

Influence of Vermicompost Extract and Spraying with Nano-iron and Nano-boron on the Mineral Content of Papaya Fruit (*Carica papaya* L.)

Zahraa Aqeel Hasan Al-Khatib^{1*}, Sabaa Jawad Abdulkadhim², Raad Taha Muhammad Ali³

¹ Babylon Governorate Office / Babylon Agriculture Directorate, Iraq;

^{2,3} Department of Plant Production Techniques, Al-Furat Al-Awsat Technical University, Al-Mussaib Technical College, 51006, Babylon, Iraq

Correspondence: Zahraa Aqeel Hasan Al-Khatib; zahra.aqeel.x2018@gmail.com

Received 16/06/2026, Received in revised form 05/07/2026

Accepted 13/07/2026, Available online 10/10/2026

FJIAS 2026, 2(S1): 183-194

Special Issue: Selected Papers from the 3rd International Conference on Sustainable Development and Climate Change (ICSDCC 2026). Organized by Al-Mussaib Technical College / Al-Furat Al-Awsat Technical University, Iraq, in cooperation with Delta University for Science and Technology, Egypt. Held at Delta University for Science and Technology, Mansoura, Egypt, on 18 July 2026.

ABSTRACT

Papaya has been introduced to Iraq recently, necessitating the development of integrated fertilization programs tailored to local climatic and soil conditions to ensure optimal growth and high yields. Fertilization management is a key determinant of papaya tree growth and productivity, as the integrated use of organic and mineral fertilizers improves soil properties and increases nutrient absorption efficiency. Therefore, a field trial was conducted on a private papaya farm from the beginning of October 2024 to the end of June 2025 to study the effects of Vermicompost extract and spraying with Nano-iron and boron on papaya tree growth, yield, and mineral content. A three-factor factorial experiment was conducted using a completely randomized block design. The experiment included three factors. The first factor was the addition of Vermicompost extract at two levels (0 and 50) m L^{-1} . The second factor was the spraying of boron nanoparticles at four levels (0, 5, 15, and 10) m L^{-1} . The third factor was the spraying of iron nanoparticles at four levels (0, 2, 4, and 6 m L^{-1}). The results showed that the Vercompost extract (at a concentration of V50) was significantly superior in terms of the highest average content of mineral elements in the fruits (percentage of calcium, magnesium, potassium, sodium, boron, and iron), respectively, compared to the control treatment. Spraying with nano-iron and Nano-boron significantly outperformed the (F6) and (B15) levels respectively, giving the highest average fruit content of the aforementioned mineral elements compared to the control treatment. The two-way interference coefficients (V50×Fe6), (V50×B15), and (Fe6×B15) were significantly superior in the same indices. The triple interaction treatment (V50×Fe6×B15) significantly increased the fruit content of the above mineral elements by (0.193%, 0.362%, 2.534%, 0.340%, 0.143%, 26.033 g.kg^{-1} , 353.64 g.kg^{-1}) respectively, compared to the control treatment.

