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ORIGINAL RESEARCH ARTICLE

Influence of Bokashi Organic Fertilizer, Balanced Mineral Fertilizer, and Foliar Application of Selenium and Silicon Nanoparticles on Soil Sustainability and the Growth and Yield of Cabbage (Brassica oleracea)

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ABSTRACT

The study aimed to evaluate the impact of organic, mineral, and nano-enabled fertilizers on soil sustainability and the growth and yield of cabbage (Brassica oleracea). A field experiment was conducted during the autumn season of 2024 in District 41, Babil Governorate, Iraq, using 16 treatments arranged in a randomized complete block design (RCBD). Treatments included EM Bokashi bio-organic fertilizer, balanced NPK mineral fertilizer, and foliar sprays of silicon and selenium nanoparticles, applied individually or in combinations. The integrated treatment of EM Bokashi + NPK + SiNPs + SeNPs significantly improved soil fertility indicators (N, P, K, organic matter, and cation exchange capacity), enhanced microbial populations, and produced the highest plant growth and yield attributes, including a marketable yield of 100.42 Mg ha^{-1}. These findings highlight the potential of combining organic, mineral, and nano-fertilizers as a sustainable strategy to improve soil health, crop productivity, and future agricultural profitability.

Keywords: EM Bokashi bio-organic fertilizer; balanced NPK mineral fertilizer; silicon nanoparticles; selenium nanoparticles; cabbage

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1. Introduction

Soil fertility and sustainability are fundamental factors determining crop productivity and agricultural profitability, especially in regions with fragile soils [1]. In Iraq, and particularly in calcareous soils, the agricultural sector faces persistent challenges due to the limited availability of essential nutrients, low microbial activity, and gradual degradation of soil structure [2]. Excessive reliance on chemical fertilizers has further aggravated these problems, resulting in reduced nutrient use efficiency and declining soil health [3]. Therefore, sustainable strategies that combine productivity with long-term soil improvement are urgently required.

Organic fertilizers have been widely recognized as a sustainable input that can improve the physical, chemical, and biological properties of soil [4]. Among them, Effective Microorganisms (EM) Bokashi has attracted considerable attention. This bio-organic amendment contains a consortium of beneficial microorganisms that accelerate organic matter decomposition, enhance nutrient release, and stimulate soil microbial populations, ultimately contributing to better plant growth and resilience [5,6]. Balanced mineral fertilizers such as NPK, on the other hand, provide readily available macronutrients essential for crop development, ensuring rapid vegetative growth and yield formation when applied appropriately [7]. However, their exclusive use, without organic amendments, is insufficient to maintain soil fertility in the long term [8].

In recent years, nanotechnology has emerged as a promising tool in sustainable agriculture. Nano-enabled fertilizers, including silicon nanoparticles (SiNPs) and selenium nanoparticles (SeNPs), offer unique physicochemical properties that can increase nutrient uptake efficiency, regulate physiological processes, and improve plant tolerance to both biotic and abiotic stresses [9]. Silicon is well documented for its role in strengthening plant cell walls and enhancing photosynthetic efficiency [10], while selenium has been associated with antioxidative defense and improved metabolic activity [11]. Foliar application of these nanoparticles in small, precise concentrations has shown considerable potential to boost productivity without contributing to environmental pollution [12].

Although numerous studies have investigated the effects of organic, mineral, or nano-fertilizers individually, research exploring the integrated application of these inputs remains limited [13]. In particular, little is known about how combining EM Bokashi, balanced NPK fertilizer, and foliar sprays of SiNPs and SeNPs can jointly influence soil fertility parameters, microbial populations, and agronomic performance of high-value crops such as cabbage (*Brassica oleracea* var. *capitata*). Cabbage is not only a nutritionally important vegetable crop but also highly responsive to fertilization strategies, making it a suitable model for evaluating the benefits of integrated nutrient management [14,15].

Research Gap and Objectives: Despite the growing interest in sustainable nutrient management, there is still insufficient evidence on the synergistic effects of combining organic, mineral, and nano-fertilizers under calcareous soil conditions. Previous studies have largely examined these inputs in isolation, leaving a knowledge gap regarding their interactive influence on soil fertility, microbial activity, and crop productivity. To address this gap, the present study was designed to evaluate the combined effects of EM Bokashi bio-organic fertilizer, balanced NPK mineral fertilizer, and foliar applications of SiNPs and SeNPs on soil health, plant growth, and yield performance of cabbage. The outcomes are expected to provide new insights into integrated fertilization strategies that support sustainable agriculture and long-term soil productivity.

A field experiment was conducted in District 41 of the Babil Governorate in Iraq, which is part of the Al-Husseiniya – Al-Tali'a Subdistrict. Perpendicular plowing was used to carefully prepare the trial area, which was then smoothed and laser leveled. To precisely describe the field soil, which is categorized as alluvial with a silty clay loam texture and characteristics listed in Table 1, a soil sample was taken at five carefully selected representative locations (the field's center and the four corners) at a depth of 30 cm.

Table 1. Physical, chemical, and biological properties of the field soil before cultivation

	Value	**Unit**
Soil reaction (pH)	7.71	....
(EC)	2.65	dS m^{-1}
(CEC)	27.80	cmol(+) kg^{-1}
OM	0.97	g kg^{-1}
Carbonate minerals	217	g kg^{-1}
Bulk density	1.38	Mg m^{-3}
Available nitrogen	18.26	mg kg^{-1}
Available phosphorus	10.30	Mg kg^{-1}
Available potassium	257.39	mg kg^{-1}

	Value	Unit
Soil separates		
- Sand	134	g kg^{-1}
- Silt	560	g kg^{-1}
- Clay	306	g kg^{-1}
Soil texture	Silty Clay Loam	

Table 1. (*Continued*)

Using a Randomized Complete Block Design (RCBD) with three repetitions, the experimental treatments were assigned to the experimental units at random in a straightforward one-way experiment. 16 treatments were dispersed at random throughout the blocks in each replication. The soil fertilizers that were applied were balanced NPK mineral fertilizer (20:20:20) at a rate of 300 kg ha^{-1} and EM Bokashi organic biofertilizer at a rate of 5000 kg ha^{-1}. In addition to a control treatment, foliar sprays of silicon nanoparticles (SiNPs) and selenium nanoparticles (SeNPs) at concentrations of 15 mg L^{-1} were administered. 48 experimental units were produced as a result, as shown in Table (2).

Table 2. Fertilization treatments applied in the experiment, including the amount of added fertilizers (kg ha^{-1}), concentrations of sprayed nanomaterials (mg L^{-1}), and the number of foliar spray applications.

