Effect of Nano-NPK fertilizer and humic acid on vegetative growth and chemical properties of the vegetative parts of broccoli (*Brassica oleracea var. Italica*) in gypsiferous soil

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Abstract

This study investigated the growth response of broccoli (*Brassica oleracea var. Italica*) to soil-applied nano NPK fertilizer and humic acid in gypsiferous soil, with particular emphasis on vegetative growth parameters. Field experiments were conducted at the Research Station of the Department of Soil Science and Water Resources, College of Agriculture, Tikrit University, Iraq, during the 2024–2025 growing season. A Randomized Complete Block Design (RCBD) was adopted in a factorial arrangement, incorporating three rates of nano NPK fertilizer (20-20-20) at 0, 8, and 16 kg ha^{-1}, and three levels of humic acid at 0, 5, and 10 kg ha^{-1}, yielding nine treatment combinations with three replicates (n = 27 experimental units).

Results demonstrated that the application of nano NPK fertilizer at 16 kg ha^{-1} significantly enhanced key vegetative growth indices, including plant height, leaf area, leaf chlorophyll content, shoot nitrogen concentration, and shoot potassium concentration, with percentage increases over the control of 9.93%, 31.83%, 12.74%, 25.12%, and 33.52%, respectively. The 8 kg ha^{-1} nano NPK treatment yielded the highest improvements in leaf number and shoot phosphorus concentration, recording increases of 13.47%, 21.94%, and 24.14% above the control, respectively.

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Humic acid application at 10 kg ha^{-1} produced significant improvements across all assessed vegetative growth traits, namely plant height, leaf number, leaf area, leaf chlorophyll content, and shoot N, P, and K concentrations, with percentage increases over the control of 4.29%, 7.58%, 14.52%, 5.47%, 12.72%, 16.83%, and 23.14%, respectively. Furthermore, a significant interaction effect between nano NPK fertilizer and humic acid was observed. The $H_2 N_2$ interaction treatment most effectively promoted plant height, leaf area, shoot nitrogen concentration, and shoot potassium concentration, while the $H_2 N_1$ combination was superior in enhancing leaf number, leaf chlorophyll content, and shoot phosphorus concentration relative to the untreated control.

These findings suggest that the combined application of nano NPK fertilizer and humic acid represents a promising strategy for optimizing broccoli production in gypsiferous soils, offering potential benefits for sustainable crop management under challenging edaphic conditions.

Keywords: *Brassica oleracea var. Italica;* nano NPK fertilizer; humic acid; vegetative growth; gypsiferous soil; sustainable agriculture

Introduction

Arid and semi-arid soils are generally characterized by their limited capacity to supply essential nutrients to growing plants, a constraint that is particularly pronounced in gypsiferous soils [9]. Gypsiferous soils occupy extensive areas across Iraq and globally; in Iraq alone, they account for approximately 20% of the total land area [25]. These soils are inherently characterized by low fertility, primarily attributed to the dissolution of gypsum ($CaSO_4 \cdot 2H_2O$) in the soil solution, which induces nutritional imbalances and consequently reduces the bioavailability of essential nutrients required for optimal

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plant growth [21]. To compensate for such nutrient deficiencies, the application of macronutrient fertilizers, particularly nitrogen (N), phosphorus (P), and potassium (K), is considered essential. Fertilization is recognized as one of the principal factors governing crop productivity, as the application of compound NPK fertilizers has been shown to enhance both vegetative and reproductive growth rates [31]. However, the indiscriminate and excessive use of conventional fertilizers has been associated with numerous adverse environmental consequences, including soil contamination and elevated soil salinity. This has necessitated a shift toward the adoption of alternative, environmentally sustainable fertilization strategies capable of supplying essential nutrients while preserving soil integrity [33].

Among the emerging alternatives, nano-fertilizers have attracted considerable attention owing to their environmentally compatible nature and their capacity to enhance photosynthetic efficiency and increase the production of bioactive plant compounds, thereby contributing to environmental sustainability [45]. The distinctive feature of nano-fertilizers lies in their high specific surface area relative to their particle size, which facilitates a slow and controlled release of nutrients, thereby improving nutrient use efficiency and minimizing losses to the environment. In parallel, recent research has increasingly highlighted the potential of organic-derived amendments, particularly humic acid, as effective tools for improving plant growth and productivity. Humic acid plays a multifaceted role in enhancing soil physical, chemical, and biological properties, while simultaneously acting as a reservoir of nutrients essential for plant development and supporting the soil's buffering capacity [34].

