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Effect of Liquid Organic Fertilizers on Garlic Performance and Soil Properties

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ABSTRACT

Currently, there is growing interest in improving the use of organic fertilizers, especially in their liquid forms, which offer a promising alternative to traditional fertilizers. Therefore, this research work aimed to assess the influence of liquid organic fertilizers (compost tea, vermicompost extract, and biogas digestate) at different levels (0.0, 1.5, 3.0, 4.5, and 6.0 m^3 fed^{-1}) on garlic plant performance and soil properties. biogas digestate application resulted in the highest values of garlic yield components and quality such as average bulb weight (g), bulb diameter (cm), neck diameter (cm), total bulb yield (ton fed^{-1}), carbohydrate content (%), total dissolved solids (TDS, %), vitamin C content (mg 100 g^{-1}), followed by vermicompost extract, while compost tea showed the lowest values. Noting that, increasing the application level of each fertilizer consistently improved all traits, with the highest values recorded at 6.0 m^3 fed^{-1} under each fertilizer, compared to the lowest levels. Generally, the superior treatment was biogas digestate at a level of 6.0 m3 fed^{-1}. Also, among the studied organic fertilizers, biogas digestate led to the highest improvements in soil traits like NPK (mg kg^{-1}), OM (%) and CEC (cmol kg^{-1}), followed by vermicompost extract then compost tea. Therefore, it can be recommended to integrate biogas digestate into fertilization programs.

Keywords: Compost tea, biogas, vermicompost

INTRODUCTION

Currently, there is growing interest in improving the use efficiency of organic fertilizers, especially in their liquid forms, which offer a promising alternative to traditional fertilizers (Shabana *et al.* 2024). Compost tea which produced by steeping mature compost in water is a nutrient-rich solution containing microbial metabolites and bioactive compounds which can improve soil microbial activity (Yin *et al.* 2025) and suppress plant pathogens as well as improve crop productivity (Pilla *et al.* 2023). Its composition varies depending on the raw substances used and the brewing circumstances, but it typically includes macronutrients like NPK, which are crucial for higher plant growth. Moreover, it provides essential micronutrients such as Mg, Ca, Fe and Mn. The presence of beneficial microbial communities, including fungi, bacteria, and actinomycetes may help in enhancing nutrient cycling and suppress higher plant pathogens. This liquid fertilizer is also rich in humic substances, amino acids, dissolved organic matter and polysaccharides, which improve soil structure and improve nutrient availability to plants (Garg& Rakshit, 2024). Vermicompost extract is derived from the breakdown of organic matter by earthworms. It is rich in humic materials, plant growth-promoting microorganisms, and available nutrients (Yusof *et al.* 2018). It improves soil structure, nutrient uptake, and the tolerance of higher plants to biotic and abiotic stresses (Tikoria *et al.* 2022). It is known for its high concentration of beneficial microbes and plant-available nutrients such as NPK, along with trace elements like Ca, Fe, and Mn. Additionally, it is rich in nitrogen-fixing bacteria, beneficial fungi, and phosphate-solubilizing microbes (Bouchtaoui *et al.* 2024). Biogas digestate is a byproduct of anaerobic digestion (Møller *et al.* 2020). The composition of digestate depends on the feedstock used in the digestion process. It is an excellent source of organic matter and plant-available nutrients (Ai *et al.* 2020). It generally contains high levels of N, P, K, B, Cu, Mo, and S, which are essential for plant metabolism. Moreover, the organic matter in digestate enhances the soil structure and improves its water-holding capacity (Rolka et al. 2024). Garlic (*Allium sativum* L.) is a so important crop due to its medicinal and economic significance, as it is rich in bioactive compounds such as sulfur-containing compounds, vitamins and antioxidants (Thakur *et al.* 2024). on the other hand, optimizing garlic yield and quality requires an adequate supply of nutrients; thus, the integration of liquid organic fertilizers in the agricultural sector is a potential strategy for sustainability (Preciado-Rangel *et al.* 2025).

Therefore, the objective of the current research work is to assess the influence of compost tea, vermicompost and biogas at different levels on garlic yield and quality and soil properties.

MATERIALS AND METHODS

1.Experimental Site and Initial Soil Analysis

The field experiment was conducted at the Agricultural Research Station in Sakha, affiliated with the Agricultural Research Center, Egypt, during the 2022/23 and 2023/24 growing seasons. Soil samples were collected before planting for physicochemical analysis following the standard methods described by Tandon (2005). The initial soil characteristics, presented as combined data over both seasons, are shown in Table 1.