No.	Fertilizer Treatment Description	Treatment Code	Added Fertilizer Amounts (kg ha^{-1})	Nanomaterial Spray Concentration (mg L^{-1})			
				Spray 1	Spray 2	Spray 3	Spray 4
1	Control (water spray only)	C.O.	0	—	—	—	—
2	Soil application of EM Bokashi	EM B.	5000	0	0	0	0
3	Soil application of balanced NPK	NPK	300	0	0	0	0
4	Foliar application of Si-NPs	SiNPs	0.024	15	15	15	15
5	Foliar application of Se-NPs	SeNPs	0.024	15	15	15	15
6	Foliar application of Si-NPs + Se-NPs	SiNPs + SeNPs	0.024 + 0.024	15 + 15	15 + 15	15 + 15	15 + 15
7	NPK + foliar spray of Si-NPs	NPK + SiNPs	300 + 0.024	15	15	15	15
8	NPK + foliar spray of Se-NPs	NPK + SeNPs	300 + 0.024	15	15	15	15
9	NPK + foliar spray of Si-NPs + Se-NPs	NPK + SiNPs + SeNPs	300 + 0.024 + 0.024	15 + 15	15 + 15	15 + 15	15 + 15
10	EM B. + foliar spray of Si-NPs	EM B. + SiNPs	5000 + 0.024	15	15	15	15
11	EM B. + foliar spray of Se-NPs	EM B. + SeNPs	5000 + 0.024	15	15	15	15
12	EM B. + foliar spray of Si-NPs + Se-NPs	EM B. + SiNPs + SeNPs	5000 + 0.024 + 0.024	15 + 15	15 + 15	15 + 15	15 + 15
13	EM B. + balanced NPK fertilizer	EM B. + NPK	5000 + 300	0	0	0	0
14	EM B. + NPK + foliar Si-NPs	EM B. + NPK + SiNPs	5000 + 300 + 0.024	15	15	15	15
15	EM B. + NPK + foliar Se-NPs	EM B. + NPK + SeNPs	5000 + 300 + 0.024	15	15	15	15
16	EM B. + NPK + foliar Si-NPs + Se-NPs	EM B. + NPK + SiNPs + SeNPs	5000 + 300 + 0.024 + 0.024	15 + 15	15 + 15	15 + 15	15 + 15

The cumulative area designated for the research encompassed 8642 m^2, apportioned into three equivalent replicates, with each replicate comprising 16 experimental units. Each individual unit exhibited dimensions of 3 m × 4 m, yielding an area of 12 m^2, accompanied by a separation of 1 m between replicates and 0.5 m between treatments. The planting was done on ridges spaced 0.75 m apart, with 0.5 m between plants. Irrigation furrows were established and simple drainage ditches were opened for excess water removal. Seedlings of hybrid cabbage cultivar *Cabbage Top White F1* were sourced from a local nursery and transplanted directly into the prepared soil on 15/09/2024, at a planting density of 13,364 plants ha^{-1}. All standard agricultural practices were applied uniformly across all experimental units during transplanting and plant growth. and a replanting (gap filling) operation was carried out on 22/09/2024 to replace dead seedlings using ones of the same age as originally used. Irrigation was conducted based on plant requirements.

3. Soil application of EM bokashi organic biofertilizer and NPK mineral fertilizer

15 days after planting, a furrow was dug 5 cm deep and 5 cm away from the planting line to apply a single dose of EM Bokashi Organic Biofertilizer at a rate of 5 Mg ha^{-1}. The experimental unit area was used to calculate the amount. Using the same technique, four doses of the balanced NPK mineral fertilizer were applied at a rate of 300 kg ha^{-1}. Beginning one month after transplanting, foliar spraying of SeNPs at 15 mg L^{-1} (Figure 1) and SiNPs at 15 mg L^{-1} (Figure 2) was carried out four times at seven-day intervals. As indicated in Table 3, the plant canopy was sprayed in the late evening at a rate of 400 L ha^{-1} in accordance with the manufacturer's instructions.

Table 3. The components of the experiment's fertilizers and nanomaterials

Fertilizer Name	Fertilizer Type	Composition / Purity Description
EM Bokashi	Organic biofertilizer	*Nocardia* (45.45%), *Streptomyces* (36.36%), *Terrabacter* (9.1%), *Micromonospora* (4.54%), *Mycobacterium* (4.54%), *Aspergillus* sp., *Phcomycetes* spp., *Dactylium* sp., Moisture (7.74%), EC (7.30 dS m^{-1}), (1.45 × 10^6 CFU)
NPK	Chelated mineral fertilizer	NPK 20:20:20 + other chelated micronutrients
SiNPs	Dry nanomaterial	99.9% Silicon
SeNPs	Dry nanomaterial	99.9% Selenium