Keywords: Papaya, Vermicompost, nano-boron, nano-iron

1. Introduction

The papaya tree (*Carica papaya* L.) is one of the most important tropical fruit crops, possessing high nutritional and economic value. Its fruit is distinguished by its content of medicinally active compounds that contribute to promoting human health and preventing many diseases. Papaya has been introduced to Iraq recently, and its cultivation has seen considerable interest in recent years, despite the lack of suitable growing conditions. This necessitates the development of integrated fertilization programs tailored to local climatic and soil conditions to ensure optimal growth and high productivity. Several strategies have been adopted to improve the growth and yield of various fruit plants cultivated in Iraq to overcome unfavorable soil and climatic conditions (Abdulkadhim, 2024; Abbas & Abdulkadhim, 2024; Hashim, et al., 2026). Many studies have been conducted to improve the growth and production of papaya trees and their suitability to regional conditions (Easmin, et al., 2021; Abdulkadhim and Hashim, 2024; Manavi et al., 2025). Vermicompost is one of the most important organic fertilizers, distinguished by its ability to improve the physical and chemical structure of the soil, increase biological activity, and provide readily available nutrients to plants. Studies have shown that the use of vermicompost leads to improved vegetative growth, increased yield, and enhanced quality characteristics of papaya fruit, including its sugar, carotenoid, and ascorbic acid content (Rahman et al., 2020; Kumar et al., 2022; Oyege & Bhaskar, 2023). On the other hand, micronutrients such as iron and boron play a crucial role in plant physiological processes. Iron is essential for chlorophyll formation, photosynthesis, and respiration. It also participates in many vital enzyme systems, and its deficiency leads to yellowing, reduced growth and yield (Pestana et al., 2012; Abdeldaym et al., 2022; Mondal & Paul, 2026). Boron is necessary for cell division, cell wall formation, and sugar transport, in addition to its important role in fruit set and improving production quality. Several studies have shown that foliar spraying with iron and boron improves growth characteristics and yield in fruit trees by increasing photosynthetic efficiency and improving the plant's nutritional balance (Yadav et al., 2023; Singh et al., 2024; Mor, et al., 2025). With the rapid development of modern technologies, nano-fertilizer technology has emerged as a promising solution for improving nutrient utilization efficiency and reducing losses (Mahmoud et al., 2022; Abdulkadhim & Hashem, 2025; Mor, et al., 2025). Nanofertic fertilizers are characterized by their small particle size and high surface area, which increases their ability to penetrate and be absorbed into plant tissues, thus improving nutrient utilization compared to traditional fertilizers. Numerous studies have demonstrated that using iron and boron in their nano-forms leads to improved vegetative growth, increased productivity, and stimulation of the formation of medicinally important secondary compounds, as a result of enhancing photosynthesis and activating antioxidant systems within the plant (Nemati Lafmejani et al., 2022; El-Araby et al., 2024; He et al., 2025; Yadav et al., 2023). Many sustainable strategies have been used to improve the growth and production of different fruit plants and their suitability to regional conditions (Abdulkadhim, 2019; Hashem, and Abdulkadhim, 2024). Therefore, the importance of this study stems from the fact that papaya is a tropical plant that has been recently introduced to Iraq, and due to the lack of studies on papaya trees in the conditions of Babylon Governorate. Furthermore, the study highlights the importance of the spread of this fruit, which is nutritionally and medicinally beneficial, and its suitability to the region's conditions, especially the high temperatures in summer. The aim is to evaluate the complementary effect of vermicompost extract and foliar spraying with iron and boron in their nano-forms on the mineral content of papaya (*Carica papaya* L.) fruits under local environmental conditions.

2. Material and methods

2.1. Experiment Implementation

A field experiment was conducted on a private farm in the Musayyib Project (located at 32.5°N latitude and 44.3°E longitude) planted with papaya trees. The experiment took place from the beginning of October 2024 to the end of June 2025. The experiment investigated the effect of adding Vermicompost extract and spraying with nano-iron and nano-boron on the growth, yield, and mineral content of papaya trees. The experiment included three factors:

1- The first factor was the addition of vermicompost extract at two levels (0 and 50 ml L⁻¹).

2- The second factor was spraying with nano-boron at four levels (0, 5, 15, and 10 ml L⁻¹). Three sprays were applied on March 10, April 1, and May 2, 2025. Boric Acid Nano powder fertilizer containing 99.9% boron nanoparticles was used.

3- The third factor is the application of nano-iron at four levels (0, 2, 4, and 6 mg/L). Three applications were carried out on March 11, April 2, and May 3, 2025. Iron Oxide (Fe₂O₃) Nano powder fertilizer was used.

A factorial experiment was conducted using a completely randomized block design with three replicates. Each replicate contained 32 trees, with one tree per experimental unit, resulting in a total of 96 experimental units and 32 factorial treatments per replicate.

Table 1: Some Chemical and Physical Properties of Orchard Soil

Properties	Value	Units
pH	7.7	
Electrical Conductivity (EC) 1:1	1.9	dSm ⁻¹
Clay%	415	g kg ⁻¹
Sand%	186	g kg ⁻¹
Silt %	399	g kg ⁻¹
Soil texture	silty clay	g kg ⁻¹
Organic Matter (OM)	0.92	g kg ⁻¹
Total Nitrogen	31.6	g kg ⁻¹
Available Phosphorus	12.4	mg kg ⁻¹
Total Potassium	172.5	mg kg ⁻¹
Na	11	mg kg ⁻¹
Mg	3	mg kg ⁻¹
Ca	6	mg kg ⁻¹
Cl	8.8	mg kg ⁻¹
SO ₄	9.4	mg kg ⁻¹
HCO ₃	3	mg kg ⁻¹
B	1.15	mg kg ⁻¹

The soil sample was analyzed in the laboratories of the Science College, Baghdad University.