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Table 1. Initial soil characteristics (combined data over both seasons)

Particle size distribution		Chemical traits		Availability of nutrients	
Sand,%	19.5	O.M,%	1.35	N, $mgkg^{-1}$	32.1
Silt,%	30.5	EC, dSm^{-1}	3.34	P, $mgkg^{-1}$	7.90
Clay,%	50.0	pH	8.26	K, $mgkg^{-1}$	215.8
Texture class is clay		CEC, cmol kg^{-1}	51.0		

2. Preparation of Liquid Organic Fertilizers

Compost tea was prepared by steeping well-matured compost in aerated water for 48 hours, followed by filtration. Vermicompost extract was produced by soaking vermicompost in water at a 1:5 (w/v) ratio for 48 hours under aeration, then filtering the extract. The biogas digestate effluent was collected from an anaerobic digester, allowed to undergo sedimentation to separate solids and then filtered before application. Additionally, liquid fertilizers, including compost tea, vermicompost extract and biogas digestate, were analyzed before application to determine their nutrient composition following the standard methods described by Tandon (2005), as their characteristics are shown in Table 2.

Table 2. Attributes of the liquid organic fertilizers studied

Soil characteristics	Biogas digestate	Vermicompost extract	Compost tea
pH	7.52	8.45	8.30
EC,dSm^{-1}	13.69	10.2	9.97
Humic acid,%	1.60	/	/
Fulvic acid,%	0.35	/	/
Total potassium humate,%	2.10	/	/
Nitrogen,%	1.50	/	/
Phosphorus ,%	0.50	/	/
Potassium ,%	0.20	/	/
Zn, $mgkg^{-1}$	/	19.15	22.0
Mn, $mgkg^{-1}$	/	18.95	20.0
Fe, $mgkg^{-1}$	/	0.90	1.00
Cu, $mgkg^{-1}$	/	45.9	46.2
B, $mgkg^{-1}$	/	27.6	31.3

3. Plant Material and Experimental Design

The garlic cultivar "Sids 40" was used in this study. A split-plot experimental design was employed with three replications per treatment. The main factor consisted of different liquid organic fertilizers, including compost tea, vermicompost extract and biogas digestate. The sub-main factor was the application rate, which included five levels: 0.0, 1.5, 3.0, 4.5, and 6.0 m^3 fed^{-1}.

4. Cultivation and Harvest

Garlic cloves were planted on November 1st in both growing seasons. Each plot measured 3 m × 3 m, with cloves spaced 15 cm apart on both sides of a planting row. Liquid organic fertilizers were applied according to the treatments studied during the first and second irrigation events. Additionally, nitrogen (N) as urea (46.5% N), phosphorus (P) as calcium superphosphate (6.6% P) and potassium (K) as potassium sulfate (38% K) were applied at rates of 120 units of nitrogen, 60 units of phosphorus, and 48 units of potassium per feddan across all plots. Nitrogen fertilization was administered in two equal doses during the first and second irrigation events, whereas potassium fertilization was applied in two equal doses during the third and fourth irrigation events. Phosphorus fertilization was incorporated as a single pre-planting dose. Irrigation was managed using a flood irrigation system, with water application based on crop requirements and local climatic conditions. Herbicides, fungicides and insecticides were added as recommended by the Egyptian Ministry of Agriculture and Soil Reclamation (MASR). The harvest was conducted 170 days after planting.

5. Sampling and Measurements

At the harvest stage (170 days after planting), the following parameters were evaluated:

- Yield and yield components: Average bulb weight (g), bulb diameter (cm), neck diameter (cm), bulbing ratio, number of cloves $bulb^{-1}$, total bulb yield (ton fed^{-1}), and marketable yield (ton fed^{-1}).
- Bulb quality parameters: Total carbohydrate content (%), total dissolved solids (TDS, %), vitamin C content (mg 100 g^{-1}), dry matter content (%), and pungency (pyruvate content, πmol ml^{-1}) were determined according to the AOAC (2000) procedures.
- Post-harvest soil analysis: Soil samples were analyzed according to the standard methods as described by Tandon (2005), to determine the following properties. Available Nitrogen (mg kg^{-1}): It was determined using the micro-Kjeldahl method, which involves the digestion of soil samples with concentrated sulfuric acid to convert organic nitrogen into ammonium, followed by distillation and titration to quantify the nitrogen content. Available Phosphorus (mg kg^{-1}): It was measured using the Olsen method, which involves extracting phosphorus from the soil with sodium bicarbonate solution, followed by colorimetric determination using a spectrophotometer. Available Potassium (mg kg^{-1}): It was quantified using flame photometry after extraction with a neutral ammonium acetate solution, which allows for the accurate measurement of potassium concentration based on its emission intensity in the flame.. Organic Matter (O.M, %): It was estimated using the Walkley and Black method, which involves oxidizing organic carbon in the soil with a mixture of potassium dichromate and sulfuric acid, followed by titration to determine the organic matter content Cation Exchange Capacity (CEC, cmol kg^{-1}): It was determined using the ammonium acetate method, where soil is saturated with ammonium ions, then displaced with a neutral salt solution to measure the total exchangeable cations held by the soil.

