

Growth and productivity response of local pepper plants to compost fertilization, mineral fertilizers and foliar spraying with micronutrients under sandy soil conditions in the Waddan region, Libya

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استجابة نمو وإنتاجية نبات الفلفل المحلي للتسميد العضوي والأسمدة المعدنية والرش الورقي بالعناصر الصغرى تحت ظروف التربة الرملية في منطقة ودان، ليبيا

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Abstract:

This study was conducted in the Waddan region (Al-Jufra) to evaluate the response of a local pepper cultivar to seven fertilization treatments, which included a balanced mineral fertilizer NPK (20-20-20), an organic fertilizer, and micronutrient foliar application. The results demonstrated statistically significant differences ($P \leq 0.05$) among all studied treatments, where the integrated nutrient management treatment (T7: 100% NPK + Organic Fertilizer + Micronutrients) exhibited a distinct superiority across all growth and yield parameters. Treatment T7 recorded the maximum values for plant height (76.0 cm), stem diameter (18.8 mm), and total chlorophyll content (59.2 mg/g FW). This physiological enhancement reflected positively on the yield components, as the same treatment achieved the highest weight for a 20-fruit sample (435.0 g) and the maximum total crop yield per experimental plot (1235.0 g). Conversely, the control treatment (T1) consistently recorded the lowest values.

The study underscores the critical importance of integrating organic fertilizer with mineral and foliar applications, a combination that provided a natural chemical shield that effectively minimized nutrient leaching within the porous sandy soil profile. Consequently, treatment T7 retained the highest concentrations of available soil macronutrients, recording 53.10 mg/kg for N, 23.30 mg/kg for P, and 350. mg/kg for K, as well as available micronutrients with values of 3.77 mg/kg for Mn, 3.65 mg/kg for Fe, and 1.38 mg/kg for Zn. Furthermore, available soil boron exhibited a precise and progressive response, reaching 0.82 mg/kg which physiologically optimized fruit-set success, reduced flower drop, and ensured uniformity in fruit size.

Keywords: Al-Jufra, *Capsicum annum*, Integrated Nutrient, Organic fertilizer, Sandy soil.

المخلص:

أجريت هذه الدراسة في منطقة ودان (الجفرة) لتقييم استجابة صنف الفلفل المحلي لسبع معاملات تسميدية تشمل السماد المعدني المتعادل (NPK 20-20-20)، والسماد العضوي، والرش الورقي بالعناصر الصغرى. أظهرت النتائج وجود فروق معنوية ($P \leq 0.05$) بين جميع المعاملات المدروسة، حيث تفوقت معاملة التسميد المتكامل + (NPK 100% سماد العضوي + عناصر صغرى) في جميع مؤشرات النمو والمحصول. حيث سجلت المعاملة (T7) أعلى قيم في طول النبات (76.0 سم)، وقطر الساق (18.8 ملم)، والمحتوى الكلي للكوروفيل (59.2 ملجم/جم وزن طازج). وانعكس هذا التحفيز الفسيولوجي إيجابياً على مكونات المحصول، حيث حققت المعاملة ذاتها أعلى وزن لـ 20 ثمرة (435.0 جم) وأقصى إنتاجية كلية للقطعة التجريبية (1235.0 جم). وفي المقابل، سجلت معاملة المقارنة (T1) باستمرار أدنى القيم.

تؤكد الدراسة على أهمية دمج السماد العضوي مع الإضافات المعدنية والورقية وقر حماية كيميائية طبيعية حذت بكفاءة من غسل العناصر الغذائية (Leaching) داخل القطاع الرمل المسمامي. واحتفظت المعاملة (T7) بأعلى تركيزات من العناصر الكبرى المتاحة $N = 53.1 \text{ mg/kg}$ و $P = 23.3 \text{ mg/kg}$ و $K = 350.50 \text{ mg/kg}$ ، والعناصر الصغرى $Mn = 3.77 \text{ mg/kg}$ و $Fe = 3.65 \text{ mg/kg}$ و $Zn = 1.38 \text{ mg/kg}$ علاوة على ذلك، أظهر البورون المتاح استجابة دقيقة وتصاعدية 0.82 mg/kg مما ساهم فسيولوجياً في تعزيز نجاح عقد الثمار، والحد من تساقط الأزهار، وضمان تماثل حجم الثمار.

