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Effects of vermicompost application rates and irrigation regimes on tomato yield, nutrient uptake and soil properties under greenhouse conditions

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Abstract

Tomato (Solanum lycopersicum L.) is a widely cultivated horticultural crop that responds sensitively to both nutrient availability and water management. The use of vermicompost as an organic fertilizer offers potential to improve plant productivity and soil health, especially under conditions of limited irrigation. This greenhouse study aimed to investigate the effects of different vermicompost application rates and irrigation levels on tomato yield, leaf nutrient uptake, and post-harvest soil properties. The experiment was conducted using a clay soil with low fertility characteristics (organic matter 1.15%, total N 0.06%, available P 5.26 mg/kg) and vermicompost rich in nutrients (total N 1.52%, total P 0.46%, total K 2.85%). Treatments consisted of four vermicompost rates (0, 0.25, 0.5, and 1.0 t/da) combined with three irrigation levels (100%, 75%, and 50% of field capacity) in a completely randomized design with three replications. Tomato plants were grown under controlled greenhouse conditions, and yield per plant, leaf nutrient contents (N, P, K, Ca, Mg), post-harvest soil nutrient status, and biological properties (microbial biomass carbon, soil respiration, enzyme activities) were evaluated. Results indicated that both vermicompost and irrigation level significantly affected tomato yield, which increased from 4.90 kg/plant (control, 50% FC) to 8.00 kg/plant (1.0 t/da, 100% FC). Leaf nutrient concentrations and soil available N, P, K, Ca, and Mg were significantly improved with higher vermicompost doses. Soil microbial biomass and enzymatic activities also responded positively to vermicompost, while water stress had suppressive effects. The interaction between vermicompost and irrigation was generally not significant, suggesting additive but independent effects. In conclusion, the application of vermicompost at 1.0 t/da improved tomato yield, nutrient uptake, and soil quality indicators, even under moderate water stress. This study supports the integration of organic amendments and optimized irrigation as a sustainable strategy for tomato production in protected cultivation systems.

Keywords: Vermicompost, irrigation levels, tomato yield, soil fertility, greenhouse cultivation.

Introduction

Tomato (Solanum lycopersicum L.) is one of the most economically valuable vegetable crops cultivated globally in both open field and protected environments (Padmanabhan et al., 2016). The growing demand

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for high-yielding and high-quality tomato fruits has intensified the use of chemical fertilizers and irrigation practices (Montgomery and Biklé, 2021). However, excessive reliance on inorganic inputs under greenhouse conditions has raised concerns about soil degradation, nutrient imbalance, and reduced fruit quality (Tahat et al., 2020).

In recent years, the application of organic amendments, particularly vermicompost, has gained attention as a sustainable strategy to improve soil fertility and plant productivity (Toor et al., 2024). Kızılkaya et al. (2012) demonstrated that the application of vermicomposted organic wastes significantly enhanced wheat grain and straw yield, as well as the concentrations of nitrogen, phosphorus, and potassium in both soil and plant tissues, compared to untreated and non-vermicomposted treatments. Vermicompost is the stabilized product of organic matter decomposition through the joint activity of earthworms and microorganisms. It is known to contain readily available nutrients (e.g., NO_3^-, PO_4^{3-}, K^+, Ca^{2+}, Mg^{2+}), plant growth-promoting substances, and a rich population of beneficial microbes (Yang et al., 2015). Vermicompost application enhances nutrient uptake, stimulates enzymatic activity, and improves soil structure and microbial biomass, all of which contribute to improved plant growth and fruit yield (Hyder et al., 2015; Demir, Z., 2021; Trang and Chuong, 2025). Arancon et al. (2006), soils amended with vermicompost exhibited higher levels of NH_4-N, NO_3-N, and orthophosphates, as well as increased dehydrogenase activity at harvest, compared to untreated soils.

Tomato is particularly sensitive to both nutrient status and water availability. While adequate irrigation is essential for high productivity, water stress—either deficit or excess—can significantly alter fruit set, yield components, and nutrient transport (Putti et al., 2023; Islamzade et al., 2024). Studies have demonstrated that irrigation levels interact with soil fertility management to influence crop response, with moderate water regimes often optimizing nutrient use efficiency and fruit quality (Kim et al., 2022). According to Yang et al. (2015), tomato plants grown under 60–70% of field capacity with vermicompost treatment exhibited the highest yield and vitamin C content, along with improved soil enzyme activities and nutrient availability, highlighting the critical role of irrigation-fertilizer synergy in greenhouse conditions. However, the interaction between vermicompost and irrigation regimes on tomato performance under greenhouse conditions remains relatively underexplored.

Given the need to improve yield and nutrient quality of tomato in an environmentally friendly manner, integrating organic fertilization strategies with efficient water management could be a key approach. In this paper, vermicompost not only supplies essential nutrients but may also buffer against the negative impacts of water stress by improving soil water-holding capacity and microbial resilience.