2.2. The parameters studied:

1. Calcium (Ca) % in Fruits: Calcium in the sample was estimated using EDTA titration. Ten milliliters of the digestion solution were taken, and sodium hydroxide (NaOH) was added to neutralize the solution. Murexide indicator was then added. Titration was performed using standard EDTA solution until a color change was observed, indicating the endpoint (AOAC, 2016).

2. Magnesium (Mg %) in Fruits: Magnesium in the sample was determined using EDTA titration. Ten milliliters of the sample were taken, a buffer solution at pH 10 was added, and then Eriochrome Black T indicator was added. Titration was performed using standard EDTA solution until a color change occurred, indicating the equivalence point (AOAC, 2016).

3. Potassium(K%) in Fruit: Potassium was estimated using a flame-photometer according to the method proposed by Hanson and Horneck (1998).

4. Sodium (Na%) in the fruit (%): Sodium % was determined using a flame photometer, according to the method proposed by Hanson and Horneck (1998).

5. Boron content of the fruit (mg kg⁻¹): Boron was estimated using the Azomethine-H colorimetric method, which relies on the formation of a yellow complex resulting from the reaction of boron with the reagent. Absorption was measured at 420 nm using a UV-Visible Spectrophotometer (Wolf, 1971).

6. Iron content of the fruit (mg kg⁻¹ dry weight): was estimated using an Atomic Absorption Spectrophotometer according to the methods of Allan (1961).

Statistical Analysis

Statistical analysis of the data was performed using Genstat 2010 software. The means of the treatments were compared using the LSD (Least Significant Difference) test at a significance level of 0.05 (Al-Khafaji & Al-Khamisi, 2012).

Results

1- Calcium (Ca) % in Fruits

Table (2) shows a significant positive effect of the percentage of calcium in the fruits. Vermicompost (V50) application resulted in the highest average (0.126%). Iron (Fe6) spraying also resulted in the highest average (0.136%). Boron (B15) treatment resulted in the highest average (0.108%) compared to the control treatment. Regarding the binary interactions, the combined treatments (V50 × Fe6), (V50 × B15), and (Fe6 × B15) achieved significant superiority, recording the highest percentages of (0.177%), (0.137%), and (0.162%), respectively. The response reached its maximum in the triplet interference (V50 × Fe6 × B15), which recorded the highest calcium percentage of (0.193%), absolutely superior to the comparison treatment, which gave the lowest values (0.077%).

Table (2) Impact of vermicompost and spraying iron and boron nanoparticles and their interactions on Ca%

Vermicompost	Nano B	Nano Fe				Vermicompost x Fe
		F0	F2	F4	F6	
V0	B0	0.021	0.043	0.068	0.081	0.053
	B5	0.032	0.056	0.071	0.085	0.061
	B10	0.036	0.060	0.075	0.087	0.065
	B15	0.040	0.064	0.079	0.131	0.078
V50	B0	0.077	0.101	0.123	0.164	0.116
	B5	0.085	0.105	0.128	0.172	0.123
	B10	0.092	0.110	0.132	0.178	0.128
	B15	0.099	0.115	0.141	0.193	0.137
LSD 5%		0.004**				0.002**
Vermicompost		Vermicompost x Fe				Vermicompost average
V0		0.032	0.056	0.073	0.096	0.064

Vermicompost	Nano B	Nano Fe				Vermicompost x Fe
V50		0.088	0.108	0.131	0.177	0.126
LSD 5%		0.002**				0.001**
Nano B		B x Fe				Boron Average
B0		0.049	0.072	0.096	0.122	0.085
B5		0.059	0.081	0.100	0.129	0.092
B10		0.064	0.085	0.104	0.133	0.096
B15		0.069	0.089	0.110	0.162	0.108
LSD 5%		0.003**				0.001**
Iron Average		0.060	0.082	0.102	0.136	
LSD 5%		0.001**				

2. Magnesium (Mg %) in Fruits

The results in Table (3) show a significant positive effect on the percentage of magnesium in the fruit. The addition of vermicompost extract (V50) resulted in the highest average (0.099%). Similarly, spraying with iron (Fe6) resulted in the highest average (0.126%). Spraying with boron (B15) achieved the highest average (0.105%) compared to the control treatments. Regarding the binary interactions, the combined treatments (V50 × Fe6), (V50 × B15), and (Fe6 × B15) showed significant superiority, recording the highest percentages of (0.178%), (0.151%), and (0.224%) respectively, compared to the control treatments. The response was at its peak with the triple interaction (V50 × Fe6 × B15), which achieved the highest magnesium percentage of (0.362%), absolutely surpassing the control treatment, which gave the lowest values (0.030%).