الكلمات المفتاحية: التربة الرملية، التسميد المتكامل، الجفرة، السماد العضوي، الفلفل المحلي.

1. Introduction

Pepper (*Capsicum annum L.*) is one of the most vital vegetable crops belonging to the Salicaceae family both globally and locally, owing to its high nutritional value and rich content

of vitamins (such as A and C), mineral elements, and antioxidants. In Libya, the local cultivar known as "Belad Pepper" (Fefel Al-Belad) stands out as a distinct indigenous strain, particularly in the Waddan region within the Al-Jufra municipality, possessing unique morphological and physiological characteristics that enable it to adapt to arid desert environmental conditions.

The qualitative value of Belad pepper is reflected in its pungent flavor and firm, compact texture. The pungency of this cultivar ranges from 30,000 to 50,000 Scoville Heat Units (SHU), classifying it within the medium-to-high pungency range, which makes it highly desirable for local consumption patterns and traditional food industries.

Despite these genetic advantages, pepper cultivation in the Waddan region faces critical challenges related to low soil fertility and high soil alkalinity. These limitations adversely affect nutrient availability, leaf chlorophyll content, and consequently, the final yield. Therefore, there is a pressing need to adopt Integrated Nutrient Management (INM) strategies that combine mineral fertilizers (NPK), organic amendments (compost), and foliar application of micronutrients. This approach aims to enhance vegetative growth indicators, photosynthetic efficiency, and optimize the fruit's physical characteristics to reach its ideal standard specifications in terms of length, diameter, and specific weight.

This research aims to investigate the effect of different combinations of these fertilizers on the productive performance of Belad pepper under the environmental conditions of the Waddan region. Furthermore, it seeks to determine the optimal treatment that achieves the best balance between vegetative growth and pungent fruit quality, as well as to estimate the post-harvest availability of macrolelements (nitrogen, phosphorus, and potassium) and microelements (manganese, zinc, iron, and boron) remaining in the soil under the arid climatic conditions of Waddan city in Al-Jufra.

Research Problem:

The primary problem in the Waddan region lies in the decline of pepper crop productivity due to several environmental and technical factors, most notably:

1. **Sandy Soil Characteristics:** The soil in Waddan suffers from low organic matter content and a poor capacity to retain water and essential nutrients, which leads to the loss of applied mineral fertilizers through leaching.
2. **Climatic Conditions:** The arid climate and elevated temperatures increase the plant's requirement for micronutrients, which are often difficult for the roots to absorb from alkaline soils, thereby rendering foliar application necessary.
3. **Over-reliance on Chemical Fertilizers:** Excessive reliance on mineral fertilizers deteriorates the structure of sandy soils over the long term; hence, there is a pressing need to incorporate compost to enhance both the physical and chemical properties of the soil.

Study Objectives:

This study primarily aims to identify the optimal fertilizer combination (organic, mineral, and foliar) to achieve the highest productivity of pepper in Waddan, through the following specific objectives:

1. To investigate the interaction effect of compost, mineral fertilizer, and micronutrient foliar application on vegetative growth indicators (plant length and stem diameter) and yield parameters (number of fruits and total yield).
2. To evaluate the contribution of compost amendment in reducing the required amounts of mineral fertilizers while improving the post-harvest availability of macronutrients (N, P, and K) in sandy soil.
3. To determine the efficacy of foliar spraying in compensating for nutrient deficiencies (such as zinc and iron) that commonly manifest in the soils of the Al-Jufra region.

Materials and Methods

A field experiment was conducted during the 2025 growing season, where planting operations commenced in March on my private farm in Waddan city (Al-Jufra municipality), located at longitude 16°12'03.72" E and latitude 29°04'99.67" N.

Soil Sampling and Chemical Analysis:

Table (1): Physical and chemical properties of the experimental soil before planting:

Mechanical analysis (%)				Texture	Physical and chemical properties of tested soil. (Parameters)			Avail. nutrients mg/kg						
C. Sand	F. Sand	Silt	Clay		C (%)	SP (%)	O.M g/kg	N	P	K	Mn	Zn	Fe	B
3	67	12	8	Sandy loam	0.22	38	0.4	18.4	4.4	150	2.5	0.60	2.14	0.48

Soil samples were collected from each experimental plot at the end of the harvest season. The samples were immediately transported to the laboratory, where they were air-dried, carefully crushed, and passed through a 2-mm sieve to ensure particle homogeneity prior to conducting the required chemical analyses. Chemical analyses of the soil samples were performed to determine the available nutrient content both before planting and post-harvest, utilizing the following laboratory techniques and instrumentation:

Available Nitrogen (N): It was determined using the Kjeldahl distillation unit after acid digestion. The titration was performed against dilute sulfuric acid in accordance with the methodology described by (Bremner, 1982).