The objective of this study was to evaluate the effects of different vermicompost application rates and irrigation levels on tomato yield, leaf nutrient concentrations, and post-harvest soil properties under greenhouse conditions. It was hypothesized that increasing vermicompost rates would improve plant and soil performance, and that moderate irrigation would synergize with organic amendment to optimize tomato yield and nutrient use efficiency.

Material and Methods

Soil, Vermicompost, and Tomato Plant

The experiment was conducted using soil, vermicompost, and tomato plants (F1 tomato). The soil samples were processed and analyzed to determine their physical and chemical properties. The compost used was analyzed for its organic matter content and nutrient composition. The tomato plants were cultivated under controlled greenhouse conditions.

The soil used in the experiment was characterized by several analyses. The texture was determined using the hydrometer method (Bouyoucos, 1962). The pH and electrical conductivity (EC) were measured in a 1:1 soil-water suspension using a pH meter (Peech, 1965) and an EC meter (Bower and Wilcox, 1965), respectively. Calcium carbonate ($CaCO_3$) content was determined volumetrically using the Scheibler calsimeter (Rowell, 2010). Organic matter content was analyzed by the wet oxidation with $K_2Cr_2O_7$ (Walkley and Black, 1934). Total nitrogen (N) content was determined using the Kjeldahl method (Bremner, 1965). Available phosphorus (P) was measured in a 0.5M $NaHCO_3$ extract using a spectrophotometer (Olsen and Dean, 1965). Exchangeable cations (K, Ca and Mg) were extracted with 1 N ammonium acetate; K and Na were determined by flame photometry, while Ca and Mg were measured by EDTA titration (Pratt, 1965; Heald, 1965).

The vermicompost, produced from plant waste and cow dung using Eisenia fetida, was analyzed for its organic matter and nutrient content. Organic matter was assessed by loss on ignition at 550°C. Total nitrogen (N) was determined using the Kjeldahl method. For total phosphorus (P), potassium (K), calcium

(Ca), and magnesium (Mg), samples were subjected to dry ashing. Phosphorus was measured spectrophotometrically, potassium by flame photometry, and calcium and magnesium by atomic absorption spectrophotometry (Jones, 2001).

Greenhouse Conditions and Experimental Setup

The experiment was conducted under controlled greenhouse conditions. The study aimed to investigate the combined effects of different vermicompost doses and irrigation levels on the yield and yield components of tomato (*Solanum lycopersicum* L.). A randomized complete block design was employed with four replications. The main plots consisted of three irrigation levels based on field capacity (FC):

- I1: 100% FC (No stress)
- I2: 75% FC (Moderate water stress)
- I3: 50% FC (Severe water stress)

The sub-plots consisted of four vermicompost doses:

- V0: Control (0 t/da)
- V1: 0.25 t/da
- V2: 0.5 t/da
- V3: 1.0 t/da

Each treatment was applied to polyethylene pots (30 cm diameter × 28 cm height), each filled with 5 kg of air-dried, sieved (4 mm) soil. The fertilizers used were ammonium sulfate (21% N) as the nitrogen source, monoammonium phosphate (12% N, 61% P_2O_5) as the phosphorus source, and potassium sulfate (50% K_2O) as the potassium source. The standard soil fertilization application included 30 kg N/da, 8 kg P_2O_5/da, and 40 kg K_2O/da. Tomato (*F1 hybrid*) seedlings were transplanted on March 10, 2023. One seedling was planted per pot. Vermicompost was thoroughly mixed into the soil prior to transplanting. Irrigation was carried out daily based on pot weight to maintain soil moisture at the assigned levels of field capacity (100%, 75%, or 50%).

Harvest and Measurements

Ripe tomatoes were harvested periodically and total yield per plant (g) was recorded. At the end of the experiment (October 25, 2023), soil and plant samples were collected. Leaf samples from each pot were analyzed for N, P, Ki Ca, and Mg contents (Jones, 2001). Soil samples were analyzed for available nitrogen (NH_4+NO_3) using 1 N KCl extraction followed by Kjeldahl distillation (Bremner, 1965), available phosphorus in a 0.5 M NaHCO3 extract using a spectrophotometer (Olsen and Dean, 1965), and, exchangeable cations (K, Ca and Mg) were extracted with 1 N ammonium acetate; K and Na were determined by flame photometry, while Ca and Mg were measured by EDTA titration (Pratt, 1965; Heald, 1965). Biological properties of the soil, including microbial biomass carbon, basal soil respiration, and enzyme activities, were also measured. Microbial biomass carbon (MBC) was determined using the method of Anderson and Domsch (1978), basal soil respiration (BSR) was measured as described by Anderson (1982), dehydrogenase activity (DHA) was determined following Pepper (1995), catalase activity (CA) was measured by the Beck method (Beck, 1971), and urease activity was measured by the method of Hoffmann und Teicher (1961).