6. Statistical Analysis

Data were statistically analyzed according to the method described by Gomez and Gomez (1984). Analysis of variance (ANOVA) was performed using CoStat software (Version 6.303, CoHort, USA, 1998-2004), and means were compared using Duncan's Multiple Range Test (DMRT) at a significance level of $P \leq 0.05$.

RESULTS AND DISCUSSION

1.Yield and Its Components at Harvest Stage (170 days from Sowing)

Table 3 presents the impact of different levels (0.0, 1.5, 3.0, 4.5, and 6.0 m^3 fed^{-1}) of three organic fertilizers (compost tea, vermicompost extract, and biogas digestate) on garlic bulb yield and its components at harvest in two growing seasons (2022/23 and 2023/24). The parameters measured include average bulb weight (g), bulb diameter (cm), neck diameter (cm), bulbing ratio, number of cloves per bulb, total bulb yield (ton fed^{-1}) and marketable yield (ton fed^{-1}). For the main factor (fertilizer type), biogas digestate application resulted in the highest values for all measured parameters, followed by vermicompost extract, while compost tea showed the lowest values. Among the sub-main factor (fertilizer levels), increasing the application rate consistently improved all traits, with the highest values recorded at 6.0 m^3 fed^{-1}. The interaction effect further emphasized that the combination of biogas digestate at the highest level (6.0 m^3 fed^{-1}) led to the best garlic performance.

Table 3. Impact of different levels (0.0, 1.5, 3.0, 4.5, and 6.0 m^3 fed^{-1}) of organic fertilizers (compost tea, vermicompost, and biogas digestate) on garlic bulb yield and its components at harvest during seasons of 2022/23 and 2023/24

Parameters		Average bulb weight, g		Bulb diameter, cm		Neck diameter, cm		Bulbing ratio	
Treatments		**1st season**	**2nd season**	**1st season**	**2nd season**	**1st season**	**2nd season**	**1st season**	**2nd season**
Main factor									
Compost tea		35.60c	36.38c	3.66c	3.82c	0.70c	0.70c	0.19b	0.18c
Vermicompost extract		41.40b	42.40b	4.16b	4.38b	0.87b	0.89b	0.21a	0.20b
Biogas digestate		47.00a	48.07a	4.73a	4.95a	1.06a	1.10a	0.22a	0.22a
LSD at 5%		0.38	0.83	0.06	0.07	0.04	0.05	0.02	0.02
Sub main factor									
L_1:At rate of 0.0 m^3 fed^{-1}		38.96d	39.78d	3.98e	4.17e	0.80d	0.81d	0.20c	0.19d
L_2:At rate of 1.5 m^3 fed^{-1}		40.61c	41.58c	4.08d	4.27d	0.81d	0.85cd	0.20c	0.20cd
L_3:At rate of 3.0 m^3 fed^{-1}		41.01c	42.04c	4.17c	4.37c	0.87c	0.89c	0.21b	0.20bc
L_4:At rate of 4.5 m^3 fed^{-1}		42.12b	43.04b	4.30b	4.52b	0.92b	0.94b	0.21ab	0.21ab
L_5:At rate of 6.0 m^3 fed^{-1}		43.98a	44.97a	4.38a	4.59a	0.97a	0.99a	0.22a	0.21a
LSD at 5%		0.52	0.53	0.05	0.03	0.04	0.04	0.01	0.01
Interaction									
Compost tea	L_1	32.14	32.81	3.43	3.60	0.63	0.63	0.18	0.18
	L_2	34.33	35.03	3.59	3.71	0.63	0.66	0.18	0.18
	L_3	35.13	36.02	3.62	3.80	0.72	0.71	0.20	0.19
	L_4	36.75	37.42	3.78	3.96	0.71	0.74	0.19	0.19
	L_5	39.67	40.60	3.86	4.05	0.79	0.76	0.20	0.19
Vermicompost extract	L_1	32.14	32.81	3.43	3.60	0.63	0.63	0.18	0.18
	L_2	40.84	41.90	3.94	4.23	0.79	0.82	0.20	0.19
	L_3	40.94	41.99	4.17	4.37	0.87	0.90	0.21	0.21
	L_4	41.30	42.37	4.33	4.54	0.94	0.94	0.22	0.21
	L_5	43.50	44.50	4.40	4.62	0.94	0.98	0.21	0.21
Biogas digestate	L_1	32.14	32.81	3.43	3.60	0.63	0.63	0.18	0.18
	L_2	46.65	47.82	4.72	4.87	1.02	1.07	0.22	0.22
	L_3	46.96	48.10	4.72	4.94	1.02	1.06	0.22	0.21
	L_4	48.32	49.34	4.80	5.05	1.10	1.15	0.23	0.23
	L_5	48.77	49.80	4.88	5.10	1.18	1.23	0.24	0.24
LSD at 5%		0.91	0.91	0.09	0.06	0.07	0.07	0.01	0.02

Means within a column followed by a different letter (s) are statistically different at 5%

Table 3. Cont.

