Influence of Soil Application of Vermicompost Combined with Spraying of Melatonin on the Productivity and Fruit Quality of Mango

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Using organic materials in fruit production is an effective way to reduce dependency on chemical fertilization. This can cause many problems for the soil, increase beneficial microbes, and improve fruit quality. Organic fertilization provides the necessary nutrients to fruit trees safely, without causing any undesirable effects on soil fertility. Therefore, this study was conducted to examine the effects of soil application of vermicompost (VC), either alone or combined with spraying melatonin (MT), on the vegetative growth, productivity, and nutritional status of mango cv. Keitt. Mango trees were fertilized in January 2024 and 2025 with VC at 0, 3, and 5 kg for tree, then sprayed three times starting mid-February with 0, 50, and 100 mg L^{-1} MT at 20-day intervals compared to untreated trees. The treatments were arranged in a split-plot design within a randomized block design with five replicates. The results indicated that adding VC to the soil and spraying MT significantly enhanced the growth, productivity, and fruit quality of mango trees. The combined application of VC with MT spraying showed a notably greater increase than the individual treatments. The best results were achieved with 5 VC + 100 MT, followed by 5 VC + 50 mg L^{-1} MT, outperforming other treatments across the two seasons.

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INTRODUCTION

Mango (*Mangifera indica* L.) is a member of the family Anacardiaceae. The mango tree is evergreen and is regarded as one of the most important fruits in tropical and subtropical countries. To achieve optimal growth and yield, mango trees need a significant annual intake of nutrients, including both micro- and macronutrients, in readily available forms (Paull and Duarte 2011).

Organic fertilizers improve soil fertility by supplying essential nutrients while also providing environmental benefits, including reducing water eutrophication and soil compaction from excessive chemical fertilizer use, enhancing nitrogen fixation, and thereby lowering emissions and helping to mitigate the greenhouse effect (Ning *et al*. 2017). Organic fertilizers can sustain soil fertility and enhance plant development, with VC being particularly valued for improving soil structure. They boost fertility and increase crop productivity. They contain key nutrients such as phosphorus and potassium that support growth, flowering, and yield even at low application rates. Their effectiveness is also attributed to bioactive compounds, including plant hormones and humic acids (Gashaw 2019; Mosa *et al*. 2024). Applying organic fertilizers to soil enhances microbial activity and nutrient content, thereby promoting nutrient decomposition and release, and improving plant uptake and utilization of essential elements (Przemieniecki *et al.* 2021). Organic fertilizers enhance soil fertility and crop productivity while also helping to mitigate soil degradation and water pollution associated with long-term chemical fertilizer use (Madjar *et al.* 2024; Sachdeva *et al.* 2025).

Vermicompost (VC) is an organic fertilizer characterized by low carbon content, high nutrient levels, and easy biodegradability (Dominguez and Edwards 2011). Additionally, VC has a relatively high cation exchange capacity, allowing it to retain and gradually release nutrients, thereby ensuring a continuous supply of essential elements to plants (Aalok *et al.* 2008). Moreover, VC improves soil exchange capacity, mineral composition, and nutrient availability, making it an effective soil conditioner that enhances soil fertility (Srivastava *et al.* 2011). Due to its high nutrient content, active microbial population, and water-holding capacity, VC is regarded as a sustainable and eco-friendly alternative to chemical fertilizers (Joshi *et al.* 2015; Ducasse *et al.* 2022). It acts as a natural growth stimulant and soil conditioner because it is enriched with beneficial microorganisms and nutrients during the vermicomposting process (Bellitürk 2018; Aransiola *et al.* 2024). Furthermore, VC contributes to the decomposition of organic residues and improves soil fertility, while exhibiting a limited capacity to aid in the breakdown of certain inorganic compounds, thereby enhancing overall soil quality (Lukashe *et al.* 2019). Numerous studies have demonstrated that VC improves nutrient availability and crop productivity by supplying essential nutrients, humic substances, growth hormones, and enzymes that enhance plant nutrition, photosynthesis, and crop quality, while also reducing soil degradation and promoting organic carbon sequestration (Oyege and Balaji Bhaskar, 2023). Produced through the combined activity of earthworms and microorganisms, VC is an environmentally friendly and cost-effective soil amendment that accelerates organic matter decomposition, enriches soil nutrients, increases microbial diversity, and promotes plant growth and productivity (Lirikum *et al.* 2022; Vyas *et al.* 2022). In addition, VC improves soil physical properties. Rivier *et al*. (2022) reported that VC application enhanced soil structure, increased water-holding capacity and macro-aggregate formation, and reduced soil bulk density, even at low application rates. Li *et al*. (2023) further demonstrated that VC stimulates the growth and activity of plant-growth-promoting fungi, thereby improving nutrient uptake. In addition, VC supplies a wide range of minerals, organic matter, and micronutrients necessary for sustained plant nutrition and enhanced microbial activity (Rupani *et al*. 2023). According to Prisa and Jamal (2025), VC promotes shoot and leaf development, improves produce quality and shelf life, enhances soil aeration and water-holding capacity, supports beneficial microorganisms, and facilitates the decomposition of organic matter.

Melatonin (MT) is a useful plant growth stimulator and can act throughout the life cycle, including adventitious root regeneration, lateral root development, flowering and fruit ripening, and delaying leaf senescence (Chen *et al*. 2019). The exogenous application of MT has demonstrated multiple beneficial effects, such as protecting chloroplasts from photo-synthetic damage (Wang *et al.* 2012), maintaining higher leaf water content and turgor pressure, and preserving the integrity of spongy tissues under drought conditions (Meng *et al.* 2014). The application of MT has been shown to enhance the photosynthetic rate by reducing chlorophyll degradation and alleviating the detrimental impacts of water stress (Zhang *et al*. 2013). Furthermore, MT is reported to play a positive role in improving plant photosynthetic efficiency under drought conditions (Yu *et al.* 2018). Arnao and Hernández-Ruiz (2019) documented that the application of MT regulates several physiological processes, such as metabolism, osmoregulation, photosynthesis, anti-senescence mechanisms, and the modulation of plant hormones. The MT acts as a hormone-like compound that supports nutrient absorption and encourages plant growth and root formation, particularly in adventitious and lateral roots. Ren *et al*. (2019) documented that MT works with IAA to promote lateral root growth in wild-type *Arabidopsis* by affecting auxin distribution through the regulation of IAA translocation. The effect of MT as a plant growth regulator is attributed to its growth-promoting properties and its capacity to enhance yield by regulating ion homeostasis (Sadak *et al.* 2020). Moreover, MT application significantly mitigates drought-induced damage by sustaining nutrient uptake, preventing growth inhibition, and protecting stomatal aperture, photosynthesis, and relative water content, while also eliminating oxidative stress (Rehaman *et al.* 2021).