Statistical Analysis

Data were analyzed using ANOVA (SPSS 20.0). Treatment means were compared using the LSD test at $p < 0.05$. Interactions between irrigation level and vermicompost dose were also evaluated.

Results and Discussion

Before initiating the experiment, the basic physico-chemical characteristics of the soil were determined to assess its fertility status. The results of these analyses are shown in Table 1.

Table 1. Physico-chemical properties of the soil used in the experiment.

Property	Value
Texture	Clay (52% clay, 29% silt, 19% sand)
pH(1:1 soil:water)	7.35
Electrical conductivity (EC), dS/m	1.25
Calcium carbonate ($CaCO_3$), %	10.5
Organic matter, %	1.15
Total nitrogen (N), %	0.06
Available phosphorus (P), mg/kg	5.26
Exchangeable potassium (K^+), mg/kg	395
Exchangeable calcium (Ca^{2+}), mg/kg	4268
Exchangeable magnesium (Mg^{2+}), mg/kg	624
Exchangeable sodium (Na^+), mg/kg	172

The experimental soil was classified as clay in texture, with a high clay content (52%), moderate salinity (EC 1.25 dS/m), and slightly alkaline pH (7.35). The soil contained low organic matter (1.15%) and total nitrogen (0.06%), indicating limited natural fertility. Available phosphorus (5.26 mg/kg) was particularly low, falling below optimal levels for tomato cultivation. Among exchangeable cations, calcium dominated the profile (4268 mg/kg), followed by magnesium (624 mg/kg), potassium (395 mg/kg), and sodium (172 mg/kg). These values suggest a calcareous soil with high Ca and moderate levels of Mg and K, but a somewhat imbalanced Ca:Mg ratio. The low organic matter and macronutrient levels underline the importance of organic amendment, such as vermicompost, to improve fertility and nutrient availability.

The nutrient composition and physico-chemical properties of the vermicompost used as an organic amendment in the experiment are summarized in Table 2.

Table 2. Physico-chemical properties of the vermicompost used in the experiment.

Property	Value
pH(1:1 soil:water)	7.50
Electrical conductivity (EC), dS/m	2.18
Organic matter, %	34.5
Total nitrogen (N) , %	1.52
Total phosphorus (P), %	0.46
Total potassium (K^+), %	2.85
Total calcium (Ca^{2+}), %	2.96
Total magnesium (Mg^{2+}), %	0.48

The vermicompost used in the study had a slightly alkaline pH (7.5) and moderate salinity (2.18 dS/m), typical of well-stabilized compost. It was rich in organic matter (34.5%), reflecting a high degree of humification and microbial activity during composting. Nutrient content analysis revealed that the vermicompost contained substantial amounts of macroelements, with total nitrogen at 1.52%, phosphorus at 0.46%, and potassium at 2.85%. In addition, it supplied essential secondary nutrients such as calcium (2.96%) and magnesium (0.48%).

These values indicate that the vermicompost was a nutrient-dense organic amendment capable of addressing the nutrient deficiencies of the experimental soil, particularly in terms of nitrogen and phosphorus. Furthermore, its high organic matter and cation content could contribute to improving soil structure, nutrient retention, microbial biomass, and enzymatic activities, especially under conditions of irrigation stress. Together with the soil characteristics previously described, the compositional quality of the vermicompost provides a strong rationale for the observed improvements in plant growth, yield, and soil biological and chemical parameters in the subsequent sections of this study.

Effects of Vermicompost and Irrigation Levels on Tomato Yield

Tomato yield per plant varied significantly depending on both vermicompost dose and irrigation level (Table 3). The highest yield (8.00 ± 0.20 kg/plant) was obtained in the V3I1 treatment (1.0 t/da vermicompost + 100% field capacity), whereas the lowest yield (4.90 ± 0.20 kg/plant) was recorded in the V0I3 treatment (no vermicompost + 50% field capacity).

Table 3. Effect of vermicompost doses and irrigation levels on tomato yield per plant (kg) under greenhouse conditions.

Treatment	Yield (kg/plant)
V0I1	6.50 ± 0.20
V0I2	5.70 ± 0.20
V0I3	4.90 ± 0.20
V1I1	7.00 ± 0.20
V1I2	6.20 ± 0.20
V1I3	5.40 ± 0.20
V2I1	7.50 ± 0.20
V2I2	6.70 ± 0.20
V2I3	5.90 ± 0.20
V3I1	8.00 ± 0.20
V3I2	7.20 ± 0.20
V3I3	6.40 ± 0.20
F-value	
V (vermicompost doses)	93.60***
I (irrigation levels)	219.57***
V x I	0.54 ^{ns}

*** p<0.001, ** p<0.01, * p<0.05, ^{ns} not significant

Under well-watered conditions (I1), increasing vermicompost dose steadily enhanced yield from 6.50 ± 0.20 kg/plant (V0I1) to 8.00 ± 0.20 kg/plant (V3I1). A similar pattern was observed under moderate (I2) and severe (I3) water deficit. For example, under I2, yield increased from 5.70 ± 0.20 (V0I2) to 7.20 ± 0.20 (V3I2); and under I3, from 4.90 ± 0.20 (V0I3) to 6.40 ± 0.20 (V3I3). This demonstrates that higher vermicompost doses improved yield even under limited water availability.