Parameters		No. of cloves $bulb^{-1}$		Bulb yield, ton fed^{-1}		Marketable yield, ton fed^{-1}	
Treatments		**1st season**	**2nd season**	**1st season**	**2nd season**	**1st season**	**2nd season**
Main factor							
Compost tea		25.07c	29.00c	5.70c	5.86c	4.35c	5.25c
Vermicompost extract		29.27b	32.60b	6.62b	6.78b	5.34b	5.94b
Biogas digestate		33.07a	37.20a	7.52a	7.69a	6.32a	6.62a
LSD at 5%		1.35	0.83	0.06	0.17	0.08	0.03
Sub main factor							
L_1:At rate of 0.0 m^3 fed^{-1}		27.44d	31.00d	6.23d	6.49d	5.03e	5.72e
L_2:At rate of 1.5 m^3 fed^{-1}		28.22cd	32.11cd	6.50c	6.65c	5.16d	5.82d
L_3:At rate of 3.0 m^3 fed^{-1}		29.11bc	32.78bc	6.56c	6.73c	5.33c	5.93c
L_4:At rate of 4.5 m^3 fed^{-1}		30.11ab	33.89ab	6.74b	6.89b	5.48b	6.04b
L_5:At rate of 6.0 m^3 fed^{-1}		30.78a	34.89a	7.04a	7.19a	5.68a	6.17a
LSD at 5%		1.40	1.68	0.08	0.08	0.06	0.07
Interaction							
Compost tea	L_1	23.33	27.67	5.14	5.22	4.16	5.04
	L_2	24.67	28.33	5.49	5.60	4.20	5.14
	L_3	25.00	28.67	5.62	5.76	4.32	5.23
	L_4	25.33	30.00	5.88	5.99	4.43	5.34
	L_5	27.00	30.33	6.35	6.50	4.66	5.49
Vermicompost extract	L_1	23.33	27.67	5.14	5.22	4.16	5.04
	L_2	27.67	32.33	6.53	6.71	5.11	5.83
	L_3	29.33	33.00	6.55	6.72	5.35	5.92
	L_4	31.00	33.33	6.61	6.78	5.54	6.04
	L_5	31.00	33.67	6.96	7.12	5.74	6.18
Biogas digestate	L_1	23.33	27.67	5.14	5.22	4.16	5.04
	L_2	32.33	35.67	7.46	7.65	6.18	6.49
	L_3	33.00	36.67	7.51	7.69	6.31	6.64
	L_4	34.00	38.33	7.73	7.89	6.48	6.72
	L_5	34.33	40.67	7.80	7.97	6.62	6.85
LSD at 5%		2.43	2.92	0.15	0.14	0.11	0.12

Means within a column followed by a different letter (s) are statistically different at 5%

The results indicate a significant improvement in garlic bulb yield and its components with the application of organic fertilizers, particularly biogas digestate. The superiority of biogas digestate over vermicompost and compost tea suggests that its nutrient composition and microbial activity contribute more effectively to plant growth. The increase in fertilizer level from 0.0 to 6.0 m^3 fed^{-1} resulted in a gradual increase in all yield parameters, confirming that higher organic matter availability enhances garlic productivity. The interaction effects reveal that, regardless of the fertilizer type, applying 6.0 m^3 fed^{-1} consistently produced the best results. However, biogas digestate at 6.0 m^3 fed^{-1} was particularly effective in increasing bulb weight, bulb diameter, and total yield, demonstrating its significant impact on garlic growth and quality. Compost tea, while beneficial, was the least effective among the three fertilizers, likely due to its lower nutrient content compared to biogas digestate and vermicompost extract. The observed improvements in garlic yield and its components can be attributed to the beneficial effects of organic fertilizers on soil fertility and microbial activity. Organic amendments enhance soil structure, increase microbial biomass, and improve nutrient availability, which collectively promote better plant growth and yield formation. Biogas digestate, being rich in essential nutrients and beneficial microorganisms, likely improved nitrogen mineralization and availability, leading to higher chlorophyll content and better photosynthetic efficiency. This explains the significant increase in bulb weight, diameter, and overall yield compared to vermicompost and compost tea. Vermicompost, which is known to contain plant growth-promoting substances and humic acids, also contributed positively but to a lesser extent than biogas digestate. The progressive increase in yield components with higher application rates suggests that organic fertilizers play a crucial role in supplying essential nutrients in a sustainable manner. The improved bulbing ratio and marketable yield indicate that organic amendments not only increased overall production but also enhanced the commercial quality of garlic. Furthermore, the increased number of cloves per bulb at higher application rates suggests that the physiological processes related to bulb differentiation and development were positively influenced by organic nutrition. The results are in agreement with those of El-Gizawy *et al.* (2013); Gouda & Gahwash (2015); Allahyari *et al.* (2014); Xu and Mou, (2016); Pan *et al.* (2025).

