ORIGINAL RESEARCH ARTICLE | UHD JOURNAL OF SCIENCE AND TECHNOLOGY

Impact of Humic Acid on Growth, Yield, and Nitrogen, Phosphorus, and Potassium Uptake of Eggplant (*Solanum melongena* L.) in Coarse-texture Soils

Azad Salih Abdullah Krusk

Department of Horticulture, College of Agricultural Engineering Science, University of Raparin, Ranya/Sulaimani, Iraq.

ABSTRACT

To study how coarse-textured soils affect plant growth, yield, and Nitrogen (N), Phosphorus (P), and Potassium (K) content in eggplant (*Solanum melongena* L.), this study was carried out in pots using a factorial completely randomized design with three replications, and five different levels of humic acid (HA) (0, 40, 60, 80, and 120 kg/ha) was used during the 2024–2025 growing season. Field validation is recommended before making broad agronomic recommendations. Growth parameters, fruit yield components, N, P, and K concentrations in soil and plant organs were determined based on dry weight. Generally, plant height, leaf number, fruit diameter, and fruit weight increased significantly with HA application; the highest values were recorded at 80–120 kg/ha. Studied parameters were significantly affected by soil texture, loamy sand, and sandy loam, responding more strongly to HA than to loam. Most growth, yield, and nutrient concentrations recorded significant interaction effects between HA and soil texture. The availability of N, P, and K in soil increased with an increase in HA, as well as their accumulation in roots, shoots, and fruits. These results show that HA is effective as a soil improver and bio-stimulant for increasing eggplant productivity in coarse-textured soils; an ideal approach is the application of 80–120 kg/ha, which represents an optimal management strategy.

Index Terms: Coarse-texture, Growth, Humic Acid, Nutrient Uptake, *Solanum melongena*

1. INTRODUCTION

Eggplant (*Solanum melongena* L.) is a significant horticultural crop due to its nutritional value and versatility in cooking [1]. After tomato (*Solanum lycopersicon*) and potato (*Solanum tuberosum*), eggplant (*S. melongena*) is regarded as the most important crop in the Solanaceae family [2]. A wide variety of eggplant has been observed in natural product shape, color, size, branching propensity, flowering time, length of product development, weight, and number of products per plant [3]. Vegetable production, processing, and exchange play a crucial role in the economies of all countries, providing income for millions of people [4].

The cultivation of eggplant could be done across diverse climatic regions and production systems; however, it often faces challenges related to soil characteristics, particularly in coarse-textured soils [5]. Due to its complex effects on soil properties (physical, chemical, and biological) and its direct influence on plant metabolism, humic acid (HA) becomes an effective soil improver [6]. Its application improved nutrient availability, enhanced water retention, and increased plant growth across various crops. Russo

Access this article online

DOI: 10.21928/uhdjst.v10n2y2026.pp22-30	E-ISSN: 2521-4217 P-ISSN: 2521-4209

Corresponding author's e-mail: Azad Salih Abdullah Krusk, Department of Horticulture, College of Agricultural Engineering Science, University of Raparin, Ranya/Sulaimani, Iraq. E-mail: azad.abdullah@uor.edu.krd

Received: 03-05-2026 Accepted: 04-07-2026 Published: 15-07-2026

and Berlyn [7] reported that 65–70% of the organic matter in the soil is constituted by humic substances (humic and fulvic acids). Plant growth-promoting hormones such as auxin and cytokinin, which aid stress resistance, nutrient metabolism, and photosynthesis, increase with increasing levels of HA. HAs benefit plant nutrient uptake and are particularly important for the transport and availability of micronutrients [8].

Soil physical, chemical, and microbiological properties can be improved by increasing HA, thereby increasing the availability of plant nutrients for crop production [9]. Carboxyl, phenolic hydroxyl, alcoholic hydroxyl, ketone, and quinoid are the major functional groups of HAs. The mechanism of HA in stimulating plant growth is not completely known, but several explanations have been proposed by Russo and Berlyn [7], Vaughan [10], and Cacco and Dell'Agnola [11], such as increasing cell membrane permeability, oxygen uptake, respiration and photosynthesis, phosphate uptake, root cell elongation, and plant growth factors.

Water-holding capacity, permeability, aggregation, aeration, organic matter mineralization, solubilization, and nutrient availability can be improved by humus, which indirectly affects plant growth [12]. HAs play several important roles, such as increasing soil nutrients availability, especially micronutrients, by chelating and co-transporting micronutrients to plants [13], reducing the transportation of toxic heavy metals by precipitating them, thus reducing the poisonous heavy metals that plants can absorb [14].

The dominance of sand particles in coarse-textured soils has several inherent limitations for crop production [15]. These soils exhibit low water-holding capacity, rapid drainage, and reduced cation exchange capacity (CEC), resulting in significant leaching of essential nutrients and reduced nutrient retention. Such environments often involve nutrient deficiencies and water stress, directly affecting plant growth, physiological functions, and final yield [16].

Since these textures cover a large area of agricultural lands in the Raparin district, there is a lack of studies about the impact of soil texture on eggplant in our area. Due to this reason, the study was done to qualify the effect of different HA concentrations on the growth parameters, yield components of eggplant, and macro-nutrient concentration of eggplant when cultivated in coarse-textured soil types, namely loam, sandy loam, and loamy sand.

