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Improving the Growth and Productivity of the *Nigella sativa* L. Plant by Using Some Natural Stimulants

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Abstract: Recently, there is a growing global trend to reduce the use of chemical fertilizers in agriculture due to their negative effects on soil quality, environmental health, and rising production costs. Therefore, recent agricultural strategies focus on integrating natural growth stimulants and eco-friendly inputs. Accordingly, this study was conducted during the 2021/2022 and 2022/2023 seasons at El Barmoon Farm, Mansoura Horticultural Research Station, Dakahlia Governorate, Egypt, to evaluate the response of *Nigella sativa* L. plants to reduced mineral fertilization combined with potassium humate as a soil amendment, along with natural foliar stimulants. The main plot treatments included three fertilization levels: 100% of the recommended NPK dose, 75% NPK plus potassium humate at 2 kg/fed, and 50% NPK plus potassium humate at 2 kg/fed. The subplot treatments involved five foliar applications: no spray, seaweed extract at 0.5 mL/L, compost tea at 20 L/ha, sodium selenite at 8 g/L, and potassium silicate at 4 mL/L. The results showed that mineral fertilizers can be safely reduced to 75% and even 50% of the recommended dose when combined with potassium humate as a soil amendment, without compromising plant performance. All foliar treatments significantly improved the studied characteristics. The compost tea foliar application was the most effective. The interaction between 75% NPK plus potassium humate combined with foliar application of compost tea achieved the highest overall performance in vegetative growth, seed yield, and fixed oil productivity across both seasons. These findings confirm that combining natural soil amendments with eco-friendly foliar stimulants can effectively reduce the use of mineral fertilizers while maintaining high growth and productivity in *Nigella sativa* L.

Key words: *Nigella sativa* L., mineral fertilization, potassium humate, natural growth stimulants.

1. Introduction

Black cumin (*Nigella sativa* L.) is an annual aromatic and medicinal plant belonging to the Ranunculaceae family **(Randhawa and Alenazi, 2016)**. It is widely cultivated in the Mediterranean region, the Middle East, and parts of Asia for its seeds. Egypt is one of the best sources of the seeds. It grows optimally in temperatures between 15°C and 25°C and tolerates a range from 5°C to 30°C **(Kant *et al*., 2010)**. The seeds contain two main types of oil: a volatile aromatic oil and a larger portion of fixed oil that is rich in essential fatty acids, especially linoleic acid, which makes up more than 50% of the total fatty acids (**Atta, 2003)**. Additionally, the black cumin seeds contain more than one hundred bioactive compounds, including thymoquinone, alkaloids, flavonoids, saponins, tannins, proteins, minerals, and various phytochemicals. These confer significant health benefits as antibacterial, anti-inflammatory, antihistaminic, antioxidant, antitumor, anti-diabetic, and hepatoprotective agents **(Ahmad *et al*., 2013)**. It has also demonstrated protective effects against kidney injuries, bone infections, and various chronic disorders. The growing global interest in medicinal plants has further emphasized *Nigella sativa* L.as an important crop for producing pharmaceutical and nutritional oils, serving as a natural alternative to synthetic drugs and chemical additives **(Salama *et al*., 2023)**.

Potassium humate, containing macro- nutrients and micronutrients, further enhances soil structure, cation exchange capacity, and water-holding capacity, while reducing soil compaction. It also synergizes effectively with mineral fertilizers such as NPK to achieve higher efficiency and economic benefits. Additionally, potassium humate is a vital organic substance that enhances plant growth, productivity and stress tolerance by improving soil physical chemical, and biological properties, increasing microbial activity, and boosting nutrient availability and uptake **(Idrees *et al*., 2018)**. They stimulate hormonal activity, particularly auxins and cytokinins, which increase enzyme functions, chlorophyll content, membrane permeability, and photosynthesis, which promotes better plant growth under both normal and stress conditions **(Abu-Zinada and Sekh-Eleid, 2015)**. Humic substances act as hormone- growth stimulants, improve plant metabolism, facilitate nutrient recycling, and contribute significantly to sustainable agriculture and improved crop performance across various environmental conditions **(Waraich *et al*., 2011)**. Many studies have shown significant improvements in yield and quality for certain crops; for example, **Awaad *et al*. (2020)** on faba beans summarized that increasing rates of potassium humate individually led to notable increases in growth, yield parameters, and mineral content. **Abou Basha *et al*. (2021)** concluded that applying potassium humate is important for improving maize growth, yield characteristics, production, and nutrient contents (N, P, and K) under water stress conditions. **Mahdi *et al*. (2021)** reported that potassium humate application improved tissue water status by increasing membrane stability index and relative water content, along with enhanced growth traits, physio-biochemical properties, and nutrient levels. These improvements translated into higher yields and better components of faba bean plants grown in newly reclaimed soils. **Mohammed *et al*. (2021)** indicated that potassium humate can serve as a partial, inexpensive supplement for potassium fertilization in tomato plants, significantly affecting growth and all measured yield characteristics when grown in sandy soil. **Hassan *et al*. (2024)** on potatoes confirmed that potassium humate application can enhance tolerance to water shortages by increasing total chlorophyll content, soluble sugars, and proline levels. *Vicia faba* L.

Sodium selenite is one of the main inorganic forms of selenium used for supplementation and biofortification. Although selenium is not essential for plants, they absorb inorganic selenium from soil mainly as selenate (Se^{6+}) and selenite (Se^{4+}). Selenite, in particular, is taken up through phosphate transporters and quickly converted into organic Se forms inside plant tissues **(Gong *et al*. 2018)**. Selenite is considered more effective than selenate in stimulating plant antioxidant responses, such as increasing glutathione peroxidase activity, which helps improve cellular redox balance. Sodium selenite supports antioxidant protection, immune function, and redox regulation; however, it must be used carefully in both human nutrition and plant biofortification due to its narrow safety margin **Nothstein *et al*. (2016)**. **Boghdady *et al*. (2017)** demonstrated that a low concentration of 10 ppm promoted anatomical features of the stem and leaves, including a significant increase in stem diameter, cortex thickness, the number per vascular bundle, the average length and width of vascular bundles, the number of cortical layers, and the average diameter of Brassica oleracea vessels. **Tiji *et al*. (2022)** reported that coating black cumin (*Nigella sativa* L.) seeds with nano-sodium selenite significantly enhanced the antimicrobial activity of the extracted oil and increased its effectiveness against plant-pathogenic microorganisms. **Xu and Li (2023)** found that sodium selenate supported the growth of oilseed rape. Additionally, applying sodium selenite to *Taraxacum mongolicum* improved its nutritional and antioxidant profile by increasing soluble sugars, proteins, flavonoids, phenolics, and vitamin C, while also boosting antioxidant enzyme activity and reducing malondialdehyde levels **(Cheng *et al*., 2024)**.

