract and seaweed extract, respectively.

3.5. Nutrient elements

The effect of K fertilization, biostimulants and their interaction on N, P and K percentages during both experimental seasons were presented in Table (6). The results indicate that N, P and K percentages were increased as a result of K fertilization compared to the control. The highest N, P and K percentages were obtained by applying K2 level in the first and second seasons. Similarly, application of all used biostimulants (MLE, YE or SWE) also enhanced N, P and K percentages in comparison with the control in both seasons. Caraway plants treated with SWE recorded higher N, P and K percentages compared to MLE or YE treatments in both seasons. Regarding the interaction between K fertilization and biostimulants, results showed that N, P and K percentages were enhanced due to this combination. The highest N, P and K percentages were obtained by the interaction between the highest K level and SWE biostimulant (K2 X SWE) in both seasons.

Enhancing N, P and K percentages in this study as a result of K fertilization may be due to the role of K as an essential element in enhancing nutrient assimilation as well as photosynthesis (Mengel and Kirkby, 2001) and hence improving the growth and development and hence more nutrient absorption. These results are in agreement with the results of Al-Khamas and Al-Rubaie (2023) on *Rosmainus officinalis* and Elsayed et al. (2023) on *Prunella* who found that using optimum

potassium fertilization markedly improved N, P, and K percentages in herbs. In current study, MLE treatment also increased N, P, and K percentages in caraway. This result may be ascribed to the enrichment of MLE with macro and micro nutrients, amino acids, and phytohormones which altogether can enhance the the absorption of nutrient elements (Ali et al., 2018). In this context, Mazrou (2019a) showed that the percentages of N, P and K percentages of coriander were considerably increased due to MLE treatment relative to untreated plants which support the current results. Furthermore, Soliman (2022) on caraway and Buthelezi et al. (2023) on *Foeniculum vulgare* showed that MLE foliar spray enhanced N, P and K percentages compared to unsprayed plants.

Similarly, YE application increased N, P and K percentages in current experiment. These results may be ascribed to its role in enhancing the photosynthesis process (Kurtzman and Fell, 2005) and some endogenous hormones such as GA₃ and IAA (Khedr and Farid, 2000) which promote the vegetative growth that may reflected in improving the absorption of nutrient elements. It has been reported that YE has been considered a promising and potentially provide an environmentally friendly solution to the increased crop production through improving the nutrient solubility (Fernández et al., 2021). The positive impact of YE on N, P and K percentages have been observed in *Pimpinella anisum* (Mazrou 2019b) and sweet basil (Abou El Salehein et al., 2021). Additionally, Mahmoud et al. (2025) demonstrated that YE application markedly enhanced N, P and K percentages in coriander plants compared to untreated control.

In the same direction, SWE application improved N, P and K percentages of caraway in current study. This enhancement may be due to the presence of a considerable amount of carbohydrates, growth-promoting compounds such as auxins, cytokinins and gibberellins, and several nutrients (Mughunth et al., 2024) in SWE which encourage the photosynthesis and therefore improving the nutrient absorption. These results are in accordance with the findings of Ali et al. (2023) on fennel and Fouad et al. (2023) on rosemary who found that foliar spray with SWE had a significant influence on N, P and K percentages. Additionally, Fekri et al. (2024) on *Ocimum basilicum* and El-Nagar et al. (2025) on *Trachyspermum ammi* reported similar trends which support the current results.

Table 6. Impact of potassium fertilization, bio stimulants and their interaction on nitrogen (N), phosphorus (P) and potassium (K) percentages of caraway plants at 2022/2023 and 2023/2024 seasons.

Treatments	First Season			Second Season		
	N%	P%	K%	N%	P%	K%
K0	1.90	0.21	2.39	1.94	0.21	2.44
K1	2.11	0.26	2.88	2.22	0.31	3.13
K2	2.33	0.31	3.02	2.42	0.31	3.13
Bio0	1.92	0.20	2.38	1.93	0.22	2.41
MLE	2.49	0.39	2.91	2.59	0.43	2.99
YE	2.46	0.42	2.79	2.56	0.44	2.86
SWE	2.66	0.48	2.99	2.77	0.49	3.28
K0 X Bio0	1.95	0.22	2.43	1.98	0.22	2.51
K0 X MLE	2.46	0.38	2.88	2.55	0.40	2.98
K0 X YE	2.43	0.40	2.76	2.53	0.42	2.81
K0 X SWE	2.62	0.46	2.97	2.73	0.48	3.22
K1 X Bio0	2.14	0.28	2.90	2.24	0.30	3.10
K1 X MLE	2.54	0.41	2.95	2.64	0.43	3.53
K1 X YE	2.50	0.44	2.94	2.61	0.46	3.10
K1 X SWE	2.68	0.50	3.15	2.77	0.52	3.19
K2 X Bio0	2.35	0.30	3.06	2.45	0.32	3.16
K2 X MLE	2.61	0.45	3.08	2.72	0.47	3.12
K2 X YE	2.54	0.48	3.12	2.65	0.50	3.16
K2 X SWE	2.74	0.52	3.26	2.85	0.54	3.30

K0, K1 and K2 means potassium levels at 0, 50, 100 kg/fed., respectively. Bio0, MLE, Ye and SWE means without bio stimulants, moringa leaf extract, yeast extract and seaweed extract, respectively.

4. Conclusions

Conclusively, the growth traits, fruit yield components and essential oil content were significantly enhanced due to K fertilization or biostimulants, more so with the interaction between K2 and SWE in both seasons. Interestingly, essential oil composition was also affected by these treatments. Furthermore, K fertilization and/or biostimulants (MLE, YE or SWE) considerably enhanced total chlorophyll, carotenoids, and N, P and K elements in caraway compared to the control. Therefore, K fertilizer combined with biostimulants, particularly SWE as promise and ecofriendly bio-stimulant may be used to improve the growth, productivity and essential oil content in caraway.

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