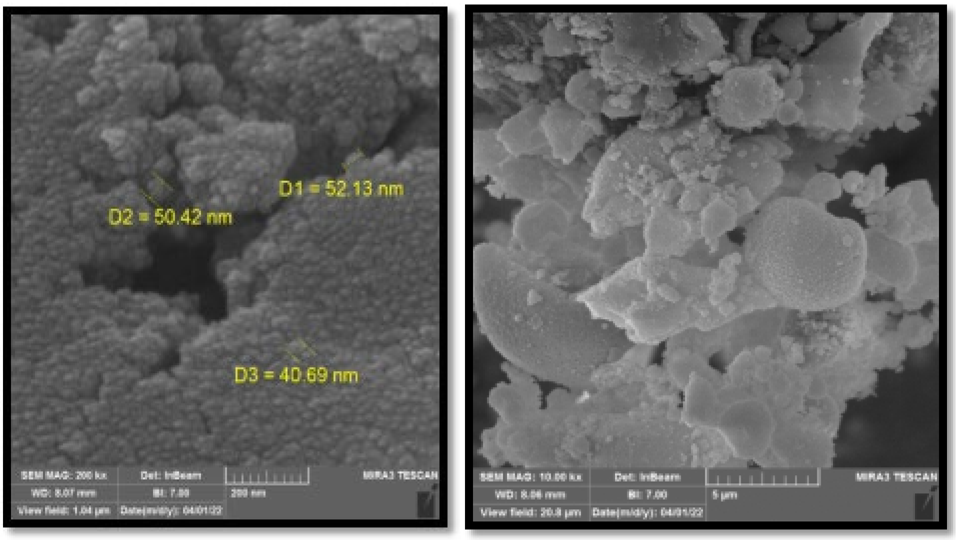

Figure 1. Scanning Electron Microscope (FE-SEM) image of

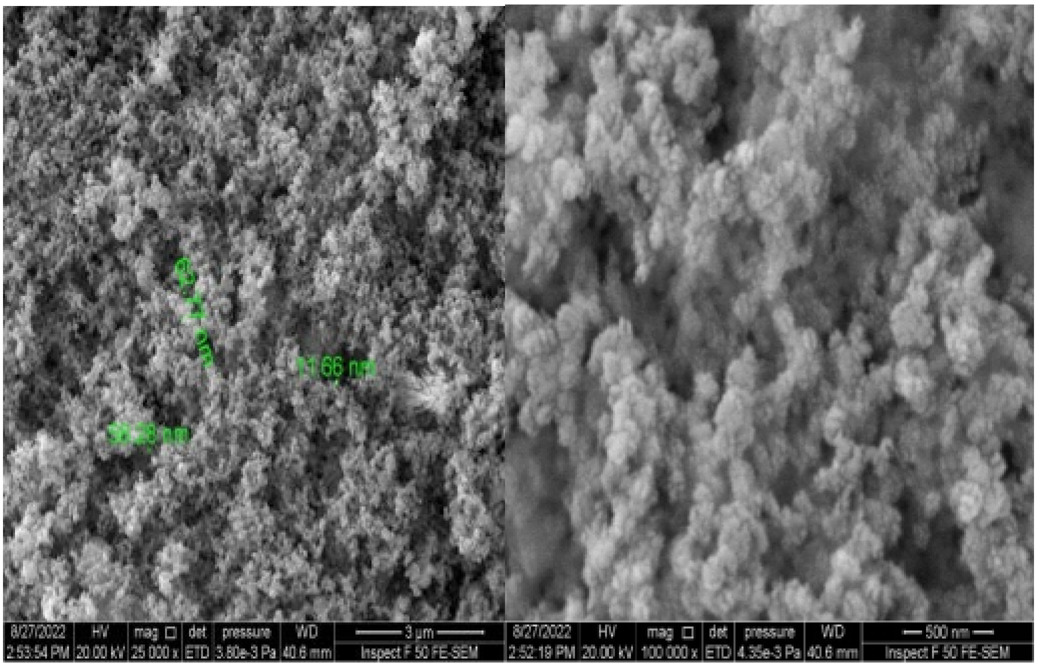

Figure 2. Scanning Electron Microscope (FE-SEM) image of the nano-silicon particles used in the experiment

First: Determination of Soil Content of Macronutrients (N, P, K), Organic Matter, Cation Exchange Capacity (CEC), and Total Counts of Soil Bacteria and Fungi

1. **Available Nitrogen Estimation:**
   The available nitrogen content was estimated using the Micro-Kjeldahl method. It was extracted using 2N KCl solution, according to the procedure described by [16].

2. **Available Phosphorus Estimation:**
   The available phosphorus concentration in the representative soil sample was measured using 0.5 M sodium bicarbonate ($NaHCO_3$) solution. The characteristic blue color was developed using ammonium molybdate and ascorbic. The phosphorus concentration was determined using a **spectrophotometer** at a wavelength of **882 nm**, based on the method outlined by [17]

3. **Available Potassium Estimation:**
   The available potassium was extracted using **1 M ammonium acetate (NH_4OAc)** solution. The potassium concentration was then measured using a **Flame Photometer**, following the method of [18].

4. **Cation Exchange Capacity (CEC):**
   CEC was determined using ammonium acetate and sodium acetate solutions, following the procedure described by [19].

5. **Organic Matter:**
   Organic matter in the soil was estimated using the **Wet Digestion Method**, following the methodology presented by [20].

6. **Total Count of Bacteria and Fungi in Dry Soil (CFU $g^{-1} \times 10^6$):**
   The total number of bacterial and fungal cells was estimated using the **Serial Dilutions Method** and **Plate Count Technique**. Nutrient Agar was used for bacterial growth, and Potato Dextrose Agar for fungal growth. All equipment was sterilized using alcohol and an open flame. A 10 g sample of the representative soil was added to 90 mL of sterilized distilled water to obtain a 1×10^8 dilution. After vigorous shaking, 1 mL of this solution was transferred into a test tube containing 9 mL of sterile

water to obtain a 2×10^8 dilution. This process was continued. One milliliter from each dilution was plated on the respective culture media using the pour plate technique, and incubated at 30°C for 5 days (fungi) and 3 days (bacteria). Colony numbers were calculated according to the following equation:

Number of colonies = Average colony count per plate × dilution factor, as described by [19].

Second: Measurement of Growth Parameters (Plant Height, Chlorophyll Index, Stem Diameter, Head Radius, Marketable Head Yield, Biological Yield, and Harvest Index)

1. **Plant Height (cm):**
   physiological maturity (100%), The height of the plant was measured from the soil surface to the top of the plant using a measuring tape of 10 randomly selected plants according to the experimental unit. The average height was calculated by dividing the total height with the number of measured plants.

2. **Leaf Chlorophyll Index (SPAD):**
   Chlorophyll content was evaluated before plant maturation using a portable chlorophyll meter **(Model Spad-502)** to achieve a quick and accurate reading. Chlorophyll reading was taken from 10 randomly selected plants according to the experimental unit, and the average price was calculated by dividing the total chlorophyll reading with the number of sample leaves [21].

3. **Stem Diameter (cm):**
   Stem diameter was measured using a **Vernier caliper** on five plants per experimental unit. The average value was calculated using the same method described above.

4. **Head Radius (cm):**
   Head radius was determined by first measuring the circumference of the head using a measuring tape. The radius was then calculated using the formula:
   Radius = Circumference ÷ (2 × 3.14).
   Five heads were measured from each experimental unit, and the mean radius was obtained.

5. **Marketable Head Yield (Mg ha^{-1}):**
   Marketable yield was calculated after removing non-marketable outer leaves. Five heads from each experimental unit were weighed, and the average was calculated to represent the marketable yield.

6. **Biological Yield (Mg ha^{-1}):**
   Biological yield was defined as the total fresh weight of the above-ground parts of the plant. Five plants were weighed per experimental unit, and values were converted to **Mg ha^{-1}** to obtain the biological yield for each treatment.

7. **Harvest Index (%):**
   The harvest index of cabbage was estimated using the following equation:
   Harvest Index (%) = (Marketable Head Yield / Biological Yield) × 100
   Both yields were calculated in **Mg ha^{-1}**, according to the methodology described by [22].