Table (3) Impact of vermicompost and spraying iron and boron nanoparticles and their interactions on Mg %

Vermicompost	Nano B	Nano Fe				Vermicompost x Fe
		F0	F2	F4	F6	
V0	B0	0.011	0.031	0.060	0.064	0.041
	B5	0.017	0.034	0.060	0.066	0.044
	B10	0.023	0.053	0.061	0.077	0.053
	B15	0.027	0.058	0.062	0.086	0.058
V50	B0	0.030	0.080	0.088	0.113	0.078
	B5	0.032	0.082	0.089	0.116	0.080
	B10	0.042	0.083	0.099	0.123	0.087
	B15	0.045	0.085	0.112	0.362	0.151
LSD 5%		Ns				Ns
Vermicompost		Vermicompos x Fe				Vermicompos average
V0		0.019	0.044	0.061	0.073	0.049
V50		0.037	0.083	0.097	0.178	0.099
LSD 5%		Ns				0.028**
Nano B		B x Fe				Boron Average
B0		0.020	0.056	0.074	0.088	0.059
B5		0.024	0.058	0.074	0.091	0.062
B10		0.033	0.068	0.080	0.100	0.070
B15		0.036	0.071	0.087	0.224	0.105
LSD 5%		Ns				Ns
Iron Average		0.028	0.063	0.079	0.126	

Vermicompost	Nano B	Nano Fe	Vermicompost x Fe
LSD 5%		0.040**	

3. Potassium(K%) in Fruit:

Table 4 shows a significant effect on the percentage of potassium in the fruit. The addition of vermicompost extract (V50) resulted in the highest average (2.148%). Similarly, spraying with iron (Fe6) and boron (B15) resulted in the highest average (2.284%), compared to the control treatments which recorded the lowest values. Regarding the binary interactions, the combined treatments (V50 × Fe6), (V50 × B15), and (Fe6 × B15) achieved significant superiority, recording the highest percentages of (2.353%), (2.235%), and (2.391%) respectively, compared to the control treatments. The response was at its peak with the triple interaction (V50 × Fe6 × B15), which achieved the highest percentage of potassium at (2.534%), absolutely surpassing the control treatment, which gave the lowest values (1.853%).

Table (4) Impact of vermicompost and spraying iron and boron nanoparticles and their

Vermicompost	Nano B	Nano Fe				Vermicompost x Fe
		F0	F2	F4	F6	
V0	B0	1.687	1.873	2.000	2.187	1.937
	B5	1.770	1.950	2.037	2.200	1.989
	B10	1.817	1.973	2.077	2.227	2.024
	B15	1.862	1.987	2.167	2.247	2.066
V50	B0	1.853	2.040	2.180	2.243	2.079
	B5	1.910	2.073	2.190	2.300	2.118
	B10	1.987	2.127	2.192	2.334	2.160
	B15	2.017	2.170	2.218	2.534	2.235
LSD 5%		0.025**				0.013**
Vermicompost		Vermicompos x Fe				Vermicompos average
V0		1.784	1.946	2.070	2.215	2.004
V50		1.942	2.103	2.195	2.353	2.148
LSD 5%		0.013**				0.006**
Nano B		B x Fe				Boron Average
B0		1.770	1.957	2.090	2.215	2.008
B5		1.840	2.012	2.113	2.250	2.054
B10		1.902	2.050	2.135	2.280	2.092
B15		1.939	2.079	2.192	2.391	2.150
LSD 5%		0.018**				0.009**
Iron Average		1.863	2.024	2.133	2.284	
LSD 5%		0.009**				

interactions on K %

4. Sodium (Na%) in the fruit (%):

Table (5) shows a significant positive effect on the percentage of sodium in the fruit. Vermicompost extract (V50) showed the highest average (0.113%). Iron (Fe6) spraying also showed the highest average (0.152%). Boron (B15) showed the highest average (0.118%) compared to the control treatment, which recorded the lowest values. Regarding the binary interactions, the combined treatments (V50 × Fe6), (V50 × B15), and (Fe6 × B15) showed a significant advantage, recording the highest percentages of (0.132%), (0.118%), and

(0.152%), respectively, compared to the control treatment. The response reached its maximum at the triplet interference ($V50 \times Fe6 \times B15$), which achieved the highest sodium percentage of (0.143%), absolutely surpassing the control treatment which gave the lowest values (0.080%).

