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The Efficiency of Bacterial Bio-Fertilization and Schanginia Aegyptiaca (Egyptian Seablite) Waste in Reducing Mineral Fertilizers and in the Growth and Yield of Cabbage

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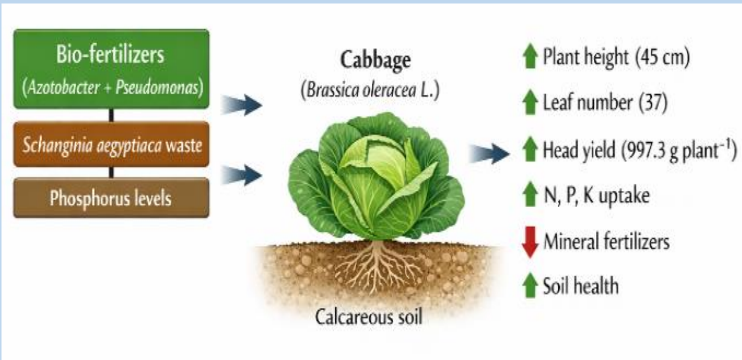
Abstract: This study investigates environmentally friendly fertilization strategies to enhance nutrient availability and reduce the use of chemical fertilizers in calcareous soils. It explores the effects of biofertilizers (Azotobacter, Pseudomonas), Changinia aegyptiaca plant residues, and phosphorus levels on cabbage growth and nutrient uptake in sandy loam soils. The results show significant increases in plant height (45 cm), number of leaves (37 leaves), head yield (997.3 g/plant), and nitrogen, phosphorus, and potassium concentrations (20.60, 8.01, and 22.96 g/kg, respectively) with the combined treatments. Standard growth-at-maturity methods were used for analysis. The combination of biofertilizers, phosphorus, and Changinia plant residues enhances cabbage productivity and fertilization efficiency, suggesting a way to reduce reliance on chemical fertilizers and improve soil health.



Keywords: Bio-fertilization, Cabbage, Reduction Of Mineral Fertilizers, Schanginia Aegyptiaca Waste, Sustainable Agriculture Soil Health; Sustainable Agriculture.

Introduction

Phosphorus is an essential element for plant growth [1], but its overuse causes problems [2], particularly in Iraqi soils, which are rich in carbonates, have a high pH, and are poor in organic matter. These conditions lead to the fixation of phosphorus in calcium phosphate, making it unavailable to plants [3]. This harms the environment, human health, and soil microorganisms, and hinders plant growth [4, 5]. Therefore, researchers are exploring the use of biofertilizers (bacterial and fungal) to reduce the use of chemical fertilizers, mitigate environmental risks, and increase crop yields to address food shortages [6].

Beneficial bacteria such as Azotobacter and Pseudomonas thrive near plant roots (the rhizosphere), where they feed on root secretions for energy [7]. Pseudomonas is particularly effective at soluble phosphate compounds, thus promoting phosphorus uptake and plant growth. It is also a key growth promoter, enhancing cellular processes and enzyme synthesis, and helping plants thrive in harsh conditions such as salinity [8].

Azotobacter bacteria promote root growth in challenging (salty and alkaline) soils by producing hormones such as auxins, gibberellins, and cytoxins, helping plants adapt to stress. They also reduce nitrate loss in sandy loam soils, giving plants a better chance to grow and thrive [9].

Changinia aegyptiaca, a wild plant belonging to the Chenopodiaceae family, thrives in the deserts, plains, and valleys of Iraq, particularly in nitrogen-rich clay soils. Iraq's arid and semi-arid climate is perfectly suited to it, making it a prevalent weed in the central and southern regions [11].

Changinia aegyptiaca, a hardy halophyte from the Chenopodiaceae family, thrives in North Africa and the arid, saline regions of the Arabian Peninsula. It is a key plant for studying adaptation to harsh environments, as it lives in poor soils and high salinity [12]. Changinia aegyptiaca contains a high percentage of phenolic compounds (gallic acid: 41.72 mg/g, coumaric acid, ferulic acid, and syringic acid) that combat

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oxidative stress. Its essential oils and extracts also exhibit antimicrobial properties, treating bacteria and fungi. This makes it a promising candidate for agricultural and industrial uses [13]. This plant's ability to grow in soil contaminated with heavy metals (copper, zinc, lead) makes it doubly beneficial: it is resistant to salinity and drought, and it also acts as an effective soil cleaner. It is an excellent choice for sustainable agriculture research in challenging regions [12].

Cabbage is a nutritional powerhouse, packed with water, protein, fats, carbs, fiber, vitamins, minerals, and phenolic compounds. This translates to some serious health perks, like boosting digestion, shielding against skin and heart issues, and even helping regulate blood sugar levels [14] [15] [16].

On the global stage, cabbage trade has undergone a major shift recently. Let's dive into the latest data to uncover the trends and patterns shaping its worldwide movement. In 2022, cabbage production hit 9,825,000 tonnes, covering 423,000 hectares (that's 232,270 100 g/ha, for those curious). China's massive agricultural output makes it the leading cabbage exporter, while India exports to every continent.

This study focuses on some important objectives:

1. Fertilizer Experiment: How do bio-fertilizers, mineral fertilizers, and Schanginia aegyptiaca residues (alone or combined) impact soil N, P, K levels and cabbage growth/yield.
2. Fertilizer Reduction Potential: Can we cut back on mineral fertilizers by leveraging bio-fertilizers and Schanginia aegyptiaca residues.

Materials and Methods

A pot experiment was conducted in Al-Anbar Governorate, Fallujah District, during the spring season of 2021-2022 in sandy loam textured soil. Representative soil samples were collected from the field's surface layer at a depth of 0–0.30 m using a soil auger before planting. The samples were air-dried, ground, and passed through a sieve with a 0.002 mm mesh size. A representative sample was taken for some physical and chemical analyses, which were carried out according to the methods described by [17].