Available Phosphorus (P): It was extracted using a sodium bicarbonate solution (Olsen method). The concentration was subsequently measured colorimetrically using a spectrophotometer at a wavelength of 882 nm.

Available Potassium (K): It was extracted using a neutral ammonium acetate solution, and the concentration was quantified using a flame photometer.

Micronutrients (Fe, Zn, and Mn): The three elements were extracted using the DTPA chelating solution. Their concentrations were precisely determined using an Atomic Absorption Spectrophotometer (AAS), which relies on measuring the intensity of light absorption by atoms at specific wavelengths designated for each element.

Available Boron (B): It was determined using the hot water extraction method. The concentration was quantified via a spectrophotometer using Azomethine-H as a specific reagent for boron detection.

Irrigation Water Sampling and Measurement

A representative water sample was collected from the irrigation well feeding the field experiment in the study area. The sample was immediately transferred to the laboratory, where it underwent routine analysis to evaluate its physical and chemical properties. These analyses included measuring the pH, electrical conductivity (EC), and estimating the concentrations of dissolved cations (calcium, magnesium, sodium, and potassium) and dissolved anions (carbonate, bicarbonate, chloride, and sulfate). These parameters serve as a baseline guide to assess the chemical impact of irrigation water on soil properties and the growth of the local pepper cultivar.

Table (2): Physical and chemical characteristics of the irrigation well water used in the experiment:

Parameters	pH	EC	TDs	Na	Ca	Mg	K	Hco ₃	Cl	So ₄
		mS/cm	ppm	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L
	7.2	1.28	821	2.96	4.17	5.55	0.101	3.25	5.25	4.25

The water sample underwent laboratory analysis according to internationally recognized protocols to assess its compliance with international standards for irrigation water suitability. The standards and their respective analytical methods are as follows:

- Calcium (Ca²⁺): EDTA Titrimetric Method (Standard Methods 3500-Ca B).
- Magnesium (Mg²⁺): Titrimetric Method (Standard Methods 3500-Mg B).
- Sodium (Na⁺): Flame Emission Photometric Method (Standard Methods 3500-Na).
- Potassium (K⁺): Flame Photometry Method (Standard Methods 3500-K B).
- Carbonates (CO₃²⁻): Alkalinity Titrimetric Method (Standard Methods 2320 B).
- Bicarbonates (HCO₃³⁻): Alkalinity Titrimetric Method (Standard Methods 2320 B).
- Chloride (Cl⁻): ISO 9297:1989(E), Mohr's Method.

Sulphates (SO₄²⁻): Gravimetric Method with ignition of residue (Standard Methods 4500-SO₄).

- Hydrogen Power (pH): ISO 10523:2008(E), Electrode method.
- Electrical Conductivity (EC): ISO 7888:1985(E), Electrode method.

Total Dissolved Solids (TDS): Gravimetric method by evaporation at 180°C (Standard Methods 2540 C).

Applied Fertilizers

1. Mineral Fertilizers:

A fully water-soluble balanced compound mineral fertilizer, NPK (20-20-20), was utilized in this experiment. Its formulation consists of the following chemical compositions:

Total Nitrogen (N): 20%, formulated into two distinct chemical forms to ensure both immediate and sustained nutrient supply to the plant: Nitrate-Nitrogen (NO₃N) at 4% and Ammoniacal-Nitrogen (NH₄N) at 16%.

Phosphorus (P): 20% in the form of water-soluble phosphorus pentoxide (P₂O₅).

Potassium (K): 20% in the form of water-soluble potassium oxide (K₂O).

The mineral fertilizers (Nitrogen, Phosphorus, and Potassium) were applied split into several doses across the different plant growth stages.