Third: Statistical Analysis

The data obtained from the experiment were statistically analyzed using the **Randomized Complete Block Design (RCBD)** to evaluate the effects of the studied treatments on various traits. Significant differences among means were tested using **Duncan's Multiple Range Test (Duncan)** at a **$P \leq 0.05$** significance level. Statistical analysis was performed using **GenStat V12.1**, based on the following statistical model:

$$Y_{ij} = \mu + T_i + P_j + e_{ij}$$

Where:

- Y_{ij} = observed value,

- μ = general mean,
- T_i = effect of treatment,
- P_j = effect of block,
- e_{ij} = experimental error.

4. Results

First: Effect of EM Bokashi, balanced NPK fertilizer, and foliar application of silicon nanoparticles (SiNPs) and selenium nanoparticles (SeNPs) on soil macronutrient content (NPK), cation exchange capacity (CEC), soil organic matter (SOM), and total bacterial and fungal counts in the soil.

4.1. Available Nitrogen Content in Soil after Harvest (mg N kg^{-1} soil)

As shown in Table (4), the combined treatment (EMB + NPK + SiNPs + SeNPs) recorded the highest value of available nitrogen in the soil (49.77 mg N kg^{-1}), It was followed by the triple combination (EMB + NPK + SeNPs), with values of 47.53 and 46.87 mg N kg^{-1} soil, respectively. except for the individual and dual nano-fertilizer treatments, which were statistically similar to the control (23.43 mg N kg^{-1} soil).

4.2. Available Phosphorus Content in Soil after Harvest (mg P kg^{-1} soil)

the highest soil phosphorus content (27.80 mg P kg^{-1} soil), significantly surpassing all other treatments. The (EMB + NPK + SeNPs) and (EMB + NPK + SiNPs) treatments also recorded elevated values (26.70 and 25.60 mg P kg^{-1} soil, respectively), significantly outperforming most other treatments. Treatments such as (EMB + NPK), (EMB + SiNPs), and (NPK + SiNPs + SeNPs) with values of 23.53, 23.33, and 23.30 mg P kg^{-1} soil.

4.3. Available Potassium Content in Soil after Harvest (mg K kg^{-1} soil)

As presented in Table (4), the quadruple treatment (EMB + NPK + SiNPs + SeNPs) also recorded the highest potassium content in soil (283.3 mg K kg^{-1} soil), which was significantly greater than all other treatments. High potassium levels were also observed in the triple treatments (EMB + NPK + SeNPs) and (EMB + NPK + SiNPs), with values of 279.7 and 280.6 mg K kg^{-1} soil, respectively. Other treatments such as (EMB + NPK), (EMB + SiNPs + SeNPs), and (NPK + SiNPs + SeNPs) also showed elevated potassium levels (279.1, 278.7, and 279.0 mg K kg^{-1} soil, respectively), The control recorded the lowest potassium content (261.4 mg K kg^{-1} soil).

4.4. Cation Exchange Capacity (CEC, cmol(+) kg^{-1} soil)

Statistical analysis results in Table (4) show a clear significant improvement in CEC for the treatment (EMB + NPK + SiNPs + SeNPs), which recorded a value of 38.53 cmol(+) kg^{-1} soil. Other treatments such as (EMB + NPK + SiNPs), (EMB + NPK + SeNPs), and (EMB + NPK) also recorded high values (36.40, 36.90, and 35.77 cmol(+) kg^{-1} soil, respectively), and all were significantly superior to the control (26.50 cmol(+) kg^{-1} soil).

4.5. Soil Organic Matter Percentage (SOM, %)

As indicated in Table (4), the treatment (EMB + NPK + SiNPs + SeNPs) achieved the highest SOM percentage (1.913%), significantly surpassing all other treatments except (EMB + NPK + SeNPs), (EMB + NPK + SiNPs), and (EMB + SiNPs + SeNPs), which had values of 1.833%, 1.870%, and 1.853%, respectively, and were not significantly different from the quadruple treatment.

4.6. Soil Bacterial Counts after Harvest (CFU × 10^6 g^{-1} soil)

Table (4) also shows a significant increase ($P \leq 0.05$) in soil bacterial counts for the quadruple treatment (EMB + NPK + SiNPs + SeNPs), which recorded 90.80 × 10^6 CFU g^{-1} soil. This was followed by the triple treatments containing EM Bokashi: (EMB + NPK + SeNPs) and (EMB + NPK + SiNPs), with values of 80.73 and 77.97 × 10^6 CFU g^{-1} soil, respectively. The (EMB + NPK) treatment also recorded a high value (74.03 × 10^6 CFU g^{-1} soil).

4.7. Soil Fungal Counts after Harvest (CFU × 10^4 g^{-1} soil)

The highest fungal count was also observed in the quadruple treatment (EMB + NPK + SiNPs + SeNPs), which reached 74.43 × 10^4 CFU g^{-1} soil and was significantly superior to all other treatments. The triple treatments containing EM Bokashi (EMB + NPK + SeNPs and EMB + NPK + SiNPs) also showed high fungal counts (69.50 and 67.43 × 10^4 CFU g^{-1} soil, respectively), with no significant difference between them. The dual and individual treatments also significantly outperformed the control (22.90 × 10^4 CFU g^{-1} soil).

Table 4. Effect of the application of organic bio-fertilizer (EM Bokashi), balanced mineral fertilizer (NPK), and foliar spraying with silicon and selenium nanoparticles on soil content of nitrogen (N), phosphorus (P), potassium (K) (mg kg^{-1}), cation exchange capacity (CEC) (cmolc kg^{-1}), soil organic matter (SOM, %), and total bacterial and fungal counts (CFU g^{-1} soil)