Seaweed extracts (SWE) contain nutrients like nitrogen, phosphorus, potassium, trace elements, amino acids, vitamins, and organic acids **(Valencia *et al*., 2018)**. These elements support the plant's basic nutrition, especially in poor soils or when chemical fertilizers are limited **(Nasir *et al.*, 2022)**. Seaweed fertilizer or extract is known for containing plant hormones such as auxins, cytokinins, and gibberellins, along with other compounds (biotins, sugars, polysaccharides, etc.) that encourage plant growth. These hormones promote increased cell division, root and stem development, leaf expansion, and enhanced photosynthesis **(Ali *et al*., 2021)**. Many studies have shown the positive effects of seaweed extract on the growth of *Nigella sativa* L., its oil content, and overall yield **(Mohamed *et al*., 2020; Danesh *et al*., 2021; Salama *et al*., 2023)**.

Potassium silicate is a highly soluble source of potassium (K) and silicon (Si), widely used in agricultural systems primarily as a silicon amendment with the added advantage of supplying available potassium. Numerous studies have demonstrated that potassium silicate improves plant growth, nutrient uptake, and yield quality across various crop species **(Massoud *et al*., 2024)**. Silicon supplied through potassium silicate plays a vital role in enhancing photosynthesis, water-use efficiency, nutrient absorption, cell division, and the development of leaf pigments. It also strengthens plant cell walls, thereby improving structural integrity and overall plant vigor. In horticultural and field crops, potassium silicate contributes significantly to improved yield, fruit quality, and storage stability. It has been reported to increase vegetative growth and promote higher concentrations of N, P, and K in plant tissues. Potassium silicate serves as an effective agricultural input, supporting plant growth, increasing stress tolerance, and enhancing both productivity and quality across diverse crop systems. Numerous studies have confirmed that Potassium silicate improves vegetative growth, chlorophyll content, and nutrient uptake, and has also been shown to stimulate root development, increase seed oil components, and enhance seed quality of *Nigella sativa* L. (**El-Leithy *et al*., 2019; Salama *et al*., 2023)**.

Compost tea (CT) is a liquid organic extract made by steeping mature compost in water at ratios usually between 1:5 and 1:10 (v/v) for 2 to 15 days. It can be prepared either aerobically (aerated compost tea) or anaerobically (non-aerated tea). The quality and biochemical properties of compost tea depend on several factors, including the type of compost used, the compost-to-water ratio, aeration conditions, and the duration of extraction **(Gonzalez-Hernandez *et al.*, 2022)**.

Compost tea contains a wide array of soluble organic compounds, macro- and micronutrients, and helpful microorganisms. These microbial communities, such as bacteria, fungi, actinomycetes, and protozoa, play a vital role in supporting plant growth and reducing pathogens through mechanisms like improved nutrient uptake (e.g., nitrogen fixation, phosphorus solubilization, and iron acquisition), production of bioactive compounds, competition, and antagonism against soil-borne pathogens **(Ibrahim *et al*., 2019)**. Compost tea is increasingly regarded as an environmentally friendly, sustainable alternative to chemical fertilizers and fungicides **(Shaban *et al*., 2015)**, helping to improve soil health, boost organic matter, enhance nutrient cycling, and build more resilient crop systems. Adding beneficial microorganisms like Trichoderma spp. to compost tea can further enhance its ability to promote growth and suppress disease effects. These results align with **Abdou *et al*. (2023) and Al-Fraihat *et al*. (2023)**, who found that compost tea application improved biochemical traits, morphophysiological characteristics, seed yield, and oil quality of *Nigella sativa.*

2. Materials and Methods

2.1. Experimental Site and Soil Characteristics

At El Barmoon Farm, Mansoura Horticultural Research Station, Dakahlia Governorate, Egypt. a field experiment was conducted during two rabi seasons at the last week of November 2021/2022 and 2022/2023.

Data in Table 1 shows the average physical and chemical properties of the initial soil at a depth of 0–0.5 m. The soil was clayey in texture.

All composite soil samples collected before the experiment were evaluated for physical properties described by **Black (1965)**, whereas chemical soil analysis was conducted according to **Page *et al*. (1982)**.

Table (1). The physical and chemical properties of the experimental soil

Mechanical analysis (%)				Chemical analysis		
soil texture	Sand %	Silt %	Clay %	CaCO3%	pH	EC ds m^{-1} (1:5)
Clay	8.2	20.4	70.4	0.001	7.20	0.17

Available (mg/100 g soil)			Cations (meq/100 g soil)				Anions (meq/100 g soil)			
N	P	K	Ca++	Mg++	Na+	K+	$CO3^{--}$	$HCO3^{-}$	Cl^{-}	$SO4^{--}$
51	7.5	129	0.40	0.33	1.61	0.08	0.00	0.22	0.69	1.12

2.2. Plant Material and Growth Conditions

Black cumin seeds were obtained from the Department of Medicinal and Aromatic Plants, Ministry of Agriculture, Giza, Egypt, and were sown during the last week of November at a rate of 4 kg·fed^{-1} in both growing seasons. Each experimental unit covered an area of 7.5 m^2 (3 × 2.5 m), consisting of three planting rows, each 3 m long and 0.6 m wide. Seeds were planted in hills 25 cm apart, with 3–4 seeds per hill, and thinning was carried out to maintain one plant per hill at 30 days after sowing. Before sowing, organic fertilizer was applied to all plots at varying rates.