2. MATERIALS AND METHODS

2.1. Soil Sampling and Preparation

This experiment was carried out in pots during the 2024 growing season. Depending on the soil texture of ten locations, three were selected with different soil texture classes. Before selecting samples, the soil textures were determined according to Bowles [17]. To select only medium to coarse textures (Loamy Sand, Sandy Loam, and Loam), the soil samples were passed through a 4 mm sieve to be homogeneous in treatments. Each pot was filled with 24 kg of soil; the pot was 43 cm in diameter and 36 cm in height.

2.2. Experimental Design

A factorial experiment was established in pots and laid out as a completely randomized design with three replications, where five levels of HA (Bio Health WSG [HA 75%] manufactured in Germany) were used (control (0), 40, 60, 80, and 120) kg/ha H.A.

2.3. Plant Seedlings

On March 10, 2024, seeds of the eggplant cultivar (Black Beauty) were sown in seedbeds 1 m wide and 1 m long. The seedlings were ready for transplanting 35 days after sowing, that is, when they were 8–10 cm in height. During transplanting, a fixed amount of nitrogen as urea fertilizer was applied. A soil sample was collected for laboratory analysis, then dried in air, sieved through a 2 mm mesh, and stored in a plastic container until analysis. A comprehensive representation of the main chemical and physical characteristics of the studied soil was presented in Table 1.

TABLE 1: Main soil chemical and physical characteristics of the studied soils

Properties	Units	Texture class		
		Loamy sand	Sandy loam	Loam
Sand	g/kg	772.3	553.90	450.549
Silt		158.9	261.10	329.126
Clay		68.8	185.00	220.324
$ECaCO_3$		196.8	323	147.3
Organic matter		9.01	9.80	9.4
Field capacity	%	16.011	19.72	22.027
Wilting point		6.98	11.05	12.281
Soluble Ca^{2+}	mmolc/L	1.9	2	2.2
Soluble Mg^{2+}		5.35	4.80	5.8
Soluble Na^{+}		1.04	1.02	1.07
Soluble K^{+}		0.87	0.13	1.5
HCO_3^-		2.78	2.80	2.95
Cl^-		2.18	2.20	2.20
SO_4^{2-}		3.05	2.95	3.11
pH		7.29	7.38	7.86
EC	mS/cm	0.73	0.67	0.5

2.4. Plant Measuring Parameters

The parameters were measured as follows: On reaching maturity, after 90 days, data on both reproductive and vegetative development metrics were collected. Measurements were collected for various growth and yield components, including plant height, shoot diameter, number of leaves per plant, fruit length, fruit diameter, and fruit weight. After the plants showed signs of maturity, they were collected and rinsed with tap water, then rinsed three times with distilled water. Subsequently, they were air-dried in a laboratory. Next, the plants were finely diced to facilitate thorough drying, then oven-dried at 70°C until a consistent weight was achieved. The plants were digested for determinations of nitrogen (N), phosphorus (P), and potassium (K).

2.5. Statistical Analysis

The data were statistically analyzed using the Statistical Package for the Social Sciences version 27. Comparisons of treatment means and their combinations were performed using the least significant difference (LSD) test at $P \leq 0.01$.

3. RESULTS

3.1. Effect of HA, Soil Texture, and their Interaction on Plant Growth Parameters

As shown in Table 2, plant height and the number of leaves per plant were significantly affected by the HA level, soil texture, and their interaction ($P \leq 0.01$).

On the other hand, shoot diameter is significantly affected only by soil texture ($P \leq 0.01$), whereas the effects of HA and interaction were not significant.

The highest value for plant height was recorded at the loamy sand texture soil with a value of 64.4 cm. The application of 80 kg/ha HA recorded the highest value, which was equal to (56.27 cm). Furthermore, the interaction effect between loamy sand and HA 120 kg/ha recorded the highest plant, with the mean value of (74.0 cm).

Loamy sand texture soil and application of 80 kg/ha HA recorded the highest mean values of shoot diameter, which were equal to (13.9 and 13.16) mm, the interaction effect between loamy sand and HA 120 kg/ha produced the biggest shoot diameter (~15.5 mm at 120 kg/ha). Similarly, the highest number of leaves was recorded for loamy sand and HA 80 kg/ha (58.7 and 42.56). The interaction between loamy sand and HA at 120 kg/ha produced the greatest leaf numbers (up to 72 leaves at 120 kg/ha). Increasing HA from 0 to 80 kg/ha markedly increased plant height, especially in Loamy Sand. Similar results were obtained by Tahoun *et al.* [18]. In contrast, Loam textured soils showed only modest improvements [19], [20].

3.2. Effect of HA, Soil Texture, and their Interaction on Fruit Parameters

Fruit length, fruit diameter, and fruit weight showed a significant effect of HA at a level of significance ($P \leq 0.01$). Fruit length was not significantly affected by soil texture, but fruit diameter was significantly affected by soil texture at a level of significance ($P = 0.02$) and fruit weight at a level of significance ($P \leq 0.01$).