Table (5) Impact of vermicompost and spraying iron and boron nanoparticles and their interactions on Na %

Vermicompost	Nano B	Nano Fe				Vermicompost x Fe
		F0	F2	F4	F6	
V0	B0	0.036	0.090	0.100	0.127	0.088
	B5	0.080	0.090	0.110	0.130	0.103
	B10	0.080	0.097	0.113	0.140	0.108
	B15	0.087	0.100	0.120	0.160	0.117
V50	B0	0.080	0.107	0.117	0.123	0.107
	B5	0.090	0.110	0.120	0.130	0.113
	B10	0.097	0.110	0.120	0.130	0.114
	B15	0.100	0.110	0.120	0.143	0.118
LSD 5%		0.009**				0.004**
Vermicompost		Vermicompos x Fe				Vermicompos average
V0		0.071	0.094	0.111	0.139	0.104
V50		0.092	0.109	0.119	0.132	0.113
LSD 5%		0.004**				0.002**
Nano B		B x Fe				Boron Average
B0		0.058	0.098	0.108	0.125	0.097
B5		0.085	0.100	0.115	0.130	0.108
B10		0.088	0.103	0.117	0.135	0.111
B15		0.094	0.105	0.120	0.152	0.118
LSD 5%		0.006**				0.003**
Iron Average		0.081	0.102	0.115	0.135	
LSD 5%		0.003**				

5. Boron content of the fruit (mg kg^{-1}):

Table 6 shows a significant positive effect on fruit boron content. Vermicompost extract (V50) recorded the highest average ($121.725 \text{ mg kg}^{-1}$). Iron (Fe6) spraying also achieved the highest average ($23.993 \text{ mg kg}^{-1}$). Boron (B15) achieved the highest average ($20.876 \text{ mg kg}^{-1}$) compared to the control treatment, which recorded the lowest values. Regarding the binary interactions, the combined treatments ($V50 \times Fe6$), ($V50 \times B15$), and ($Fe6 \times B15$) achieved significant superiority, recording the highest averages of ($24.819 \text{ mg kg}^{-1}$), ($22.786 \text{ mg kg}^{-1}$), and ($23.993 \text{ mg kg}^{-1}$), respectively, compared to the control treatment. The response reached its maximum with the triple interaction ($V50 \times Fe6 \times B15$), which achieved the highest boron content in the fruits ($26.033 \text{ mg kg}^{-1}$), absolutely surpassing the control treatment, which gave the lowest values ($16.077 \text{ mg kg}^{-1}$).

Table (6) Impact of vermicompost and spraying iron and boron nanoparticles and their interactions on B content

Vermicompost	Nano B	Nano Fe				Vermicompost x Fe
		F0	F2	F4	F6	
V0	B0	14.740	17.087	18.157	20.170	17.539
	B5	15.667	17.377	18.437	20.533	18.004
	B10	16.343	17.713	18.593	20.943	18.398
	B15	16.577	18.060	19.277	21.953	18.967
V50	B0	16.077	20.250	22.573	23.810	20.678
	B5	17.627	20.443	23.017	24.420	21.377
	B10	18.913	20.960	23.357	25.013	22.061
	B15	19.777	21.830	23.503	26.033	22.786
LSD 5%		0.394**				0.197**
Vermicompost		Vermicompos x Fe				Vermicompos average
V0		15.832	17.559	18.616	20.900	18.227
V50		18.099	20.871	23.113	24.819	21.725
LSD 5%		0.197**				0.099**
Nano B		B x Fe				Boron Average
B0		15.409	18.669	20.365	21.990	19.108
B5		16.647	18.910	20.727	22.477	19.690
B10		17.628	19.337	20.975	22.978	20.229
B15		18.177	19.945	21.390	23.993	20.876
LSD 5%		0.279**				0.139**
Iron Average		16.965	19.215	20.864	22.859	
LSD 5%		0.139**				

6. Iron content of the fruit (mg kg^{-1} dry weight):

Table (7) shows a significant positive effect on fruit iron content. Vermicompost extract (V50) recorded the highest average (141.72 g/kg^{-1}). Iron (Fe6) spraying also had the highest average ($244.76 \text{ mg kg}^{-1}$). Boron (B15) had the highest average ($168.70 \text{ mg kg}^{-1}$) compared to the control treatment, which recorded the lowest values. Regarding the binary interactions, the combined treatments ($V50 \times \text{Fe6}$), ($V50 \times \text{B15}$), and ($\text{Fe6} \times \text{B15}$) achieved significant superiority by recording the highest rates of ($246.08 \text{ mg kg}^{-1}$), ($125.640176.87 \text{ mg kg}^{-1}$), and (350.84 g.kg^{-1}) respectively, compared to the control treatment. The response reached its peak with the triple interaction ($V50 \times \text{Fe6} \times \text{B15}$), which achieved the highest iron content in the fruits, reaching ($353.64 \text{ mg kg}^{-1}$), absolutely superior to the control treatment, which gave the lowest values (31.4 mg kg^{-1}).