No.	Treatment	N (mg kg^{-1})	P (mg kg^{-1})	K (mg kg^{-1})	CEC (cmolc kg^{-1})	SOM (%)	Bacteria (×10^6 CFU g^{-1})	Fungi (×10^4 CFU g^{-1})
1	Control (C.O.)	23.43 g	13.43 h	261.4 G	0.907 H	26.50 ef	35.70 L	22.90 n
2	EM Bokashi (EM B.)	40.47 ef	22.60 cde	275.1 E	1.567 Cd	31.47 abcde	50.47 I	40.20 h
3	NPK	40.20 ef	20.67 e	275.9 De	1.347 E	20.90 f	41.87 J	33.33 k
4	Si-NPs	24.60 g	15.48 g	263.4 Fg	1.107 Fg	27.37 def	38.03 K	27.07 m
5	Se-NPs	23.87 g	14.71 gh	262.2 G	1.067 G	26.93 def	38.57 K	29.80 l
6	Si-NPs + Se-NPs	24.73 g	17.48 f	266.5 F	1.203 F	28.90 cde	39.80 K	37.07 ij
7	NPK + Si-NPs	41.73 def	21.07 de	278.2 bcde	1.423 E	30.83 bcde	49.63 I	34.90 jk
8	NPK + Se-NPs	39.97 f	22.13 cde	278.0 bcde	1.380 E	30.10 bcde	54.37 H	37.50 i
9	NPK + Si-NPs + Se-NPs	42.77 d	23.30 c	279.0 bcd	1.530 D	31.67 abcde	58.33 G	46.13 g
10	EM B. + Si-NPs	42.93 d	23.33 c	276.2 cde	1.727 B	34.20 abcd	56.77 G	48.47 f
11	EM B. + Se-NPs	42.30 de	22.77 cd	276.6 cde	1.653 bc	32.53 abcde	62.23 F	54.83 e
12	EM B. + Si-NPs + Se-NPs	43.73 cd	25.53 b	278.7 bcd	1.853 A	34.13 abcd	65.23 E	57.63 d
13	EM B. + NPK	45.57 bc	23.53 c	279.1 bcd	1.717 B	35.77 abc	74.03 D	64.93 c
14	EM B. + NPK + Si-NPs	46.87 b	25.60 b	280.6 Ab	1.870 A	36.40 ab	77.97 C	67.43 b
15	EM B. + NPK + Se-NPs	47.53 b	26.70 ab	279.7 Bc	1.833 A	36.90 ab	80.73 B	69.50 b
16	EM B. + NPK + Si-NPs + Se-NPs	49.77 a	27.80 a	283.3 A	1.913 A	38.53 a	90.80 A	74.43 a

*Significance level: **

Different letters within the same column indicate significant differences among treatments at the 0.05 probability level ($p < 0.05$).

Secondly, The effect of applying bio-organic fertilizer (EM Bokashi), balanced NPK fertilizer, and foliar spraying with nano-silicon (SiNPs) and nano-selenium (SeNPs) on:

1. Plant Height (cm): Statistical analysis of the data in Table (5) revealed a significant difference in plant height among the studied treatments. The highest significant mean height (49.60 cm) was recorded by the quadruple combination (EMB + NPK + SiNPs + SeNPs), significantly surpassing the control treatment (34.93

cm). The triple combination (EMB + NPK + SiNPs) also achieved a significant height of 47.36 cm. Among the dual combinations, (EMB + NPK) reached 46.50 cm, while the individual treatments of EMB and NPK recorded 42.63 cm and 39.66 cm, respectively.

2. Stem Diameter (cm): The highest stem diameter (3.667 cm) was observed in the quadruple combination (EMB + NPK + Si + Se), followed by the treatments (EMB + NPK + Se), (EMB + NPK + Si), (EMB + NPK), and (EMB + Si + Se), which recorded 3.400, 3.300, 3.167, and 3.100 cm, respectively. The lowest value was recorded in the control (1.137 cm), as shown in Table (5).

3. Marketable Head Radius (cm): The quadruple treatment (EMB + NPK + Si + Se) recorded the highest value for head radius (10.77 cm), significantly outperforming all other treatments. The triple treatments (EMB + NPK + Si) and (EMB + NPK + Se) also had high values (9.87 and 9.27 cm, respectively). Conversely, the control treatment recorded the smallest radius (5.10 cm).

4. Chlorophyll Index (SPAD): Chlorophyll index results in Table (5) mirrored the trend observed in plant height. A significant improvement was noted with all treatments involving EM Bokashi, NPK, and foliar application of SiNPs and SeNPs ($P \leq 0.05$), compared to the control value of 68.3 SPAD. The highest value was recorded by the quadruple combination (84.3 SPAD), followed by the triple combinations (81.8 and 80.3 SPAD for EMB + NPK + SiNPs and EMB + NPK + SeNPs, respectively).

5. Biological Yield (Mg ha^{-1}): According to Table (5), the highest biological yield was obtained from the quadruple treatment (EM Bokashi + NPK + SiNPs + SeNPs), reaching 149.6 Mg ha^{-1}, which was significantly superior ($P \leq 0.05$) to all other treatments. It was followed by EMB + NPK + SeNPs (128.0 Mg ha^{-1}) and EMB + NPK + SiNPs (137.7 Mg ha^{-1}). The lowest yield was recorded in the control (66.6 Mg ha^{-1}).

6. Marketable Head Yield (Mg ha^{-1}): As shown in Table (5), the results of marketable head yield closely followed the trends of biological yield. All combinations of EM Bokashi, NPK, SiNPs, and SeNPs showed significant improvements ($P \leq 0.05$) over the control (33.24 Mg ha^{-1}). The highest yield was recorded in the quadruple treatment (100.42 Mg ha^{-1}), followed by EMB + NPK + SeNPs (89.13 Mg ha^{-1}) and EMB + NPK (76.87 Mg ha^{-1}).

7. Harvest Index (%): Table (5) shows that the treatments (EMB + NPK + SiNPs + SeNPs, EMB + NPK + SeNPs, EMB + NPK, and EMB + SeNPs) achieved higher harvest index values (67.75%, 69.74%, 68.75%, and 67.51%, respectively.

Table 5. Effect of Organic Biofertilizer (EM Bokashi), Balanced Mineral Fertilizer (NPK), and Foliar Application of Silicon and Selenium Nanoparticles on Growth Indicators Plant Height cm,Stem Diameter cm, Head Radius cm, Chlorophyll Index SPAD, Marketable Yield Mg ha^{-1}, and Harvest Index (%)

No.	Treatments	Plant Height (cm)	Stem Diameter (cm)	Head Radius (cm)	Chlorophyll Index (SPAD)	Marketable Yield (Mg ha^{-1})	Harvest Index (%)
1	Control	34.93 L	1.137 I	5.10 k	68.3 H	66.6 f	50.00 C
2	EM B.	42.63 F	2.100 G	7.40 ef	75.6 F	109.5 cd	59.47 abc
3	NPK	39.67 I	2.200 G	7.27 fg	75.3 F	91.5 e	62.92 Ab
4	Si-NPs	36.40 K	1.400 H	5.57 jk	70.7 G	68.3 f	59.89 abc
5	Se-NPs	36.20 K	1.367 H	5.90 ij	70.3 G	68.8 f	61.03 abc
6	Si-NPs + Se-NPs	38.53 J	2.233 Fg	6.33 Hi	74.7 F	89.8 e	54.49 Bc
7	NPK + Si-NPs	41.73 G	2.467 De	6.70 Gh	75.3 F	97.8 de	61.50 Ab
8	NPK + Se-NPs	40.50 H	2.433 Ef	6.97 Fgh	75.9 F	103.1 de	60.53 abc
9	NPK + Si-NPs + Se-NPs	42.73 F	2.667 D	7.63 Def	78.4 De	102.2 de	63.90 Ab
10	EM B. + Si-NPs	43.30 E	2.633 De	7.57 Def	77.6 E	111.1 cd	58.84 abc
11	EM B. + Se-NPs	43.33 E	2.467 De	8.00 Cde	77.3 E	105.8 cde	67.51 A
12	EM B. + Si-NPs + Se-NPs	44.57 D	3.100 C	8.23 Cd	78.9 D	120.9 bc	60.83 abc