2. Micronutrients:

A highly concentrated micronutrient fertilizer commercialized as Grand Max Plus was employed. This product features an integrated blend of chelated micronutrients designed to maximize absorption efficiency under unfavorable soil conditions. The formulation comprises: Zinc (Zn) 5%, Iron (Fe) 5%, Manganese (Mn) 4%, Magnesium (Mg) 2%, Copper (Cu) 0.5%, Boron (B) 0.5%, Molybdenum (Mo) 0.05%, and Sulfur (S) 10.48%.

Due to the alkaline nature of the soil in the Waddan region, which typically induces nutrient fixation and restricts root absorption of micronutrients, foliar application was adopted as the delivery method in this study. The application dosage was calibrated at a rate of 200 g per 200 L of water. The micronutrient solution was sprayed onto the vegetative canopy twice during the growing season: the first application was performed during the active vegetative growth stage, and the second was executed at the onset of flowering, targeting the specific treatment plots (T6 and T7).

3. Organic Compost:

The organic amendment used in this experiment was a 100% bio-based granulated organic fertilizer. It consists of a scientifically processed poultry manure blend, advanced-treated to ensure it is completely free from weed seeds, fungal pathogens, and insect pests. The manure underwent a complete stabilized aerobic fermentation process to ensure its biochemical maturity.

This organic fertilizer is characterized by a high concentration of organic macromolecules, particularly humic and folic acids. These organic substances play a critical role in mitigating salinity stresses and modifying the physical and chemical properties of sandy soils, especially in arid ecosystems.

The compost was broadcasted manually prior to transplantation at a rate of 135 kg per 1000 m² (equivalent to 1.35 tons/ha) and thoroughly incorporated into the topsoil layer to ensure optimal nutrient uptake by the establishing root system of the local pepper cultivar.

Table (3): Physical and chemical properties of the organic fertilizer used in the experiment:

Parameters	EC 1:8	pH	OM %	TN %	M.C %	NO ₃ g/kg	NH g/kg	K ₂ O %	CaO %	P ₂ O ₅ %
	3.4	6.5	45	3.0	9.5	1.98	4.95	2	26.5	2

Cultivation Method:

The experiment was implemented using a row-cropping system. A spacing of 50 cm between plants within the same row and 60 cm between adjacent rows was strictly maintained. This planting density was designed to provide adequate growing space for both the vegetative canopy and root systems of the local pepper seedlings, thereby minimizing inter-plant competition for essential nutrients and moisture within the sandy soil of the Waddan region.

Experimental Design

The field trial was laid out in a Randomized Complete Block Design (RCBD) with seven primary treatments, and each treatment was replicated four times, resulting in a total of 28 experimental plots. The seven experimental treatments were structured as follows:

Treatment 1 (T1 - Control): No application of compost, mineral fertilizers, or micronutrients.

Treatment 2 (T2): NPK at 50% of the recommended dose.

Treatment 3 (T3): NPK at 100% of the recommended dose.

Treatment 4 (T4): NPK at 50% + Organic Compost.

Treatment 5 (T5): NPK at 100% + Organic Compost.

Treatment 6 (T6): NPK at 50% + Organic Compost + Micronutrients.

Treatment 7 (T7): NPK at 100% + Organic Compost + Micronutrients.

The local pepper seedlings were transplanted in mid-March into planting holes at a depth of 5 cm, maintaining the designated 50 cm intra-row spacing to optimize physiological growth.

Growth and Yield Measurements:

At the end of the growing season, a random sample of 10 plants was selected from each experimental plot to measure morphological growth parameters, specifically plant length (cm) and stem diameter (mm). At full physiological maturity and harvest, fruits were gathered from the designated plants within each plot to evaluate yield components.

Fruit physical characteristics were assessed by determining the weight of a 20-fruit sample (g) from each plot. Fruit length (cm) and fruit diameter (mm) were measured precisely using a digital vernier caliper. Additionally, the total fruit yield per plant (g/plant) was calculated to

assess the overall performance and responsiveness of the local pepper cultivar to the various fertilization treatments under the environmental conditions of Waddan.

Qualitative and Biochemical Parameters

Total chlorophyll content in the actively growing leaves was determined colorimetrically following the scientific protocol described by (Gavrilenko and Zigalova, 2003; (Lamma & Moftah, 2016) to evaluate photosynthetic efficiency under the experimental conditions.