Hence, the objective of the present investigation was to evaluate the impact of the soil addition of vermicompost, solely or combined with the spraying of melatonin, on the growth and productivity of mango trees.

EXPERIMENTAL

Experimental Site Description and Its Design

The current study investigated the effect of applying vermicompost (VC) at levels of 0, 3, and 5 kg per tree or replicate in January. Trees were foliar-sprayed three times starting in mid-February at 20-day intervals with melatonin (MT) at concentrations of 0, 50, and 100 mg L^{-1}. The total spray volume was 20 L, with 4 L applied per tree (or replicate). The experiment was conducted on the 10-year-old mango cv. Keitt grafted onto Sukkary rootstock. The mango trees were planted at 3 m × 3 m spacing in Nubaria (latitude 30°26′28″ N, longitude 30°18′0″ E), El Beheira Governorate, Egypt, during the 2024 and 2025 seasons using 45 uniform trees in size and vigor. A split-plot design was used with five replicates (five trees) per treatment. The VC soil application was allocated to the main plots, while the MT foliar spray was assigned to the sub-plots. Soil properties are presented in Table 1.

Table 1. Physical and Chemical Composition of the Experimental Soil

Mechanical Analysis (%)									
Sand		Silt	Clay	Textural class	$CaCO_3$ (%)	Organic matter (%)	pH	EC (dS/m^{-1}) (Soil extraction 1:5)	
92.5		4.5	3.0	Sandy	4.8	0.27	7.75	0.812	
Available nutrients (mg kg^{-1})			Soluble anions (meq L^{-1})			Soluble cations (meq L^{-1})			
N	P	K	HCO_3^-	CL^-	SO_4^{--}	Ca^{++}	Mg^{++}	Na^+	K^+
117.5	18.2	190	3.12	3.75	4.10	2.20	1.50	3.60	0.42

Tables 2 and 3 present the corresponding physicochemical properties of the vermicompost and weather information during the study period.

Table 2. Physicochemical Properties of Vermicompost

OM %	OC %	C/N	CEC (Meq 100 g^{-1})	pH (1:5)	EC (1:5) dSm^{-1}	Moisture content (%)
26.44	15.34	11.62	128	6.93	4.82	37

Macronutrients					Micronutrients (mg kg^{-1})			
N %	K %	P %	Ca %	Mg %	Fe	Mn	Cu	Zn
1.32	0.95	1.07	3.17	0.54	3000	100.3	56.24	149

OC: Organic carbon; OM: Organic matter; C/N: Corbon/nitrogen ratio; EC: Electrical conductivity

Table 3. Monthly Meteorological Data for the Experimental Site During the 2024 and 2025 Seasons

Year	2024				2025			
Months	Min Temp (°C)	Max Temp (°C)	Avg RH (%)	Precipitation (mm)	Min Temp (°C)	Max Temp (°C)	Avg RH (%)	Precipitation (mm)
January	12.20	19.84	66.88	28.20	11.95	21.09	73.76	2.10
February	11.50	20.30	71.17	13.90	10.80	18.96	63.19	5.50
March	12.55	23.27	64.55	8.90	13.05	25.22	60.65	2.50
April	15.70	28.03	63.53	2.80	14.67	26.22	60.42	2.10
May	18.07	29.92	55.40	0.00	18.04	30.25	53.75	7.40
June	22.39	35.66	58.55	0.30	20.28	32.29	63.50	10.10
July	24.64	35.61	60.53	0.00	23.11	35.12	60.97	1.60
August	24.73	35.54	59.61	0.00	24.60	34.95	59.28	0.00
September	23.87	33.45	60.04	0.00	22.71	32.29	63.35	11.20
October	20.47	29.77	62.07	0.00	19.87	29.86	62.10	1.30
Average	18.61	29.14	62.23	54.10	17.91	28.62	62.10	43.80

Min Air Temp (°C) = Minimum Air Temperature [°C] ; Max Air Temp (°C) = Maximum Air Temperature [°C] ; Avg RH (%) = Average Relative Humidity (%); Precip. (mm) = Total Precipitation (mm)

The trees were sprayed three times, in April, mid-April, and early May of the 2024 and 2025 seasons. The effects of these treatments were evaluated by examining their impact on subsequent parameters.

Vegetative growth parameters

In October, after harvesting fruits in 2024 and 2025, shoot length and diameter were measured in cm, and shoot number was counted. Leaf chlorophyll index was estimated using a chlorophyll meter (SPAD-502, Minolta, Japan). Ten readings per tree (replicate) were recorded and expressed as SPAD values. Trunk girth was measured in cm. Leaf area (cm^2) was measured in the first week of October using 20 leaves and the following Eq. 1 (Demirsoy 2009),

$$LA = 0.70\,(L \times W) - 1.06 \qquad (1)$$

where LA = leaf area (cm^2), L = maximum length of leaf (cm), and W = maximum width of leaf (cm).

Fruit set percentages, fruit drop percentages, and fruit yield

Fruit set and fruit drop percentages were calculated according to Eqs. 2 and 3, respectively:

$$\text{Fruit set \%} = \frac{\text{Number of fruit setting}}{\text{Total number of flowers}} \text{ X } 100 \tag{2}$$

$$\text{Fruit drop \%} = \frac{\text{Number of fruit setting} - \text{Number of mature fruits}}{\text{Number of fruit setting}} \text{ X } 100 \tag{3}$$

Fruit yield was assessed by calculating each replicate/tree's yield in kilograms (kg), then converting to tons per hectare by multiplying the average tree yield by the total number of trees in a hectare.