Plant residues of Schanginia aegyptiaca were collected from lands near the agricultural areas associated with the studied region. The plant material was chopped using an electric machine designed for this purpose. The residues were left to decompose aerobically for 4 months, with appropriate conditions of moisture and temperature provided to facilitate decomposition. The process was supported by adding some mineral fertilizers: 1% nitrogen in the form of urea and 0.5% phosphorus in the form of phosphate fertilizer to enhance microbial activity. The residues were regularly turned every week to maintain adequate moisture and a temperature range of 40-50°C, following the method used by [18].

A total of 20 kg of soil was weighed, and bio-fertilization treatments were applied at four levels: no bio-inoculant added, labeled as A0; inoculation with Azotobacter chroococcum, labeled as A1; inoculation with Pseudomonas fluorescens, labeled as A2; and dual inoculation with Azotobacter chroococcum and Pseudomonas fluorescens, labeled as A3. A liquid bacterial bio-fertilizer (broth) prepared in the Microbiology Laboratory at the College of Agriculture, University of Anbar, was used for the inoculation treatments. Azotobacter and Pseudomonas bacteria were grown in sterile liquid Nutrient broth. 50 ml of the sterile liquid Nutrient broth was placed in a 100 ml conical flask and inoculated with a one-day-old culture of these bacteria using a carrier and incubated in a shaking incubator at 28°C for 3 days. To prepare a sufficient quantity of vaccine to be used in field experiments, 100 ml of the activated culture medium where placed in 250 ml conical flasks. The activated culture medium was inoculated with 1 ml of the prepared liquid culture using sterile pipettes. The prepared flasks were incubated in a shaking incubator at 28°C for 3 days. Before inoculation, the bacterial density was estimated by dilution and plate counting, as mentioned in Bremner [19]. The density of the prepared inoculum was 3.2×108 colony-forming units (CFU) per milliliter. The biofertilizer of Azotobacter and Pseudomonas bacteria was prepared separately by filling a quantity of peat moss in thermal bags, each bag containing 1 kg of peat moss, and sterilized in an autoclave at 121°C. After that, it was placed in sterile flasks, and the bacterial inoculum was added to the carrier, as 100 ml of Nutrient broth containing bacteria was added to the bag containing 1 kg of sterile peat moss. The two inoculants were added gradually until the substrate was at a uniform moisture content and left for 24 hours in an incubator at 28°C to ensure the spread, distribution, and colonization of the bacterial inoculum cells on the peat substrate. 10g of peat soil loaded with bacteria was taken and added to each pot according to the treatment distribution.

The experiment involved adding Schanginia aegyptiaca residues (0 or 50 g kg^{-1}) and phosphorus fertilizer (50% or 100% of the recommended dose) to the soil. Phosphate fertilizer (140 kg P h-1 as triple superphosphate) was added during land prep, while nitrogen (146 kg N h-1 as urea) was applied in two doses (15 and 45 days post-planting), and potassium (as potassium sulfate) was added pre-planting.

Cabbage seedlings were sown on October 20, 2021, and thinned to one per pot after 30 days. Euphrates River water was used for irrigation, and its quality was analyzed (pH, EC, cations, anions). At harvest (Feb 15, 2022), head weight, plant height, and leaf count were measured. Leaf samples were analyzed for N, P, K content using standard methods (Kjeldahl, spectrophotometer, flame photometer). Data was analyzed using GenStat (RCBD, LSD at 0.05 significance).

Table (1): Some chemical properties of the water irrigation.

Parameter	Value	Unit
Ec	1.42	dS m-1
pH	7.7	-
TDS	691	mg l-1
Ca++	97.29	mg l-1
Na	89.31	mg l-1
Mg++	60.30	mg l-1
K+	6.18	mg l-1
Hco3	420.6	mg l-1
Co3	Nil	mg l-1
Cl-	207.4	mg l-1
So4++	63.11	mg l-1

Results

Chemical and physical properties of the considered soil before planting

Laboratory analysis showed that the soil texture was sandy loam (61% sand, 29.5% silt, 9.5% clay), with a pH of 7.43 and an electrical conductivity of 3.15 dS/m, indicating slightly alkaline and moderately saline soil.

Pre-planting soil assessment (Table 2) showed average fertility levels: 77.35 mg/kg nitrogen, 13.88 mg/kg phosphorus, and 140.55 mg/kg potassium. However, organic matter content was relatively low at 2.08 g/kg.

The anionic composition of the soil included bicarbonates (3.22 mmol/L), chlorides (10.16 mmol/L), and sulfates (11.14 mmol/L), while the cationic composition included calcium (8.97 mmol/L), sodium (5.2 mmol/L), magnesium (6.94 mmol/L), and potassium (5.15 mmol/L), all of which influence soil structure and nutrient uptake.

Overall, the soil is considered moderately fertile and well-drained; however, the low levels of organic matter and nitrogen indicate the need for improvements to enhance crop productivity.

Table (2): Some chemical and physical properties of the soil before planting.

Parameter	Value	Unit
Soil Separates		
Sand	610	g kg-1
Silt	295	
Clay	95	
Texture	Sandy loam	
pH	7.43	-
EC	3.15	dS m-1
N	77.35	mg kg-1
P	13.88	mg kg-1
K+	140.55	mg kg-1
Organic Matter	2.08	g kg-1
Lime	9.1	g kg-1
Anions		
Hco3	3.22	mmol L-1
Co3	Nill	
Cl-	10.16	
So4++	11.14	
Cations		
Ca++	8.97	mmol L-1
Na	5.2	
Mg++	6.94	
K+	5.15	

Effect of adding bio-fertilizers, mineral fertilizers, and Schanginia aegyptiaca residues on plant height (cm)

The results of the statistical analysis in Table 3 indicate that adding biofertilizers to the soil significantly increased ($P \le 0.05$) the height of the cabbage plants. Double inoculation with Azotobacter and Pseudomonas aeruginosa (A3) resulted in the highest height of 42.92 cm, representing a 46.33% increase compared to the non-biofertilized treatment (A0), which resulted in a height of 29.33 cm. Additionally, the application of Schanginia aegyptiaca manure (organic fertilizer) significantly increased plant height ($P \le 0.05$), with treatment S1 (50 g/kg) resulting in a height of 37.03 cm, a 7.71% increase compared to the control treatment (no manure), which resulted in a plant height of 35.04 cm.