2.3. Treatment Applications and Experimental Design

NPK Applications: The recommended N, P, and K doses of 150, 70, and 60 kg·fed^{-1}, respectively, were applied. Phosphorus was supplied as calcium superphosphate (15.5% P_2O_5) during soil preparation. Nitrogen was applied as ammonium sulfate (20.6% N), along with potassium as potassium sulfate (48% K_2O), in three separate applications. In addition, treatments receiving 75% of the recommended dose, as well as those receiving 50% of the recommended dose, were also included during the growing season, according to the recommendations of the Ministry of Agriculture and Land Reclamation.

Potassium humate, sodium selenite, and potassium silicate were obtained from El-Ahram Company for Mining and Natural Fertilizers, Maadi, Cairo, Egypt, at a rate of 96% by weight.

A commercial seaweed extract product was applied containing 1% nitrogen, 2.5% potassium, 0.17% calcium, 0.43% magnesium, 0.06% iron, 2.2% sulfur, 0.99 ppm zinc, 3.87 ppm boron and 10–12% alginic acids.

Compost tea (CT) was produced from mature compost derived from garden wastes (grass clippings and pruning residues). The compost was prepared in aerated piles for 180 days with regular turning and moisture maintained at 60%. The mature compost was then mixed with previously aerated tap water at a 1:5 (v/v) ratio and brewed for five days under continuous daily aeration. After filtration, the CT was stored in dark containers at room temperature until use. According to the authors **(Gonzalez-Hernandez *et al*., 2022).** The chemical composition and microbial content of the compost tea used in this study are presented in Table 2.

Table (2). The chemical composition of compost tea

Chemical composition of compost tea	
Properties	**Value**
pH [at a soil-to-water(w/v) ratio of 1:2.5]	7.26
Ece (dS·m^{-1}; soil paste extract)	2.90
CaCO3(g·kg^{-1})	1.52
O.M (%)	55.43
O.C (%)	35
N (%)	1.29
P (g·kg^{-1})	7.10
K (g·kg^{-1})	9
N-fixing bacteria cfu mL^{-1}	2.7 × 107
Trichoderma sp. and fungi cfu mL^{-1}	2.7 and 8.8 × 102

A split-plot arrangement in a complete randomized block design, in three replicates and nine plants/ replicate, was executed in this experiment with three treatments (NPK recommended dose), 75% NPK plus potassium humate at 2 kg/fed, and 50% NPK plus potassium humate at 2 kg/fed in the main plots. the sub-plot treatments involved five foliar applications {control (no spray), sodium selenite (8 g/L), seaweed extract (0.5 ml/L), potassium silicate (4 ml/L) and compost tea (20 L/fed)}. Foliar spraying was performed three times during the growing season at 45, 75 and 105 days after sowing.

2.4. Morphological Characteristics and Yield Attributes Recorded

Morphological Characteristics: Nine plants were randomly selected from each treatment at full bloom (120 DAS) to assess the morphological parameters, including plant height (cm), number of branches/plants, and plant fresh and dry weights.

Yield Attributes*:* At maturity (180 DAS), all plants from each experimental unit were harvested to estimate the number of capsules/plants, seed yield/plant (g), and seed yield/Fed (Kg).

2.5. Seed Fixed Oil and Composition

The percentage of fixed oil in seed samples was determined using the Soxhlet extraction method (**AOAC,2007**). Fixed oil was extracted from 100 g of seeds using a Soxhlet apparatus with petroleum ether (40–60 °C). The extracted oil was then dried over anhydrous sodium sulfate and stored in darkness at −20 °C until further analysis. The weight was recorded and calculated by using the following formula,

$$\text{Fixed oil (\%)} = \frac{W2 - W1}{W} \times 100$$

W1 Initial weight of the jar (g), W2 Final weight of the jar (g) and W Weight of the sample (g)

oil yield per plant and per feddan was calculated by using the following formula

$$\text{Fixed oil yield per plant or feddan} = \frac{fixed\ oil\ content\% \times seed\ yieldper\ plant\ or\ feddan\ kg}{100}$$

2.6. Minerals Content (N, P, and K+)

The nutrient content (N, P, and K^+) of *Nigella sativa* L. leaves was determined **(AOAC, 1990),** Nitrogen content was assessed using the Kjeldahl method **(Cottenie *et al*., 1982)**. Leaves were oven-dried and wet-digested in a mixture of HCO_4 and H_2SO_4 (1:3, v/v). Phosphorus content was measured using a spectrophotometer, while potassium was determined by flame photometry **(Jackson, 1967)**.

2.7. Statistical Analysis

The present data were statistically analyzed using analysis of variance (ANOVA) for a split-plot arrangement in a randomized complete block design (RCBD), after testing for homogeneity of error variances with the Statistical Analysis System (Co Stat). Significant differences between means were compared at ($p \leq 0.05$) using the LSD test, following the procedure outlined by **(Gomez and Gomez, 1984).**

3. Results and Discussion

3.1. Morphological Characteristics

The data in Table 3 clearly show that the morphological characteristics of *Nigella sativa* L. plants, including plant height, number of branches per plant, and fresh and dry weights, were significantly affected by both (A) mineral fertilization with NPK, whether applied alone or combined with potassium humate as a soil amendment, and (B) foliar application treatments (seaweed extract, compost tea, sodium selenite and potassium silicate) during the two growing seasons (2021/2022 and 2022/2023).

Regarding soil-addition fertilizers, although the NPK recommended dose resulted in significant improvements in morphological characteristics, the combination of 75% NPK plus potassium humate at 2 kg/fed showed superior performance in plant height, number of branches per plant, and both fresh and dry weights compared to the NPK recommended dose. Additionally, 50% NPK plus potassium humate at 2 kg/fed achieved results comparable to those of the full NPK recommended dose. the results above, which show a mix of reduced rates at 75% NPK or 50% of the recommended dose combined with natural amendments fertilizer, significantly improved vegetative growth characteristics in line with the findings of **Harb *et al.* (2011), Mohamed *et al.* (2020), Al-Fraihat *et al.* (2023), and El-Banna (2024)** on *Nigella sativa*.