Fruit Quality

Fruit physical characteristics

During the harvesting period (October 2024 and 2025), 10 fruits were randomly selected from each replicate, and the average weight and size were measured. The dimensions of the fruits, including length and thickness, were determined using a digital Vernier caliper from Cangxian Sanxing Hose Clamp Co., Ltd., China. Fruit firmness was measured using a Magness–Taylor pressure tester, according to the method described by Magness and Taylor (1925). Firmness was determined on two opposite peeled sides of each fruit, and the results were expressed as pounds per square inch (lb inch^{-2}).

Fruit chemical characteristics

Total soluble solids (TSS%) were gauged using a handheld refractometer. The fruit's acidity was quantified calorimetrically by estimating citric acid content *via* titration of 5 mL of fruit juice with 0.1 N NaOH using phenolphthalein (AOAC 2005). The vitamin C or ascorbic acid (AsA) content (mg 100 mL^{-1} juice) was assessed with 3% oxalic acid and 2,6-dichlorophenol indophenols (Nielsen 2017). Total, reducing, and non-reducing sugars were determined from fresh fruit pulp. Five grams of fresh pulp were homogenized with distilled water, and the volume was adjusted to a known volume. The extract was filtered and used to determine sugar content. Total sugars were determined colorimetrically using the phenol–sulfuric acid method according to Nielsen (2010), in which 1 mL of the extract was mixed with 1 mL of 5% phenol solution, then rapidly added to 5 mL of concentrated sulfuric acid. After standing for 20 to 30 min at room temperature, absorbance was measured at 490 nm using a spectrophotometer, and total sugar concentration was calculated from a glucose standard curve and expressed as g 100 g^{-1} fresh weight. Reducing sugars were determined by the 3,5-dinitrosalicylic acid (DNS) method (Miller 1959), in which 1 mL of the extract was mixed with 1 mL DNS reagent and heated in a boiling water bath for 5 to 10 min. After cooling, distilled water was added to a fixed volume, and absorbance was measured at 540 nm. Reducing sugar concentration was calculated using a glucose standard curve and expressed as g 100 g^{-1} fresh weight. Non-reducing sugars were calculated as the difference between total sugars and reducing sugars according to Nielsen (2010) and expressed as g 100 g^{-1} fresh weight.

Mineral Content in Mango Leaves and Fruits

At the end of the growing season, 20 leaves were collected in October 2024 and 2025 (Arrobas *et al*. 2018) for the determination of mineral contents, including nitrogen (N), phosphorus (P), and potassium (K). The collected leaves were washed with tap water followed by distilled water, dried at 70 °C until a constant weight was reached, and then finely ground. The powdered leaf samples were digested using a mixture of sulfuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2) to completely decompose organic matter and convert nutrients into a clear solution suitable for analysis. In the digestion process, sulfuric acid was first added to break down plant tissues and convert nitrogen into inorganic forms, followed by gradual addition of hydrogen peroxide to ensure complete oxidation and obtain a transparent digest. Nitrogen was then determined using the micro-Kjeldahl method (Wang *et al*. 2016). Phosphorus was measured by the vanadomolybdate colorimetric method (Wieczorek *et al*. 2022) with spectrophotometric reading at 405 nm. Potassium was quantified using a flame photometer (Asch *et al*. 2022) based on the emission intensity of the element in a flame.

Statistical Analysis

The data were statistically analyzed using a split-plot design, and the least significant difference at 5% was used to compare the means of the treatments (Snedecor and Cochran 1990) using CoHort Software (Pacific Grove, CA, USA).

RESULTS

The results indicate that both soil application of VC and foliar spraying of MT significantly improved plant growth parameters, including shoot number, trunk girth, and chlorophyll index (SPAD) in both 2024 and 2025 (Table 4).

Table 4. Effect of Soil Application of VC and Foliar Spraying of MT, Alone or in Combination, on Shoot Number, Trunk Girth and Leaf Chlorophyll Index of Mango cv. Keitt during the 2024 and 2025 Seasons

Soil Application	Foliar Spray	Shoot Number		Trunk Girth (cm)		Chlorophyll Index (SPAD value)	
		2024	2025	2024	2025	2024	2025
Zero VC	0 mg L⁻¹ MT	38.80f	38.49e	7.56f	9.23e	38.16e	41.06e
	50 mg L⁻¹ MT	40.84e	43.13d	7.73f	9.64d	41.44d	43.41de
	100 mg L⁻¹ MT	44.10d	45.12d	8.93d	10.59c	44.01d	44.92d
3 kg VC	0 mg L⁻¹ MT	43.11d	43.13d	8.51e	9.85d	42.18d	43.42de
	50 mg L⁻¹ MT	45.38d	48.19c	9.61c	10.82c	47.55c	46.15d
	100 mg L⁻¹ MT	47.257c	48.39c	9.81c	11.96b	50.81b	50.43c
5 kg VC	0 mg L⁻¹ MT	43.55d	44.09d	8.68de	10.41c	42.57d	45.43d
	50 mg L⁻¹ MT	49.87b	53.23b	10.52b	12.30b	52.80b	54.47b
	100 mg L⁻¹ MT	53.35a	56.04a	11.98a	13.59a	55.25a	56.77a
$LSD_{0.05}$		1.75	2.10	0.32	0.37	2.20	2.01

Note: $LSD_{0.05}$ represents: Least significant difference at the 0.05 significance level; Treatments sharing the same letter within a column are not significantly different.

Increasing VC levels from 0 to 5 kg, combined with higher MT concentrations, consistently enhanced all measured traits. The highest values were recorded under the combined treatment of 5 kg VC with 100 mg L^{-1} MT, which produced the greatest shoot number, trunk girth, and chlorophyll content in both seasons. In contrast, the control treatment (0 VC and 0 MT) showed the lowest performance across all parameters. Overall, the results demonstrate a strong positive interaction between organic soil amendment and foliar nutrition, indicating that integrated nutrient management significantly improves vegetative growth and plant physiological status over time.