Against this backdrop, there is a growing need to evaluate the effects of these amendments on economically and nutritionally significant vegetable crops, among which broccoli (*Brassica oleracea var. Italica*, family Brassicaceae) holds particular importance. Broccoli is regarded as a nutritionally superior vegetable owing to its rich content of carbohydrates, vitamins, and carotenoids. It is notably rich in antioxidant compounds that have been associated with a reduced risk of cancer, including glucoraphanin, in addition to essential mineral nutrients such as phosphorus, potassium, calcium, iron, and sulfur [38]. Given its high nutritional value, consumer demand for broccoli has increased substantially in recent years, prompting growing interest among farmers in Iraq in expanding its cultivation [15]. Consequently, there is an urgent need to establish a comprehensive fertilization management database for this crop under gypsiferous soil conditions.

The present study therefore aimed to: (i) evaluate the effects of nano NPK fertilizer and humic acid on the vegetative growth and selected qualitative characteristics of broccoli in gypsiferous soil; (ii) assess the potential of nano fertilization in minimizing environmental pollution risks; and (iii) investigate the interaction effects of nano NPK fertilizer and humic acid on broccoli growth performance under gypsiferous soil conditions.

Materials and Methods

Experimental Site and Design

The experiment was conducted at the Research Station of the Department of Soil Science and Water Resources, College of Agriculture, Tikrit University, during the 2024-2025 agricultural season. Which lies within the geographical coordinates between (493.54 38 430) east and latitude (996.58 40 340) north growing season to evaluate the effects of nano NPK fertilizer and humic acid on the growth and productivity of broccoli (*Brassica oleracea var. Italica*) cultivated in gypsiferous soil. A factorial experiment was arranged within a Randomized Complete Block Design (RCBD), comprising nine treatment combinations with three replicates, yielding a total of 27 experimental units. Data were subjected to analysis of variance (ANOVA), and treatment means were compared using Duncan's Multiple Range Test (DMRT) at a probability level of 0.05, as implemented in the GenStat statistical software package [11].

Soil Sampling and Analysis

Prior to the initiation of the experiment, composite soil samples were collected from multiple locations within the experimental field at a depth of 0–30 cm, corresponding to the primary root zone. The samples were air-dried, ground, and passed through a 2 mm sieve, then stored in polyethylene bags and subjected to comprehensive physicochemical characterization. Selected physical and chemical properties of the experimental soil prior to planting are presented in Table 1.

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Table 1. Selected physical and chemical properties of the experimental soil prior to planting.

Value	Unit	Soil Property
523	$g\ kg^{-1}$ soil	Sand
269		Silt
208		Clay
	Sandy Clay loam (SCL)	Soil texture
38.51	$mg\ kg^{-1}$ soil	Available nitrogen
9.12		Available phosphorus
149.54		Available potassium
2.7	$dS\ m^{-1}$	Electrical conductivity (EC)
7.6	—	Soil reaction (pH)
13.15	$cmol\ kg^{-1}$ soil	Cation exchange capacity (CEC)
8.13	$g\ kg^{-1}$ soil	Organic matter
40.23		Gypsum content ($CaSO_4 \cdot 2H_2O$)

Experimental Factors

The field experiment examined the effects of two factors, as outlined in Table 2

First Factor: A commercially available nano NPK fertilizer (20:20:20; KHAZRA Company) was applied to the soil using the

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fertigation method in two split doses during plant growth stages at three rates: 0 (N_0 , control), 8 (N_1), and 16 kg ha^{-1} (N_2).

Second Factor: A commercially available humic acid product (Huminsat, Germany) in liquid form was applied directly to the soil in three split doses during plant growth stages at three rates: 0 (H_0 , control), 5 (H_1), and 10 kg ha^{-1} (H_2).

Table 2. Treatment combinations included in the study.