Fertilizing with phosphorus at 100% of the recommended dose (P2) resulted in a plant height of 37.79 cm, an increase of 10.20% compared to the control treatment (P1), where the plant height was 34.29 cm. Similarly, combining bacterial biofertilizer with phosphorus fertilization at 100% of the recommended dose (A3P2) had a statistically significant effect ($P \le 0.05$), achieving a higher plant height of 44.50 cm compared to the control treatment, which recorded 26.83 cm. Likewise, fertilizing with phosphorus at 100% of the recommended dose along with Schanginia aegyptiaca plant residues (organic fertilizer) (A3S2) had a statistically significant effect ($P \le 0.05$) on this trait, resulting in a plant height of 43.67 cm compared to the control treatment, which recorded 28.67 cm.

The interaction between 100% of the recommended phosphorus fertilization and Schanginia aegyptiaca plant residue (organic fertilizer) (P2S2) had a significant effect ($P \le 0.05$), with plant height reaching 38.92 cm, compared to 33.42 cm in the control treatment. Furthermore, the triple interaction between bacterial biofertilizer, 100% of the recommended phosphorus fertilization, and Schanginia aegyptiaca plant residue (P2S2A3) also significantly affected plant height, with this treatment recording the highest value of 45.00 cm, compared to 26.00 cm in the control treatment.

Table (3): The effect of adding bio-fertilizers, mineral fertilizers, and Schanginia aegyptiaca residues(compost) on plant height Cabbage (Brassica oleracea var. capitata) (cm).

Phosphorus (p)	Compost (S)	Bio-fertilizer A				S * P
		A0	A1	A2	A3	
P1(50%)	S1 (0 g/kg)	26.00d	34.00c	33.33h	40.33e	33.42d
	S2 (50 g/kg)	27.67c	35.33b	35.33g	42.33c	35.17c
P2(100%)	S1 (0 g/kg)	31.33b	32.00d	39.33f	44.00b	36.67b
	S2 (50 g/kg)	32.33a	37.33a	41.00d	45.00a	38.92a
LSD (0.05)*		1.593				0.796
		P * A				Mean P
P1(50%)		26.83g	34.67d	34.33e	41.33b	34.29b
P2(100%)		31.83f	34.67d	40.17c	44.50a	37.79a
LSD (0.05)		1.126				0.563
		S * A				Mean S
S1 (0 g/kg)		28.67g	33.00e	36.33d	42.17b	35.04b
S2 (50 g/kg)		30.00f	36.33d	38.17c	43.67a	37.03a
LSD (0.05)		1.126				0.563
Mean A		29.33a	34.67b	37.25c	42.92d	
LSD (0.05)		0.796				

A0 = control; A1 = Azotobacter; A2 = Pseudomonas; A3 = dual inoculation

Effect of adding bio-fertilizers, mineral fertilizers, and Schanginia aegyptiaca residues on the number of leaves per cabbage plant (leaves plant⁻¹)

The results show that adding biofertilizers to the soil significantly increased the number of leaves in cabbage plants, as shown in Table 4. Double inoculation with Azotobacter and Pseudomonas aeruginosa (A3) resulted in the highest number of leaves, 33.34 per plant, representing a 48.70% increase compared to the non-biofertilized treatment (A0), which had 22.42 leaves per plant. There was a statistically significant difference between the two treatments ($P \le 0.05$). Additionally, the use of Schanginia aegyptiaca residue (organic fertilizer) significantly increased the number of leaves, with treatment S2 (50 g/kg) recording 29.29 leaves per plant, a 6.67% increase compared to the control group, which had 27.46 leaves per plant.

The results showed that adding biofertilizers to the soil led to a significant increase in the number of leaves, reaching 29.29 leaves/plant in treatment S2 (50 g/kg), representing a 6.67% increase compared to the control group, which had 27.46 leaves/plant. Applying phosphorus at 100% of the recommended dose (P2) resulted in the highest value of 30.33 leaves per plant, representing a 10.45% increase compared to the control treatment (P1), which recorded 26.42 leaves per plant. This difference was statistically significant according to Duncan's test ($P \le 0.05$).

Furthermore, the combination of bacterial biofertilizer and phosphorus fertilization at 100% of the recommended dose (A3P2) was statistically significant, resulting in the highest number of leaves, 35.83 per plant, compared to the control treatment which recorded 20.84 leaves per plant, with statistically significant differences ($P \le 0.05$). Similarly, phosphorus fertilization at 100% of the recommended dose, in addition to Schanginia aegyptiaca residue (organic fertilizer) (A3S2), had a significant effect on this trait, resulting in 34.31 leaves per plant, compared to the control group which recorded 21.67 leaves per plant.

The interaction between phosphorus fertilization at 100% of the recommended dose and Schanginia aegyptiaca plant residues (organic fertilizer) (P2S2) also had a significant effect, with the highest number of leaves reaching 31.42 leaves per plant, compared to the control group which recorded 25.67 leaves per plant, with statistically significant differences at the 0.05 level. Moreover, the triple interaction between bacterial biofertilizer, phosphorus fertilization at 100% of the recommended dose, and Schanginia aegyptiaca plant residues (organic fertilizer) (P2S2A3) showed a significant effect at ($P \le 0.05$) on the number of leaves, with the treatment recording the highest value of 37.00 leaves per plant compared to the control, which recorded 20.33 leaves per plant.

Table (4): The effect of adding bio-fertilizers, mineral fertilizers, and Schanginia aegyptiaca residues (compost) on number of leaves per plant Cabbage (Brassica oleracea var. capitata) (Leaves plant-1).