As shown in Table 3, at an HA level of 80 kg/ha, sandy loam soil recorded the highest fruit length value, which is equal to 8.7 cm. The interaction effect of HA and soil texture was not significant. The maximum mean length was recorded at 80 kg/ha in sandy loam, which was equal to (11.5 cm), which demonstrates the role of HA in fruit elongation regardless of soil type, consistent with [21].

TABLE 2: Influence of different levels of HA, soil texture, and interactions on growth parameters

HA (kg/ha)	Soil texture											
	Plant height (cm)				Shoot diameter (mm)				Number of leaves			
	Mean			HA Mean	Mean			HA Mean	Mean			HA Mean
	L	LS	SL		L	LS	SL		L	LS	SL	
0	33.67	52.00	42.32	42.66	9.64	12.87	10.80	11.10	10.33	51.33	19.33	27.00
40	37.17	61.40	50.73	49.77	11.72	13.11	11.86	12.23	13.00	52.00	33.67	32.89
80	49.10	70.25	49.45	56.27	10.97	14.06	14.44	13.16	20.33	59.67	47.67	42.56
120	40.00	74.00	46.47	53.49	8.16	15.54	13.28	12.33	15.33	72.00	37.00	41.44
Texture mean	39.9	64.4	47.2		10.1	13.9	12.6		14.7	58.7	34.4	
Texture		LSD=3.440				LSD=2.302				LSD=5.114		
HA		LSD=3.972				LSD=2.658				LSD=5.905		
Interaction		LSD=5.077				LSD=3.397				LSD=7.547		

L: Loam, LS: Loamy sand, SL: Sandy loam, LSD: Least significant difference, HA: Humic acid

TABLE 3: Influence of different levels of HA, soil texture, and their interactions on fruit parameters

HA (kg/ha)	Soil texture											
	Fruit length (cm)				Fruit diameter (mm)				Fruit weight (g)			
	Mean			HA Mean	Mean			HA Mean	Mean			HA Mean
	L	LS	SL		L	LS	SL		L	LS	SL	
0	0.0	4.33	5.1	3.1	0.0	21.53	19.56	13.70	0.00	24.00	18.67	14.22
40	8.3	8.33	7.9	8.2	27.95	34.48	34.36	32.26	30.33	49.67	55.25	45.08
80	10.67	9.00	11.56	10.41	37.38	37.61	39.80	38.26	59.00	59.00	81.33	66.44
120	9.3	9.67	10.33	9.8	32.23	39.73	33.92	35.29	38.00	67.00	61.83	55.61
Texture mean	7.1	7.8	8.7		24.4	33.3	31.9		31.8	49.9	54.2	
Texture		LSD=2.356				LSD=8.917				LSD=11.500		
HA		LSD=2.720				LSD=10.296				LSD=13.279		
Interaction		LSD=3.477				LSD=13.160				LSD=16.972		

L: Loam, LS: Loamy sand, SL: Sandy loam, LSD: Least significant difference, HA: Humic acid

Regarding fruit diameter, the height value recorded in loamy sand texture soil, which was equal to (33.3 cm) and HA application of 80 kg/ha was recorded the highest value of fruit diameter (39.80 cm); control plants produced very small fruits, whereas HA application (40 and 80 kg/ha) increased fruit diameters to nearly 35–40 mm across textures. Loamy sand generally produced wider fruits than loam; similar results were found by [22]. Fruit weight is also significantly affected by soil texture. The highest value was recorded for the sandy loam texture (54.2 g), and the application of HA also significantly affected fruit weight, with 80 kg/ha showing the highest value (66.4 g).

The interaction effect showed that the highest mean weight (81.33 g) was recorded in sandy loam at 80 kg/ha HA, as shown in Table 3. The biological mechanism driving this maximum response lies in the complementary relationship between the soil's physical structure and the organic acid. Sandy Loam provides high microporosity and optimal root aeration, while the high application of HA (80 kg/ha) compensates for the soil's naturally low nutrient retention by significantly increasing its CEC. In contrast, loam soil produced the lowest weights across all HA levels. Because loam naturally possesses a higher baseline CEC and holds more moisture, the physiological benefit of added HA is less pronounced, and the heavier moisture retention may reduce the optimal root aeration seen in the sandy loam. This aligns with previous studies showing HA improves fruit biomass in solanaceous crops [12].

3.3. Effect of HA and Soil Textures on (N, P, and K) Concentration in Soil

3.3.1. Effect of HA and soil textures on N concentration

The analysis of variance (ANOVA) was conducted to assess the effects of soil texture (loamy sand, sandy loam, and loam) and HA application (HA0, HA40, HA80, HA120) on soil N concentration. The analysis revealed a statistically significant main effect for texture. A *post hoc* test showed that the three soil types had significantly different mean N levels. Loamy sand had the highest soil N (514.50), followed by loam (416.50), and sandy loam had the lowest (367.50).

There was also a highly significant main effect of HA. The *post hoc* test showed that all four application levels differed significantly from one another, indicating a positive trend. The HA80 application resulted in the highest soil N (555.3), while the control group HA0 had the lowest (359.33), as shown in Table 4. The interaction effect of sandy loam and HA0 recorded the lowest mean value, which was equal to (249 ppm). Most importantly, a statistically significant interaction between texture and HA was found.