Application	Symbol	Treatment
No humic acid + No nano NPK fertilizer (Control)	H_0 N_0	T1
Humic acid at 5 kg ha^{-1} + No nano NPK fertilizer	H_1 N_0	T2
Humic acid at 10 kg ha^{-1} + No nano NPK fertilizer	H_2 N_0	T3
No humic acid + Nano NPK fertilizer at 8 kg ha^{-1}	H_0 N_1	T4
Humic acid at 5 kg ha^{-1} + Nano NPK fertilizer at 8 kg ha^{-1}	H_1 N_1	T5
Humic acid at 10 kg ha^{-1} + Nano NPK fertilizer at 8 kg ha^{-1}	H_2 N_1	T6
No humic acid + Nano NPK fertilizer at 16 kg ha^{-1}	H_0 N_2	T7
Humic acid at 5 kg ha^{-1} + Nano NPK fertilizer at 16 kg ha^{-1}	H_1 N_2	T8

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Humic acid at 10 kg ha^{-1} + Nano NPK fertilizer at 16 kg ha^{-1}	H_2 N_2	T9

Seedling Preparation and Transplantation

Broccoli hybrid seeds (F1 Besty, Syngenta, Switzerland) were sown on 6 August 2024 in polystyrene seedling trays (198-cell capacity) at a commercial nursery in the Al-Yusufiyyah area, under controlled environmental conditions conducive to uniform germination and seedling development. Upon reaching the four true-leaf stage, seedlings were transplanted to the experimental field on 26 September 2024 on raised beds at a within-row spacing of 50 cm, with eight plants per experimental unit.

Field Preparation

Prior to transplanting, the soil was prepared by cross-plowing, then left fallow for approximately 20 days to allow for solar sterilization (solarization). The soil was subsequently harrowed to achieve a fine tilth and divided into three replicates, each comprising nine experimental units arranged as three raised beds with an inter-bed spacing of 1.5 m and a unit length of 4.5 m. A drip irrigation system was installed prior to transplanting to ensure uniform water distribution throughout the growing season. The harvest date was 3/1/2025.

Measured Parameters

Vegetative Growth Indicators

At harvest, five plants were randomly selected from each experimental unit across all three replicates, and the following vegetative growth parameters were measured and averaged: plant height (cm), total leaf number (leaves $plant^{-1}$), leaf area (cm^2 $plant^{-1}$), and total leaf chlorophyll content (mg 100 g^{-1} fresh weight).

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Shoot Nutrient Concentrations

Flower discs were collected from the vegetative portion of each plant at full maturity, as indicated by the yellowing of plant leaves and the hardness of the floral disc. The samples were thoroughly washed to remove surface dust and debris, and then oven-dried following the method described by [12]. The dried samples were ground and digested according to the procedure outlined by Cresser and Parsons [20], and the following nutrient concentrations were determined: shoot nitrogen (N%), shoot phosphorus (P%), and shoot potassium (K%).

Results and Discussion

1 .Effects of nano NPK fertilizer, humic acid, and their interaction on vegetative growth characteristics of broccoli

1.1 Plant Height (cm)

The data presented in Table 3 reveal significant differences among nano NPK fertilizer levels, humic acid levels, and their interaction with respect to plant height of broccoli grown in gypsiferous soil. The N_2 treatment (16 kg ha^{-1}) significantly outperformed both N_1 and N_0, recording the highest mean plant height of 75.24 cm compared to 68.44 cm in the untreated control (N_0), representing a significant increase of 9.93%. With respect to humic acid, the H_2 treatment (10 kg ha^{-1}) yielded the highest mean plant height of 73.86 cm, which was significantly superior to the control (H_0) recording the lowest mean of 70.82 cm, corresponding to an increase of 4.29%. Analysis of the interaction between nano NPK fertilizer and humic acid further revealed significant differences among treatment combinations, whereby the $H_2 N_2$ treatment recorded the highest mean plant height of 76.16 cm compared to 67.00 cm under $H_0 N_0$, representing a significant

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superiority of 13.67% in favor of H_2 N_2 .

Table 3. Effects of nano NPK fertilizer, humic acid, and their interaction on plant height of broccoli (cm).

H Mean	Nano NPK fertilizer (kg ha^{-1})			Humic Acid (kg ha^{-1})
	N_2 (16)	N_1 (8)	N_0 (0)	
70.82 c	74.28 bc	71.17 d	67.00 f	H_0 (0)
72.48 b	75.27 ab	74.05 c	68.12 e	H_1 (5)
73.86 a	76.16 a	75.20 ab	70.22 d	H_2 (10)
	75.24 a	73.47 b	68.44 c	N Mean

Means sharing the same letter are not significantly different according to Duncan's Multiple Range Test (DMRT) at $p \leq 0.05$.