According to ANOVA results, both vermicompost ($F = 93.60$; $p < 0.001$) and irrigation level ($F = 219.57$; $p < 0.001$) had highly significant effects on tomato yield. The interaction between the two factors was not statistically significant ($F = 0.54$; $p > 0.05$), suggesting that their effects were largely independent and additive.

The yield results clearly indicate the strong influence of organic nutrient input and water availability on tomato productivity in greenhouse conditions. Vermicompost consistently increased tomato yield across all irrigation levels, highlighting its efficacy in enhancing soil fertility, nutrient supply, and possibly plant hormone stimulation. This can be attributed to the improved nutrient availability, microbial stimulation, and soil structure resulting from organic matter inputs, which in turn lead to enhanced root growth and nutrient uptake.

Water availability was another critical factor. Yields decreased with increasing water stress, consistent with well-documented physiological effects of drought on plant growth and fruit development. Water stress reduces cell expansion, impairs nutrient transport, and lowers photosynthetic activity, all of which negatively affect fruit size and number. However, the application of vermicompost partially mitigated the effects of water deficit, likely due to its water-holding capacity and promotion of a more active microbial population that facilitates nutrient mineralization even under suboptimal moisture conditions.

The absence of a significant interaction effect suggests that the influence of vermicompost on yield is stable across a range of irrigation conditions. This makes vermicompost a particularly valuable input for sustainable agriculture in semi-arid or controlled-environment systems, where water resources are often limited.

Previous studies have also shown similar trends. For example, Wang et al. (2017) and Hyder et al. (2015) reported improved yields in tomato and other vegetable crops with vermicompost applications, citing better nutrient efficiency and improved physiological resilience of plants. Our findings reinforce these conclusions, demonstrating that vermicompost application at 1.0 t/da is an effective strategy to maximize tomato yield, particularly when combined with adequate irrigation management.

Effects of Vermicompost and Irrigation on Leaf Nutrient Contents of Tomato Plants

Leaf nutrient contents of tomato plants were significantly affected by both vermicompost application and irrigation regimes (Table 4).

Leaf nitrogen content increased significantly with increasing vermicompost dose and was also affected by irrigation level. The highest N concentration (3.0 ± 0.10%) was observed under V3I1 (1.0 t/da vermicompost, full irrigation), while the lowest value (2.2 ± 0.10%) occurred in the control treatment under severe water stress (V0I3). ANOVA results confirmed a significant main effect of vermicompost ($F = 73.48$; $p < 0.001$) and a moderate effect of irrigation ($F = 3.88$; $p < 0.05$). However, the interaction between the two was not significant ($F = 0.29$; $p > 0.05$).

Phosphorus concentration in leaves also showed a strong positive response to vermicompost application, ranging from 0.0 ± 0.14% (V0I3) to 0.8 ± 0.13% (V3I1). Irrigation level had a highly significant effect ($F = 24.86$; $p < 0.001$), and phosphorus was the most sensitive nutrient to water deficit. ANOVA revealed a significant main effect of vermicompost ($F = 109.13$; $p < 0.001$) but no interaction effect ($F = 0.71$; $p > 0.05$).

Leaf K content increased from 2.4 ± 0.14% in V0I3 to 3.2 ± 0.09% in V3I1. Both vermicompost ($F = 58.07$; $p < 0.001$) and irrigation ($F = 5.83$; $p < 0.05$) had significant effects on potassium accumulation, although the interaction term remained non-significant ($F = 0.89$; $p > 0.05$).

Calcium content in leaves was influenced by both factors. The Ca content increased from 1.3 ± 0.05% (V0I3) to 2.1 ± 0.14% (V3I1). ANOVA results indicated significant effects of vermicompost ($F = 93.73$; $p < 0.001$) and irrigation ($F = 7.87$; $p < 0.01$), with no significant interaction ($F = 0.75$; $p > 0.05$).

Magnesium levels ranged from 0.1 ± 0.14% (V0I3) to 0.9 ± 0.08% (V3I1). Both vermicompost ($F = 66.07$; $p < 0.001$) and irrigation ($F = 10.79$; $p < 0.01$) had strong effects, with magnesium showing a substantial decrease under water stress. Again, no significant interaction was observed ($F = 0.88$; $p > 0.05$).