Phosphorus (p)	Compost (S)	Bio-fertilizer A				S * P
		A0	A1	A2	A3	
P1(50%)	S1 (0 g/kg)	20.33m	25.00k	27.33h	30.00f	25.67d
	S2 (50 g/kg)	21.33n	26.67j	29.00g	31.67b	27.17c
P1(50%)	S1 (0 g/kg)	23.00l	27.00i	32.33d	34.67e	29.25b
	S2 (50 g/kg)	25.00k	30.00f	33.67c	37.00a	31.42a
LSD (0.05)*		1.513				0.757
P * A						Mean P
P1(50%)		20.84h	25.83f	28.17e	30.83c	26.42b
P2(100%)		24.00g	28.50d	33.00b	35.83a	30.33a
LSD (0.05)		1.070				0.535
S * A						Mean S
S1 (0 g/kg)		21.67h	26.00f	29.83d	32.33b	27.46b
S2 (50 g/kg)		23.17g	28.33e	31.33c	34.31a	29.29a
LSD (0.05)		1.070				0.535
Mean A		22.42d	27.17c	30.58b	33.34a	
LSD (0.05)		0.757				

A0 = control; A1 = Azotobacter; A2 = Pseudomonas; A3 = dual inoculation

Effect of Adding Bio-fertilizers, Mineral Fertilizers, and *Schanginia aegyptiaca* Residues on Head Yield (g)

The results indicate that adding biofertilizers to the soil significantly increased their effect at a probability level of 0.05 ($P \le 0.05$), as shown in the cabbage head in Table 5. The double inoculation with Azotobacter and Pseudomonas (A3) achieved the highest yield of 868.80 grams, which represents an increase of 57.61% compared to the non-biofertilized treatment (A0), which yielded 551.20 grams. This difference was statistically significant at ($P \le 0.05$). In addition, the use of Schanginia aegyptiaca plant residues (organic fertilizer) resulted in a significant increase in maize head yield, reaching 725.00 grams in treatment S2 (50 g/kg), a 10.84% increase compared to the control treatment (P1) which yielded 654.10 grams. This difference was statistically significant ($P \le 0.05$). Furthermore, fertilization with phosphorus at 100% of the recommended dose (P2) also resulted in a significant increase, with a yield of 728.50 grams, compared to the control treatment (P1) which yielded 650.50 grams. This difference was also statistically significant ($P \le 0.05$).

Furthermore, combining bacterial biofertilizer with phosphorus fertilization at 100% of the recommended dose (A3P2) had a significant effect, achieving the highest head yield of 945.80 grams compared to the control treatment, which produced 541.00 grams. This difference was confirmed at a statistically significant level ($P \le 0.05$). Similarly, fertilizing with phosphorus at 100% of the recommended dose along with Schanginia aegyptiaca residue (organic fertilizer) (A3S2) also had a significant effect on this trait, resulting in a yield of 899.0 grams compared to the control treatment, which produced 536.00 grams. This demonstrates a clear and statistically significant improvement at a statistically significant level ($P \le 0.05$).

The interaction between 100% of the recommended phosphorus fertilization and Schanginia aegyptiaca plant residue (organic fertilizer) (P2S2) had a significant effect, achieving the highest value of 786.20 grams compared to the control treatment, which recorded 637.20 grams. Furthermore, the triple interaction between bacterial biofertilizer, 100% of the recommended phosphorus fertilization, and Schanginia aegyptiaca plant residue (organic fertilizer) (P2S2A3) also had a significant effect ($P \le 0.05$) on head yield, achieving the highest value of 997.30 grams compared to the control treatment, which recorded 532.20 grams.

Table (5): Effect of adding bio-fertilizers, mineral fertilizers, and Schanginia aegyptiaca residues (compost) on head yield Cabbage (Brassica oleracea var. capitata) (g).

Phosphorus (p)	Compost (S)	Bio-fertilizer A				S * P
		A0	A1	A2	A3	
P1(50%)	S1 (0 g/kg)	532.20p	548.30n	685.30g	782.70e	637.20d
	S2 (50 g/kg)	549.70m	636.80j	668.00i	800.70d	663.70c
P1(50%)	S1 (0 g/kg)	539.60o	565.70l	684.70h	894.40b	671.10b
	S2 (50 g/kg)	583.00k	711.30f	853.00c	997.30a	786.20a
LSD (0.05)*		21.08				10.54
P * A						Mean P
P1(50%)		541.00h	592.50f	676.70d	791.70b	650.50b
P2(100%)		561.30g	638.40e	768.90c	945.80a	728.60a
LSD (0.05)		14.91				7.45
S * A						Mean S
S1 (0 g/kg)		536.00h	557.00g	685.00d	838.50b	654.10b
S2 (50 g/kg)		566.30f	674.00e	760.50c	899.00a	725.00a
LSD (0.05)		14.91				7.45
Mean A		551.20d	615.50c	722.80b	868.80a	
LSD (0.05)		10.54				

A0 = control; A1 = Azotobacter; A2 = Pseudomonas; A3 = dual inoculation

Effect of adding bio-fertilizers, mineral fertilizers, and *Schanginia aegyptiaca* residues on available nitrogen concentration in soil (mg kg⁻¹)

The results showed that adding biofertilizers to the soil significantly increased ($P \leq 0.05$) the available nitrogen concentration in the soil, as shown in Table 6. Double inoculation with Azotobacter and Pseudomonas aeruginosa (A3) resulted in the highest value of 44.51 mg/kg, an increase of 78.32% compared to the untreated (A0) treatment, which recorded 24.96 mg/kg. This difference was statistically significant at the $P \leq 0.05$ level. Furthermore, the use of Schanginia aegyptiaca plant residues significantly increased the available nitrogen concentration in the soil, reaching 35.45 mg/kg in treatment S2 (50 g/kg), an increase of 3.99% compared to the control treatment (A0), which recorded a nitrogen concentration of 34.09 mg/kg. These differences were confirmed statistically significant by Duncan's test ($P \leq 0.05$).