1.2 Number of Leaves (leaves $plant^{-1}$)

The data presented in Table 4 indicate significant differences among nano NPK fertilizer levels, humic acid levels, and their interaction with respect to leaf number of broccoli grown in gypsiferous soil. The N_1 treatment (8 kg ha^{-1}) significantly outperformed both N_2 and N_0 , recording the highest mean leaf number of 36.47 leaves $plant^{-1}$ compared to 32.14 leaves $plant^{-1}$ in the untreated control (N_0), representing a significant increase of 13.47%. With respect to humic acid, the H_2 treatment (10 kg ha^{-1}) recorded the highest mean leaf number of 34.76 leaves $plant^{-1}$, which did not differ significantly from H_1 but was significantly superior to the control (H_0) recording the lowest mean of 32.31 leaves $plant^{-1}$, corresponding to an increase of 7.58%. Analysis of the binary interaction between nano NPK fertilizer and humic acid further revealed significant differences among

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treatment combinations, whereby the $H_2 N_1$ treatment recorded the highest mean leaf number of 37.97 leaves plant^{-1} compared to 29.0 leaves plant^{-1} under $H_0 N_0$, representing a significant superiority of 30.93%.

Table 4. Effects of nano NPK fertilizer, humic acid, and their interaction on leaf number of broccoli (leaves plant^{-1}).

H Mean	Nano NPK fertilizer (kg ha^{-1})			Humic Acid (kg ha^{-1})
	N_2 (16)	N_1 (8)	N_0 (0)	
32.31 b	34.00 bc	33.94 bc	29.00 e	H_0 (0)
34.61 a	33.22 c	37.50 a	33.12 c	H_1 (5)
34.76 a	32.00 d	37.97 a	34.31 b	H_2 (10)
	33.07 b	**36.47 a**	**32.14 c**	**N Mean**

Means sharing the same letter are not significantly different according to Duncan's Multiple Range Test (DMRT) at $p \leq 0.05$.

1.3 Leaf Area (cm² plant^{-1})

The data presented in Table 5 reveal significant differences among nano NPK fertilizer levels, humic acid levels, and their interaction with respect to leaf area of broccoli grown in gypsiferous soil. The N_2 treatment (16 kg ha^{-1}) significantly outperformed both N_1 and N_0, recording the highest mean leaf area of 570.2 cm² plant^{-1} compared to 432.5 cm² plant^{-1} in the untreated control (N_0), representing a significant increase of 31.83%. With respect to humic acid, the H_2 treatment (10 kg ha^{-1}) recorded the highest mean leaf area of 551.2 cm² plant^{-1}, which was significantly superior to the control (H_0), recording the lowest mean of 481.3 cm² plant^{-1}, corresponding to an increase of 14.52%. Analysis of the interaction between nano NPK fertilizer

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and humic acid further revealed significant differences among treatment combinations, whereby the H_2 N_2 treatment recorded the highest mean leaf area of 586.8 cm² plant⁻ ¹ compared to 385.7 cm² plant⁻ ¹ under H_0 N_0 , representing a significant superiority of 52.13%.

Table 5. Effects of nano NPK fertilizer, humic acid, and their interaction on leaf area of broccoli (cm² plant⁻ ¹).

H Mean	Nano NPK fertilizer (kg ha⁻ ¹)			Humic Acid (kg ha⁻ ¹)
	N_2 (16)	**N_1 (8)**	**N_0 (0)**	
481.3 c	550.9 d	507.3 e	385.7 g	**H_0 (0)**
512.5 b	573.0 b	556.2 cd	408.3 f	**H_1 (5)**
551.2 a	586.8 a	563.3 c	503.5 e	**H_2 (10)**
	570.2 a	542.3 b	432.5 c	**N Mean**

Means sharing the same letter are not significantly different according to Duncan's Multiple Range Test (DMRT) at $p \leq 0.05$.