The increase in vegetative growth with potassium humate application may be due to its function in enhancing nutrient availability, stimulating root growth, and supporting physiological processes in plants **(Nassar *et al.*, 2021)** Humic substances are recognized as natural bio-stimulants that improve nutrient absorption efficiency and promote plant growth even at lower mineral fertilizer levels.

Across all foliar treatments, each one improved vegetative growth parameters compared to the control. Compost tea showed the most notable increases in plant height (75.10 and 78.77 cm), number of branches per plant (7.77 and 9.10), and fresh (103.29 and 110.55 g) and dry weights (22.33 and 24.02 g). Similarly, potassium silicate produced close results in plant height (72.82 and 76 cm), number of branches per plant (6.99 and 8.22), and fresh (101.03 and 107.32 g) and dry weights (21.10 and 22.87 g), across both seasons. These were followed by seaweed extract and sodium selenite, while the control treatment consistently recorded the lowest values. Many studies have highlighted the positive effect of natural foliar stimulants on the vegetative growth of *Nigella sativa* L., as shown by **Ibrahim *et al.* (2019), Abdou *et al.* (2023)**, and **Al-Fraihat *et al.* (2023)**. Compost tea was more effective for plant growth; additionally, **El-Leithy *et al.* (2019)** explained the beneficial role of potassium silicate. Based on the collected studies, seaweed increased growth parameters, as demonstrated by **Mohamed *et al.* (2020)**, **Danesh *et al.* (2020)**, **Salama *et al.* (2023)**, and **Tiji *et al.* (2021)**, showed that sodium selenite led to better performance in plant height, the number of branches per plant, and both fresh and dry weights.

The interaction effect showed that combining 75% NPK with potassium humate and either compost tea or potassium silicate foliar application resulted in the greatest plant height, number of branches, and both fresh and dry weights in both seasons.

Natural bio-stimulants such as compost tea, seaweed extracts, silicon, and selenium compounds enhance vegetative growth through several physiological, biochemical, and microbial mechanisms, rather than acting as direct nutrient sources. Their main modes of action can be summarized as follows: compost tea introduces beneficial microorganisms into the soil, including nitrogen-fixing bacteria and growth-promoting fungi (such as *Trichoderma*), which secrete natural growth regulators. Soluble phosphorus stimulants encourage root growth, increase root branching, and promote the development of root hairs, thereby improving the absorption of nitrogen, phosphorus, potassium and micronutrients. Additionally, seaweed extracts contain compounds similar to plant hormones (auxins, cytokinin and gibberellins), which lead to increased chlorophyll content, photosynthetic efficiency, cell division rate, and cell elongation. This explains how natural materials support vegetative growth.

Table (3). Effect of soil amendment and foliar applications and their interaction on the morphological characteristics *of Nigella sativa* L. plants for the two different growing seasons

	2021/2022 season						2022/2023 season					
Fertilizer addition (A)	Foliar application (B)											
	Control	Sodium Selenite	Seaweed extract	Potassium Silicate	Compost Tea	Mean (A)	Control	Sodium Selenite	Seaweed extract	Potassium Silicate	Compost Tea	Mean (A)
Plant height (cm)												
100%NPK	57.66	61.16	66.16	70.66	72.33	**65.59**	59	62.66	71.66	73	75.66	**68.46**
75%NPK +Potassium Humate	61.33	68	72.66	76.66	79.66	**71.66**	63.33	71.33	76.66	81	84.66	**75.39**
50%NPK +Potassium Humate	56.66	62.16	67.66	71.16	73.33	**66.19**	59.66	63.33	70.66	74	76	**68.66**
Mean (B)	**58.55**	**63.77**	**68.82**	**72.82**	**75.10**		**60.66**	**65.77**	**72.99**	**76**	**78.77**	
LSD 5%	A= 0.93 B= 0.49 AB= 1.48						A=1.23 B= 1.37 AB=1.78					
Number of branches / plants												
100%NPK	5	5.66	5.66	6.66	7.33	**6.06**	6	6	6.66	7.66	9	**7.06**
75%NPK +Potassium Humate	6.33	7	7.33	7.66	8.33	**7.33**	8	8	9	9	9.66	**8.72**
50%NPK +Potassium Humate	5.33	6	6.33	6.66	7.66	**6.39**	6	7.33	8	8	8.66	**7.59**
Mean (B)	**5.55**	**6.22**	**6.44**	**6.99**	**7.77**		**6.66**	**7.11**	**7.88**	**8.22**	**9.10**	
LSD 5%	A=0.55 B= 0.70 AB=1.62						A= 0.52 B=0.47 AB=0.37					
Plant fresh weight (g)												
100%NPK	91.29	96.31	99.27	98.91	100.26	**97.20**	95.35	99.27	103.84	103.92	107.36	**101.94**
75%NPK +Potassium Humate	95.82	95.98	100.85	104.85	107.28	**100.33**	99.09	102.12	104.87	112.86	115.59	**106.90**
50%NPK +Potassium Humate	93.85	94.86	98.47	99.34	102.33	**98.38**	96.49	101.34	104.28	105.18	108.72	**103.20**
Mean (B)	**93.65**	**95.71**	**99.53**	**101.03**	**103.29**		**96.97**	**100.91**	**104.33**	**107.32**	**110.55**	
LSD 5%	A= 0.38 B=2.29 AB= 2.17						A= 0.87 B=1.12 AB= 2.76					
Plant dry weight (g)												
100%NPK	17.53	18.41	19.59	19.42	19.61	**18.91**	18.71	19.44	20.49	20.85	21.35	**20.16**
75%NPK +Potassium Humate	18.60	19.38	21.12	23.69	25.23	**21.60**	20.36	23.04	23.78	25.40	26.72	**23.86**
50%NPK +Potassium Humate	18.18	18.44	20	20.20	22.16	**19.79**	19.74	21.42	19.89	22.37	23.99	**21.48**
Mean(B)	**18.10**	**18.74**	**20.23**	**21.10**	**22.33**		**19.60**	**21.30**	**21.38**	**22.87**	**24.02**	
LSD 5%	A=0.88 B= 1.04 AB=1.43						A=1.44 B= 1.86 AB=2.13					

3.2. Yield Attributes

The revealed data in Table 4 clearly demonstrate that yield attributes, including (capsule number per plant, seed yield per plant, and seed yield per feddan) of *Nigella sativa* L. were significantly affected by fertilizer addition, foliar application treatments and their interaction during both growing seasons (2021/2022 and 2022/2023).