The results presented in Table 5 demonstrated that soil application of VC and foliar spraying with MT, either individually or in combination, significantly enhanced leaf area, shoot length, and shoot diameter during the 2024 and 2025 growing seasons compared with the untreated control. In general, increasing VC levels from 0 to 5 kg $plant^{-1}$ and MT concentrations from 0 to 100 mg L^{-1} led to progressive improvements across all measured vegetative growth parameters. The greatest values of leaf area (85.98 and 90.67 cm^2), shoot length (49.22 and 51.64 cm), and shoot diameter (8.20 and 8.45 cm) in 2024 and 2025, respectively, were recorded with the combined treatment of 5 kg VC and 100 mg L^{-1} MT, whereas the lowest values were observed in the untreated control.

Table 5. Effect of Soil Application of VC and Foliar Spraying of MT, Alone or in Combination, on Leaf Area, Shoot Length and Diameter of Mango cv. Keitt during the 2024 and 2025 Seasons

Soil Application	Foliar Spray	Leaf Area (cm^2)		Shoot Length (cm)		Shoot Diameter (cm)	
		2024	2025	2024	2025	2024	2025
0 VC	0 mg L^{-1} MT	71.05e	73.21g	32.02f	35.11d	6.23g	6.55f
	50 mg L^{-1} MT	74.16d	75.98f	34.71e	37.71d	6.41f	6.83e
	100 mg L^{-1} MT	79.70b	82.94d	40.87d	44.15c	7.02d	7.30d
3 kg VC	0 mg L^{-1} MT	76.45c	77.85e	35.33e	38.10d	6.79e	6.84e
	50 mg L^{-1} MT	79.94b	83.06c	44.04c	46.74bc	7.38c	7.62c
	100 mg L^{-1} MT	80.96	83.88c	44.81c	47.59b	7.53c	7.91b
5 kg VC	0 mg L^{-1} MT	77.12c	80.82d	36.04e	43.65c	6.97de	7.25d
	50 mg L^{-1} MT	81.68b	87.09b	46.74b	49.10ab	7.96b	8.37a
	100 mg L^{-1} MT	85.98a	90.67a	49.22a	51.64a	8.20a	8.45a
$LSD_{0.05}$		2.03	1.20	1.64	2.61	0.18	0.18

Fruit set percentage was significantly affected by both soil application of VC and foliar application of MT during the 2024 and 2025 seasons (Table 6). The lowest fruit set was recorded in untreated trees (0 VC + 0 mg L^{-1} MT), reaching 7.81 and 8.72% in 2024 and 2025, respectively, while the highest values were obtained with the combined treatment of 5 kg VC and 100 mg L^{-1} MT, which increased fruit set to 10.67 and 11.21% in the respective seasons. Intermediate treatments showed gradual improvements in fruit set as the rates of VC and MT increased. In contrast, fruit drop percentage decreased significantly with increasing VC and MT levels. The highest fruit drop was observed in the control treatment (0 VC + 0 mg L^{-1} MT), recording 83.06 and 80.87% in 2024 and 2025, respectively. Application of 3 and 5 kg VC combined with MT sprays progressively reduced fruit drop, with the lowest values (70.72 and 65.46% in 2024 and 2025, respectively) recorded under the combined treatment of 5 kg VC and 100 mg L^{-1} MT. These results indicate that the combined application of VC and MT enhanced fruit retention by increasing fruit set and reducing fruit drop during both seasons.

Table 6. Effect of Soil Application of VC and Foliar Spraying of MT, Alone or in Combination, on Fruit Set and Fruit Drop Percentages of Mango cv. Keitt during the 2024 and 2025 Seasons

Soil Application	Foliar Spray	Fruit Set (%)		Fruit Drop (%)	
		2024	2025	2024	2025
0 VC	0 mg L^{-1} MT	7.81f	8.72e	83.06a	80.87a
	50 mg L^{-1} MT	8.32e	8.77e	81.88ab	79.44a
	100 mg L^{-1} MT	9.66c	10.17c	77.17cd	73.69cd
3 kg VC	0 mg L^{-1} MT	9.13d	9.00e	80.82b	76.74b
	50 mg L^{-1} MT	9.80c	10.21c	75.95de	72.86d
	100 mg L^{-1} MT	10.20b	10.42c	74.50ef	70.77e
5 kg VC	0 mg L^{-1} MT	9.54c	9.63d	78.47c	75.71bc
	50 mg L^{-1} MT	10.28b	10.77b	73.49f	69.04e
	100 mg L^{-1} MT	10.67a	11.21a	70.72g	65.46f
$LSD_{0.05}$		0.30	0.32	1.51	2.03

The effect of VC soil application and MT foliar spray on fruit weight and fruit yield (kg $tree^{-1}$ and ton ha^{-1}) during the 2024 and 2025 seasons is shown in Fig. 1. In general, all treatments increased fruit weight and yield compared with the untreated control (0 VC + 0 mg L^{-1} MT). Fruit weight increased progressively with increasing rates of both VC and MT. The lowest fruit weight was recorded in the control treatment, reaching 443.9 and 458.1 g in 2024 and 2025, respectively, whereas the highest values were obtained with 5 kg VC combined with 100 mg L^{-1} MT, reaching 566.5 and 564.8 g in the two seasons, respectively. Similarly, fruit yield per tree and per hectare responded positively to the treatments. The control treatment produced the lowest yields, with 32.1 and 34.1 kg $tree^{-1}$, corresponding to 34.2 and 36.3 ton ha^{-1} in 2024 and 2025, respectively. Increasing VC and MT concentrations resulted in gradual improvements in yield. The highest yields were achieved by the combination of 5 kg VC and 100 mg L^{-1} MT, recording 42.0 and 43.0 kg $tree^{-1}$ and 44.8 and 45.9 ton ha^{-1} during the first and second seasons, respectively. The combination of 5 kg VC with 50 mg L^{-1} MT also yielded high values, indicating that VC and MT interacted synergistically to enhance fruit size and overall productivity. Overall, the results demonstrate that the combined application of VC and MT was more effective than either treatment alone, with the greatest improvements observed at 5 kg VC and 100 mg L^{-1} MT in both seasons.