No.	Treatments	Plant Height (cm)	Stem Diameter (cm)	Head Radius (cm)	Chlorophyll Index (SPAD)	Marketable Yield (Mg ha⁻¹)	Harvest Index (%)
13	EM B. + NPK	46.50 C	3.167 C	8.57 C	79.6 Cd	112.9 bcd	68.55 A
14	EM B. + NPK + Si-NPs	47.37 B	3.300 Bc	9.27 B	81.8 B	137.7 a	59.86 abc
15	EM B. + NPK + Se-NPs	46.43 C	3.400 B	9.87 B	80.3 C	128.0 ab	69.74 A
16	EM B. + NPK + Si-NPs + Se-NPs	49.60 A	3.667 A	10.77 A	84.3 A	149.6 a	67.75 A

Table 5. (*Continued*)

Significance level: * indicates significant differences at (P ≤ 0.05). Different letters within the same column indicate significant differences between treatments according to Duncan's multiple range test

5. Discussion

The observed increase in nitrogen, phosphorus, and potassium content in soils treated with EM Bokashi, NPK fertilizer, and foliar-applied nano-silicon and nano-selenium is attributed to the synergistic effects of these inputs. The biofertilizer EM Bokashi enhances microbial activity in the soil, leading to improved nitrogen availability and reduced losses through leaching, volatilization, or chemical fixation. Moreover, it facilitates the decomposition of organic matter and solubilization of phosphorus and potassium bound to soil minerals, increasing their bioavailability [23-25].

The application of NPK fertilizer provides a direct source of essential macronutrients; however, its combination with EM Bokashi ensures sustained nutrient supply over time [26,27]. Additionally, selenium and silicon have been shown to improve nutrient uptake and enhance plant resistance to abiotic stress. Silicon is known to boost nutrient absorption efficiency and stress tolerance [28], while selenium contributes to enzymatic activities that influence nutrient stability in the soil [29].

The integrated use of organic and inorganic sources improved soil nutrient content, while the significant differences among treatments suggest that using EM Bokashi and NPK alone did not achieve maximal nutrient retention.. The addition of silicon and selenium enhanced nutrient uptake synergistically. These findings align with previous studies [30,31]. that emphasize the benefits of integrated fertilization in enhancing soil fertility and minimizing nutrient losses.

Statistical analysis (Duncan's test, $P \leq 0.05$) in Table 4 also revealed significant differences in biochemical soil indicators, including soil organic matter (SOM), cation exchange capacity (CEC), and microbial counts (bacteria and fungi). Treatments incorporating Si, Se, NPK, and EM Bokashi showed the highest SOM levels, especially the triple and quadruple combinations, indicating a cumulative effect on organic matter accumulation.

The beneficial microbes in EM Bokashi break down organic residues and recycle nutrients, enhancing soil structure and SOM [32]. Treatments combining EM Bokashi with Si or NPK showed moderate improvements compared to triple treatments, suggesting that silicon alone may not significantly improve SOM but may contribute indirectly by improving SOM stability [10]. While NPK contributes to microbial activity, it lacks the biodegradative role of EM Bokashi. Single-factor treatments did not show significant improvements, and the control treatment recorded the lowest SOM, indicating continuous SOM depletion in the absence of biostimulants [33]. Similarly, treatments combining SiNPs, SeNPs, NPK, and EM Bokashi achieved the highest CEC values, reflecting improved nutrient retention capacity. This can be explained by:

1. Silicon enhancing soil structure through clay particle stabilization [4]
2. EM Bokashi promoting microbial activity and organic acid release, improving nutrient retention [34].
3. NPK providing a consistent source of ions in the soil solution.

Finally, synergistic treatments, particularly the quadruple combination, showed the highest bacterial and fungal populations, while single treatments had limited effects. EM Bokashi alone improved microbial activity compared to control but was less effective than combined treatments. As a microbial inoculant containing effective microorganisms, EM Bokashi significantly enhances biological activity, promoting soil health and crop productivity [35,36]. Nano-Si and Se may also increase nutrient availability and stimulate plant–microbe interactions.

The significant rise in fungal populations under combined treatments indicates improved soil conditions and a thriving beneficial fungal community that supports nutrient absorption and disease resistance. The significant improvement in growth parameters such as plant height, stem diameter, and marketable head radius, as shown in Table (5), under the quadruple combination treatment compared to the control is attributed to the synergistic effect of EM Bokashi biofertilizer, balanced NPK fertilizer, and foliar application of silicon and selenium nanoparticles.

These findings are consistent with the results [37].This was attributed to the elevated antioxidant enzyme activity in plants treated with silicon and NPK, which helped scavenge reactive oxygen species caused by oxidative stress, in addition to increasing the secretion of organic acids and reducing boron concentrations in plant roots and shoots. The study concluded that the application of silicon and macronutrients could mitigate boron toxicity and enhance plant growth under metal stress through balanced organic acid exudation.

Regarding the chlorophyll index (SPAD), a significant increase was observed under the quadruple combination compared to the other treatments. This improvement is due to the positive interaction among the combined elements: silicon enhances photosynthetic efficiency by stabilizing cell membranes and protecting chloroplasts from oxidative stress; selenium may indirectly contribute to chlorophyll biosynthesis at certain concentrations; and nitrogen, a component of NPK, is directly involved in chlorophyll molecule formation. Similar results were reported by [38], in their study on potatoes, where NPK application led to improved growth traits such as increased stem diameter and tuber yield, alongside enhanced physiological attributes including total chlorophyll and carotenoid content. Moreover, NPK fertilization improved tuber quality by increasing starch and sucrose levels and boosting enzymatic activity associated with sugar metabolism. Lipid peroxidation markers were also reduced, indicating improved plant resistance to environmental stress.

Treatments combining balanced nutrient sources (N, P, K) with silicon, selenium, and EM Bokashi significantly outperformed single-factor or untreated control treatments. EM Bokashi improved soil biological activity and nutrient absorption efficiency, which positively affected plant growth and productivity [39]. Furthermore, [40], demonstrated that mineral fertilization significantly increased fruit yield in strawberry (*Duch Fragaria × ananassa*) compared to the control.