Fertilization with phosphorus at 100% of the recommended dose (P2) resulted in a significant increase in available nitrogen concentration, reaching 36.16 mg/kg, an increase of 8.29% ($P \leq 0.05$) compared to the control treatment (P1), which recorded 33.39 mg/kg. Furthermore, the combination of bacterial biofertilizer and phosphorus fertilization at 100% of the recommended dose (A3P2) showed a significant effect, with the highest available nitrogen concentration reaching 46.24 mg/kg, compared to the control treatment which recorded 23.75 mg/kg. Similarly, fertilization with phosphorus at 100% of the recommended dose using Schanginia aegyptiaca plant residues (A3S1) had a significant effect, with an available nitrogen concentration of 45.25 mg/kg, compared to the control treatment which recorded 24.83 mg/kg. The interaction between 100% of the recommended phosphorus fertilization and Schanginia aegyptiaca plant residue (P2S2) had a significant effect, reaching a maximum value of 37.05 mg/kg, compared to the control treatment which recorded 23.91 mg/kg. Furthermore, the triple interaction between bacterial biofertilizer, 100% of the recommended phosphorus fertilization, and Schanginia aegyptiaca plant residue (P2S2A3) resulted in a significant increase in soil nitrogen concentration, reaching a maximum value of 47.09 mg/kg, compared to the control treatment which recorded 23.65 mg/kg.

Table (6): Effect of adding bio-fertilizers, mineral fertilizers, and Schanginia aegyptiaca residues(compost) on available nitrogen concentration N in soil (mg kg⁻¹).

Phosphorus (p)	Compost (S)	Bio-fertilizer A				S * P
		A0	A1	A2	A3	
P1(50%)	S1 (0 g/kg)	23.65p	33.75k	32.11l	42.17d	32.91d
	S2 (50 g/kg)	23.84o	33.77j	34.42i	43.40c	33.85c
P1(50%)	S1 (0 g/kg)	26.02n	35.12g	34.50h	45.39b	35.25b
	S2 (50 g/kg)	26.33m	36.31f	38.47e	47.09a	37.05a
LSD (0.05)*		0.83				0.41
		P * A				Mean P
P1(50%)		23.75j	33.75f	33.26h	42.78b	33.39b
P2(100%)		26.17i	35.71e	36.49c	46.24a	36.16a
LSD (0.05)		0.59				0.29
		S * A				Mean S
S1 (0 g/kg)		24.83h	34.43e	33.30f	43.78b	34.09b
S2 (50 g/kg)		25.08g	35.03d	36.45c	45.25a	35.45a
LSD (0.05)		0.59				0.29
Mean A		24.96a	34.73b	34.87d	44.51c	
LSD (0.05)		0.41				

A0 = control; A1 = Azotobacter; A2 = Pseudomonas; A3 = dual inoculation.

Effect of adding bio-fertilizers, mineral fertilizers, and Schanginia aegyptiaca residues on available phosphorus concentration in soil (mg kg⁻¹)

The results indicate that the addition of biofertilizers to the soil significantly affects ($P \leq 0.05$) the concentration of available phosphorus in cabbage plants, as shown in Table 7. Double inoculation with Azotobacter and Pseudomonas aeruginosa (A3) resulted in the highest value of 9.50 g/kg, representing a 54.13% increase compared to the non-biofertilized treatment (A0), which recorded 6.16 mg/kg. Furthermore, the application of Schanginia aegyptiaca plant residues significantly increased the soil's available phosphorus concentration, reaching 8.15 mg/kg in treatment S2 (50 g/kg), a 3.42% increase compared to the control treatment (7.88 mg/kg), with these differences confirmed at a significance level of ($P \leq 0.05$).

Fertilization with phosphorus at 100% of the recommended dose (P2) resulted in a phosphorus concentration of 8.3 mg/kg, representing a 7.80% increase compared to the control treatment (P1), which recorded 7.71 mg/kg. Furthermore, the combination of bacterial biofertilizer and phosphorus fertilization at 100% of the recommended dose (A3P2) was statistically significant, achieving the highest available phosphorus concentration in the soil at 9.76 mg/kg, compared to the control treatment at 5.93 mg/kg. Similarly, fertilization with phosphorus at 100% of the recommended dose using residues of the Schanginia aegyptiaca (A3S2) had a significant effect, resulting in a phosphorus concentration of 9.58 mg/kg, compared to the control treatment at 6.04 mg/kg.

The interaction between 100% of the recommended phosphorus fertilization and Schanginia aegyptiaca plant residue (P2S2) had a statistically significant effect at the ($P \leq 0.05$) level, resulting in the highest phosphorus concentration of 8.44 mg/kg, compared to the control treatment, which also recorded 8.44 mg/kg. Furthermore, the triple interaction between bacterial biofertilizer, 100% of the recommended phosphorus fertilization, and Schanginia aegyptiaca plant residue (P2S2A3) had a statistically significant effect on the soil's available phosphorus concentration, reaching a maximum value of 9.83 mg/kg, compared to 5.92 mg/kg in the (P1S2A0) treatment. These differences were statistically significant at the ($P \leq 0.05$) level.

Table (7): Effect of adding bio-fertilizers, mineral fertilizers, and Schanginia aegyptiaca residues(compost) on available phosphorus P concentration in soil (mg kg⁻¹).

Phosphorus (p)	Compost (S)	Bio-fertilizer A				S * P
		A0	A1	A2	A3	
P1(50%)	S1 (0 g/kg)	5.94k	7.09h	8.10e	9.16c	7.57d
	S2 (50 g/kg)	5.92k	7.31g	8.85d	9.34b	7.85c
P1(50%)	S1 (0 g/kg)	6.14j	7.80f	9.14c	9.68a	8.19b

Phosphorus (p)	Compost (S)	Bio-fertilizer A				S * P
		A0	A1	A2	A3	
	S2 (50 g/kg)	6.67i	7.95e	9.14c	9.83a	8.44a
LSD (0.05)*		0.21				0.11
P * A						Mean P
P1(50%)		5.93d	7.20c	8.47b	9.25a	7.71b
P2(100%)		6.40d	7.87c	9.22b	9.76a	8.31a
LSD (0.05)		0.15				0.07
S * A						Mean S
S1 (0 g/kg)		6.04d	7.44c	8.62b	9.42a	7.88b
S2 (50 g/kg)		6.29d	7.63c	9.08b	9.58a	8.15a
LSD (0.05)		0.15				0.076
Mean A		6.16d	7.539c	8.85b	9.50a	
LSD (0.05)		0.42				

A0 = control; A1 = Azotobacter; A2 = Pseudomonas; A3 = dual inoculation

Effect of adding bio-fertilizers, mineral fertilizers, and Schanginia aegyptiaca residues on potassium concentration in the plant (mg kg⁻¹)

The results in Table 8 show that adding biofertilizers to the soil significantly increased ($P \le 0.05$) the available potassium concentration in cabbage plants. Double inoculation with Azotobacter and Pseudomonas aeruginosa (A3) resulted in the highest value of 179.76 mg/kg, representing an 11.71% increase compared to the non-biofertilized treatment (A0), which recorded 160.91 mg/kg ($P \le 0.05$). Furthermore, the application of Schanginia aegyptiaca plant residues significantly increased the available potassium concentration in the soil, with treatment S2 (50 g/kg) recording 181.15 mg/kg, a 3.12% increase compared to the control treatment (A0), which recorded 175.66 mg/kg ($P \le 0.05$).