1.4. Leaf Chlorophyll Content of Broccoli (mg 100 g⁻ ¹ fresh weight)

The data presented in Table 6 reveal significant differences among nano NPK fertilizer levels, humic acid levels, and their interaction with respect to leaf chlorophyll content of broccoli grown in gypsiferous soil. The N_2 treatment (16 kg ha⁻ ¹) recorded the highest mean leaf chlorophyll content of 20.43 mg 100 g⁻ ¹ fresh weight, which did not differ significantly from N_1 but was significantly superior to the untreated control (N_0) recording the lowest mean of 18.12 mg 100 g⁻ ¹ fresh weight, representing a significant increase of 12.74%. With respect to humic acid, the H_2 treatment (10 kg ha⁻ ¹) recorded the highest mean leaf chlorophyll content of 20.04 mg 100 g⁻ ¹ fresh weight, which was significantly superior to the control (H_0), recording the lowest mean of 19.0 mg 100 g⁻ ¹ fresh weight, corresponding to an increase of 5.47%. Analysis of the interaction between nano NPK fertilizer

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and humic acid further revealed significant differences among treatment combinations, whereby the $H_2 N_1$ treatment recorded the highest mean of 21.02 mg 100 g^{-1} fresh weight compared to 17.43 mg 100 g^{-1} fresh weight under $H_0 N_0$, representing a significant superiority of 20.59%.

Table 6. Effects of nano NPK fertilizer, humic acid, and their interaction on leaf chlorophyll content of broccoli (mg 100 g^{-1} fresh weight).

H Mean	Nano NPK fertilizer (kg ha^{-1})			Humic Acid (kg ha^{-1})
	N_2 (16)	N_1 (8)	N_0 (0)	
19.00 c	20.58 b	19.00 d	17.43 f	H_0 (0)
19.82 b	20.41 bc	20.92 a	18.13 e	H_1 (5)
20.04 a	20.29 c	21.02 a	18.81 d	H_2 (10)
	20.43 a	20.31 a	18.12 b	N Mean

Means having the same letter are not significantly different according to Duncan's Multiple Range Test (DMRT) at $p \leq 0.05$.

The data presented in Tables 3, 4, 5, and 6 demonstrate that nano NPK fertilizer played a pivotal role in enhancing nitrogen use efficiency. Nitrogen is known to be a highly mobile element in the soil, rendering it susceptible to substantial losses through leaching and volatilization. Nano-fertilizers mitigate these losses by regulating the rate of nutrient release and improving uptake efficiency. Within the plant, nitrogen is rapidly translocated to meristematic tissues responsible for active growth, thereby promoting cell division and elongation, which ultimately results in enhanced vegetative development. Furthermore, nitrogen is a fundamental constituent of chlorophyll and cytochrome molecules, both of which are indispensable for photosynthetic activity. The synergistic role of nitrogen and phosphorus in the synthesis of nucleic acids and nitrogenous bases further contributes to protein biosynthesis. Additionally, nitrogen serves as a key precursor for

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amino acid formation, which in turn stimulates the biosynthesis of the growth hormone indole-3-acetic acid (IAA), thereby promoting cell elongation [46].

Nitrogen and phosphorus participate jointly in numerous vital physiological processes, including the activation of enzymatic activities within plant tissues and their direct incorporation into the chlorophyll molecule, specifically as components of the porphyrin ring structure. These processes collectively enhance photosynthetic efficiency and promote carbohydrate accumulation [8]. Moreover, nitrogen stimulates the production of cytokinins [22], which play a critical role in promoting new growth, increasing shoot density, and enhancing chlorophyll biosynthesis [13], thereby further augmenting photosynthetic capacity and vegetative growth.

With respect to phosphorus, it promotes root system development and increases root surface area in the soil, thereby enhancing the absorption of essential nutrients, which positively influences cell elongation and overall vegetative growth [10]. Potassium, on the other hand, contributes to cell division and elongation and activates a range of enzymes involved in the biosynthesis of structural plant compounds. Additionally, potassium plays a regulatory role in stomatal opening and closure, facilitating water and nutrient uptake, stimulating photosynthetic activity, and increasing photosynthate accumulation, all of which collectively promote plant growth [32, 36].

Beyond their nutritional roles, nano-fertilizers possess unique physicochemical properties arising from their reduced particle size and increased effective surface area, which enhance their penetration, uptake, and metabolic utilization, as well as amplify enzymatic activity and accelerate biological processes [30]. Nano-fertilizers may also contribute to increased gibberellin biosynthesis, which directly enhances cell wall plasticity and elasticity, thereby facilitating cell elongation and stimulating the production of amino acids and enzymes that promote cell division [27]. These processes collectively enhance plant growth activity and height increment [14, 23], ultimately manifesting as significant improvements in shoot biomass, including plant height, leaf number, leaf area, and leaf chlorophyll content.