The results presented in Tables 7 and 8 demonstrated that soil application of VC, combined with foliar spraying of MT, significantly improved fruit physical characteristics during the two growing seasons. Regarding fruit firmness and fruit size, increasing compost levels from 0 to 10 kg, along with increasing MT concentration from 0 to 100 mg L^{-1}, resulted in a progressive and significant enhancement in both traits. The combined treatment of 10 kg compost and 100 mg L^{-1} MT recorded the highest fruit firmness values (24.3 and 24.3 lb $inch^{-1}$ in 2024 and 2025, respectively) and the greatest fruit size (586.5 and 585.3 cm^3 in 2024 and 2025, respectively), whereas the untreated control showed the lowest values.

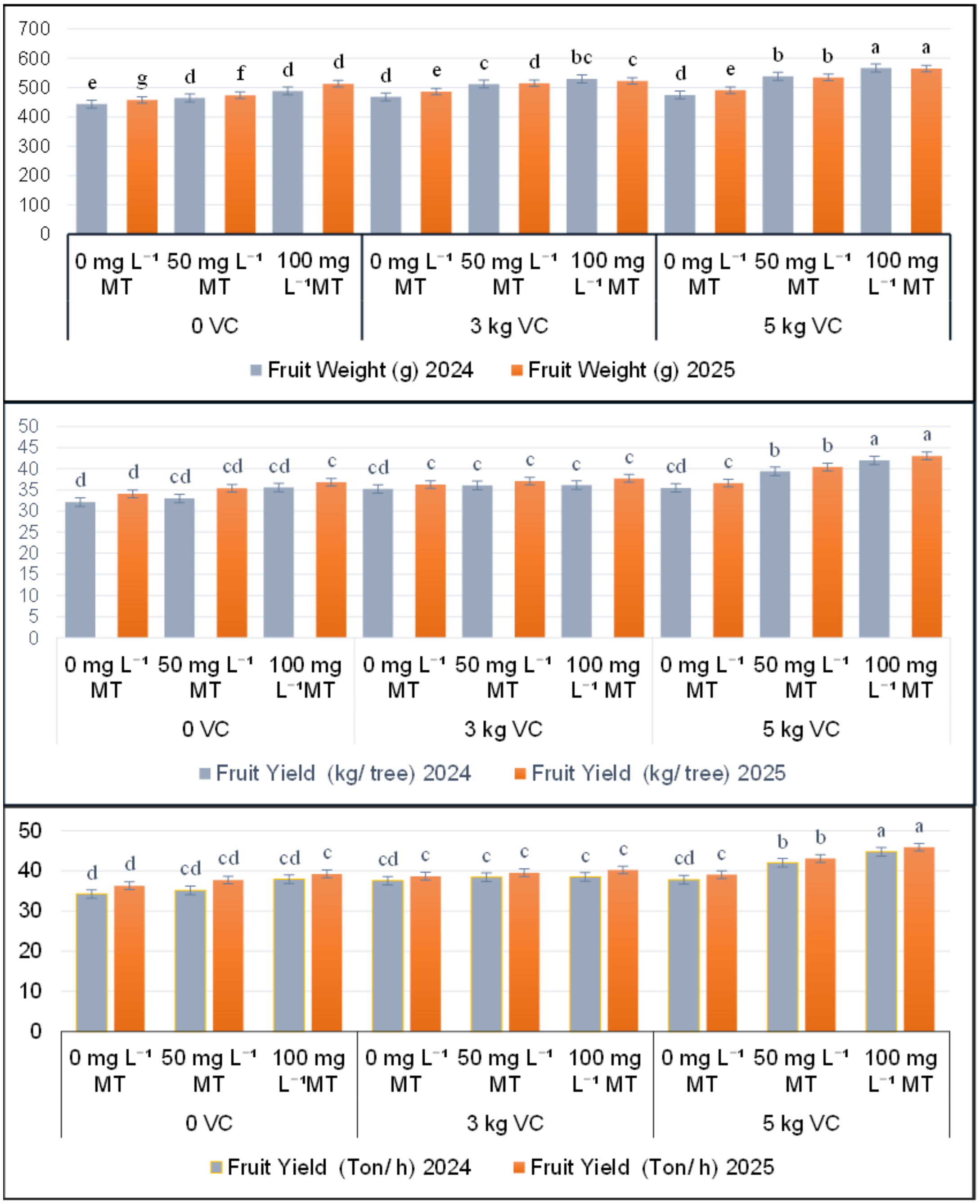

Fig. 1. Effect of soil application of VC and foliar spraying of MT, alone or in combination, on fruit weight and fruit yield in kg per tree or in tons per hectare of mango cv. Keitt during the 2024 and 2025 seasons

Similarly, fruit length and diameter were significantly enhanced by increasing VC levels from 0 to 5 kg and MT concentration up to 100 mg L^{-1}. The treatment consisting of 5 kg VC combined with 100 mg L^{-1} MT produced the longest fruits (12.7 and 13.0 cm in 2024 and 2025, respectively) and the largest fruit diameter (10.3 and 11.0 cm, respectively), while the control treatment recorded the lowest values (10.2 and 10.3 cm for fruit length, and 8.23 and 8.20 cm for fruit diameter). Overall, the interaction between organic soil amendments and MT foliar application exhibited a synergistic effect, leading to marked improvements in fruit quality attributes, including firmness, size, length, and diameter, as confirmed by the significant differences exceeding the LSD values at the 0.05 probability level.

Table 7. Effect of Soil Application of VC and Foliar Spraying of MT, Alone or in Combination, on Fruit Firmness and Fruit Size, of Mango cv. Keitt during the 2024 and 2025 Seasons

Soil Application	Foliar spray	Fruit firmness (Kg cm^{-2})		Fruit Size (cm^3)	
		2024	2025	2024	2025
Zero Compost	0 mg L^{-1} MT	1.17f	1.20f	460.88f	478.87g
	50 mg L^{-1} MT	1.25e	1.29e	482.54e	494.71f
	100 mg L^{-1} MT	1.29e	1.32e	509.22d	534.28d
5 kg Compost	0 mg L^{-1} MT	1.29e	1.32e	488.36de	510.89e
	50 mg L^{-1} MT	1.47c	1.50cd	532.32c	534.75d
	100 mg L^{-1} MT	1.52b	1.52c	549.64bc	543.90c
10 Kg Compost	0 mg L^{-1} MT	1.37d	1.44d	495.16de	511.78e
	50 mg L^{-1} MT	1.54b	1.58b	559.36b	556.25b
	100 mg L^{-1} MT	1.71a	1.71a	586.50a	585.26a
$LSD_{0.05}$		0.055	0.054	19.18	7.24