The results in Table 8 show that adding biofertilizers to the soil significantly increased the available potassium concentration in cabbage plants ($P \le 0.05$). Fertilization with phosphorus at 100% of the recommended dose (P2) resulted in the highest potassium concentration of 182.12 mg/kg, an increase of 4.25% compared to the control treatment (P1), which recorded 174.69 mg/kg ($P \le 0.05$). Furthermore, combining bacterial biofertilizer with phosphorus fertilization at 100% of the recommended dose (A3P2) had a significant effect, achieving the highest available potassium concentration of 181.86 mg/kg, compared to the control treatment. Similarly, fertilization with phosphorus at 100% of the recommended dose using Schanginia aegyptiaca (A3S2) had a significant effect, reaching a concentration of 181.27 mg/kg, compared to the control treatment which recorded 159.10 mg/kg.

The interaction between 100% of the recommended phosphorus fertilization and Schanginia aegyptiaca plant residue (P2S2) had a significant effect, reaching a maximum value of 184.55 mg/kg compared to the control treatment, which recorded 171.63 mg/kg. Furthermore, the triple interaction between bacterial biofertilizer, 100% of the recommended phosphorus fertilization, and Schanginia aegyptiaca plant residue (P2S2A3) also had a significant effect, with the highest available potassium concentration reaching 183.05 mg/kg compared to the control treatment, which recorded 157.45 mg/kg.

Table (8): Effect of adding bio-fertilizers, mineral fertilizers, and Schanginia aegyptiaca residues(compost) on available potassium K^+ concentration in soil (mg kg⁻¹).

Phosphorus (p)	Compost (S)	Bio-fertilizer A				S * P
		A0	A1	A2	A3	
P1(50%)	S1 (0 g/kg)	157.45o	176.11j	177.13i	175.83k	171.63d
	S2 (50 g/kg)	159.43n	188.10d	184.00e	179.50h	177.76c
P1(50%)	S1 (0 g/kg)	160.75m	189.27c	188.10d	180.67g	179.70b
	S2 (50 g/kg)	166.00i	198.39a	190.77b	183.05f	184.55a
LSD (0.05)*		1.579				0.789
P * A						Mean P
P1(50%)		158.44h	182.10c	180.57e	177.67f	174.69b
P2(100%)		163.37g	193.83a	189.43d	181.86d	182.12a
LSD (0.05)		1.116				0.558
S * A						Mean S
S1 (0 g/kg)		159.10h	182.69c	182.62d	178.25f	175.66
S2 (50 g/kg)		162.71g	193.24a	187.38b	181.27e	181.15
LSD (0.05)		1.116				0.558
Mean A		160.91a	187.97b	185.00c	179.76d	
LSD (0.05)		0.789				

A0 = control; A1 = Azotobacter; A2 = Pseudomonas; A3 = dual inoculation

Effect of adding bio-fertilizers, mineral fertilizers, and Schanginia aegyptiaca residues on nitrogen concentration in the plant (g kg⁻¹)

The statistical analysis in Table 9 shows that adding biofertilizers to the soil significantly increased the available nitrogen concentration in cabbage plants. Double inoculation with Azotobacter and Pseudomonas aeruginosa (A3) resulted in the highest value of 19.78 g/kg, representing a 69.34% increase compared to the non-biofertilized treatment (A0), which recorded 11.68 g/kg ($P \le 0.05$). Furthermore, the application of Schanginia aegyptiaca plant residues led to a significant increase in soil available nitrogen concentration, reaching 16.77 g/kg in treatment S2 (50 g/kg), a 4.09% increase compared to the control treatment (no residues added), which recorded 16.11 g/kg ($P \le 0.05$).The results of the analysis are shown in Table 9.

Fertilization with phosphorus at 100% of the recommended dose (P2) resulted in the highest nitrogen concentration of 17.18 g/kg, an increase of 9.43% compared to the control treatment (P1), which recorded 15.70 g/kg. The combination of bacterial biofertilizer and phosphorus fertilization at 100% of the recommended dose (A3P2) was also effective, achieving the highest soil nitrogen concentration of 20.60 g/kg, compared to the control treatment of 10.88 g/kg. Similarly, fertilization with phosphorus at 100% of the recommended dose, combined with residues of the Schanginia aegyptiaca plant (A3S2), significantly increased the nitrogen concentration to 20.14 g/kg, compared to the control group of 10.88 g/kg ($P \le 0.05$).

The interaction between 100% of the recommended phosphorus fertilization and Schanginia aegyptiaca (P2S2A3) residue also had a significant effect, with the highest nitrogen concentration reaching 17.60 g/kg compared to the control group, which recorded 15.46 g/kg. Furthermore, the triple interaction between bacterial biofertilizer, 100% of the recommended phosphorus fertilization, and Schanginia aegyptiaca (P2S2A3) residue had a substantial impact on nitrogen concentration, achieving a maximum value of 20.89 g/kg compared to the control, which recorded 10.58 g/kg ($P \leq 0.05$).

Table (9): Effect of adding bio-fertilizers, mineral fertilizers, and Schanginia aegyptiaca residues(compost) on nitrogen concentration Nitrogen concentration expressed as total nitrogen per unit dry weight (g/kg) in the plant Cabbage (Brassica oleracea var. capitata) (g kg^{-1}).