These findings are consistent with those reported by Konjengbam and Menon [29], and are further corroborated by Abdalrahman *et al.* [1], who observed significant differences in leaf chlorophyll content following the application of nano NPK fertilizer to broccoli plants.

The enhancement of vegetative growth observed in response to humic acid application can be attributed to its well-established role as an organic soil amendment that improves the physical, chemical, and fertility properties of gypsiferous soils. Specifically, humic acid increases the cation exchange capacity (CEC) of the soil, enhances the availability and uptake of essential nutrients, and promotes root system development and proliferation, all of which collectively contribute to increased plant height and overall vegetative growth [16]. Furthermore, humic acid stimulates the activity and proliferation of rhizosphere microorganisms, which in turn secrete organic acids and growth-promoting hormones such as auxins and gibberellins. These phytohormones stimulate stem cell elongation, increase plant height, and enhance shoot density [7]. Humic acid also acts as a physiological regulator with auxin-like properties, promoting leaf expansion and increasing leaf number [37, 47].

At the cellular level, humic acid enhances cell membrane permeability and improves carbon assimilation efficiency, thereby stimulating root growth [41]. It also plays an indirect role in improving the uptake efficiency of available and applied nutrients, as well as a direct role in enhancing numerous physiological processes within the plant [35], including increased nutrient availability and their incorporation into photosynthetic pathways, augmented cell division and

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elongation, enhanced vegetative growth, and elevated leaf chlorophyll content. Additionally, humic acid exerts a stimulatory effect on plant hormone biosynthesis and the production of plant pigments; gibberellins in particular have been shown to increase leaf chlorophyll content through their direct influence on plastid development [2]. These findings are consistent with those reported by [4] and [26], both of whom observed similar responses in broccoli plants treated with humic acid.

With regard to the interaction between nano NPK fertilizer and humic acid, the observed enhancements in vegetative growth can be attributed to a comprehensive synergistic effect that integrates soil improvement, enhanced macronutrient utilization, and the regulation of physiological and cellular processes within the plant. Humic acid contributes to the establishment of a more biologically active and stable rhizosphere environment, while nano NPK fertilizer ensures a sustained and efficient supply of macronutrients most notably nitrogen, which serves as the fundamental building block for protein and chlorophyll biosynthesis. The concurrent improvement of soil properties through humic acid application further amplified these effects, collectively resulting in significant enhancements in shoot biomass, as reflected by increases in plant height, leaf number, leaf area, and leaf chlorophyll content [1, 16].

2. Effects of nano NPK fertilizer, humic acid, and their interaction on shoot nutrient concentrations of broccoli

2.1. Shoot Nitrogen Concentration (%)

The data presented in Table 7 reveal significant differences among nano NPK fertilizer levels, humic acid levels, and their interaction with respect to shoot nitrogen concentration of broccoli grown in gypsiferous soil. The N_2 treatment (16 kg ha^{-1}) recorded the highest mean shoot nitrogen concentration of 2.201%, which was significantly superior to the untreated control (N_0) recording the lowest mean of 1.759%, representing a significant

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increase of 25.12%. With respect to humic acid, the H_2 treatment (10 kg ha^{-1}) recorded the highest mean shoot nitrogen concentration of 2.135%, which differed significantly from both H_0 and H_1, with the lowest mean recorded under H_0 at 1.894%, corresponding to a superiority of 12.72%. Analysis of the binary interaction between nano NPK fertilizer and humic acid further revealed significant differences among treatment combinations, whereby the $H_2 N_2$ treatment recorded the highest mean shoot nitrogen concentration of 2.25% compared to 1.573% under $H_0 N_0$, representing a significant superiority of 43.03%.

Table 7. Effects of nano NPK fertilizer, humic acid, and their interaction on shoot nitrogen concentration of broccoli (%).

H Mean	Nano NPK fertilizer (kg ha^{-1})			Humic Acid (kg ha^{-1})
	N_2 (16)	N_1 (8)	N_0 (0)	
1.894 c	2.229 a	1.880 bc	1.573 d	H_0 (0)
2.023 b	2.124 a	2.182 a	1.763 c	H_1 (5)
2.135 a	2.250 a	2.217 a	1.939 b	H_2 (10)
	2.201 a	2.093 b	1.759 c	N Mean

Means sharing the same letter are not significantly different according to Duncan's Multiple Range Test (DMRT) at $p \leq 0.05$.