3.3.2. Effect of HA and soil textures on P concentration

P concentration was significantly affected by soil texture, as shown in Table 4. Sandy loam had the lowest concentration (2.73 ppm), while loam had the highest P concentration (7.32 ppm), followed by loamy sand (4.05 ppm). The statistical significance of the differences between the three soil textures was proven by *post hoc* pairwise comparisons.

The use of HA also has a significant effect. The application of 120 kg/ha HA recorded the highest soil P (5.91 ppm). The control groups HA0 and HA80 showed statistically non-significant differences from each other and had the lowest P levels, which were equal to (3.93 ppm) and (4.22 ppm), respectively. The lowest interaction mean value was recorded at sandy loam and HA0, which was equal to (0.77 ppm). In addition, a strong interaction impact between HA and soil texture was recorded.

TABLE 4: Effect of HA and soil texture on (N, P, and K) concentration in soil

HA (kg/ha)	N (ppm)			HA Mean	P (ppm)			HA Mean	K (ppm)			HA Mean
	L	SL	LS		L	SL	LS		L	SL	LS	
0	294.0	249.0	490.0	359.3	6.89	0.77	4.12	3.93	9.5	15.0	6.5	10.3
40	294.0	490.0	490.0	424.7	7.60	3.06	3.53	4.73	12.5	15.0	9.0	12.2
80	686.0	392.0	588.0	555.3	6.48	2.36	3.83	4.22	11.0	15.0	11.5	12.5
120	392.0	294.0	490.0	392.0	8.30	4.71	4.71	5.91	13.5	14.0	8.0	11.8
Texture mean	416.5	367.5	514.5		7.32	2.73	4.05		11.63	14.75	8.75	
Texture			LSD=15.62				LSD=0.286				LSD=0.394	
HA			LSD=18.03				LSD=0.330				LSD=0.456	
Interaction			LSD=31.24				LSD=0.572				LSD=0.780	

L: Loam, LS: Loamy sand, SL: Sandy loam, LSD: Least significant difference, HA: Humic acid, N: Nitrogen, P: Phosphorus, K: Potassium

3.3.3. Effect of HA and soil textures on K concentration

The analysis revealed a statistically significant effect on texture. Sandy loam had the highest soil K (14.75 ppm), followed by loam (11.63 ppm), and loamy sand had the lowest (8.75 ppm). There was also a significant main effect for HA. The LSD test showed a generally positive trend, with soil K increasing with HA application. The control group HA0 had the lowest K Concentration (10.3 ppm), while the HA80 application resulted in the highest (12.5 ppm), as shown in Table 4.

The abundance of oxygen-containing functional groups, specifically carboxyl (COOH) and phenolic hydroxyl (OH) groups, is inherent to humic macromolecules. These active sites augment the soil's net negative charge and enhance its CEC. Consequently, this facilitates the electrostatic retention of exchangeable K^+ ions on soil colloids, minimizing leaching losses while simultaneously promoting the desorption of fixed K into the soil solution [23], [24].

Moreover, the H.A0 and Loamy sand texture recorded the lowest interaction mean, which was equal to (6.50 ppm). Most importantly, a statistically significant interaction effect was found.

3.4. Effect of HA and Soil Textures on (N, P, and K) Concentration in Fruit

3.4.1. Effect of HA and soil textures on N concentration

The three soil types significantly differ from each other in N content, as indicated by a *post hoc* test. As shown in Table 5, the highest N concentration (26242.0 ppm) was recorded in sandy loam, and the lowest N concentration, which was equal to (23430.5 ppm), was recorded in loamy sand. The LSD *post hoc* test indicated that all four application levels of HA were significantly different from one another.

The highest N concentration was found with the HA120 application (30147.00 ppm), followed by HA40 (27930.3 ppm), HA80 (25920.3 ppm), and finally, the control group HA0 had the lowest N concentration (15982.7 ppm). The mean value (14543 ppm) was the lowest interaction value recorded for the loamy sand and HA0 interaction. Most importantly, ANOVA showed a statistically significant interaction effect between Texture and HA.

3.4.2. Effect of HA and soil textures on P concentration

The LSD *post hoc* test revealed that all three soil types were significantly different from one another. Table 5 shows that the highest mean P concentration was found in loam (7.6), followed by sandy loam (7.1), and the lowest was in loamy sand (6.5). A significant main effect was also found for HA. The HA40 application resulted in the highest P concentration (8.3). This was followed by HA120 (6.9).

The control group HA0 (6.4) and the HA80 application (6.6) did not differ significantly and had the lowest P levels. Crucially, ANOVA revealed a very strong, statistically significant interaction effect between texture and HA, with the lowest interaction value recorded for sandy loam HA80 (3.7 ppm). This indicates that the influence of HA on P varies significantly across soil types.

3.4.3. Effect of HA and soil textures on K concentration

Table 5 demonstrated that sandy loam had a higher mean K concentration, which was equal to (330.2 ppm), and had significantly different means as shown by *post hoc* tests. On the other hand, both loamy sand (319.0 ppm) and loam (316.2 ppm) were not significantly different from each other.