Regarding fertilizer addition, the partial substitution of mineral fertilization with potassium humate enhanced nutrient use efficiency and improved seed productivity.

The treatment of 50% NPK plus potassium humate produced yields comparable to those obtained with 100% NPK. Meanwhile, the application of 75% NPK combined with potassium humate significantly outperformed the full recommended dose of NPK in all studied yield attributes through both seasons. Whereas it recorded the highest mean values for the number of capsules per plant (44.99 and 44.59), seed yield per plant (16.84 and 18.89 g), and seed yield per feddan (363.94 and 408.17 kg). suggesting the possibility of using potassium humate to reduce mineral fertilizer inputs without compromising yield. The obtained results are in agreement with earlier studies on *Nigella sativa* L. that demonstrated significant improvements in seed yield traits **(Harb *et al*., 2011; Mohamed *et al*., 2020; Al-Fraihat *et al*., 2023** and **El-Banna, 2024)**.

Concerning foliar application treatments, all bio-stimulant treatments significantly increased yield attributes compared with the untreated control in both seasons (Table 4). Compost tea proved to be the most effective foliar treatment, resulting in the highest mean capsule number per plant (47.88 and 49.10), seed yield per plant (17.82 and 19.86 g), and seed yield per feddan (385.10 and 429.16 kg). This was followed by potassium silicate capsule number per plant (43.22 and 44.77), seed yield per plant (15.67 and 17.45 g), and seed yield per feddan (338.54 and 376.99 kg), seaweed extract capsule number per plant (38.99 and 40.33), seed yield per plant (13.91 and 15.24 g), and seed yield per feddan (300.52 and 329.34 kg) respectively, while sodium selenite recorded the least effective foliar treatment in enhancing capsule number per plant, seed yield per plant, and seed yield per feddan. The control treatment showed the lowest values. The superior effect of compost tea may be attributed to its rich content of nutrients, organic compounds, beneficial microorganisms, and growth-promoting substances that enhance flowering, seed set, and assimilate translocation. Several studies have reported the positive effects of compost tea on the seed yield of *Nigella sativa* L. is (**Ibrahim *et al*., 2019; Abdou *et al*., 2023; Al-Fraihat *et al*., 2023)**. Moreover, the beneficial role of potassium silicate on *Nigella sativa* L. was highlighted by **El-Leithy *et al*. (2019)**. Based on previous studies, seaweed extracts significantly enhanced capsule number per plant, seed yield **(Mohamed *et al*., 2020; Danesh *et al*., 2020; Salama *et al*., 2023)**. In addition, sodium selenite improved all seed yield attributes of *Nigella sativa* L. **(Tiji *et al*., 2021)**.

The interaction effect was significant for all studied traits. The combination of 75% of the recommended NPK dose plus potassium humate, combined with foliar application treatments was more effective at enhancing growth and yield parameters of *Nigella sativa* L. plants than either 50% NPK plus potassium humate combined with foliar treatments or the full recommended dose of mineral fertilization alone. The best combination was 75% NPK plus potassium humate with a foliar application of compost tea, resulting in the maximum values of capsule number per plant, seed yield per plant and seed yield per feddan in both seasons, confirming a strong synergistic effect between soil-applied potassium humate and foliar bio-stimulants. These results emphasize that integrating reduced mineral fertilization with natural bio-stimulants is an effective strategy to improve the yield and sustainability of *Nigella sativa* L. production.

Table (4). Effect of soil amendment and foliar applications and their interaction on the yield attributes of *Nigella sativa* L. plants for the two different growing seasons

	2021/2022 season							2022/2023 season				
Fertilizer addition (A)	**Foliar application (B)**											
		Sodium Selenite	Seaweed extract	Potassium Silicate	Compost Tea	Mean (A)	Control	Sodium Selenite	Seaweed extract	Potassium Silicate	Compost Tea	Mean (A)
Capsules number/plant												
100%NPK	30.33	33.33	35.66	41	45.66	**37.19**	32.33	33.66	37.33	42	46.66	**38.39**
75%NPK +Potassium Humate	38.33	41.66	45.33	48.33	51.33	**44.99**	40	34	46.33	49.66	53	**44.59**
50%NPK +Potassium Humate	28	34.33	36	40.33	46.66	**37.06**	29.33	35.66	37.33	42.66	47.66	**38.52**
Mean (B)	**32.22**	**36.44**	**38.99**	**43.22**	**47.88**		**33.88**	**34.44**	**40.33**	**44.77**	**49.10**	
LSD 5%	A= 1.02 B= 1.58 AB= 1.72						A=0.91 B= 0.78 AB=1.01					
Seed yield/plant (g)												
100%NPK	10.26	11.33	12.58	13.87	16.76	**12.96**	11.33	12.41	13.05	15.17	18.82	**14.15**
75%NPK +Potassium Humate	13.35	15.48	16.48	18.78	20.14	**16.84**	14.86	17.53	18.48	21.05	22.55	**18.89**
50%NPK +Potassium Humate	10.25	11.57	12.67	14.36	16.57	**13.08**	11.75	12.99	14.20	16.13	18.23	**14.66**
Mean (B)	**11.28**	**12.79**	**13.91**	**15.67**	**17.82**		**12.64**	**14.31**	**15.24**	**17.45**	**19.86**	
LSD 5%	A=1.71 B= 0.86 AB= 1.21						A= 0.99 B=1.28 AB=1.63					
Seed yield/Fed. (Kg)												
100%NPK	221.61	244.87	271.80	299.66	362.16	**280.02**	244.72	268.20	282.02	327.74	406.44	**305.82**
75%NPK +Potassium Humate	288.50	334.51	355.96	405.64	435.09	**363.94**	321.12	378.64	399.16	454.75	487.22	**408.17**
50%NPK +Potassium Humate	221.47	250.05	273.81	310.32	358.05	**282.74**	253.87	280.65	306.86	348.48	393.84	**316.74**
Mean (B)	**243.86**	**276.47**	**300.52**	**338.54**	**385.10**		**273.23**	**309.16**	**329.34**	**376.99**	**429.16**	
LSD 5%	A=27.07 B=18.76 AB=27.26						A= 21.02 B=27.14 AB=35.21					

3.3. Seed Fixed Oil Productivity and Composition

The data in Table 5 clearly revealed that the fixed oil production percentage, yield/plant (ml), and feddan (L) of *Nigella sativa* L. were affected by fertilizer addition, foliar application treatments, and their interaction during both growing seasons (2021/2022 and 2022/2023).