2.Bulb Quality Parameters at Harvest Stage (170 Days from Sowing)

Table 4 illustrates the impact of different levels of organic fertilizers (compost tea, vermicompost extract, and biogas digestate) on the bulb quality parameters of garlic at harvest (170 days after sowing) during the 2022/23 and 2023/24 growing seasons. The analyzed parameters include carbohydrate content (%), total dissolved solids (TDS, %), vitamin C content (mg 100g^{-1}), dry matter (%), and pungency (pyruvate content, πmol.ml^{-1}). Among the three organic fertilizers, biogas digestate showed the highest values across all quality parameters in both seasons, followed by vermicompost extract, while compost tea recorded the lowest values. Similarly, increasing the application rate of organic fertilizers improved bulb quality parameters, with the highest values observed at 6.0 m^3 fed^{-1}, while the control treatment (0.0 m^3 fed^{-1}) recorded the lowest values. The interaction effects further confirm that biogas digestate at the highest application rate consistently produced superior quality traits compared to other treatment.

Table 4. Impact of different levels (0.0, 1.5, 3.0, 4.5, and 6.0 m^3 fed^{-1}) of organic fertilizers (compost tea, vermicompost, and biogas digestate) on garlic bulb quality at harvest during seasons of 2022/23 and 2023/24

Parameters / Treatments		Carbohydrates, %		TDS, %		Vitamin C, mg 100g^{-1}		Dry matter, %		Pungency (purvate content, πmol.ml^{-1})	
		1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor											
Compost tea		16.50c	16.81b	18.09	18.78c	10.44c	10.60c	15.21c	15.55c	7.34c	7.53c
Vermicompost extract		17.04b	17.33b	18.75	19.42b	10.81b	10.97b	16.33b	16.68b	7.99b	8.15b
Biogas digestate		17.95a	18.32a	19.46	20.23a	11.13a	11.36a	17.35a	17.75a	8.68a	8.80a
LSD at 5%		0.24	0.58	0.63	0.24	0.10	0.10	0.16	0.24	0.10	0.14
Sub main factor											
L_1:At rate of 0.0 m^3 fed^{-1}		16.85b	17.17c	18.48b	19.16c	10.60d	10.80c	15.93c	16.28d	7.74e	7.93d
L_2:At rate of 1.5 m^3 fed^{-1}		17.11ab	17.33bc	18.68ab	19.29bc	10.75c	10.86c	16.17b	16.47cd	7.86d	8.03c
L_3:At rate of 3.0 m^3 fed^{-1}		17.14ab	17.54abc	18.67ab	19.45abc	10.76bc	11.01b	16.26b	16.67bc	8.00c	8.17b
L_4:At rate of 4.5 m^3 fed^{-1}		17.33a	17.65ab	18.96a	19.69ab	10.95ab	11.07ab	16.48a	16.86ab	8.15b	8.23b
L_5:At rate of 6.0 m^3 fed^{-1}		17.39a	17.73a	19.05a	19.80a	10.90a	11.16a	16.64a	17.02a	8.27a	8.45a
LSD at 5%		0.45	0.38	0.40	0.48	0.14	0.13	0.19	0.20	0.11	0.07
Interaction											
Compost tea	L_1	16.27	16.53	17.86	18.45	10.26	10.42	14.90	15.25	7.08	7.33
	L_2	16.41	16.77	17.92	18.64	10.30	10.51	14.93	15.23	7.18	7.35
	L_3	16.54	16.89	18.00	18.85	10.41	10.64	15.17	15.54	7.40	7.57
	L_4	16.61	16.92	18.39	18.95	10.67	10.67	15.50	15.81	7.44	7.60
	L_5	16.67	16.95	18.30	19.04	10.54	10.74	15.54	15.92	7.60	7.80
Vermicompost extract	L_1	16.27	16.53	17.86	18.45	10.26	10.42	14.90	15.25	7.08	7.33
	L_2	17.18	17.20	18.78	19.22	10.86	10.87	16.39	16.58	7.90	8.06
	L_3	16.96	17.38	18.60	19.30	10.74	10.99	16.20	16.65	7.96	8.14
	L_4	17.21	17.48	18.84	19.62	10.92	11.03	16.39	16.83	8.04	8.19
	L_5	17.20	17.57	19.10	19.85	10.92	11.16	16.76	17.13	8.32	8.50
Biogas digestate	L_1	16.27	16.53	17.86	18.45	10.26	10.42	14.90	15.25	7.08	7.33
	L_2	17.73	18.03	19.35	20.00	11.09	11.20	17.20	17.62	8.49	8.67
	L_3	17.91	18.36	19.40	20.21	11.14	11.41	17.41	17.82	8.63	8.81
	L_4	18.19	18.55	19.65	20.51	11.25	11.49	17.55	17.95	8.96	8.89
	L_5	18.31	18.67	19.74	20.51	11.24	11.56	17.62	18.01	8.88	9.05
LSD at 5%		0.78	0.65	0.70	0.83	0.23	0.22	0.33	0.36	0.20	0.12