The application of different levels of HA showed a significant difference, as tested by the LSD *post hoc* test. Interestingly, the relationship was inverse: The control group HA0 had the highest K concentration (355.7), which decreased with each application level down to HA120, which had the lowest (296.0).

Furthermore, there was a statistically significant interaction effect between texture and HA. The lowest value of interaction, which was equal to (291 ppm), was recorded at sandy loam, HA120 interaction. This indicates that the effect of HA on K concentration depends on soil type.

3.5. Effect of HA and Soil Textures on (N, P, and K) Concentration in the Root

3.5.1. Effect of HA and soil textures on N concentration

The analysis showed a statistically significant main effect for texture. Loamy sand had the highest mean root N (7154 ppm), followed by sandy loam (6664 ppm), with loam having the lowest (5782 ppm), as shown in Table 6. *Post hoc* tests revealed that all three soil types differed significantly from one another. The HA120 application had the highest root N (7709.3 ppm), while the HA40 application had the lowest (5880.0 ppm), even lower than the control group HA0 (6141.3 ppm).

A statistically significant interaction between texture and HA was found. The lowest interaction effect mean value was recorded at the interaction between HA40 and loamy textured soil, which was equal to (5096 ppm).

3.5.2. Effect of HA and soil textures on P concentration

A *post hoc* test showed that sandy loam resulted in significantly higher root P (6.6 ppm) than both loam (5.2 ppm) and loamy sand (5.4 ppm). Loam and loamy sand were not significantly different. There was also a significant main effect for HA. The HA40 application yielded the highest P concentration (6.5 ppm). The control groups HA0 (6.1 ppm) and HA120 (5.8 ppm) did not differ significantly.

The HA80 application resulted in the lowest root P concentration (4.5 ppm), and the lowest interaction mean (2.94 ppm) was recorded for sandy loam under HA80 application, as shown in Table 6. Most importantly, the analysis revealed a highly significant interaction effect between texture and HA.

3.5.3. Effect of HA and soil textures on K concentration

The analysis found a statistically significant main effect for texture. Table 6 demonstrated that loam soil had the highest root K (100 ppm), followed by sandy loam (87.5 ppm),

TABLE 5: Effect of HA and soil texture on (N, P, and K) concentration in fruit

HA (kg/ha)	N (ppm)			HA Mean	P (ppm)			HA Mean	K (ppm)			HA Mean
	L	SL	LS		L	SL	LS		L	SL	LS	
0	15840.0	17565.0	14543.0	15982.7	7.5	4.4	7.4	6.4	375.0	354.0	338.0	355.7
40	29767.0	27568.0	26456.0	27930.3	9.2	9.3	6.3	8.3	307.0	354.0	326.0	329.0
80	25840.0	26879.0	25042.0	25920.3	9.4	3.7	6.6	6.6	292.0	322.0	306.0	306.7
120	29804.0	32956.0	27681.0	30147.0	4.4	10.8	5.7	6.9	291.0	291.0	306.0	296.0
Texture mean	25312.7	26242.0	23430.5		7.6	7.1	6.5		316.2	330.2	319.0	
Texture			LSD=42.13				LSD=0.168				LSD=4.21	
HA			LSD=48.65				LSD=0.195				LSD=4.86	
Interaction			LSD=84.26				LSD=0.337				LSD=8.43	

L: Loam, LS: Loamy sand, SL: Sandy loam, LSD: Least significant difference, HA: Humic acid, N: Nitrogen, P: Phosphorus, K: Potassium

TABLE 6: Effect of HA and soil texture on (N, P, and K) concentration in the root

HA (kg/ha)	N (ppm)			HA Mean	P (ppm)			HA Mean	K (ppm)			HA Mean
	L	SL	LS		L	SL	LS		L	SL	LS	
0	5880	6664	5880	6141.3	6.4	5.5	6.3	6.1	100	75	50	75
40	5096	5880	6664	5880.0	5.1	8.9	5.7	6.6	75	100	75	83.3
80	5880	6272	7056	6402.7	5.3	2.9	5.1	4.5	100	125	75	100
120	6272	7840	9016	7709.3	4.0	9.1	4.4	5.8	125	50	50	75
Texture mean	5782	6664	7154		5.2	6.6	5.4		100	87.5	62.5	
Texture			LSD=29.10				LSD=0.168				LSD=0.394	
LSD HA			LSD=33.60				LSD=0.195				LSD=0.456	
LSD Interaction			LSD=58.20				LSD=0.337				LSD=0.780	

L: Loam, LS: Loamy sand, SL: Sandy loam, LSD: Least significant difference, HA: Humic acid, N: Nitrogen, P: Phosphorus, K: Potassium and loamy sand had the lowest (62.5 ppm). A significant main effect was also found for HA. The HA80 application resulted in the highest K concentration (100 ppm), followed by HA40 (83.3 ppm). The control group HA0 (75 ppm) and the HA120 application (75 ppm) did not differ significantly. They had the lowest K levels, also the lowest interaction recorded at loamy sand, HA0 application, which was equal to (50 ppm). Most importantly, the analysis revealed a highly significant interaction effect between texture and HA.