Post-harvest soil chemical analyses were conducted using the following standard methods:

Available Nitrogen (N): Quantified using a Kjeldahl distillation unit following acid digestion, and titrated against dilute sulfuric acid according to (Bremner, 1982).

Available Phosphorus (P): Extracted using a sodium bicarbonate solution (Olsen method) and measured colorimetrically with a spectrophotometer at a wavelength of 882 nm.

Available Potassium (K): Extracted using a neutral ammonium acetate solution and quantified via a flame photometer.

Available Micronutrients (Fe, Zn, and Mn): Extracted simultaneously using a DTPA chelating solution. Their concentrations were determined via an Atomic Absorption Spectrophotometer (AAS) based on atomic light absorption intensity at element-specific wavelengths.

Available Boron (B): Extracted using the hot water method and quantified via a spectrophotometer using Azomethine-H as a boron-specific chromogenic reagent.

Statistical Analysis:

All collected data were subjected to statistical analysis of variance (ANOVA) in accordance with the Randomized Complete Block Design (RCBD) protocol. The Least Significant Difference (L.S.D.) test at a probability level of $P \leq 0.05$ was employed to separate and compare the differences among treatment means. All statistical computations were performed using the IBM SPSS software package.

Results and Discussion:

Table (4). Effect of mineral fertilizers, compost, and micronutrient fertilizer on growth and harvesting stage parameters of pepper plant:

Treatments	plant height (cm)	Leg diameter (mm)	pod length (cm)	Pod diameter (mm)	20 grain weight /g)	yield (g/plot)	chlorophyll mg g ⁻¹
T(1)	45	10.0	3.2	12.5	152	420	31.2
T(2)	49	11.8	3.8	14.0	255	515	35.9
T(3)	55.3	12.5	4.3	16.6	325	730	43.3
T(4)	60.8	13.1	4.8	17.1	340	795	47.5
T(5)	62.2	13.8	5.1	17.8	385	955	51.1
T(6)	70.4	16.3	5.3	19.2	415	1030	53.5
T(7)	76	18.8	5.7	20.3	435	1235	59.2
F test	*	*	*	*	*	*	*
LSD at 5%	4.15	1.12	0.38	1.05	22.80	68.50	3.24

1. Plant Height (cm)

The data presented in Table (4) indicated that all treatments led to a significant increase in the plant height of pepper. Treatment (T7) achieved the highest value, recording 76.0 cm, followed by treatment (T6) with a value of 70.4 cm. Conversely, the control treatment (T1) recorded the lowest plant height at 45.0 cm.

These findings are in structural agreement with modern trends in plant nutrition. (Rai et al. , 2022) confirmed that combining organic amendments (compost) with mineral fertilizers enhances the longitudinal growth parameters of pepper plants more effectively than using chemical fertilizers alone, owing to improved soil structure and nutrient supply capacity. (Furthermore, Omidvari et al., 2021; Lamma & Amaref, 2025) reported that integrated nutrient management boosts absorption efficiency, which directly promotes cell elongation and increases plant height in Solanaceous crops.

This longitudinal increment is attributed to the fundamental role of nitrogen and micronutrients in stimulating cell division and synthesizing the essential proteins required for vegetative growth. This explanation is further supported by (López-Serrano et al., 2023) who demonstrated that micronutrient foliar application stimulates enzymatic and hormonal activities within pepper plants, resulting in a significant increase in plant height, leaf number, and total leaf area compared to the control group. (Alhadad & Aloraibi, 2025)

2. Stem Diameter (mm)

The highest value for stem diameter was recorded in treatment T7, reaching 18.8 mm, whereas the control treatment (T1) recorded the lowest value at 10.0 mm.

The biological superiority observed in treatment T7 is attributed to the role of the integrated fertilization system (mineral, organic, and foliar application) in supplying the plant with essential nitrogen and zinc. This nutrient synergy stimulated the activity of the vascular cambium cells, which are responsible for secondary growth (the increase in stem thickness). Additionally, zinc plays a critical role in the biosynthesis of natural auxins, particularly Indole-3-Acetic Acid (IAA), which promotes lateral cell expansion in sandy soils. Conversely, the absence of fertilization in the control treatment led to diminished lateral meristematic activity, resulting in thin and weak stems.