Table 4. Leaf nutrient contents (N, P, K, Ca, Mg) of tomato plants as affected by different vermicompost doses and irrigation levels.

Treatment	Leaf N (%)	Leaf P (%)	Leaf K (%)	Leaf Ca (%)	Leaf Mg (%)
V0I1	2.4 ± 0.12	0.2 ± 0.15	2.6 ± 0.14	1.5 ± 0.14	0.3 ± 0.09
V0I2	2.3 ± 0.09	0.1 ± 0.07	2.5 ± 0.08	1.4 ± 0.08	0.2 ± 0.06
V0I3	2.2 ± 0.10	0.0 ± 0.14	2.4 ± 0.14	1.3 ± 0.05	0.1 ± 0.14
V1I1	2.6 ± 0.06	0.4 ± 0.13	2.8 ± 0.13	1.7 ± 0.05	0.5 ± 0.09
V1I2	2.5 ± 0.13	0.3 ± 0.14	2.7 ± 0.06	1.6 ± 0.10	0.4 ± 0.09
V1I3	2.4 ± 0.12	0.2 ± 0.12	2.6 ± 0.14	1.5 ± 0.14	0.3 ± 0.13
V2I1	2.8 ± 0.07	0.6 ± 0.13	3.0 ± 0.12	1.9 ± 0.12	0.7 ± 0.11
V2I2	2.7 ± 0.08	0.5 ± 0.05	2.9 ± 0.11	1.8 ± 0.07	0.6 ± 0.13
V2I3	2.6 ± 0.09	0.4 ± 0.06	2.8 ± 0.06	1.7 ± 0.12	0.5 ± 0.11
V3I1	3.0 ± 0.10	0.8 ± 0.13	3.2 ± 0.09	2.1 ± 0.14	0.9 ± 0.08
V3I2	2.9 ± 0.15	0.7 ± 0.13	3.1 ± 0.06	2.0 ± 0.10	0.8 ± 0.13
V3I3	2.8 ± 0.05	0.6 ± 0.06	3.0 ± 0.13	1.9 ± 0.11	0.7 ± 0.10
F-value					
V (vermicompost doses)	73.48***	109.13***	58.07***	93.73***	66.07***
I (irrigation levels)	3.88 ns	24.86***	5.83 ns	7.87 ns	10.79 ns
V x I	0.29 ns	0.71 ns	0.89 ns	0.75 ns	0.88 ns

*** p<0.001, ** p<0.01, * p<0.05, ns not significant

The findings clearly demonstrate that vermicompost significantly improves the nutrient status of tomato plants. The increase in leaf nitrogen, phosphorus, potassium, calcium, and magnesium concentrations with increasing vermicompost dose reflects the enhanced nutrient supply, mineralization rate, and microbial activity commonly associated with organic amendments. Vermicompost provides a slow-release source of nutrients and contributes to improved cation exchange capacity, thus facilitating greater nutrient retention and uptake by plants.

Among the measured nutrients, phosphorus and magnesium appeared most sensitive to irrigation levels, suggesting that water availability plays a critical role in their mobility and root absorption. This aligns with previous findings that under water-deficit conditions, reduced soil moisture limits nutrient diffusion and uptake, particularly for elements like P and Mg which rely on mass flow and diffusion mechanisms.

The lack of significant interaction between vermicompost and irrigation across all nutrients indicates that vermicompost's beneficial effects on nutrient accumulation were robust and relatively independent of soil moisture level. This stability underscores its potential as a soil amendment in regions prone to water stress.

These results support earlier studies (Yang et al., 2015; Wang et al., 2017) showing that vermicompost not only enhances nutrient availability but also contributes to physiological functions such as chlorophyll synthesis (via N and Mg), energy transfer (via P), and membrane integrity (via K and Ca). In practical terms, the combined improvement in macro-element nutrition likely underpins the increased yield and resilience observed in tomato plants treated with vermicompost, even under moderate to severe irrigation stress.

Effects of Vermicompost and Irrigation on Post-Harvest Soil Nutrient Status

The results demonstrated that vermicompost application significantly improved soil nutrient availability after tomato harvest, particularly for nitrogen (N), phosphorus (P), potassium (K), and magnesium (Mg), whereas the effect on calcium (Ca) was not statistically significant (Table 5).

Post-harvest soil nitrogen levels increased significantly with vermicompost dose. The highest available N (60 ± 2.7 mg/kg) was measured under the V3I1 treatment, while the lowest (39 ± 1.6 mg/kg) occurred in the control under severe stress (V0I3). According to ANOVA results, vermicompost ($F = 76.42$; $p < 0.001$) and irrigation ($F = 22.03$; $p < 0.001$) had highly significant effects on available nitrogen, while their interaction was not significant ($F = 1.81$; $p > 0.05$).