3. Effects of Nano NPK fertilizer, humic acid, and their interaction on shoot nutrient concentrations of broccoli

3 1.Shoot Nitrogen Concentration(%)

The data presented in Table 7 reveal significant differences among nano NPK fertilizer levels, humic acid levels, and their interaction with respect to shoot nitrogen concentration of broccoli grown in gypsiferous soil. The N_2 treatment (16 kg ha^{-1}) recorded the highest mean shoot nitrogen concentration of 2.201%, which was significantly superior to the untreated control (N_0) recording the lowest mean of 1.759%, representing a significant increase of 25.12%. With respect to humic acid, the H_2 treatment (10 kg ha^{-1}) recorded the highest mean shoot nitrogen concentration of 2.135%, which differed significantly from both H_0 and H_1, with the lowest mean recorded under H_0 at 1.894%, corresponding to a superiority of 12.72%. Analysis of the binary interaction between nano NPK fertilizer and humic acid further revealed significant differences among treatment combinations, whereby the H_2 N_2 treatment recorded the highest mean shoot nitrogen concentration of 2.25% compared to 1.573% under H_0 N_0, representing a significant superiority of 43.03%.

Table 8. Effects of nano NPK fertilizer, humic acid, and their interaction on shoot nitrogen concentration of broccoli(%)

H Mean	**Nano NPK fertilizer (kg ha^{-1})**			**Humic Acid (kg ha^{-1})**
	N_2 (16)	**N_1 (8)**	**N_0 (0)**	
0.291 c	0.318 c	0.318 c	0.238 e	H_0 (0)
0.322 b	0.346 b	0.338 b	0.283 d	H_1 (5)
0.340 a	0.345 b	0.361 a	0.315 c	H_2 (10)
	0.336 a	0.339 a	0.278 b	N Mean

Means sharing the same letter are not significantly different according to Duncan's Multiple Range Test (DMRT) at $p \leq 0.05$.

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2.3. Shoot Potassium Concentration(%)

The data presented in Table 9 reveal significant differences among nano NPK fertilizer levels, humic acid levels, and their interaction with respect to shoot potassium concentration of broccoli grown in gypsiferous soil. The N_2 treatment (16 kg ha^{-1}) recorded the highest mean shoot potassium concentration of 2.127%, which was significantly superior to the untreated control (N_0) recording the lowest mean of 1.593%, representing a significant increase of 33.52%. With respect to humic acid, the H_2 treatment (10 kg ha^{-1}) recorded the highest mean shoot potassium concentration of 2.107%, which differed significantly from both H_0 and H_1, with the lowest mean recorded under H_0 at 1.711%, corresponding to a superiority of 23.14%. Analysis of the interaction between nano NPK fertilizer and humic acid further revealed significant differences among treatment combinations, whereby the H_2N_2 treatment recorded the highest mean of 2.262% compared to 1.391% under H_0N_0, representing a significant superiority of 62.61%.

Table 9. Effects of nano NPK fertilizer, humic acid, and their interaction on shoot potassium concentration of broccoli(%) .

H Mean	Nano NPK fertilizer (kg ha^{-1})			Humic Acid (kg ha^{-1})
	N_2 (16)	N_1 (8)	N_0 (0)	
1.711 c	2.004 c	1.737 e	1.391 g	H_0 (0)
1.916 b	2.114 b	2.072 b	1.563 f	H_1 (5)
2.107 a	2.262 a	2.231 a	1.827 d	H_2 (10)
	2.127 a	2.013 b	1.593 c	N Mean

Means sharing the same letter are not significantly different according to Duncan's Multiple Range Test (DMRT) at $p \leq 0.05$.