3.6. Effect of HA and Soil Textures on (N, P, and K) Concentration in the Shoot

3.6.1. Effect of HA and soil textures on N concentration

A *post hoc* test showed that all three soil types were significantly different from one another. Sandy loam had the highest mean shoot N (14994 ppm), followed closely by loamy sand (14700 ppm), while loam had the lowest N concentration (10388 ppm). A highly significant main effect of HA was indicated by the LSD *post hoc* test. The application of HA40 recorded the highest shoot N, which was equal to (14765.3 ppm). This was followed by the control group HA0 (13850.7 ppm) and HA80 (13328.0 ppm), with the HA120 application resulting in the lowest N concentration (11498.7 ppm), as shown in Table 7. The analysis found a statistically significant interaction effect between texture and HA. The lowest mean value was recorded at the interaction between HA120 and loamy textured soil, with a value of (9408 ppm).

3.6.2. Effect of HA and soil textures on P concentration

There was also a highly significant main effect of HA. Table 7 showed that the HA40 application yielded the highest P concentration (6.24 ppm), followed by HA120 (5.14 ppm), HA80 (4.87 ppm), and the control group (HA0), which recorded the lowest value (4.04 ppm). The mean P level of all the mentioned soil types significantly differs from each other. The highest shoot P concentration was recorded in loam soil (5.84 ppm), followed by loamy sand (4.89 ppm), and the lowest value was recorded in sandy loam (4.49 ppm). Remarkably, a great, statistically significant interaction effect was found between texture and HA. The lowest mean value was recorded for the HA0 and sandy loam texture interaction (1.53 ppm).

3.6.3. Effect of HA and soil textures on K concentration

LSD test identified two distinct groups: Loamy sand (275 ppm) and sandy loam (275 ppm) had significantly higher shoot K concentration than loam soil (200 ppm). There was also a significant main effect for HA. The test showed that all four application levels were significantly different from one another. The HA40 application resulted in the highest K concentration (266.7 ppm), followed by the control group HA0 (258.3 ppm), then HA80 (241.7 ppm), with the HA120 application yielding the lowest amount (233.3 ppm).

On the other hand, the interaction between HA120 and loamy texture soil recorded the lowest mean value, which is equal to (175 ppm), as shown in Table 7. A statistically significant interaction effect was found between texture and HA.

4. DISCUSSION

The results confirmed that the application of HA, in coarse-textured soils, significantly enhanced eggplant vegetative growth and yield. These results align with the study's objectives and point to several significant trends. Plant growth parameters such as plant height, fruit length, diameter, weight, and leaf number are continuously increased by the application of HA.

The application of 80–120 kg/ha was identified as the most effective for growth rate response among the treatments

TABLE 7: Effect of HA and soil texture on (N, P, and K) concentration in the shoot

HA (kg/ha)	N (ppm)			HA Mean	P (ppm)			HA Mean	K (ppm)			HA Mean
	L	SL	LS		L	SL	LS		L	SL	LS	
0	10584	16856	14112	13850.7	5.30	1.53	5.30	4.04	225	275	275	258.3
40	10976	17248	16072	14765.3	8.83	5.65	4.24	6.24	200	300	300	266.7
80	10584	15680	13720	13328.0	6.30	2.94	5.36	4.87	200	275	250	241.7
120	9408	10192	14896	11498.7	2.94	7.83	4.65	5.14	175	250	275	233.3
Texture mean	10388	14994	14700		5.84	4.49	4.89		200	275	275	
Texture			LSD=42.13				LSD=0.168				LSD=4.21	
LSD HA			LSD=48.65				LSD=0.195				LSD=4.86	
LSD Interaction			LSD=84.25				LSD=0.337				LSD=8.43	

L: Loam, LS: Loamy sand, SL: Sandy loam, LSD: Least significant difference, HA: Humic acid, N: Nitrogen, P: Phosphorus, K: Potassium tested in this study. The positive effects of HA are recognized for its roles in enhancing photosynthesis, stimulating hormone-like activity, expanding root systems, and improving nutrient availability [25], [26].

Eggplant performance was significantly influenced by soil texture. Plants growing in loamy sand were the tallest, had the most leaves, and had the largest fruit, whereas sandy loam plants were the smallest. This suggests that eggplant benefits from soils with increased drainage and aeration, and that HA is particularly effective in improving the fertility of coarse soils by increasing water retention and CEC [21], [22].

The interaction between HA and soil texture was highly significant for plant height and leaf number, indicating that HA was especially beneficial under sandy conditions, where nutrient and water limitations are more pronounced. In contrast, fruit diameter and weight showed mainly additive effects, suggesting that HA improved yield regardless of soil texture [27]. Shoot diameter was not affected by HA but was significantly influenced by soil texture, which may reflect structural adaptation to soil physical properties rather than nutrient availability [28].

Overall, HA substantially enhances eggplant growth and yield, particularly in coarse soils. Application rates of 80–120 kg/ha are most effective, especially in loamy sand textured soils, which demonstrated superior performance.

The heightening of N, P, and K concentrations at a medium rate of HA application may be attributed to the beneficial effects of HA on nutrient availability and plant nutrient uptake. Humic substances stimulate root growth, increase root surface area, enhance plasma membrane H+-ATPase activity, and improve nutrient acquisition efficiency [26].