Table 8. Effect of Soil Application of VC and Foliar Spraying of MT, Alone or in Combination, on Length and Diameter of Mango cv. Keitt during the 2024 and 2025 Seasons

Soil Application	Foliar Spray	Fruit Length (cm)		Fruit Diameter (cm)	
		2024	2025	2024	2025
0 VC	0 mg L^{-1} MT	10.20f	10.32f	8.23e	8.20f
	50 mg L^{-1} MT	10.65e	10.39f	8.27e	8.49e
	100 mg L^{-1} MT	11.37d	11.65d	8.72d	9.32d
3 kg VC	0 mg L^{-1} MT	10.78 e	10.78e	8.44de	8.63e
	50 mg L^{-1} MT	11.90c	11.93cd	9.09c	9.41d
	100 mg L^{-1} MT	11.99c	12.07c	9.59b	9.81c
5 Kg VC	0 mg L^{-1} MT	10.86e	10.80e	8.60de	8.66e
	50 mg L^{-1} MT	12.35b	12.49b	9.82b	10.37b
	100 mg L^{-1} MT	12.72a	13.03a	10.27a	10.97a
$LSD_{0.05}$		0.29	0.33	0.28	0.26

The results presented in Table 9 indicate that both soil application of VC and foliar spray with MT had a significant effect on fruit quality parameters during the 2024 and 2025 seasons. In general, TSS (%) increased progressively with increasing VC and foliar spray levels, with the highest values recorded under the combined treatment of 5 kg VC and 100 mg L^{-1} MT (16.4% and 17.3% in 2024 and 2025, respectively). In contrast, acidity (%) decreased with increasing treatment levels, reaching its lowest values under the same combined treatment (1.24% and 1.22% in 2024 and 2025, respectively). Similarly, ascorbic acid content increased markedly with higher application rates, reaching maximum values of 39.8 and 41.6 mg 100 mL $^{-1}$ in 2024 and 2025, respectively, under 5 kg VC combined with 100 mg L^{-1} MT. Overall, the interaction between soil and foliar applications exhibited a clear synergistic effect, improving fruit quality by enhancing TSS and ascorbic acid content while reducing acidity. Additionally, values recorded in 2025 were generally higher than those in 2024, indicating a consistent and positive response over time.

Table 9. Effect of Soil Application of VC and Foliar Spraying of MT, Alone or in Combination, on the Fruit Chemical Characteristics of Mango cv. Keitt during the 2024 and 2025 Seasons

Soil Application	Foliar Spray	TSS (%)		Acidity (%)		Ascorbic acid (mg 100 mL^{-1})	
		2024	2025	2024	2025	2024	2025
0 VC	0 mg L^{-1} MT	13.30d	13.76e	1.42a	1.43a	34.95c	35.56e
	50 mg L^{-1}	13.42d	14.23de	1.41a	1.40b	35.55bc	36.10de
	100 mg L^{-1}	14.79c	15.95b	1.33c	1.34c	36.15bc	37.50cd
3 kg VC	0 mg L^{-1} MT	13.82d	14.42d	1.38b	1.38b	35.84bc	36.18de
	50 mg L^{-1} MT	14.90c	16.37b	1.30d	1.31c	37.04b	38.58bc
	100 mg L^{-1} MT	15.60b	16.45b	1.28d	1.27d	37.15b	38.61bc
5 Kg VC	0 mg L^{-1} MT	14.44c	15.15c	1.36bc	1.33c	36.12bc	36.23de
	50 mg L^{-1} MT	15.85b	16.50b	1.28d	1.23e	37.17b	39.03b
	100 mg L^{-1} MT	16.42a	17.27a	1.24e	1.22e	39.83a	41.64a
$LSD_{0.05}$		0.55	0.49	0.02	0.03	1.16	1.05

The data in Table 10 demonstrated that soil application of VC and foliar spraying with MT markedly influenced total, reduced, and non-reduced sugar contents during the 2024 and 2025 growing seasons. The control treatment (0 kg VC + 0 mg L^{-1} MT) produced the lowest total sugar contents, recording 9.32 and 9.59% in 2024 and 2025, respectively. Progressive increases in VC and MT levels led to higher sugar accumulation, with the maximum total sugar values (12.2% and 12.8%) achieved under the combined application of 5 kg VC and 100 mg L^{-1} MT. Reduced sugar content followed a similar pattern, increasing from 5.70% and 5.62% in the untreated plants to 6.60% and 7.30% with the highest VC and MT treatments in the respective seasons. Likewise, non-reduced sugars increased from 3.62 and 3.97% in the control to 5.55 and 5.47% under the combined treatment of 5 kg VC and 100 mg L^{-1} MT.

Table 10. Effect of Soil Application of VC and Foliar Spraying of MT, Alone or in Combination, on the Total, Reduced and Non-Reduced Sugars Content of Mango cv. Keitt during the 2024 and 2025 Seasons

Soil Application	Foliar Spray MT	Total Sugars (%)		Reduced Sugars (%)		Non-reduced Sugars (%)	
		2024	2025	2024	2025	2024	2025
0 VC	0 mg L^{-1} MT	9.32e	9.59f	5.70c	5.62d	3.62e	3.97g
	50 mg L^{-1} MT	9.41e	9.69f	5.80c	5.57d	3.61e	4.11fg
	100 mg L^{-1} MT	10.33d	10.48d	5.84c	5.74cd	4.49d	4.74bc
3 kg VC	0 mg L^{-1} MT	9.41e	9.90ef	5.80c	5.63d	3.61e	4.26ef
	50 mg L^{-1} MT	10.58d	10.55d	5.88c	5.98c	4.70cd	4.56cd
	100 mg L^{-1} MT	11.00c	11.42c	6.19b	6.54b	4.80c	4.88b
5 kg VC	0 mg L^{-1} MT	9.68e	10.11e	5.82c	5.71cd	3.85e	4.40de
	50 mg L^{-1} MT	11.33b	12.03b	6.27b	6.76b	5.06b	5.27a
	100 mg L^{-1} MT	12.16a	12.77a	6.60a	7.30a	5.55a	5.47a
$LSD_{0.05}$		0.29	0.26	0.21	0.23	0.26	0.21

Moderate improvements were observed with the intermediate treatments (3 kg VC and/or 50 mg L⁻¹ MT). Overall, the interaction between VC and MT enhanced carbohydrate accumulation, with the greatest effect obtained when both were applied at their highest levels.