Table (7) Impact of vermicompost and spraying iron and boron nanoparticles and their interactions on Fe content

Vermicompost	Nano B	Nano Fe				Vermicompost x Fe
		F0	F2	F4	F6	
V0	B0	38.74	67.10	96.60	171.27	93.43
	B5	44.55	76.17	106.33	190.53	104.40
	B10	49.87	86.29	141.09	263.95	135.30
	B15	55.27	94.24	152.62	348.03	162.54
V50	B0	31.54	107.93	143.86	169.33	113.17
	B5	36.45	131.42	145.89	214.30	132.02
	B10	48.90	134.60	148.73	247.06	144.82
	B15	58.06	138.75	157.02	353.64	176.87
LSD 5%		7.10**				3.55**
Vermicompost		Vermicompos x Fe				Vermicompos average
V0		47.11	80.95	124.16	243.45	123.92
V50		43.74	128.18	148.88	246.08	141.72
LSD 5%		3.55**				1.78**
Nano B		B x Fe				Boron Average
B0		35.14	87.52	120.23	170.30	103.30
B5		40.50	103.80	126.11	202.42	118.21
B10		49.39	110.45	144.91	255.51	140.06
B15		56.67	116.50	154.82	350.84	169.70
LSD 5%		5.02**				2.51**
Iron Average		45.42	104.56	136.52	244.76	
LSD 5%		2.51**				

Discussion

The results in the tables above show a clear and significant effect of increasing vermicompost levels and spraying with nano-iron and boron on improving the nutrient content (Ca, Mg, K, Na, Fe, B) of fruits. The higher treatments (V50, F6, and B15) recorded the highest values compared to the other levels. This is attributed to the complementary role of these treatments in improving soil fertility and the efficiency of absorption and transport within the plant. Vermicompost is a rich source of readily available nutrients and improves the physical and chemical properties of the soil, such as increasing cation exchange capacity, improving aeration and water retention, and activating beneficial microorganisms. These combined factors lead to increased availability of macronutrients (K ,Ca, Mg, Na) in the root zone, resulting in higher accumulations in the fruit (Gutiérrez-Miceli et al.,2007; Pant et all, 2009; Easmin, et al.,2021; Oyege & Bhaskar, 2023). Nano-iron is characterized by high absorption efficiency due to its small particle size and high surface area, facilitating its entry through the leaves and translocation within plant tissues. Iron plays a pivotal role in chlorophyll formation and the activation of numerous enzymes involved in photosynthesis and respiration, leading to increased carbohydrate synthesis and improved plant growth, thus enhancing the absorption and accumulation of various nutrients in the fruit (Pestana et al., 2012; Khan et all, 2021; Ding et all, 2023; He et all, 2025; Mondal & Paul , 2026). Nano-boron contributes to improved sugar transport, regulation of cell wall structure, and enhanced cell division. It also improves calcium absorption and translocation, explaining the significant increase in Ca and B content in the fruit. Furthermore, the positive interaction between boron and other elements leads to improved nutrient utilization efficiency within the plant (Kumar et all, 2024; Singh et all, 2024; Mor, et al., 2025). The results of the two- and three-part interactions show significant superiority, with the combined treatment (V50 × F6 × B15) yielding the highest values for most of the studied elements. This is attributed to the synergistic effect of

improving the soil environment (via vermicompost) and increasing foliar uptake efficiency (via nanoparticles), which enhances physiological and biological processes within the plant, thereby increasing nutrient accumulation in the fruit. Overall, these results confirm that using high levels of vermicompost in conjunction with spraying nanoparticles (iron and boron) is an effective strategy for improving fruit nutritional value by enhancing the absorption, assimilation, and transport of elements within the plant.