Means within a column followed by a different letter (s) are statistically different at 5%

The results demonstrate a clear and consistent trend where organic fertilizer application positively influences the quality parameters of garlic bulbs. The significant differences among treatments highlight the superiority of biogas digestate over vermicompost extract and compost tea in enhancing carbohydrate content, TDS, vitamin C, dry matter, and pungency. Additionally, increasing the application rate significantly improved these traits, confirming the beneficial role of organic fertilizers in enhancing bulb quality. One of the most notable findings is the enhancement of pungency (pyruvate content), which is crucial for garlic's flavor and medicinal properties. Biogas digestate-treated garlic exhibited the highest pungency, while compost tea resulted in the lowest values. Similarly, vitamin C, which plays a crucial role in the antioxidant properties of garlic, was significantly higher in biogas digestate-treated plants. These results suggest that biogas digestate, due to its high nutrient availability, particularly nitrogen and organic acids, significantly enhanced the biosynthesis of secondary metabolites related to pungency and nutritional quality. The incremental improvement with increasing application rates suggests that higher doses of organic fertilizers provide better nutritional support for bulb development. However, the diminishing differences at the highest rates (4.5 and 6.0 m^3 fed^{-1}) suggest that there might be a saturation point where further additions do not significantly enhance the results. The improvement in garlic bulb quality traits due to organic fertilizer application can be attributed to several physiological and biochemical mechanisms. Organic fertilizers, particularly biogas digestate, enhance soil microbial activity, improve nutrient availability, and contribute to better soil structure and moisture retention, which collectively enhance plant growth and development. The higher carbohydrate and TDS levels in garlic bulbs treated with biogas digestate and higher organic fertilizer rates can be explained by the improved uptake of essential nutrients, especially nitrogen, phosphorus, and potassium (NPK). These nutrients play a crucial role in photosynthesis, enzyme activation, and carbohydrate metabolism, leading to increased sugar accumulation in bulbs. The microbial activity stimulated by organic fertilizers also enhances the mineralization of organic matter, making nutrients more bioavailable for plant uptake.The increase in vitamin C content, particularly in the biogas digestate treatment, can be attributed to the presence of organic acids and bioavailable micronutrients, such as iron and zinc, which play a role in ascorbic acid biosynthesis. Organic fertilizers also enhance the plant's antioxidant defense mechanisms, leading to higher vitamin C accumulation as part of the plant's stress response and metabolic regulation. The significant increase in dry matter percentage in garlic bulbs treated with biogas digestate and higher fertilizer levels suggests better nutrient translocation and biomass accumulation. Organic fertilizers improve root development, leading to more efficient nutrient uptake and conversion into structural and storage components within the bulb. The enhancement of pungency in garlic bulbs treated with organic fertilizers, particularly biogas digestate, can be explained by increased sulfur uptake. Sulfur-containing amino acids (such as cysteine and methionine) are precursors for alliin and allicin biosynthesis, which are responsible for garlic's pungency and medicinal properties. Biogas digestate, being rich in organic matter and microbial metabolites, likely improved sulfur availability in the soil, leading to greater biosynthesis of these sulfur compounds. The incremental improvement in all quality parameters with increasing application rates confirms the positive role of organic fertilizers in improving nutrient efficiency and plant metabolism. However, the relatively small differences between the 4.5 and 6.0 m^3 fed^{-1} treatments suggest that beyond a certain threshold, additional organic fertilizer does not proportionally enhance garlic quality, possibly due to nutrient saturation or reduced microbial efficiency at excessive levels. The obtained results are in harmony with those of Shabana *et al.* (2024).