3. Fruit Length (cm)

The results illustrated in Table (4) showed a significant increase in pepper fruit length as a result of the different treatments. Treatment T7 (100% NPK + Organic Compost + Micronutrients) achieved the highest value, recording 5.7 cm, compared to the control treatment (T1), which recorded the lowest value at 3.2 cm.

These findings corroborate those obtained by (Al-Juthery et al. , 2020) who reported that integrating mineral fertilizers with organic amendments (compost) improves fruit growth parameters and increases pepper fruit length due to the role of organic matter in enhancing soil characteristics and facilitating the uptake of macroelements.

Moreover, these results are supported by (Kaur et al. , 2023) who confirmed that foliar spraying with micronutrients (specifically zinc and manganese) stimulates vital physiological processes and the synthesis of endogenous hormones within the plant, positively influencing fruit elongation and quality in Solanaceous crops. In the same context, (Zaki et al., 2021) indicated that utilizing integrated fertilization regimes that combine foliar nutrients with soil fertilization enhances photosynthetic efficiency. This mechanism explains the distinct superiority of the combined treatment (NPK + compost + micronutrients) in the current study.

4. Fruit Diameter (mm)

The tabulated data in Table (4) illustrated the prominent effect of the main treatments on the fruit diameter of pepper plants. It is evident that the treatment which recorded the highest values and a significant increase in fruit diameter was T7, reaching 20.3 mm, whereas the control treatment recorded the lowest value at 12.5 mm.

These results are in line with (Abu-Shahba et al., 2021) who confirmed that combining compost with mineral NPK fertilization improves the physical properties of the soil and provides plants with a balanced nutrient supply, which positively reflects on the size and diameter of pepper fruits. The results also match the findings of (Al-Juthery et al., 2020) who indicated that foliar

application of nano or chelated micronutrients (especially zinc and iron) plays a vital role in activating enzymes and photosynthetic processes, leading to a significant increase in the length, diameter, and weight of pepper fruits compared to the control plants.

(Furthermore, El-Habbasha et al., 2022) emphasized that the integration between organic (compost) and mineral fertilization minimizes nutrient leaching and maintains nutrient availability for longer periods, explaining the remarkable superiority in fruit quality when using the triple combination (NPK + compost + micronutrients).

5. Weight of 20 Fruits (g)

The data arranged in Table (4) revealed that under the combined effect of the fertilization treatments, T7 (100% NPK + Organic Compost + Micronutrients) recorded the highest value, reaching 435.0 g per pepper plant. On the other hand, the control group recorded the lowest value for the weight of 20 fruits compared to the other treatments, yielding only 152.0 g.

These outcomes are consistent with (Abdelkhalek et al., 2020), who reported that the integration between organic and mineral fertilization leads to a significant improvement in the fruit characteristics of pepper, particularly fruit weight and length, as a result of enhanced soil traits and nutrient availability.

Additionally, (Hamad et al., 2021) noted that foliar application of micronutrients (such as zinc, iron, and manganese) onto the vegetative canopy of pepper plants promotes photosynthesis and carbohydrate synthesis, which positively influenced the final weight of the 20-fruit sample compared to plants that did not receive micronutrient treatments.

6. Total Yield (g/experimental plot)

The results documented in Table (4) demonstrated that all experimental treatments led to a substantial increase in pepper crop yield (g/experimental plot). The combined treatment, which included 100% NPK + Organic Compost + Micronutrients (T7), achieved the highest productivity, recording 1235.0 g during the season. In contrast, the control treatment recorded the minimum yield value of 420.0 g.

These findings are in high agreement with (Al-Dulaimi et al., 2022) who asserted that integrated nutrient management combining organic matter and mineral fertilizers significantly improves fruit traits and the total weight of the pepper crop.

(Furthermore, Sani et al., 2023) pointed out that introducing micronutrients via foliar application, alongside organic compost, boosts photosynthetic efficiency and consequently increases the final yield. (Similarly, Zhang et al., 2021) stated that a balanced supply of nitrogen, phosphorus, and potassium (NPK) combined with organic matter contributes to enhancing soil quality and increasing pepper productivity compared to using mineral fertilizers alone.