Conclusion

We can conclude that the integration of vermicompost addition and spraying with nano-elements (iron and boron) is an effective strategy for improving plant nutrition and increasing fruit nutritional value. It is recommended to adopt the higher levels studied within integrated fertilization programs to achieve the best production and quality results. These results are of particular importance because papaya is a crop that has recently been introduced to Iraq, and it appears to respond highly to improved root environment and balanced nutrition under local conditions. Therefore, it is recommended to adopt integrated fertilization using vermicompost at appropriate levels, along with periodic spraying with nano-iron and boron, especially given the alkaline conditions prevalent in most Iraqi soils, which limit the availability of micronutrients such as iron and boron. Emphasis should be placed on the higher levels studied (V50, F6, B15) to enhance growth efficiency, yield, and fruit quality. It is also advisable to implement these treatments within integrated management programs that include improved drainage and irrigation regulation, and to conduct further field studies to adapt these recommendations to the specific conditions of different regions in Iraq.

Acknowledgments

We extend our sincere thanks to the owner of the papaya orchard for his cooperation and for allowing the research to be conducted on his land. We also thank the Middle Euphrates Technical University/Al-Musayyib Technical College for their support in completing this study. Finally, we thank the laboratories of the College of Science at the University of Baghdad for their assistance in conducting the chemical analyses.

Disclosure

None

References

- Abbas, AT and Abdulkadhim, SJ, 2024. The Impact of Biofertilization and Rootstock Type on the Development of Grafted Citrus *aurantifolia* Seedlings. *IOP Conference Series: Earth and Environmental Science*, [doi:10.1088/1755-1315/1371/4/042061](https://doi.org/10.1088/1755-1315/1371/4/042061)
- Abdeldaym, E. A., Mahmoud, A. W. M., Ayad, A. A., Abdel-Aziz, H. S. M., Williams, L. L., & El-Shazoly, R. M. (2022). Foliar application of different iron sources improves morpho-physiological traits and nutritional quality of broad bean grown in sandy soil. *Plants*, 11(19), 2599.
- Abdulkadhim, S. J. (2024). Influence of Bio-fertilization on Physical and Biochemical Parameters of Grapefruit Saplings Citrus *paradisi* Macfad. Under Salt Stress. *Basrah Journal of Agricultural Sciences*. 37(2), 78-89. doi.org/10.37077/25200860.2024.37.2.7
- Abdulkadhim, S. J. , Hashim, A. H. & Hadi, A. A. (2024). Impact of Nano-Chitosan on Proline, Antioxidant Defense Enzyme, Growth and Biochemical Parameters of Papaya

- Saplings (*Carica papaya* L.) Exposed to Water Stress. *Tikrit Journal for Agricultural Sciences*. 24 (4): 177-192. DOI: <https://doi.org/10.25130/tjas.24.4.15>
- Abdulkadhim, S. J. and Hashem, A. H. (2025). Influence of nano-silicon in antioxidants enzymes, ions absorption, and biochemical indicators of King Mandarin saplings leaves (*Citrus nobilis*) under salt stress. *Journal of Applied and Natural Science*, 17 (1), 126 - 132. <https://doi.org/10.31018/jans.v17i1.6148>
- Abdulkadhim, S.J. (2019). Influence of Bio- fertilizer and spraying with palm Pollen grains Extracts on some Growth indicators and Leaves Content of Nutrient in Pomegranate cv. salimi. *Plant Archives*, 19 (1), 1458-1464. DOI: [https://www.plantarchives.org/PDF%2019-1/1458-1464%20\(4777\).pdf](https://www.plantarchives.org/PDF%2019-1/1458-1464%20(4777).pdf)
- Al-Khafaji, H. G. & Al-Khamisi, S. B. A. (2012). Principles of statistics, design and analysis of agricultural experiments. Al Falah Library for Publishing and Distribution. Amman. Jordan
- Allan, J. E. (1961). The determination of iron and manganese by atomic absorption. *Spectrochimica Acta*, 17(4), 467-473.
- AOAC. (2016). Official Methods of Analysis of AOAC International (20th ed.). Association of Official Analytical Chemists, Rockville, MD.USA.
- Ding, H., Zhang, L., & Li, M. (2023). Penetration and mobility of iron nanoparticles in plant leaves. *Plant Physiology and Biochemistry*, 192, 45-53.
- Easmin, S. et al. (2021). Influence of organic and inorganic fertilizers on papaya. *Annals of Bangladesh Agriculture*, 24(2), 69–83.
- El-Araby, M., Ibrahim, A., & Hassan, S. (2024). Synergistic effects of Vermicompost and foliar micronutrients on papaya (*Carica papaya* L.) yield. *Horticultural Science*, 51(3), 201-215.
- Gutiérrez-Miceli, F. A., et al. (2007). Mechanisms of humic acids from Vermicompost in plant root enhancement. *Soil Biology and Biochemistry*, 39(12), 3051-3058.
- Hanson, C. G., & Horneck, D. A. (1998). Plant tissue analysis. In *Soil, Plant and Water Reference Methods for the Western Region* (pp. 137-146). Western Regional Extension Publication.
- Hashem, AH and Abdulkadhim, S J, 2024. Impact of Foliar Application with Amino Alexin and a Mixture of Marvel Fertilizer with Growth Regulator (Floratone) in Physio-Biochemical Parameters of Bitter Orange Saplings (*Citrus aurantium* L.), *IOP Conference Series: Earth and Environmental Science*, [doi:10.1088/1755-1315/1371/4/042056](https://doi.org/10.1088/1755-1315/1371/4/042056)
- Hashim, A. H., Abdulkadhim, S. J. & Hadi, A. A. (2026). Influence of IBA (Indole-3-butyric acid) dipping and BA (Benzyle adenine)–GA3 (Gibberellic acid) spraying on vegetative and biochemical traits of sour orange cuttings. *Journal of Applied and Natural Science*, 18(1), 89 - 95. <https://doi.org/10.31018/jans.v18i1.7134>
- He, M., Yu, J., Wei, Y., Munir, F., Haider, F. U., & Cai, L. (2025). Foliar application of iron nanoparticles improves plant growth and physiological traits in Chinese cabbage. *Plants*, 14(22), 3509. <https://doi.org/10.3390/plants14223509>
- Khan, A., Tariq, M., & Riaz, M. (2021). Physiological responses of fruit crops to foliar iron application. *Journal of Plant Nutrition*, 44(8), 1150-1165.