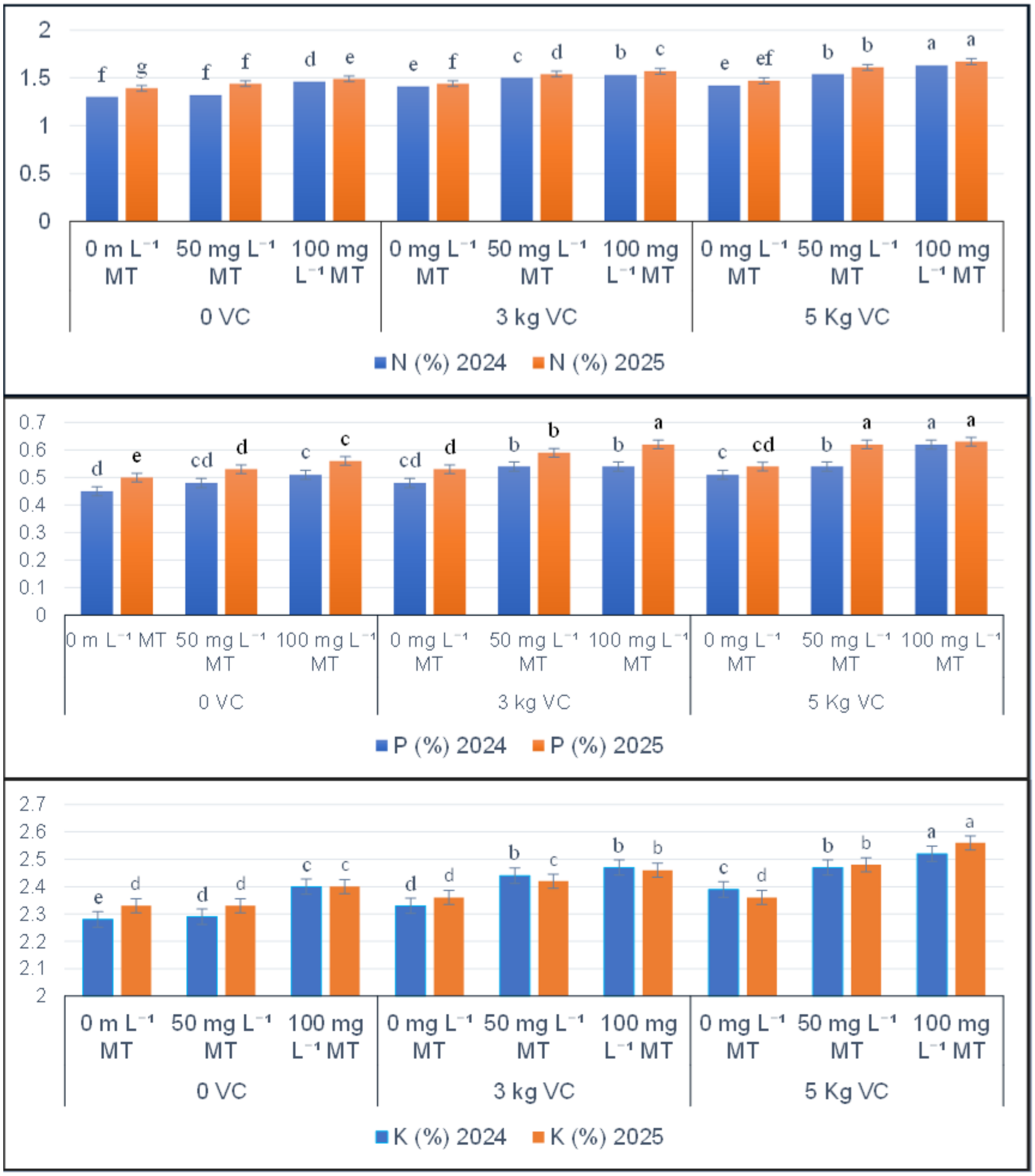

Fig. 2. Effect of soil application of VC and foliar spraying of MT, alone or in combination, on leaf mineral content from nitrogen, phosphorus and potassium of mango cv. Keitt during the 2024 and 2025 Seasons

The results in Fig. 2 showed that both VC soil application and MT foliar spray enhanced leaf N, P, and K contents during the 2024 and 2025 seasons. The lowest values were recorded in the untreated control (0 kg VC + 0 mg L^{-1} MT), where N, P, and K contents reached 1.30 and 1.39%, 0.45 and 0.50%, and 2.28 and 2.33% in 2024 and 2025, respectively. Increasing VC rates and MT concentrations generally resulted in progressive increases in nutrient contents. The highest N content was obtained with 5 kg VC combined with 100 mg L^{-1} MT, reaching 1.63 and 1.67% in 2024 and 2025, respectively. Similarly, the highest P content was recorded under the same treatment, reaching 0.62 and 0.63% in the two seasons, respectively. K content also increased with VC and MT applications, with the maximum values (2.52 and 2.56% in 2024 and 2025, respectively) observed under 5 kg VC plus 100 mg L^{-1} MT. Overall, the combined application of VC and MT was more effective than either treatment alone, indicating a synergistic effect in improving plant nutritional status and enhancing the uptake of essential macronutrients.