7. Chlorophyll Content (mg/g Fresh Weight)

The data presented in Table (4) showed the interaction effect of mineral NPK fertilizers, organic compost, and micronutrient foliar spraying on the total chlorophyll content in pepper leaves. It was revealed that the combined treatment (T7) recorded the highest value for total chlorophyll content, reaching 59.2 mg/g FW, outperforming all other treatments significantly. In contrast, the control treatment (T1) recorded the lowest chlorophyll level at 31.2 mg/g FW.

These results align with (Zhou et al., 2022) who verified that combining organic and mineral fertilizers improves photosynthetic efficiency and increases the concentration of plant pigments in pepper. These findings are further strengthened by (Hassan et al. 2021) who indicated that foliar spraying with micronutrients (such as iron and zinc) plays a crucial role as co-factors in the biosynthesis of the chlorophyll molecule and prevents its degradation.

Table (5): The effect of mineral, organic, and micronutrient fertilizers on the post-harvest availability of macronutrients (N, P, K) and micronutrients (Mn, Zn, Fe, B) in the soil (mg/kg).

Treatments	Post-Harvest Available Macroelements (N, P, and K) and Available Micronutrients (Fe, Zn, Mn) and Boron (B) in the Soil (mg/kg).						
	N	P	K	Mn	Fe	Zn	B
T(1)	18.50	4.2	150	2.50	2.14	0.60	0.48
T(2)	22.10	7.8	220	2.57	2.23	0.68	0.55
T(3)	30.25	10.2	235.1	2.72	2.60	0.85	0.63
T(4)	36.60	14.5	285.6	2.98	2.80	0.94	0.68
T(5)	44.25	18.6	310	3.15	3.10	1.10	0.72
T(6)	47.1	20.1	320	3.40	3.25	1.22	0.76
T(7)	53.1	23.1	350.5	3.77	3.65	1.38	0.82
F test	*	*	*	*	*	*	*
LSD at 5%	3.45	1.88	21.30	0.24	0.21	0.11	0.05

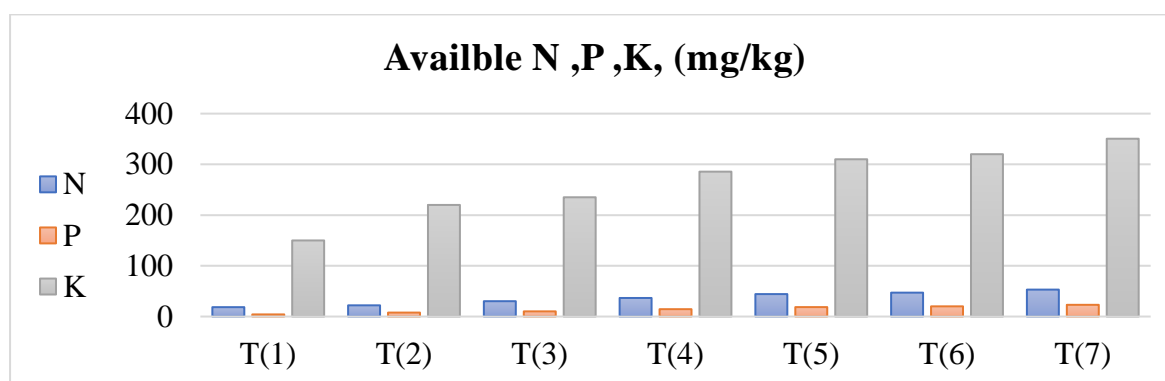


Figure (1): Effect of different fertilization treatments on the concentration of post-harvest available macronutrients (N, P, and K) in the soil (mg/kg)

The results illustrated in Table (5) revealed that all fertilization treatments induced a significant increase in the concentration of available macronutrients (N, P, and K) in the soil of the Waddan region compared to the control treatment. Owing to the porous and sandy nature of Waddan soil, compost amendment played a pivotal role in mitigating nutrient leaching and maintaining nutrient retention within the active root zone.

The integrated treatment (T7) achieved the highest concentrations of available nutrients remaining in the soil, recording 53.10 mg/kg for N, 23.30 mg/kg for P, and 350.50 mg/kg for K. Conversely, the control treatment (T1), which received no organic or chemical amendments, recorded the minimum values.

Based on these findings, available soil nitrogen increased remarkably due to the progressive mineralization of the organic compost, which acts as a slow-release nutrient reservoir. This mechanism effectively reduces nitrogen losses via volatilization or leaching in Waddan's coarse-textured soil.