3.Post-harvest Soil Analyses

Table 5 presents the post-harvest soil properties as influenced by different levels of organic fertilizers, including compost tea, vermicompost extract and biogas digestate, applied at rates of 0.0, 1.5, 3.0, 4.5, and 6.0 m^3 fed^{-1} during the 2022/23 and 2023/24 seasons (combined data). The analyzed soil properties include nitrogen (N, mg kg^{-1}), phosphorus (P, mg kg^{-1}), potassium (K, mg kg^{-1}), organic matter (OM, %) and cation exchange capacity (CEC, cmol kg^{-1}). The initial soil conditions showed low nutrient availability, with 32.1 mg kg^{-1} nitrogen, 7.90 mg kg^{-1} phosphorus, 215.8 mg kg^{-1} potassium, 1.35% organic matter and a cation exchange capacity (CEC) of 51.0 cmol kg^{-1}. Among the three organic fertilizers, biogas digestate resulted in the highest increases across all soil parameters, followed by vermicompost extract, while compost tea showed the least improvement. Increasing the application rate of organic fertilizers consistently improved N, P, K, OM, and CEC in the soil, with the 6.0 m^3 fed^{-1} rate producing the most significant enhancements across all treatments.

Table 5. Impact of different levels (0.0, 1.5, 3.0, 4.5, and 6.0 m^3 fed^{-1}) of organic fertilizers (compost tea, vermicompost, and biogas digestate) on soil properties (average values) at harvest during seasons of 2022/23 and 2023/24 (combined data over both seasons)

Parameters /Treatments		N, $mgkg^{-1}$	P, $mgkg^{-1}$	K, $mgkg^{-1}$	OM,%	CEC, cmol kg^{-1}
Initial soil		32.1	7.90	215.8	1.35	51.0
Compost tea	L_1:At rate of 0.0 m^3 fed^{-1}	32.1	7.88	215.5	1.32	51.0
	L_2:At rate of 1.5 m^3 fed^{-1}	34.6	8.20	220.3	1.36	51.5
	L_3:At rate of 3.0 m^3 fed^{-1}	36.2	8.29	222.6	1.38	51.9
	L_4:At rate of 4.5 m^3 fed^{-1}	38.4	8.45	226.5	1.39	52.3
	L_5:At rate of 6.0 m^3 fed^{-1}	40.2	8.55	229.3	1.41	52.8
Vermicompost extract	L_1:At rate of 0.0 m^3 fed^{-1}	32.1	7.88	215.5	1.32	51.0
	L_2:At rate of 1.5 m^3 fed^{-1}	43.3	9.25	225.3	1.38	52.0
	L_3:At rate of 3.0 m^3 fed^{-1}	45.3	9.36	228.2	1.40	52.4
	L_4:At rate of 4.5 m^3 fed^{-1}	48.1	9.56	233.1	1.42	52.8
	L_5:At rate of 6.0 m^3 fed^{-1}	50.1	9.68	236.6	1.43	53.3
Biogas digestate	L_1:At rate of 0.0 m^3 fed^{-1}	32.1	7.88	215.5	1.32	51.0
	L_2:At rate of 1.5 m^3 fed^{-1}	45.5	9.71	226.5	1.40	52.5
	L_3:At rate of 3.0 m^3 fed^{-1}	47.5	9.82	229.6	1.41	52.9
	L_4:At rate of 4.5 m^3 fed^{-1}	50. 5	10.03	234.7	1.44	53.4
	L_5:At rate of 6.0 m^3 fed^{-1}	52.5	10.16	238.4	1.45	53.9