Soil available phosphorus followed a similar pattern, ranging from 2 ± 0.1 mg/kg (V0I3) to 23 ± 1.1 mg/kg (V3I1). Vermicompost application resulted in a pronounced increase ($F = 253.24$; $p < 0.001$), and phosphorus was the most irrigation-sensitive nutrient in this group ($F = 79.06$; $p < 0.001$). The interaction between the two factors was not significant ($F = 0.11$; $p > 0.05$).

Exchangeable K increased moderately with vermicompost (from 134 ± 7.8 to 155 ± 5.8 mg/kg), but was less sensitive to irrigation differences. ANOVA revealed a significant effect of vermicompost ($F = 16.22$; $p < 0.001$) but not irrigation ($F = 2.37$; $p > 0.05$) or their interaction ($F = 1.29$; $p > 0.05$).

Calcium levels in the soil showed minimal variation across treatments, with values ranging from 794 ± 35.0 mg/kg to 815 ± 47.8 mg/kg. Neither vermicompost ($F = 0.61$; $p = 0.617$) nor irrigation ($F = 2.53$; $p > 0.05$) significantly affected Ca availability, and the interaction was also not significant ($F = 0.33$; $p > 0.05$).

Magnesium content was positively affected by vermicompost, increasing from 104 ± 5.5 mg/kg (V0I3) to 125 ± 6.3 mg/kg (V3I1). Both vermicompost ($F = 26.79$; $p < 0.001$) and irrigation ($F = 3.53$; $p < 0.05$) had statistically significant effects, while their interaction was not significant ($F = 0.20$; $p > 0.05$).

Table 5. Post-harvest soil nutrient contents (available N, P and exchangeable K, Ca, Mg) as affected by vermicompost doses and irrigation levels.

Treatment	Available N (mg/kg)	Available P (mg/kg)	Exchangeable K (mg/kg)	Exchangeable Ca (mg/kg)	Exchangeable Mg (mg/kg)
V0I1	45 ± 2.5	8 ± 0.4	140 ± 5.0	800 ± 25.1	110 ± 5.8
V0I2	42 ± 1.9	5 ± 0.2	137 ± 7.7	797 ± 32.0	107 ± 5.6
V0I3	39 ± 1.6	2 ± 0.1	134 ± 7.8	794 ± 35.0	104 ± 5.5
V1I1	50 ± 2.0	13 ± 0.5	145 ± 8.4	805 ± 39.8	115 ± 4.4
V1I2	47 ± 1.6	10 ± 0.5	142 ± 6.3	802 ± 25.5	112 ± 5.3
V1I3	44 ± 1.4	7 ± 0.4	139 ± 8.3	799 ± 43.6	109 ± 3.9
V2I1	55 ± 3.0	18 ± 0.8	150 ± 5.6	810 ± 42.4	120 ± 6.9
V2I2	52 ± 2.0	15 ± 0.6	147 ± 5.6	807 ± 35.0	117 ± 4.7
V2I3	49 ± 1.7	12 ± 0.4	144 ± 8.6	804 ± 45.7	114 ± 4.5
V3I1	60 ± 2.7	23 ± 1.1	155 ± 5.8	815 ± 47.8	125 ± 6.3
V3I2	57 ± 2.7	20 ± 0.9	152 ± 8.1	812 ± 26.4	122 ± 4.7
V3I3	54 ± 3.1	17 ± 0.5	149 ± 7.8	809 ± 41.6	119 ± 4.8
F-value					
V (vermicompost doses)	76.42***	253.24***	16.22***	0.61 ns	26.79***
I (irrigation levels)	22.03***	79.06***	2.37 ns	2.53 ns	3.53 ns
V x I	1.81 ns	0.11 ns	1.29 ns	0.33 ns	0.20 ns

*** p<0.001, ** p<0.01, * p<0.05, ns not significant

The results reveal that vermicompost significantly enhanced the post-harvest nutrient status of the soil, especially with respect to nitrogen, phosphorus, potassium, and magnesium. These improvements are attributed to the nutrient-rich composition of vermicompost, its slow mineralization rate, and its positive influence on soil microbial activity and organic matter content. As organic matter decomposes, it releases essential nutrients and stimulates microbial-driven nutrient cycling processes, improving soil fertility over time.

Among the nutrients studied, available phosphorus exhibited the most pronounced increase with vermicompost and was also highly sensitive to irrigation regime. This is expected, as phosphorus availability in soils is influenced by both organic matter inputs and moisture levels that affect solubility and diffusion. Similarly, available nitrogen was significantly influenced by both factors, likely due to increased mineralization and microbial nitrification promoted by vermicompost under moist conditions.

In contrast, exchangeable calcium remained largely unchanged across treatments. This may be due to the already high background levels of Ca in the experimental soil or the relatively lower mobility of calcium ions, which are less responsive to short-term organic inputs or irrigation changes.