Oil percentage, yield per plant (ml), and feddan (L) increased significantly when moving from the 100% NPK recommended dose to 50% NPK plus potassium humate, and the highest values were achieved with the application of 75% NPK plus potassium humate in both growing seasons. Foliar application treatments, including sodium selenite, seaweed, potassium silicate, and compost tea, significantly improved oil percentage, yield per plant (ml), and yield per feddan (L) compared to the control across two growing seasons. Treated *Nigella sativa* L. plants with compost tea achieved the highest values for fixed oil percentage, fixed oil yield per plant, and per feddan, which were 33.12% and 34.08%, 5.95 ml and 6.82 ml, and 128.58 L and 147.42 L, respectively, in the two seasons, surpassing results from sodium selenite, seaweed, and potassium silicate foliar applications. The control treatment resulted in the lowest value. These results align with **Roussis *et al*. (2022) and El-Banna (2024)**, who reported that bio-foliar stimulants increased the fixed oil percentage.

The data in Table 5 clearly show that fixed oil percentage, fixed oil yield (ml) /plant and fixed oil yield (L) /feddan of *Nigella sativa* L. plants were significantly influenced by reduced 100% NPK recommended dose to 75% or 50% recommended dose of NPK fertilization treatments combined with foliar applications including sodium selenite, seaweed, potassium silicate, and compost tea in the two growing season. These results are consistent with those obtained by **Salama *et al*. (2023)**, who reported that NPK fertilization combined with humate and seaweed enhances the percentage and content of fixed oil. Studies have highlighted that the highest values of percentage and fixed oil content are influenced by a natural stimulant, compost tea, on *Nigella sativa* L., as shown by **Abdou *et al*. (2023) and Al-Fraihat *et al*. (2023)**.

All foliar applications led to a significant increase in fixed oil percentage, fixed oil yield (ml) /pant and fixed oil yield (L) /feddan under 75% or 50% recommended dose of NPK fertilization plus potassium humate compared to untreated plants 100% NPK. The highest values of fixed oil percentage, fixed oil yield (ml) /plant and fixed oil yield (L) /feddan were observed in the plants treated with 75% of the recommended NPK dose plus potassium humate combined with foliar applications, followed by 50% recommended dose of NPK fertilization plus potassium humate.

Concerning the best treatment, the combined application of 75% NPK plus potassium humate with compost tea foliar spray produced the highest values of fixed oil percentage and oil yield per plant and per feddan in both growing seasons, demonstrating a strong synergistic effect between soil and foliar nutrition. Results observed from **Hassan *et al*. (2023)** indicated that half of the recommendations for NPK fertilizer and bio-stimulants led to an increase in fixed oil percentage and yield.

Table (5). Effect of soil amendment and foliar applications and their interaction on the seed fixed oil productivity of *Nigella sativa* L. plants for the two different growing seasons

	2021/2022 season						2022/2023 season					
Fertilizer addition (A)	Foliar application (B)											
	Control	Sodium Selenite	Seaweed extract	Potassium Silicate	Compost Tea	Mean (A)	Control	Sodium Selenite	Seaweed extract	Potassium Silicate	Compost Tea	Mean (A)
Fixed oil %												
100%NPK	29.35	29.46	30.31	30.57	31.21	**30.18**	29.61	30.58	31.41	31.83	32.31	**31.14**
75%NPK +Potassium Humate	35.01	35.45	35.57	36.20	37.03	**35.85**	33.02	33.99	35.40	36.62	37.90	**35.38**
50%NPK +Potassium Humate	29.30	29.28	30.30	30.47	31.14	**30.09**	29.67	29.95	30.79	31.31	32.04	**30.75**
Mean (B)	**31.22**	**31.39**	**32.06**	**32.41**	**33.12**		**30.76**	**31.50**	**32.53**	**33.25**	**34.08**	
LSD 5%	A=0.23 B=0.27 AB= 0.67						A=0.46 B=0.38 AB=0.29					
Fixed oil (ml/ plant)												
100%NPK	3.01	3.43	3.70	4.24	5.23	**3.92**	3.35	3.79	4.09	4.83	6.08	**4.42**
75%NPK +Potassium Humate	4.67	5.50	5.84	6.80	7.46	**6.05**	5.05	6.10	6.20	7.70	8.54	**6.71**
50%NPK +Potassium Humate	3.00	3.50	3.71	4.38	5.16	**3.95**	3.48	4.00	4.21	5.05	5.84	**4.51**
Mean (B)	**3.56**	**4.14**	**4.41**	**5.14**	**5.95**		**3.96**	**4.63**	**4.83**	**5.86**	**6.82**	
LSD 5%	A= 0.62 B=0.30 AB= 2.09						A=0.54 B=0.45 AB=0.35					
Fixed oil (l/ fed.)												
100%NPK	65.10	74.22	80.08	91.61	113.06	**84.81**	72.52	82.02	88.52	104.34	131.40	**95.76**
75%NPK +Potassium Humate	101.02	118.99	126.25	146.89	161.15	**130.86**	109.16	131.80	134.03	166.48	184.65	**145.22**
50%NPK +Potassium Humate	64.85	75.79	80.16	94.61	111.53	**85.38**	75.32	86.41	90.99	109.10	126.23	**97.61**
Mean (B)	**76.99**	**89.66**	**95.49**	**111.03**	**128.58**		**85.66**	**100.07**	**104.51**	**126.64**	**147.42**	
LSD 5%	A=13.43 B=6.49 AB= 0.48						A=11.84 B=9.76 AB=7.57					