Phosphorus (p)	**Compost (S)**	**Bio-fertilizer A**				S * P
		A0	**A1**	**A2**	**A3**	
P1(50%)	S1 (0 g/kg)	10.58p	16.20l	16.54j	18.52e	15.46d
	S2 (50 g/kg)	11.19o	16.66i	16.50k	19.40c	15.93c
P1(50%)	S1 (0 g/kg)	12.33n	16.96h	17.47g	20.31b	16.77b
	S2 (50 g/kg)	12.63m	18.03f	18.86d	20.89a	17.60a
LSD (0.05)*		0.83				0.41
P * A						Mean P
P1(50%)		10.88h	16.43f	16.52e	18.96b	15.701b
P2(100%)		12.48g	17.50d	18.17c	20.600a	17.188a
LSD (0.05)		0.5870				0.29
S * A						Mean S
S1 (0 g/kg)		11.46h	16.58f	17.00e	19.41b	16.11b
S2 (50 g/kg)		11.91d	17.35b	17.68c	20.14a	16.77a
LSD (0.05)		0.58				0.29
Mean A		11.68d	16.96c	17.34b	19.78a	
LSD (0.05)		0.41				

A0 = control; A1 = Azotobacter; A2 = Pseudomonas; A3 = dual inoculation

Effect of adding bio-fertilizers, mineral fertilizers, and Schanginia aegyptiaca residues on phosphorus concentration in the plant (g kg^{-1})

The results in Table 10 show that adding biofertilizers to the soil significantly increased ($P \leq 0.05$) the concentration of available phosphorus in cabbage plants. Double inoculation with Azotobacter and Pseudomonas aeruginosa (A3) resulted in the highest phosphorus concentration of 7.57 g/kg, representing a 54.17% increase compared to the non-biofertilized treatment (A0), which recorded 4.91 g/kg. The significance of these differences was confirmed at the ($P \leq 0.05$) level.

Furthermore, the application of Schanginia aegyptiaca rhizome residues resulted in a significant increase in soil phosphorus concentration, reaching 6.23 g/kg in treatment S2 (50 g/kg), a 12.45% increase compared to the control treatment (5.54 g/kg) where no residues were added. These differences were statistically significant according to Duncan's test ($P \leq 0.05$).

Fertilization with phosphorus at 100% of the recommended dose (P2) yielded the highest phosphorus concentration at 6.36 g/kg, a 17.34% increase compared to the control treatment (P1), which recorded 5.42 g/kg. Furthermore, the combination of bacterial biofertilizer and 100% of the recommended phosphorus fertilization (A3P2) was statistically significant, resulting in the highest soil phosphorus concentration of 8.01 g/kg compared to the control treatment of 4.43 g/kg.

Similarly, the combination of 100% of the recommended phosphorus fertilization with Schanginia aegyptiaca (A3S2) had a significant effect on phosphorus concentration, reaching 7.85 g/kg compared to the control treatment of 4.54 g/kg (ANOVA; $P \leq 0.05$). The interaction between 100% of the recommended phosphorus fertilization and Schanginia aegyptiaca (P2S2) also had a significant effect, resulting in the highest phosphorus concentration of 6.67 g/kg compared to the control treatment of 5.04 g/kg. Furthermore, the triple interaction between bacterial biofertilizer, phosphorus fertilization at 100% of the recommended dose, and Schanginia aegyptiaca plant residue (P2S2A3) showed a remarkable effect, with the highest phosphorus concentration reaching 8.23 g/kg compared to the control treatment which recorded 4.13 g/kg.

Table (10): Effect of adding bio-fertilizers, mineral fertilizers, and Schanginia aegyptiaca residues(compost) on P (elemental phosphorus) concentration in the plant Cabbage (Brassica oleracea var. capitata) (g kg^{-1})

Phosphorus (p)	**Compost (S)**	**Bio-fertilizer A**				**S * P**
		A0	**A1**	**A2**	**A3**	
P1(50%)	S1 (0 g/kg)	4.13o	4.53n	4.73m	6.77e	5.04d
	S2 (50 g/kg)	4.73m	4.80l	6.20g	7.48c	5.80c
P1(50%)	S1 (0 g/kg)	4.94k	5.21j	6.26f	7.79b	6.05b
	S2 (50 g/kg)	5.83h	5.71i	6.90d	8.23a	6.67a
LSD (0.05)*		0.22				0.11
P * A						Mean P
P1(50%)		4.43g	4.66f	5.46d	7.12b	5.42b
P2(100%)		5.39e	5.46d	6.58c	8.01a	6.36a
LSD (0.05)		0.15				0.07
S * A						Mean S
S1 (0 g/kg)		4.54h	4.87g	5.49d	7.28b	5.54b
S2 (50 g/kg)		5.28e	5.25f	6.55c	7.85a	6.23a
LSD (0.05)		0.15				0.07
Mean A		4.91a	5.063b	6.02d	7.57c	
LSD (0.05)		0.11				

A0 = control; A1 = Azotobacter; A2 = Pseudomonas; A3 = dual inoculation.

Effect of adding bio-fertilizers, mineral fertilizers, and Schanginia aegyptiaca residues on potassium concentration in the plant (g kg⁻¹)

The results show that adding biofertilizers to the soil significantly improved the available potassium concentration in cabbage plants ($P \leq 0.05$), as shown in Table 11. Simultaneous inoculation with Azotobacter and Pseudomonas aeruginosa (A3) resulted in the highest value of 22.17 g/kg, reflecting a 31.91% increase compared to the non-biofertilized treatment (A0), which recorded 16.81 g/kg ($P < 0.05$). Adding Schanginia aegyptiaca plant residues further increased the available potassium concentration by 3.65%, reaching 20.14 g/kg in treatment S2 (50 g/kg), compared to 19.43 g/kg in the control group. Fertilization with phosphorus at 100% of the recommended dose (P2) resulted in the highest potassium concentration of 20.14 g/kg, an increase of 4.81% compared to the control treatment (P1), which recorded 19.22 g/kg. Furthermore, the combination of bacterial biofertilizer and phosphorus fertilization at 100% of the recommended dose (A3P2) was statistically significant, achieving the highest soil potassium concentration of 22.96 g/kg, exceeding the potassium concentration in the control treatment ($P < 0.05$). Similarly, fertilization with phosphorus at 100% of the recommended dose combined with Schanginia aegyptiaca sedge (A3S2) had a significant effect, reaching 22.56 g/kg compared to the control group, which recorded 16.37 g/kg ($P < 0.05$).