The highest values recorded were for biogas digestate at 6.0 m^3 fed^{-1}, where nitrogen reached 52.5 mg kg^{-1}, phosphorus 10.16 mg kg^{-1}, potassium 238.4 mg kg^{-1}, organic matter 1.45%, and CEC 53.9 cmol kg^{-1}.The lowest values were found in the control treatments (0.0 m^3 fed^{-1}) for all organic fertilizers, where nutrient levels were similar to the initial soil properties. The results clearly indicate that organic fertilizer applications significantly improved soil fertility by increasing essential macronutrients (N, P, K), organic matter content, and cation exchange capacity (CEC). Biogas digestate application showed the greatest improvement, likely due to its high microbial activity, organic acids and readily available nutrients. Vermicompost extract also led to substantial enhancements, particularly in nitrogen and potassium content, indicating its role in nutrient mineralization and soil structure improvement. Compost tea had a modest effect, improving soil properties but to a lesser extent than vermicompost and biogas digestate. The increasing trend with higher application rates suggests that the more organic fertilizer applied, the better the soil quality. However, the improvements between 4.5 and 6.0 m^3 fed^{-1} were relatively small, indicating a possible saturation point beyond which additional organic inputs provide diminishing returns. Cation exchange capacity (CEC), a key indicator of soil fertility, increased with organic fertilizer application, with biogas digestate at 6.0 m^3 fed^{-1} recording the highest value (53.9 cmol kg^{-1}). This suggests that organic amendments enhanced the soil's ability to retain and supply nutrients to plants.The observed improvements in soil properties due to organic fertilizer application can be explained by several biochemical and microbiological mechanisms that enhance soil health and fertility. Organic fertilizers contribute to nitrogen enrichment in the soil through microbial decomposition and mineralization. Biogas digestate and vermicompost extract likely introduced beneficial nitrogen-fixing bacteria that increased nitrogen availability. The presence of amino acids, peptides, and humic substances in biogas digestate may have facilitated slow-release nitrogen supply, reducing nitrogen losses through leaching. The increase in phosphorus content is likely due to microbial solubilization of inorganic P by phosphate-solubilizing bacteria present in organic fertilizers. Organic acids released by biogas digestate and vermicompost improved phosphorus mobilization, making it more available for plant uptake. Potassium is crucial for plant metabolism, and the observed increase is due to the release of K from organic matter decomposition. Biogas digestate provided the highest K content, likely due to the rapid decomposition of organic residues and high microbial activity. Organic matter is essential for soil structure, water retention, and microbial activity. The increase in OM, particularly with biogas digestate and vermicompost, indicates enhanced carbon input into the soil, promoting microbial activity and nutrient cycling. CEC reflects the soil's ability to retain and exchange essential nutrients. Organic fertilizers, especially biogas digestate, enhanced CEC by increasing humic substances that improve nutrient-holding capacity. This explains the sustained availability of nutrients even at higher application rates. The obtained results are in harmony with those of Shabana *et al.* (2024).

CONCLUSION

The study highlights the significant impact of liquid organic fertilizers on garlic plant performance and soil properties. Among the tested fertilizers, biogas digestate demonstrated the highest efficiency in improving bulb yield, and soil fertility, followed by vermicompost extract, while compost tea exhibited the least effect. The results also confirm that increasing the application rate from 1.5 to 6.0 m^3 fed^{-1} consistently enhanced all measured parameters, with 6.0 m^3 fed^{-1} of biogas digestate producing the most favorable outcomes. Therefore, it is recommended to integrate biogas digestate at optimal rates (4.5 and 6.0 m^3 fed^{-1}) into organic fertilization programs to enhance crop productivity and soil health while reducing reliance on chemical fertilizers. Future research should focus on the long-term effects of organic fertilizers on soil microbial diversity, nutrient cycling, and carbon sequestration, as well as the integration of precision agriculture techniques to optimize their application, ensuring sustainable agricultural development.

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تأثير الأسمدة العضوية السائلة على أداء نبات الثوم وخصائص التربة

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الملخص

يشهد العالم حاليًا اهتمامًا متزايدًا بتحسين استخدام الأسمدة العضوية، لا سيما في صورتها السائلة، لما لها من إمكانات واعدة كبديل للأسمدة التقليدية. وعليه، استهدف هذا البحث تقييم تأثير ثلاثة أنواع من الأسمدة العضوية السائلة (شاي الكمبوست، مستخلص السماد الدودي، والغاز الحيوي) بمستويات مختلفة (٠,٠، ١,٥، ٣,٠، ٤,٥، و٦,٠ م^3 للفدان) على أداء نبات الثوم وخصائص التربة. أظهرت نتائج الدراسة أن استخدام الغاز الحيوي أدى إلى تحقيق أعلى القيم في محصول الثوم وصفاته النوعية مثل متوسط وزن الرأس (جم)، قطر الرأس (سم)، قطر العنق (سم)، إجمالي محصول الرؤوس (طن/فدان)، محتوى الكربوهيدرات (%)، المواد الصلبة الذائبة الكلية (%)، ومحتوى فيتامين C (ملجم/١٠٠ جم)، تلتها مستخلص السماد الدودي، بينما كانت أقل القيم مع شاي الكمبوست. وتجدر الإشارة إلى أن رفع مستوى الإضافة من كل سماد أدى إلى تحسن ملحوظ في جميع الصفات المدروسة، حيث سُجلت أفضل النتائج عند مستوى ٦,٠ م^3/فدان من كل سماد مقارنةً بالمستويات الأدنى. وبشكل عام، كانت المعاملة المتفوقة هي استخدام الغاز الحيوي بمعدل ٦,٠ م^3/فدان. كذلك، أظهرت نتائج الدراسة أن الغاز الحيوي كانت الأكثر فاعلية في تحسين خواص التربة المدروسة مثل محتوى النيتروجين والفوسفور والبوتاسيوم (ملجم/كجم)، المادة العضوية (%)، والسعة التبادلية الكاتيونية (سنتيمول/كجم)، تلتها مستخلص السماد الدودي ثم شاي الكمبوست. لذلك، يُوصى بدمج الغاز الحيوي ضمن برامج التسميد العضوي.