Table 6 shows the fatty acid composition in fixed oils extracted from black cumin seeds, influenced by the interaction between (A) mineral fertilization with NPK, whether applied alone or with potassium humate as a soil amendment, and (B) foliar application treatments. It revealed a total of 8 compounds, with the major fatty acids in *Nigella sativa* L. oil studied and expressed as the relative percentage of each fatty acid present in the sample. Specifically, the eight main fatty acids, which represented the total fatty acids, included saturated fatty acids (myristic acid C14:0, palmitic acid C16:0, stearic acid C18:0), polyunsaturated fatty acids (linoleic acid C18:2c, γ-linolenic acid C18:3, arachidic acid C20:0, eicosdienoic acid C20:0), and monounsaturated fatty acids (oleic acid C18:1c) **Khan and Afza (2016) and Hashem *et al*. (2022)**. These components ranged from 58.82% to 94.65% of the Nigella sativa L. seed oil. The primary fatty acids were linoleic and oleic acids, which were influenced by different fertilizer levels (100, 75, and 50% NPK) and various foliar treatments. At the 100% NPK recommended dose, foliar application of potassium silicate and compost tea notably increased polyunsaturated fatty acids, especially linoleic acid (30.52 and 30.78) and γ-linolenic acid (4.24 and 4.46), along with higher oleic acid content (27.08 and 27.25), respectively. While reducing the recommended dose to 50% NPK with potassium humate, a relative decline in all fatty acid contents was observed. however, foliar applications with compost tea and potassium silicate partially compensated for this reduction compared to the control. Under 75% NPK mixed with potassium humate, fatty acid contents were generally higher than those recorded at 100% NPK. When combined with foliar applications, compost tea and potassium silicate treatments produced the highest values of polyunsaturated and monounsaturated fatty acids, as well as the highest values of linoleic acid (36.24 and 36.11) and oleic acid content (31.46 and 31.46). The results align with **Al-Fraihat *et al*. (2023)** showed that compost tea was more effective to increase percentage and yield fixed oil.

These increases indicate heightened lipid biosynthesis and desaturation activity caused by these treatments, resulting in improved oil quality, and demonstrate their role in reducing the negative effects of decreased mineral fertilization. This treatment combination of NPK fertilization plus potassium humate with foliar application resulted in the highest overall fatty acid accumulation, especially for nutritionally important unsaturated fatty acids.

3.4. Minerals Content (N, P, and K^+)

Different treatments of mineral fertilization with NPK, whether applied alone or combined with potassium humate as a soil amendment, and foliar application treatments and their interaction had a substantial impact on the percentages of N, P, and K in the dry seeds of *Nigella sativa* L. plants.

The data in Table 7 illustrated that the integration of 75% or 50% NPK and potassium humate increased fertilizer efficiency, enhancing N, P and K% compared with the 100% NPK control. Specifically,75% NPK combined with potassium humate recorded the highest percentage of mineral content.

Regarding foliar applications, all treatments significantly increased the percentage of N, P, and K compared to the control. Compost tea resulted in the highest levels of nitrogen, phosphorus, and potassium, followed by potassium silicate and seaweed extract, while sodium selenite recorded the lowest increase in mineral content. Several studies have demonstrated the positive impact of natural foliar stimulants on the mineral content (N, P, and K^+) of *Nigella sativa* L., as reported by **Ibrahim *et al*. (2019), Abdou *et al*. (2023), Hashem *et al*. (2022)**, and **Hafez *et al* (2024)** on *Nigella sativa* L.

The interaction effect was significant for mineral content. The combination of 75% of the recommended NPK dose plus potassium humate, along with foliar application treatments, was more effective at increasing N, P, and K% in *Nigella sativa* L. plants than either 50% NPK plus potassium humate combined with foliar treatments or the full recommended dose of mineral fertilization alone. The combination of 75% NPK plus potassium humate with compost tea or potassium silicate resulted in the highest K% values, exceeding those obtained with the full NPK rate. This indicates that potassium humate improved soil potassium retention and root absorption, while foliar treatments enhanced potassium translocation within plant tissues.

Table (6). Effect of soil amendment and foliar applications and their interaction on the seed fixed oil composition of *Nigella sativa* L. plants

Fertilizer addition *(A)*	Foliar application (B)	Saturated fatty acids			Polyunsaturated fatty acids				Monounsaturated fatty acids	
		Myristic acid (C14:0)	Palmitic acid (C16:0)	Stearic acid (C18:0)	Linoleic acid (C18:2c)	γ- Linolenic acid (C18:3)	Arachidic acid (C20:0)	Eicosdienoic acid (C20:0)	Oleic acid (C18:1c)	Known
100%NPK	Control	-	6.24	0.74	28.35	-	-	-	23.49	**58.82**
	Sodium Selenite	0.27	9.78	1.80	29.01	-	-	-	25.16	**66.02**
	Seaweed extract	0.19	11.48	2.11	29.18	4.11	4.35	1.32	26.52	**79.26**
	Potassium Silicate	0.36	11.49	2.14	30.52	4.24	4.52	1.40	27.08	**81.75**
	Compost Tea	0.50	11.52	2.17	30.78	4.46	4.53	1.45	27.25	**82.66**
75%NPK +Potassium Humate	Control	0.38	11.19	2.23	34.44	-	4.53	1.51	28.31	**82.59**
	Sodium Selenite	0.41	11.43	2.26	35.25	4.22	4.58	1.55	29.50	**89.20**
	Seaweed extract	0.50	12.70	2.66	35.89	4.15	4.67	1.65	30.90	**93.12**
	Potassium Silicate	0.48	12.75	2.75	36.24	4.23	4.70	1.72	31.12	**93.99**
	Compost Tea	0.54	12.77	2.78	36.11	4.48	4.77	1.74	31.46	**94.65**
50%NPK +Potassium Humate	Control	0.26	11.62	2.14	31.56	4.08	4.22	1.40	24.15	**79.43**
	Sodium Selenite	0.36	11.80	0.43	32.16	4.16	4.39	1.47	26.67	**81.44**
	Seaweed extract	0.33	11.65	2.38	31.91	4.17	4.28	1.42	26.22	**82.36**
	Potassium Silicate	0.40	11.81	2.65	33.05	4.39	4.48	1.52	27.37	**85.67**
	Compost Tea	0.44	11.89	2.55	33.14	4.40	4.52	1.54	27.43	**85.91**