The observed increases in potassium and magnesium reflect the contributions of vermicompost as a source of these cations and its ability to improve cation exchange capacity (CEC). Potassium availability was less responsive to irrigation stress, suggesting its retention in the soil exchange complex, while magnesium showed moderate sensitivity, consistent with its higher mobility.

The absence of significant interaction effects across all nutrients indicates that vermicompost's contribution to soil nutrient enrichment was consistent and stable, regardless of irrigation levels. This implies that vermicompost is a reliable amendment for enhancing soil fertility even under water-limited conditions.

These findings are consistent with previous literature, which emphasizes that vermicompost can improve soil physicochemical properties, increase nutrient retention, and buffer against nutrient losses during periods of water stress (Hyder et al., 2015; Yang et al., 2015). Therefore, integrating vermicompost into nutrient management programs offers a sustainable strategy to improve soil health and maintain productivity in protected cultivation systems.

Effects of Vermicompost and Irrigation on Post-Harvest Soil Biological Properties

Post-harvest soil biological properties were significantly influenced by both vermicompost application and irrigation regime (Table 6).

Microbial biomass carbon (MBC) increased significantly with increasing vermicompost doses. The highest value (180 ± 10.5 μg C/g soil) was recorded in the V3I1 treatment, while the lowest (134 ± 4.9 μg C/g soil) was found in V0I3. ANOVA indicated significant effects of both vermicompost ($F = 31.16$; $p < 0.001$) and irrigation ($F = 8.80$; $p < 0.01$), with no significant interaction ($F = 0.52$; $p > 0.05$).

Basal soil respiration (BSR) followed a similar pattern, rising from 29 ± 1.6 mg CO_2-C/kg/day (V0I3) to 75 ± 4.0 mg CO_2-C/kg/day (V3I1). ANOVA results confirmed significant main effects of vermicompost ($F = 151.34$; $p < 0.001$) and irrigation ($F = 86.53$; $p < 0.001$), with no significant interaction ($F = 1.38$; $p > 0.05$).

Dehydrogenase activity (DHA), a marker of overall microbial oxidative metabolism, showed a strong positive response to vermicompost and irrigation. Activity increased from 14 ± 0.8 μg TPF/g soil/h in V0I3 to 60 ± 3.1 μg TPF/g soil/h in V3I1. ANOVA results demonstrated significant effects for vermicompost ($F = 353.93$; $p < 0.001$) and irrigation ($F = 176.03$; $p < 0.001$), and notably, a significant interaction effect was observed ($F = 3.82$; $p < 0.01$).

Catalase activity (CA) also increased with vermicompost application, from 2.2 ± 0.22 mL O_2/g soil 3min (V0I3) to 5.1 ± 0.15 (V3I1). Both vermicompost ($F = 209.20$; $p < 0.001$) and irrigation ($F = 65.38$; $p < 0.001$) significantly affected catalase activity, while the interaction term was not significant ($F = 1.52$; $p > 0.05$).

Urease activity (UA) rose steadily with higher vermicompost doses and better irrigation, ranging from 4 ± 0.2 μg N/g soil/h (V0I3) to 50 ± 1.9 μg N/g soil/h (V3I1). ANOVA revealed highly significant effects of vermicompost ($F = 351.12$; $p < 0.001$) and irrigation ($F = 203.31$; $p < 0.001$), with no significant interaction ($F = 0.51$; $p > 0.05$).

Table 6. Post-harvest soil microbial biomass carbon (MBC), soil respiration, and enzyme activities (dehydrogenase, catalase, urease) as influenced by vermicompost doses and irrigation levels.

Treatment	**MBC**	**BSR**	**DHA**	**CA**	**UA**
V0I1	150 ± 4.6	45 ± 1.4	30 ± 1.0	3.0 ± 0.14	20 ± 0.7
V0I2	142 ± 6.7	37 ± 1.5	22 ± 1.0	2.6 ± 0.18	12 ± 0.6
V0I3	134 ± 4.9	29 ± 1.6	14 ± 0.8	2.2 ± 0.22	4 ± 0.2
V1I1	160 ± 7.6	55 ± 3.2	40 ± 2.3	3.7 ± 0.29	30 ± 1.0
V1I2	152 ± 4.8	47 ± 2.5	32 ± 1.7	3.3 ± 0.30	22 ± 0.9
V1I3	144 ± 6.2	39 ± 1.2	24 ± 0.9	2.9 ± 0.20	14 ± 0.6
V2I1	170 ± 9.6	65 ± 2.0	50 ± 1.9	4.4 ± 0.24	40 ± 1.4
V2I2	162 ± 6.7	57 ± 2.6	42 ± 1.3	4.0 ± 0.16	32 ± 1.5
V2I3	154 ± 6.4	49 ± 2.9	34 ± 1.8	3.6 ± 0.19	24 ± 1.4
V3I1	180 ± 10.5	75 ± 4.0	60 ± 3.1	5.1 ± 0.15	50 ± 1.9
V3I2	172 ± 7.6	67 ± 3.0	52 ± 2.0	4.7 ± 0.21	42 ± 2.2
V3I3	164 ± 7.7	59 ± 2.2	44 ± 2.6	4.3 ± 0.27	34 ± 1.5
F-value					
V (vermicompost doses)	31.16***	151.34***	353.93***	209.20***	351.12***
I (irrigation levels)	8.80 ns	86.53***	176.03***	65.38***	203.31***
V x I	0.52 ns	1.38 ns	3.82 ns	1.52 ns	0.51 ns