- Kumar, S., Singh, P., & Sharma, V. (2024). Nano-boron foliar application reduces tuber cracking and improves yield and quality in potato. *Biocatalysis and Agricultural Biotechnology*, 58, 103182. <https://doi.org/10.1016/j.bcab.2024.103182>
- Kumar, V., Sharma, A., Kaur, P., & Thukral, A. K. (2022). Vermicompost and its role in plant growth promotion: A review. *Environmental Science and Pollution Research*, 29, 12345–12360.
- Mahmoud, A. W., et al. (2022). Sustainable agriculture approaches using nano-fertilizers. *Sustainability*, 14(2), 723.
- Manavi, M. et al. (2025). Effect of nano boron on growth of papaya. *International Journal of Advanced Biochemistry Research*, 9(Special Issue).
- Mondal, A., & Paul, S. (2026). Iron nanoparticles as efficient nano fertilizers for sustainable agriculture. *Discover Plants*, 3, 36. <https://doi.org/10.1007/s44372-026-00481-8>
- Mor, R. et al. (2025). Impact of foliar boron and iron on yield of fruit crops. *Bangladesh Journal of Botany*, 54(3), 531–536.
- Nemati Lafmejani, H., et al. (2022). Nanotechnology in plant nutrition: Iron oxide nanoparticles. *Journal of Nano Research*, 75, 112-128.
- Oyege, I., & Bhaskar, M.S.B. (2023). Vermicompost and plant health. *Soil Systems*, 7(4), 101.
- Pant, A. P., et al. (2009). Vermicompost extracts influence on plant membrane permeability and nutrient uptake. *Bioresource Technology*, 100(23), 5881-5886.
- Pestana, M., et al. (2012). Iron accumulation and physiological activity in plants. *European Journal of Agronomy*, 41, 1-9.
- Rahman, M., et al. (2020). The importance of Vermicompost in improving soil health and crop productivity. *Environmental Sustainability*, 3(4), 355-368.
- Singh, R., Kumar, A., & Patel, R. (2024). Influence of foliar application of zinc and boron on seedling growth of papaya (*Carica papaya* L.). *Applied Biological Research*, 26(1), 110–116. <https://doi.org/10.48165/abr.2024.26.01.16>
- Wolf, B. (1971). The determination of boron in soil extracts, plant materials, composts, manures, water and nutrient solutions. *Communications in Soil Science and Plant Analysis*, 2(5), 363-374.
- Yadav, R., et al. (2023). Importance of boron in plant division and sugar transport. *Botanical Studies*, 64(1), 12-25.