Table (7). Effect of soil amendment and foliar applications and their interaction on the mineral content (N, P, and K^+) of *Nigella sativa* L. plants for the two different growing seasons

	2021/2022 season						2022/2023 season					
Fertilizers addition (A)	**Foliar application (B)**											
	Control	Sodium Selenite	Seaweed extract	Potassium Silicate	Compost Tea	Mean (A)	Control	Sodium Selenite	Seaweed extract	Potassium Silicate	Compost Tea	Mean (A)
N %												
100%NPK	2.91	3.04	3.24	3.37	3.39	**3.19**	2.75	3.17	3.37	3.43	3.70	**3.28**
75%NPK +Potassium Humate	3.06	3.14	3.32	3.40	3.45	**3.27**	3.19	3.42	3.56	3.73	3.87	**3.55**
50%NPK +Potassium Humate	2.97	3.08	3.29	3.31	3.42	**3.21**	3.04	3.19	3.45	3.53	3.78	**3.39**
Mean (B)	**2.98**	**3.08**	**3.28**	**3.26**	**3.42**		**2.99**	**3.26**	**3.46**	**3.56**	**3.78**	
LSD 5%	A=0.046 B=0.090 AB= 2.09						A=0.078 B=0.19 AB=0.15					
P%												
100%NPK	0.40	0.44	0.53	0.55	0.57	**0.49**	0.46	0.51	0.59	0.61	0.64	**0.56**
75%NPK +Potassium Humate	0.50	0.52	0.53	0.59	0.62	**0.55**	0.57	0.59	0.60	0.66	0.68	**0.62**
50%NPK +Potassium Humate	0.42	0.46	0.50	0.53	0.57	**0.49**	0.49	0.53	0.55	0.60	0.63	**0.56**
Mean (B)	**0.44**	**0.47**	**0.52**	**0.55**	**0.58**		**0.50**	**0.54**	**0.58**	**0.62**	**0.65**	
LSD 5%	A=0.018 B=0.019 AB= 3.63						A=0.019 B=0.017 AB=0.013					
K%												
100%NPK	1.63	1.72	1.76	1.81	1.84	**1.75**	1.71	1.76	1.79	1.84	1.88	**1.79**
75%NPK +Potassium Humate	1.77	1.81	1.85	1.87	1.91	**1.84**	1.81	1.85	1.89	1.91	1.94	**1.88**
50%NPK +Potassium Humate	1.69	1.72	1.78	1.82	1.85	**1.77**	1.74	1.77	1.82	1.86	1.89	**1.81**
Mean (B)	**1.69**	**1.75**	**1.79**	**1.83**	**1.86**		**1.75**	**1.79**	**1.83**	**1.87**	**1.90**	
LSD 5%	A=0.015 B=0.016 AB= 2.56						A=0.011 B=0.017 AB=0.013					

4. Conclusions

From the above results, it can be inferred that reducing the recommended NPK rate to 75% and supplementing it with potassium humate and foliar applications significantly enhanced morphological characteristics, seed productivity, seed oil yield, fatty acid composition and N, P, and K contents of *Nigella sativa* L. during two growing seasons. Among fertilizer treatments, the application of 75% NPK combined with potassium humate and, as for foliar applications, compost tea followed by potassium silicate produced superior results across all studied parameters compared with other treatments.

The combination of 75% NPK plus potassium humate with compost tea foliar application consistently produced the highest morphological characteristics, seed productivity, seed oil yield, fatty acid composition, and N, P, and K contents.

These findings confirm that combining natural soil amendments with eco-friendly foliar stimulants can be recommended as a sustainable fertilization strategy that reduces the use of mineral fertilizers while maintaining high growth and productivity in *Nigella sativa* L.

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الملخص العربى

مؤخرا، أصبحت هناك توجهات عالمية متزايدة للحد من استخدام الأسمدة الكيميائية في الزراعة لما لها من آثار سلبية على جودة التربة وصحة البيئة، بالإضافة إلى ارتفاع تكاليف الإنتاج. لذلك هدفت هذه الدراسة، التي أُجريت خلال موسمي ٢٠٢٢/٢٠٢١ و٢٠٢٣/٢٠٢٢، إلى تقييم استجابة نبات حبة البركة (*Nigella sativa* L.) لخفض التسميد المعدني مع إضافة هيومات البوتاسيوم كمحسن أرضي، إلى جانب استخدام بعض المنشطات الطبيعية بالرش الورقي. اشتملت معاملات القطع الرئيسية على ثلاث مستويات من التسميد: ١٠٠% من الجرعة الموصى بها من NPK، و٧٥% NPK + هيومات البوتاسيوم بمعدل ٢ كجم/فدان، و٥٠% NPK + هيومات البوتاسيوم بمعدل ٢ كجم/فدان. أما معاملات القطع المنشقة فقد تضمنت خمسة معاملات رش ورقي: بدون رش، مستخلص الطحالب البحرية (٠,٥ مل/لتر)، شاي الكمبوست (٢٠ لتر/فدان)، سيلينات الصوديوم (٨ جم/لتر)، وسيليكات البوتاسيوم (٤ مل/لتر). أظهرت النتائج إمكانية خفض الأسمدة المعدنية إلى ٧٥% وحتى ٥٠% من الجرعة الموصى بها عند استخدامها مع هيومات البوتاسيوم دون التأثير السلبي على أداء النبات. كما أدت جميع معاملات الرش الورقي إلى تحسين معنوي في الصفات المدروسة، وكان شاي الكمبوست هو الأكثر كفاءة. وحقق التداخل بين معاملة ٧٥% NPK + هيومات البوتاسيوم مع الرش الورقي بشاي الكمبوست أفضل النتائج من حيث النمو الخضري، ومحصول البذور، وإنتاجية الزيت الثابت خلال الموسمين. وتؤكد هذه النتائج أن دمج المحسنات الأرضية الطبيعية مع المنشطات الورقية الصديقة للبيئة يُعد استراتيجية فعالة لتقليل الاعتماد على الأسمدة المعدنية مع الحفاظ على إنتاجية عالية لنبات حبة البركة.