In addition to the agronomic and physiological aspects, the results also have important economic implications. The combined application of bio-organic fertilizer (EM Bokashi) with balanced mineral fertilizer (NPK) and foliar spraying of silicon and selenium nanoparticles significantly enhanced the marketable yield of cabbage, with increases exceeding 70–100 Mg ha^{-1} compared to the control and single treatments. This remarkable increase in productivity translates into higher economic returns for farmers per unit area, while the additional costs of bio-organic and nano-fertilizer inputs remain relatively limited. Moreover, the integration of bio-organic and nano-enabled fertilizers reduces the required amounts of mineral fertilizers, leading to lower production costs and minimizing environmental pollution. Therefore, adopting such fertilization strategies ensures economic feasibility by improving crop productivity, increasing farmers' income, and reducing both financial and environmental burdens associated with excessive use of conventional chemical fertilizers.

6. Conclusions

The quadruple combination treatment (EM Bokashi + NPK + SiNPs + SeNPs) was the most effective in enhancing both vegetative growth and physiological performance growth of cabbage, outperforming all other treatments, particularly the control. EM Bokashi played a pivotal role in boosting microbial activity and nutrient uptake, resulting in increased plant biomass. Silicon and selenium nanoparticles contributed to enhanced stress tolerance and improved SPAD index values. using NPK alone is insufficient, while integrated fertilization serves as a powerful strategy for improving metabolic function and soil fertility. Significant improvements in soil organic matter (SOM) and cation exchange capacity (CEC) were observed under triple and quadruple treatments. the importance of synergy among organic, mineral, and nano-fertilizers in achieving sustainable improvements in yield and crop quality.

Conflict of interest

The authors declare no conflict of interest

References

1. Barman, M., S. Paul, A. G. Choudhury, P. Roy and J. SeNPsn. 2017. Biofertilizer as prospective input for sustainable agriculture in India. International Journal of Current Microbiology and Applied Sciences, 6(11), 1177-1186.
2. Al-Wardy, M., S. Khuit and H. K. Al Khafagi. 2022. The impact of different potassium concentrations on the yield of mungbean (Vigna radiata L.). Revis Bionatura;7(4) 31. http://dx.doi.org/10.21931/RB/2022.07.04.31
3. Ali Amer Dahham, A., I. Manea and H. W. A. Al-Juthery. 2025. The Effect of Bio Organic Fertilizer and Spraying with Nano-Organic Extract on the Growth and Yield of Three Hybrids of Cucumbers for Protected Cultivation. IOP Conf. Series: Earth and Environmental Science 1487 (2025) 012039. doi:10.1088/1755-1315/1487/1/012039.
4. Al-Assfar, H. S. and H. W. A. Al-Juthery. 2025. Effect of Nano Silicon, EM. Bokashi Fertilizers and Spraying Some Biostimulants on Quality Criteria Cauliflower Flowers. In IOP Conference Series: Earth and Environmental Science (Vol. 1487, No. 1, p. 012179). IOP Publishing.
5. Aljumaily, M.M., Al-Hamandi, H.M., Farhan, M.J., Kareem, H.A.: Relationship between Zn and Cd in soil and plant. Journal of Agricultural Science, 1(XXXIII): 33–42 (2022).
6. Hamid, M.Q. 2025a. Mycorrhiza and Trichoderma fungi role in improving soil physical properties planted with maize (Zea mays L.). SABRAO J. Breed. Genet. 57(1): 260-269. http://doi.org/10.54910/sabrao2025.57.1.25
7. Al-Khafagi, K. F. H., S. A. Khuit and A. H. Almaini. 2020. Response of five bread wheat cultivars to late planting conditions under middle region of Iraq. Plant Archives, 20(2), 990-995.
8. Ola, H. R., & Al-Juthery, H. W. A. 2025. Effect of Nano-Manganese, EM. Bokashi Fertilization and Spraying Nanoparticles of Iron and Carbon Nanotubes in Soil Sustainability, Enhancing Some Growth Parameters and Yield of Broccoli. In IOP Conference Series: Earth and Environmental Science (Vol. 1449, No. 1, p. 012106). IOP Publishing.
9. Kakahy, A.N.N., Alshamary, W.F.. and Kakei, A.A., 2021. The impact of forward tractor speed and depth of ploughing in some soil physical properties. In IOP Conference Series: Earth and Environmental Science (Vol. 761, No. 1, p. 012002). IOP Publishing.
10. Wang, X., Y. Liu, Y. Zhang, P. Wu, X. Liu, F. Nan. 2024. The complex relationships between diatoms, bacterial communities, and dissolved organic matter: Effects of silicon concentration. Algal Research, 79, 103460.
11. Jafaar, A. A., R. J. Mohammed, D. F. Hassan and T. Y. Thamer. 2023. Effect of Foliar Seaweed and Different Irrigation Levels on Water Consumption, Growth and Yield of Wheat. In IOP Conference Series: Earth and Environmental Science (Vol. 1252, No. 1, p. 012057). IOP Publishing.
12. Ali, Z. A., D. F. Hassan and R. J. Mohammed. 2021. Effect of irrigation level and nitrogen fertilizer on water consumption and faba bean growth. In IOP Conference Series: Earth and Environmental Science (Vol. 722, No. 1, p. 012043). IOP Publishing.
13. Atanda, S. A., R. O. Shaibu and F. O. Agunbiade. 2025. Nanoparticles in agriculture: Balancing food SeNPscurity and environmental sustainability. Discover Agriculture, 3(1), 26.
14. Hofmann, T., G. V. Lowry, S. Ghoshal, N. Tufenkji, D. Brambilla, J. R. Dutcher et al. 2020. Technology readiness and overcoming barriers to sustainably implement nanotechnology-enabled plant agriculture. Nature Food, 1(7), 416-425.
15. Aljibury, A.F., Hassan, H.M. and Kareem, H.A., 2021. Estimate of Available Soil Water and The Physical Condition of Soil for Different Use Soils. In IOP Conference Series: Earth and Environmental Science (Vol. 761, No. 1, p. 012020). IOP Publishing.