Furthermore, the decomposition of compost contributed to a localized reduction in soil pH around the rhizosphere (root zone). This localized acidification facilitated the dissolution of calcium-bound phosphorus a predominant chemical fixation phenomenon in the calcareous soils of Waddan thereby increasing its availability for plant uptake.

The concomitant application of mineral NPK fertilizers alongside organic compost also significantly elevated the level of exchangeable potassium; the organic matter provided crucial cation exchange sites that protected potassium ions (K) from heavy leaching caused by irrigation water.

In this context, (Saleh et al., 2023) stated that organic matter serves as a regulated-release buffer for plant nutrients, which directly justifies the significant increase in available N, P, and K values in Waddan soil following the integrated application of compost and micronutrients.

Moreover, these results align with (Zaid et al., 2024) who conducted a study on nutrient dynamics in poor sandy soils and found that combining balanced mineral fertilization with organic compost increased the concentration of available nitrogen in the root zone by 35% to 50%.

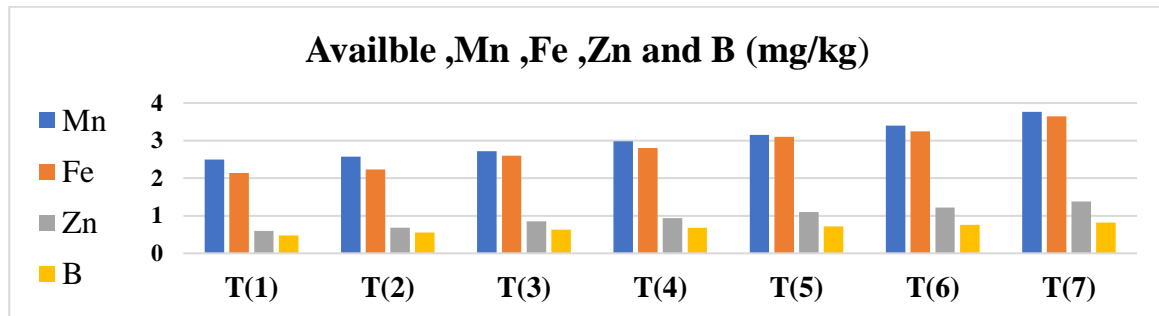


Figure (2): Effect of different fertilization treatments on the concentration of post-harvest available micronutrients and boron (Fe, Zn, Mn, and B) in the soil (mg/kg)

The incorporation of organic compost combined with the foliar application of chelated nutrients provided an effective natural chemical shield for these microelements. This synergistic interaction significantly enhanced their post-harvest residual statistical values in the soil, effectively transitioning the soil status from a nutrient-deficient medium to an enriched one.

Treatment (T7) recorded the highest available concentrations in the soil, yielding 3.77 mg/kg for Manganese (Mn), 3.65 mg/kg for Iron (Fe), and 1.38 mg/kg for Zinc (Zn). In contrast, the control treatment (T1) recorded the lowest values at 2.50, 2.14, and 0.60 mg/kg, respectively, as detailed in Table (5).

Similarly, available boron (B) exhibited a highly precise and significant progressive response. The calculated Least Significant Difference (L.S.D) value for boron was exceptionally low (0.05 mg/kg), demonstrating that the concentration increase from 0.48 mg/kg in T1 to 0.82 mg/kg in T7 represents a statistically genuine and highly impactful difference.

Physiologically, this enhanced boron availability contributed to reducing pepper flower drop, optimizing fruit-set success, and ensuring uniformity in fruit size.

These findings are strongly supported by (El-Hady et al., 2022; Sallam & Ibrahim, 2023) who confirmed that foliar spraying or soil application of chelated micronutrients in tandem with organic amendments in arid and calcareous soils (highly typical of the Al-Jufra region) markedly improves nutrient availability. The organic substances form stable complexes that prevent micronutrient precipitation and protect phosphorus from being fixed by active calcium carbonates (CaCO_3). (Abdel-Razzak et al., 2021)

Conclusion & Recommendation:

The study highly recommends adopting the triple integrated fertilization combination (T7) as a sustainable agricultural strategy to maximize local pepper productivity and restore the chemical and fertility properties of degraded sandy soils under the arid environmental conditions of the Libyan desert regions, with special emphasis on the Al-Jufra region.

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