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The data presented in Tables 7, 8, and 9 demonstrate that nano NPK fertilizer enhanced shoot nutrient concentrations through multiple complementary mechanisms. The applied phosphorus contributed to the stimulation of root system development by increasing root density and proliferation within the soil profile, thereby improving water and nutrient uptake and elevating their concentrations in the shoot [10]. Furthermore, potassium plays an indirect role in increasing the uptake of other nutrients, including nitrogen and phosphorus, as a consequence of nutritional imbalances within the leaf tissues that trigger compensatory nutrient absorption to restore ionic equilibrium [12]. The observed improvements in vegetative growth as reflected by increased plant height, leaf area, and leaf number reported in Tables 3, 4, and 5 positively enhanced carbon assimilation efficiency and energy production, which are prerequisites for active nutrient uptake. Concurrently, improved root system development further augmented nutrient absorption capacity and elevated shoot nutrient concentrations [43]. Potassium also regulates osmotic pressure within plant tissues, thereby influencing nutrient absorption dynamics [12]. The nano-form of the fertilizer, characterized by rapid root penetration and uptake, provided greater opportunities for nutrient translocation into plant tissues and elevated their concentrations in the shoot. The reduced particle size and enhanced solubility of nano-potassium improved its availability and uptake by plant roots, which was positively reflected in shoot potassium concentrations [28]. These findings are consistent with those reported by Al-Jubouri and Abdulrahman [6], Badawy [17], Chamuah *et al.* [18], and Maryoush [32]. With respect to the effect of humic acid on shoot nutrient concentrations, its application increases soil organic carbon content through decomposition processes, which reduces phosphorus adsorption in the soil. A well-established positive relationship exists between organic

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carbon concentration and dissolved phosphorus in the soil solution. Moreover, humic acid stimulates microbial biomass in the rhizosphere; upon microbial death and decomposition, organic carbon is released into the soil, further enhancing phosphorus availability and its subsequent uptake by plant roots [39]. Humic acid also increases root cell membrane permeability, facilitating nutrient absorption, and activates hormones responsible for promoting vegetative and root growth. Additionally, humic acid enhances the soil's water retention capacity, which in turn increases the solubility of phosphorus compounds naturally present in the soil [40]. Regarding nitrogen, humic acid improves nitrogen use efficiency by chelating nitrate ions and reducing leaching losses through binding with its active functional groups, as noted by Sarwar *et al.* [42]. Humic acid interacts with positively charged amine groups (NH_2) and reduces ammonia volatilization losses, thereby improving fertilizer nitrogen efficiency. The application of humic acid at varying levels significantly influenced the quantity of nitrogen absorbed by plants, as reflected in elevated shoot nitrogen concentrations [3]. The effect of humic acid on potassium availability can be attributed to the presence of negatively charged functional groups -carboxyl (COOH) and hydroxyl (OH)- carried by humic acid molecules. These groups possess the capacity to adsorb weakly held cations and facilitate their exchange, releasing them into the soil solution and establishing an equilibrium between dissolved and adsorbed potassium. This mechanism enables humic acid to regulate the rate of potassium release into the soil solution, maintaining its availability throughout the various stages of plant growth [19]. Additionally, humic acid may lower soil pH, and the resulting mild acidification can enhance the availability of essential nutrients including nitrogen, phosphorus, and potassium [5], thereby increasing their concentrations in the shoot biomass of

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broccoli. These findings are in agreement with those reported by Al-Azzawi [4], Ghathith [24], and Shabbir [44].

The data in Tables 7, 8, and 9 further indicate that the interaction between nano NPK fertilizer and humic acid in elevating shoot nutrient concentrations can be attributed to the combined effects of the macronutrients supplied by the nano fertilizer on plant physiology, alongside the role of humic acid in improving soil properties, both of which collectively enhanced shoot nutrient accumulation in broccoli [1].

Conclusions

The findings of the present study demonstrate that the combined application of nano NPK fertilizer and humic acid yielded positive outcomes with respect to vegetative growth characteristics and qualitative traits of broccoli cultivated in gypsiferous soil. Nano NPK fertilizer application significantly improved vegetative growth indicators and shoot nutrient concentrations, with the rate of 16 kg ha^{-1} demonstrating consistent superiority over 8 kg ha^{-1} across the majority of the studied parameters. Humic acid application at 10 kg ha^{-1} exerted a significant positive effect on all assessed vegetative growth characteristics and qualitative traits. Furthermore, the interaction treatment combining nano NPK fertilizer at 16 kg ha^{-1} with humic acid at 10 kg ha^{-1} proved to be the most effective treatment combination for the majority of the studied traits, producing significant enhancements in vegetative growth and improving nutrient uptake efficiency in broccoli plants.

Recommendations

The study recommends conducting further research on the application of nano NPK fertilizers on other crops using varying concentrations, given their demonstrated effect on nutrient uptake efficiency, in conjunction with humic acid, which plays a significant role in improving the chemical

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properties and fertility of gypsiferous soils.

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