16. Bremner, J. M. 1960. Determination of nitrogen in soil by the Kjeldahl method. The Journal of Agricultural Science, 55(1), 11-33.
17. Foolad, M. R. and D. R. Panthee. 2012. Marker-asSiNPssted SeNPslection in tomato breeding. Critical reviews in plant sciences, 31(2), 93-123.
18. Harper, S. M., G. L. Kerven, D. G. Edwards and Z. Ostatek-Boczynski. 2000. Characterisation of fulvic and humic acids from leaves of Eucalyptus camaldulenSiNPss and from decompoSeNPsd hay. Soil Biology and Biochemistry, 32(10), 1331-1336.
19. Black, C. A. 1965. Methods of soil analySiNPss part 1 physical properties Am. Soc. Agron. Inc. publisher, Madison WisconSiNPsn, USA.
20. Page, A. L., R. H. Miller, D. R. Keeney, D. E. Baker, J. R. Roscoe Ellis and J. D. Rhoades. 1982. Methods of soil analySiNPss-chemical and microbiology properties. American Society of Agronomy Inc.: Madison, WI, USA, 1159.
21. Jinwen, L., Y. Jingping., Pinpin, F., Junlan, S., Dongsheng, L., Changshui, G., & Wenyue, C. 2009. ResponSeNPss of rice leaf thickness, SPAD readings and chlorophyll a/b ratios to different nitrogen supply rates in paddy field. Field Crops ReSeNPsarch, 114(3), 426-432.
22. Sharma, R. C., & Smith, E. L. 1986. SeNPslection for high and low harvest index in three winter wheat populations 1. Crop science, 26(6), 1147-1150.
23. Al Hasnawi R. A., AlJanaby Z. A. A., Jaafer A. A. and Mohammed R. J. 2020 Effect of nitrogen fertilization and irrigation water quality on some soil characteristics, growth and yield of sunflower Plant Archives 20 2703-2705
24. Hamid, M.Q., E.H. Abd., Z.K. Al-Salihi, R.J. Muhammed and D.F. Hassan. 2025. Effect of organic conditioners on the physical properties of sandy soil under drip irrigation conditions. Sarhad Journal of Agriculture, 41(3): 1133-1142. https://dx.doi.org/10.17582/journal.sja/2025/41.3.1133.1142
25. Akol, A. M., n. nassif, k. a. jaddoa, k. radhi and d. f. hassan. 2021. effect of irrigation methods, tillage systems and seeding rate on water consumption, biological yield and harvest index of wheat (triticum aestivum l.). international journal of agricultural & statistical sciences, 17.
26. Basir, A., S. Iqbal, M. Adnan, M. A. Khan, R. Lal, S. Fahad and A. El Sabagh. 2025. Integration of compost with mineral NPK fertilizers for improving wheat yield and soil health. Pak. J. Bot, 57(3), 981-989.
27. Abbas, H. D., N. A. Abdul Razak and A. A. Mohsen. 2023. Maize production forecasting in Iraq: A Box-Jenkins approach for the period of 2022–2026. IOP Conference Series: Earth and Environmental Science, 1259(1), 012128. https://doi.org/10.1088/1755-1315/1259/1/012128
28. Weisany, W., J. Razmi, A. H. Eshaghabadi and D. Pashang. 2024. SiNPslicon nanoparticles (SiNPsNP): A novel and sustainable strategy for mitigating environmental stresSeNPss in plants. Journal of Soil Science and Plant Nutrition, 24(2), 2167-2191.
29. Eissa, E. S. H., W. K. Bazina, Y. M. Abd El-Aziz, N. A. Abd Elghany, W. A. Tawfik, M. I. Mossa, H. S. Khalil et al. 2024. Nano-SeNPslenium impacts on growth performance, digestive enzymes, antioxidant, immune reSiNPsstance and histopathological scores of Nile tilapia, Oreochromis niloticus against Aspergillus flavus infection. Aquaculture International, 32(2), 1587-1611.
30. Hamid, M.Q. 2025b. Response of physical properties of sandy soil treated with different levels of natural soil conditioners zeolite and perlite. Sarhad Journal of Agriculture, 41(2): 591-599. https://dx.doi.org/10.17582/journal.sja/2025/41.2.591.599
31. Erdal, İ., K. Ekinci, B. S. Kumbul and E. C. Madenli. 2025. Effect of Dairy Manure Derived Bokashi Prepared from Different Organic Materials on Lettuce Growth and Mineral Nutrition. Journal of Soil Science and Plant Nutrition, 1-14.
32. Hassan, D., T. Thamer, R. Mohammed, A. Almaeini and N. Nassif. 2023. Calibration and Evaluation of AquaCrop Model Under Different Irrigation Methods for Maize (Zea mays L.) in Central Region of Iraq. In: Kallel, A., et al. Selected Studies in Environmental Geosciences and Hydrogeosciences. CAJG 2020. Advances in Science, Technology & Innovation. Springer, Cham. https://doi.org/10.1007/978-3-031-43803-5-10
33. Olayemi, O. P., C. M. Kallenbach and M. D. Wallenstein. 2022. Distribution of soil organic matter fractions are altered with soil priming. Soil Biology and Biochemistry, 164, 108494.
34. Al-Juthery, H. W. A., N. R. Lahmoud, A. S. Alhasan, N. A. A. Al-Jassani and A. Houria. 2022. Nano-Fertilizers as a Novel Technique for Maximum Yield in Wheat Biofortification (Article Review), IOP Conf. Ser.: Earth Environ. Sci. 1060(2022) 012043.
35. Ncube, L. 2024. Effective Microorganisms (EM): A Potential Pathway for Enhancing Soil Quality and Agricultural Sustainability in Africa. In Strategic Tillage and Soil Management-New Perspectives. IntechOpen.
36. Jafaar, A. A., R. J. Mohammed and D. F. Hassan. 2022. Effect of phosphorus fertilizer and irrigation level on desert soil management and potato yield. international journal of agricultural & statistical sciences, 18(2).
37. Hundi, H. K., M. Q. Hamid and A. A. M. Noori. 2025. Role of Ochrobactrum Bacteria and Organic Matter in Plant Growth and the Content of N, P, and K Under Soil Salinity Stress. Journal of Environmental & Earth Sciences. 7(5): 130–139. https://doi.org/10.30564/jees.v7i5.8777
38. Yue, Z., G. Zhang, J. Wang, J. Wang, S. Luo, B. Zhang et al. 2024. Comparative study of the quality indices, antioxidant substances, and mineral elements in different forms of cabbage. BMC Plant Biology, 24(1), 187.

39. Al-Musawi, R. J. A. 2016. Effect of chemical, organic, and bio-fertilization on the growth and yield of strawberry. Postgraduate Diploma Thesis, College of Agriculture, University of Baghdad, Iraq.
40. Al-Shamary, W.F., Alkhateb, B.A.A.H., Abd Al-Jabbar, M.S. and Kahlel, A.S., 2021, May. Impact of Date Residues, Humic Acid and The Level of Irrigation in Growth and Yield of Onions (Allium cepa L.). In IOP Conference Series: Earth and Environmental Science (Vol. 761, No. 1, p. 012011). IOP Publishing.