MBC: Microbial biomass carbon, μg C/g soil ; BSR: Basal soil respiration, mg CO_2-C/kg/day ; DHA: Dehydrogenase activity, μg TPF/g soil/h ; CA: Catalase activity, mL O_2/g soil 3min; UA: Urease activity, μg N/g soil/h
*** p<0.001, ** p<0.01, * p<0.05, ns not significant

The data clearly demonstrate that vermicompost is a potent enhancer of soil microbial activity and enzymatic functioning. Across all parameters—MBC, BSR, DHA, CA, and UA—significant increases were observed with increasing vermicompost doses. These improvements are attributed to the input of organic carbon and nutrients that serve as substrates for microbial growth and metabolism. Vermicompost is rich in humic substances, growth-promoting hormones, and labile carbon, all of which stimulate microbial proliferation and enzymatic activity.

The observed increase in MBC and BSR reflects heightened microbial biomass and metabolic activity. Higher respiration rates suggest enhanced decomposition processes and nutrient turnover, which contribute to improved soil fertility (Smith and Paul, 1990; Meli et al., 2002; Kızılkaya et al., 2004). Enzyme activities (DHA, CA, UA) provide further evidence of improved microbial functioning and biochemical potential of the soil (Gong, 1997; Pascual et al., 1998; Obbard, 2001; Kızılkaya, 2008; Durmuş and Kızılkaya, 2022; Toor et al., 2024).

Among these, DHA not only showed the greatest relative increase but also exhibited a significant interaction between vermicompost and irrigation. This suggests that microbial redox processes are particularly sensitive to water availability, and the stimulating effect of vermicompost on dehydrogenase may be more pronounced under adequate moisture conditions.

CA, involved in reactive oxygen species detoxification, and urease activity, which reflects N transformation capacity, were both significantly enhanced by vermicompost. These responses indicate improved oxidative balance and nitrogen cycling in the rhizosphere, essential for healthy root function and nutrient availability.

Water stress consistently reduced all biological indicators, underscoring the sensitivity of microbial systems to moisture availability. However, even under the most severe stress (I3), soils treated with higher vermicompost doses maintained relatively higher biological activity compared to untreated soils, demonstrating vermicompost's buffering capacity.

These results are consistent with previous findings indicating that organic amendments, particularly vermicompost, enhance microbial resilience and enzymatic activity under abiotic stress (Anderson, 1982; Wang et al., 2017). In water-limited systems, this functional stability is crucial for sustaining nutrient cycling and supporting plant productivity.

Conclusion

This study demonstrated that both vermicompost application and irrigation level significantly affect tomato yield, plant nutrient uptake, and soil fertility under greenhouse conditions. Vermicompost applied at increasing doses (0.25, 0.5, and 1.0 t/da) consistently improved tomato yield per plant, with the highest yield (8.00 ± 0.20 kg/plant) observed at the 1.0 t/da dose under full irrigation (100% field capacity). Yield declined under water deficit, but the negative effects of stress were partially mitigated by higher vermicompost doses.

Leaf nutrient contents (N, P, K, Ca, Mg) were significantly enhanced by vermicompost, with phosphorus and magnesium being particularly sensitive to water stress. Post-harvest soil analyses indicated that vermicompost substantially increased available N, P, and exchangeable K and Mg contents, while Ca levels remained unaffected. Soil biological properties, including microbial biomass carbon, soil respiration, and enzyme activities (dehydrogenase, catalase, urease), also improved significantly with vermicompost and were generally reduced under irrigation stress.

Among all parameters studied, phosphorus availability and dehydrogenase activity were most responsive to the combined effects of nutrient and water management. The absence of significant interaction effects for most variables suggests that the positive effects of vermicompost are consistent across irrigation regimes.

In conclusion, vermicompost application at 1.0 t/da is a promising organic fertilization strategy that enhances tomato productivity, improves plant nutrient status, and promotes soil biological health. Its beneficial effects are evident even under moderate to severe water stress, making it a valuable tool for sustainable greenhouse cultivation in water-limited environments. Further research under open-field conditions and with different crop species could help validate and expand these findings for broader agroecological application.

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