Furthermore, HA can modify root architecture and physiological processes involved in nutrient absorption, resulting in improved mineral nutrition and plant growth [29].

The decline in N, P, and K concentrations at the highest HA concentration suggests that excessive HA application may negatively affect nutrient use efficiency. Higher doses may alter nutrient balance in the rhizosphere, interfere with ion uptake processes, or induce excessive vegetative growth, resulting in a dilution effect in plant tissues [29]. Olaetxea *et al*. [30] also emphasized that the physiological responses induced by humic substances vary according to their concentration, chemical characteristics, and environmental conditions.

5. CONCLUSION

This study provides strong evidence that applying HA significantly affects eggplant growth, fruit, and nutrient uptake in coarse-textured soils. HA has increased the availability of essential macronutrients; in soil, N concentration was increased by 54.55% at the application of 80 kg/ha HA. P concentration increased by 50.38% at the application of 120 kg/ha HA, and the application of 120 kg/ha HA caused an increase in K concentration by 14.56%. The application of HA had significantly affected plant growth parameters and yield across all studied textures.

Soil texture appeared to be a critical factor regulating crop response; HA had the greatest benefits in loamy sand and sandy loam compared with loamy soil. The significant relationship between the studied factors underscores the need for nutrient management techniques rather than standard application. Application of 80–120 kg/ha consistently yielded better growth and yield than other HA levels, suggesting an ideal range for optimizing agronomic efficiency in coarse soils.

The results confirm that incorporating HA into fertilization programs enhances vegetable production in low-fertility soils. HA is a viable method for reducing nutrient losses and increasing productivity by improving nutrient retention, uptake efficiency, and yield stability under challenging soil conditions. Future research should focus on long-term field evaluations and on interactions between HA and mineral fertilizers to improve application approaches and assess their broader effects on soil health and sustainable crop production.

6. ACKNOWLEDGMENT

The author would like to express their sincere gratitude to the University of Raparin for its institutional support throughout this study. The author gratefully acknowledges the technical assistance provided by the university laboratories and their dedicated staff, as well as the financial support that facilitated the successful completion of this research. The support and encouragement provided by the University of Raparin are highly appreciated.

REFERENCES

[1] P. Saha, J. Singh, N. Bhanushree, S. M. Harisha, B. S. Tomar and B. Rathinasabapathi. "Eggplant (*Solanum melongena* L.)

nutritional and health promoting phytochemicals". In: *Compendium of Crop Genome Designing for Nutraceuticals*. Springer, Berlin, pp. 1-32, 2023.

[2] W. L. Morris and M. A. Taylor. "The solanaceous vegetable crops: Potato, tomato, pepper and eggplant". In: B. Thomas, B. G. Murray and D. J. Murphy, Eds. *Encyclopedia of Applied Plant Sciences.* 2nd ed. Academic Press, Oxford, pp. 55-58, 2017.

[3] A. A. Csizinszky. "Response of tomatoes to foliar biostimulant sprays". *Proceedings of the Florida State Horticultural Society*, vol. 99, pp. 353-358, 1986.

[4] S. Nicola and L. Basoccu. "*Nitrogen and N,P,K Relation Affect Tomato Seedling Growth, Yield and Earliness*". International Society for Horticultural Science (ISHS), Leuven, Belgium, pp. 95-102, 1994.

[5] L. T. Thierry, C. P. M. Janvier, Y. S. D. Martial and A. T. Joséphine. "Vegetative growth response of eggplant (*Solanum aethiopicum* L.) to combined effects of fertilizer types and irrigation regimes applied on littoral tertiary soil in Côte d'Ivoire". *International Journal of Plant and Soil Science*, vol. 30, no. 5, pp. 1-11, 2019.

[6] Q. Sun, J. Liu, L. Huo, Y. C. Li, X. Li, L. Xia, Z. Zhou, M. Zhang and B. Li. "Humic acids derived from Leonardite to improve enzymatic activities and bioavailability of nutrients in a calcareous soil". *International Journal of Agricultural and Biological Engineering*, vol. 13, no. 3, pp. 200-205, 2020.

[7] R. O. Russo and G. P. Berlyn. "The use of organic biostimulants to help low input sustainable agriculture". *Journal of Sustainable Agriculture*, vol. 1, no. 2, pp. 19-42, 1991.

[8] M. Bohme and H. T. Lua. "*Influence of Mineral and Organic Treatments in the Rhizosphere on the Growth of Tomato Plants*". International Society for Horticultural Science (ISHS), Leuven, Belgium, pp. 161-168, 1997.

[9] J. E. Bowen, B. A. Kratky and P. Perreira. "*Adapting Crops to Troubled Soils is Key to Solving World's Food Problems*". Springer, Berlin, 1985.

[10] D. Vaughan. "A possible mechanism for humic acid action on cell elongation in root segments of *Pisum sativum* under aseptic conditions". *Soil Biology and Biochemistry*, vol. 6, no. 4, pp. 241-247, 1974.

[11] G. Cacco and G. Dell'Agnola. "Plant growth regulator activity of soluble humic complexes". *Canadian Journal of Soil Science*, vol. 64, no. 2, pp. 225-228, 1984.