The interaction between 100% of the recommended phosphorus fertilization and Schanginia aegyptiaca (P2S2A3) residue also had a significant effect, reaching a maximum value of 20.63 g/kg compared to the control group, which recorded 18.80 g/kg. Furthermore, the triple interaction between bacterial biofertilizer, 100% of the recommended phosphorus fertilization, and Schanginia aegyptiaca (P2S2A3) residue resulted in a significant increase in potassium concentration, reaching a maximum value of 23.05 g/kg compared to the control sample, which recorded 16.05 g/kg ($P < 0.05$).

Table (11): Effect of adding bio-fertilizers, mineral fertilizers, and Schanginia aegyptiaca residues(compost) on K (elemental potassium) concentration in the plant Cabbage (Brassica oleracea var. capitata) (g kg⁻¹)

Phosphorus (p)	Compost (S)	Bio-fertilizer A				S * P
		A0	A1	A2	A3	
P1(50%)	S1 (0 g/kg)	16.05p	18.12l	20.31h	20.71f	18.80d
	S2 (50 g/kg)	16.84n	19.00k	20.70g	22.06c	19.65c
P1(50%)	S1 (0 g/kg)	16.70o	19.65j	21.07e	22.87b	20.07b
	S2 (50 g/kg)	17.65m	19.94i	21.90d	23.05a	20.63a
LSD (0.05)*		0.39				0.19
		P * A				Mean P
P1(50%)		16.44h	18.56f	20.50d	21.38c	19.22a
P2(100%)		17.17g	19.80e	21.48b	22.96a	20.14c
LSD (0.05)		0.27				0.13
		S * A				Mean S
S1 (0 g/kg)		16.37h	18.88f	20.69d	21.79b	19.43a
S2 (50 g/kg)		17.24g	19.47e	21.30c	22.56a	20.14b
LSD (0.05)		0.27				0.13
Mean A		16.81a	19.18c	20.99b	22.17d	
LSD (0.05)		0.27				

A0 = control; A1 = Azotobacter; A2 = Pseudomonas; A3 = dual inoculation

Discussion

The use of the biofertilizers Azotobacter crococcum and Pseudomonas floricense, along with Schanginia aegyptiaca and phosphorus fertilization, individually and in combination, significantly improved cabbage growth, yield, and nutrient uptake. A tertiary interaction (P2A3S2) was particularly pronounced, enhancing plant height, leaf count, and head production, while also providing essential nutrients (NPK) to the soil.

This synergy resulted from the nitrogen fixation, phosphorus solubilization, and production of growth-promoting hormones by Azotobacter and Pseudomonas. Schanginia aegyptiaca residues also improved soil structure, water retention capacity, and microbial activity, gradually providing nutrients. Phosphorus fertilization further enhanced root growth and nutrient uptake.

The biofertilizers release plant growth-promoting compounds such as auxins and cytokinins. Schanginia plant residues contributed to the provision of micronutrients (iron, zinc, and manganese) and antitranspirants, thus reducing water loss. These results are consistent with previous studies, highlighting the importance of balanced fertilization with essential nutrients (NPK) and organic amendments.

This triple combination likely worked through multiple mechanisms: improving soil properties, nutrient solubility and availability, and activating microorganisms, leading to enhanced plant growth and increased nutrient content. The high content of micronutrients and gelling agents in the Schanginia aegyptiaca plant residues also contributed to improved plant performance.

Therefore, combining biofertilizers, Changinia manure, and phosphorus fertilization can significantly improve cabbage yields, offering a promising approach to sustainable agriculture.

Conclusion

This study highlights the profound impact of combining bio-fertilizers, phosphorus fertilization, and Schanginia aegyptiaca residues on cabbage production, leading to substantial improvements in growth, yield, and nutrient uptake. By leveraging the synergistic effects of these components, farmers can potentially decrease their dependence on chemical fertilizers, paving the way for more sustainable and environmentally friendly agricultural practices.

The integration of bio-fertilizers, which contain beneficial microorganisms like Azotobacter and Pseudomonas, with phosphorus fertilization and organic residues like Schanginia aegyptiaca, creates a holistic approach to soil management that not only enhances soil fertility but also promotes a balanced ecosystem. This approach stimulates microbial activity, improves nutrient cycling, and supports the overall health and resilience of the soil.

As a result, crops like cabbage can thrive, exhibiting improved growth characteristics, increased yields, and enhanced nutritional profiles. Moreover, this integrated approach can contribute to reduced environmental degradation, minimized soil erosion, and decreased greenhouse gas emissions associated with excessive chemical fertilizer use, ultimately benefiting both people and the planet.

By adopting such sustainable practices, farmers can ensure long-term soil health, promote biodiversity, and contribute to a more environmentally conscious agricultural sector. This, in turn, can lead to more sustainable food systems, improved food security, and a reduced environmental footprint for agriculture.

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- **Ethics approval and consent to participate:** Not applicable.
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- **Availability of data and materials:** The raw data required to reproduce these findings are available in the body and illustrations of this manuscript.
- **Author's contribution:** The authors confirm contribution to the paper as follows: the study was conceived and designed by Khaleel J. Farhan and Sumaya Ayad Abdulrazzaq. Experimental work and data collection were carried out by Ahmed F.M. Al-Enzy and Bassam R. Sarheed. Data analysis and interpretation were performed by Sumaya Ayad Abdulrazzaq and Ahmed F.M. Al-Enzy. The first draft of the manuscript was written by Bassam R. Sarheed and Sumaya Ayad Abdulrazzaq. All authors reviewed the manuscript, contributed to critical revisions, and approved the final version for submission.
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