DISCUSSION

Main Effects of Vermicompost

The observed enhancement in vegetative growth, fruit set, yield, fruit physical and chemical attributes, and leaf nutritional status, together with the reduction in fruit drop of mango trees, may be attributed to the positive effects of VC on soil physical, chemical, and biological properties, which improve nutrient availability, root growth, and nutrient uptake. In addition, melatonin may promote cell division and elongation, enhance photosynthetic efficiency, regulate hormonal balance, and strengthen antioxidant defense systems, thereby improving flower retention, fruit set, productivity, fruit quality, and nutrient accumulation in leaves. These findings are consistent with those reported by Ma *et al*. (2022) and Aslam *et al*. (2023), who indicated that vermicompost is a valuable bio-organic fertilizer due to its high content of organic matter, humic substances, beneficial microorganisms, plant growth regulators, amino acids, and readily available macro- and micronutrients. Such components improve soil structure, aeration, water-holding capacity, cation exchange capacity, and nutrient availability, thereby promoting root growth and nutrient absorption. In addition, VC stimulates microbial activity and supports populations of nitrogen-fixing and phosphate-solubilizing microorganisms, resulting in a continuous release of nutrients and improved plant nutritional status (Bellitürk *et al.* 2022; Vambe *et al.* 2023). These improvements in soil fertility and root activity were reflected in the present study by enhancing vegetative growth traits, increasing branch length and thickness, improving leaf photosynthetic index and leaf mineral contents, and consequently promoting photosynthetic efficiency and assimilate production. Such improvements increased flower retention and fruit set percentage while reducing fruit drop, which ultimately resulted in heavier fruits and higher yields. The superior performance obtained with 5 kg VC $tree^{-1}$ indicates that the beneficial effects of VC are attributed not only to nutrient supply but also to the presence of phytohormones, humic substances, and microbial metabolites that stimulate plant metabolism and reproductive growth (Al-Maamori *et al.* 2023; Mohite *et al.* 2024). The increase in fruit weight and yield observed in the present investigation can be explained by enhanced photosynthetic activity and improved translocation of assimilates to developing fruits, in addition to the gradual supply of nutrients, particularly potassium, calcium, and magnesium, which play important roles in carbohydrate metabolism, cell division, and fruit development. Moreover, improved leaf nutritional status led to better fruit quality characteristics and increased accumulation of sugars and other metabolites responsible for fruit quality (Scaglia *et al.* 2016). The obtained results agree with those reported by Gupta and Sangma (2017) in guava, Zuo *et al*. (2018) in strawberry, Hassan *et al*. (2022) in pomegranate, and Rohim *et al.* (2024) in apple, who observed that VC application enhanced vegetative growth, photosynthetic pigments, nutrient status, fruit set, yield, and fruit quality.

Main Effects of Melatonin

Likewise, foliar application of MT significantly improved vegetative growth, photosynthetic capacity, fruit set, and yield components. MT enhances nutrient uptake by stimulating root growth and nutrient transport systems, and it regulates hormonal crosstalk, especially between ABA and IAA, thereby improving stomatal behavior, water relations, and photosynthetic performance (Li *et al.* 2015; Yang *et al.* 2021). Furthermore, MT protects chloroplast ultrastructure and chlorophyll molecules, stimulates photosynthetic electron transport, and increases carbon fixation, thereby increasing carbohydrate production and the availability of assimilates for fruit growth and development (Liang *et al.* 2018; Teng *et al.* 2022). It acts as a multifunctional signaling molecule and plant growth regulator involved in root development, mineral nutrition, hormonal balance, photosynthesis, and stress tolerance (Xu *et al.* 2018; Ahmad *et al.* 2023). MT also enhances antioxidant defense systems and maintains membrane integrity, thereby improving flower retention and reducing oxidative stress-induced fruit abscission (Wu *et al.* 2019). The increase in fruit set percentage, accompanied by a marked reduction in fruit drop observed in this study following MT application, particularly at 100 mg L^{-1}, could be attributed to improved pollen viability, enhanced hormonal balance, better carbohydrate availability, and greater antioxidant protection during flowering and fruit development. Consequently, more fruits were retained until harvest, resulting in increased fruit weight and total yield. In addition, the enhancement in leaf mineral contents and photosynthetic efficiency promoted the synthesis and translocation of carbohydrates to fruits, thereby improving physical and chemical fruit quality attributes.

Combined Effects

The combined application of 5 kg VC $tree^{-1}$ and 100 mg L^{-1} MT produced the highest values of fruit set and the lowest fruit drop percentages, which were associated with the greatest fruit weight and yield in both seasons. This synergistic response may be attributed to the complementary roles of VC and MT. VC improved the rhizosphere environment, nutrient availability, and water-holding capacity, whereas MT enhanced nutrient utilization efficiency, photosynthetic activity, hormonal regulation, and antioxidant capacity. The interaction between the two treatments improved vegetative growth, branch development, leaf chlorophyll content, photosynthetic performance, and leaf nutrient accumulation, thereby increasing carbohydrate synthesis and translocation to reproductive organs. Consequently, fruit retention increased, fruit drop decreased, and fruits attained greater size and weight, resulting in maximum yield and superior fruit quality characteristics. These findings are in agreement with those reported by Medina-Santamarina *et al*. (2021) in pomegranate, Carrión *et al*. (2022) in sweet cherry, Cortes-Montana *et al*. (2023) in plum, and Xiao *et al*. (2024), who demonstrated that exogenous MT improved fruit growth, quality, and productivity through its positive effects on photosynthesis, antioxidant defense systems, and carbohydrate metabolism.

Overall, the results suggest that integrating VC at 5 kg tree^{-1} with foliar application of MT at 100 mg L^{-1} represents an effective strategy for improving tree productivity and fruit quality through synergistic effects on nutrient availability, photosynthetic performance, and reproductive development.

CONCLUSIONS

1. The addition of vermicompost (VC) to the soil, either alone or combined with melatonin (MT) spraying, positively affected the growth, productivity, and fruit quality of mango trees. The most effective treatments were 5 VC + 100 mg L^{-1} MT, followed by 5 kg VC + 50 mg L^{-} MT, and then 3 kg VC + 100 mg L^{-1} MT, when compared to other treatments or untreated trees across two seasons.
2. The soil addition of VC contributes to supplying mango trees with many required nutrients without causing harmful impacts on the soil properties or the fruit quality characteristics.
3. The use of 100 mg L^{-} MT effectively improved the growth, yield, and fruit quality of mango, rather than the use of 50 mg L^{-} or untreated trees.
4. Organic fertilization is a safe method to enhance the productivity and fruit quality of mango trees and to decrease reliance on chemical fertilizers, minimizing their undesirable effects.

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