[12] S. Nardi, D. Pizzeghello, A. Muscolo and A. Vianello. "Physiological effects of humic substances on higher plants". *Soil Biology and Biochemistry*, vol. 34, no. 11, pp. 1527-1536, 2002.

[13] S. Wu, R. Li, S. Peng, Q. Liu and X. Zhu. "Effect of humic acid on transformation of soil heavy metals". *IOP Conference Series Materials Science and Engineering*, vol. 207, no. 1, p. 012089, 2017.

[14] F. Yang, C. Tang and M. Antonietti. "Natural and artificial humic substances to manage minerals, ions, water, and soil microorganisms". *Chemical Society Reviews*, vol. 50, no. 10, pp. 6221-6239, 2021.

[15] G. P. Wind. "Root growth in acid soils". *Netherlands Journal of Agricultural Science*, vol. 15, no. 4, pp. 259-266, 1967.

[16] M. G. Balbaa and A. M. Awad. "Effect of humic acid and micronutrients foliar fertilization on yield, yield components and nutrients uptake of maize in calcareous soils". *Journal of Plant Production*, vol. 4, no. 5, pp. 773-785, 2013.

[17] J. E. Bowles. *Engineering Properties of Soils and their Measurement*. McGraw-Hill, United States, 1992.

[18] A. M. M. A. Tahoun, M. M. A. El-Enin, A. G. Mancy, M. H. Sheta and A. Shaaban. "Integrative soil application of humic acid and foliar plant growth stimulants improves soil properties and wheat yield and quality in nutrient-poor sandy soil of a semiarid region". *Journal of Soil Science and Plant Nutrition*, vol. 22, no. 3, pp. 2857-2871, 2022.

[19] B. Eyheraguibel, J. Silvestre and P. Morard. "Effects of humic substances derived from organic waste enhancement on the growth and mineral nutrition of maize". *Bioresource Technology*, vol. 99, no. 10, pp. 4206-4212, 2008.

[20] L. P. Canellas, F. L. Olivares, N. O. Aguiar, D. L. Jones, A. Nebbioso, P. Mazzei and A. Piccolo. "Humic and fulvic acids as biostimulants in horticulture". *Scientia Horticulturae,* vol. 196, pp. 15-27, 2015.

[21] A. M. El-Ghamry, K. M. Abd El-Hai and K. M. Ghoneem. "Amino and humic acids promote growth, yield and disease resistance of faba bean cultivated in clayey soil". *Australian Journal of Basic and Applied Sciences*, vol. 3, no. 2, pp. 731-739, 2009.

[22] V. Mora, R. Baigorri, E. Bacaicoa, A. M. Zamarreño and J. M. García-Mina. "The humic acid-induced changes in the root concentration of nitric oxide, IAA and ethylene do not explain the changes in root architecture caused by humic acid in cucumber". *Environmental and Experimental Botany*, vol. 76, pp. 24-32, 2012.

[23] M. T. Rose, A. F. Patti, K. R. Little, A. L. Brown, W. R. Jackson and T. R. Cavagnaro. "Chapter two - a meta-analysis and review of plant-growth response to humic substances: Practical implications for agriculture". *Advances in Agronomy*, vol. 124, pp. 37-89, 2014.

[24] S. Nardi, M. Schiavon and O. Francioso. "Chemical structure and biological activity of humic substances define their role as plant growth promoters". *Molecules,* vol. 26, no. 8, p. 2256, 2021.

[25] P. Rathor, P. Upadhyay, A. Ullah, L. Y. Gorim and M. S. Thilakarathna. "Humic acid improves wheat growth by modulating auxin and cytokinin biosynthesis pathways". *AoB Plants,* vol. 16, no. 2, p. plae018, 2024.

[26] A. Maffia, M. Oliva, F. Marra, C. Mallamaci, S. Nardi and A. Muscolo. "Humic substances: Bridging ecology and agriculture for a greener future". *Agronomy*, vol. 15, no. 2, p. 410, 2025.

[27] R. M. Atiyeh, S. Lee, C. A. Edwards, N. Q. Arancon and J. D. Metzger. "The influence of humic acids derived from earthworm-processed organic wastes on plant growth". *Bioresource Technology*, vol. 84, no. 1, pp. 7-14, 2002.

[28] S. Trevisan, O. Francioso, S. Quaggiotti and S. Nardi. "Humic substances biological activity at the plant-soil interface: From environmental aspects to molecular factors". *Plant Signaling and Behavior*, vol. 5, no. 6, pp. 635-643, 2010.

[29] L. P. Canellas and F. L. Olivares. "Physiological responses to humic substances as plant growth promoter". *Chemical and Biological Technologies in Agriculture*, vol. 1, no. 1, p. 3, 2014.

[30] M. Olaetxea, V. Mora, E. Bacaicoa, R. Baigorri, M. Garnica, M. Fuentes, A. M. Zamarreño, L. Spíchal and J. M. García-Mina. "Root ABA and H+-ATPase are key players in the root and shoot growth-promoting action of humic acids". *Plant Direct*, vol. 3, no. 10, p. e00175, 2019.