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# Morphological and Physiological Response of Tomato to Sole and Combined Application of Vermicompost and Chemical Fertilizers

**Muhammad Qasim [1,2,*], Jing Ju [1,2,*], Haitao Zhao [1,2], Saleem Maseeh Bhatti [3], Gulnaz Saleem [4], Saima Parveen Memon [2], Shahzaib Ali [5], Muhammad Usama Younas [6], Nimra Rajput [6] and Zameer Hussain Jamali [7]**

[1] Key Laboratory of Arable Land Quality Monitoring and Evaluation, Ministry of Agriculture and Rural Affairs, Yangzhou University, Yangzhou 225127, China; htzhao@yzu.edu.cn
[2] College of Environmental Science and Engineering, Yangzhou University, Yangzhou 225127, China
[3] Department of Soil Science, Sindh Agriculture University Tandojam, Tandojam 70060, Pakistan; smbhatti@gmail.com
[4] College of Food Science and Technology, Yangzhou University, Yangzhou 225127, China
[5] Department of Agroecosystems, Faculty of Agriculture and Technology, University of South Bohemia Ceske Budejovice, Branišovská 1645/31A, 370 05 Ceske Budejovice, Czech Republic; alisha00@fzt.jcu.cz
[6] Department of Crop Breeding and Genetics, Agriculture College, Yangzhou University, Yangzhou 225012, China
[7] Institute of Ecological and Environmental Sciences, Sichuan Agricultural University, No. 211 Huimin Road, Chengdu 611130, China
* Correspondence: qrajput64@gmail.com (M.Q.); jujing@yzu.edu.cn (J.J.)

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**Abstract:** Chemical fertilizers are commonly used to meet the nutritional demands of crops and boost their yields. However, their high costs and excessive application in soils increase the cost of production and have negative effects on the soil and environmental health. Vermicompost is an organic amendment that can potentially lessen the dependence on chemical fertilizers, with the additional advantages of sustainable nutrient supply to crops and maintaining soil health. To evaluate the potential of the two diverse vermicompost, the sole and combined applications of these vermicompost with reduced rates of chemical fertilizers were used for tomato cultivation in a field study. The results indicated that vermicompost produced from cattle manure combined with chemical fertilizers was more effective in improving tomato growth, physiology, yield, and nutritional attributes. Compared to the control treatment (NP applied), the combined application of vermicompost and chemical fertilizer significantly improved the root length (21.6%), plant height (167%), SPAD value (13.5%), chlorophyll 'a' (96%), chlorophyll 'b' (161%), relative water content (16%), membrane stability index (18%), carotenoid (87%), yield (82%), photosynthetic rate (148%), fruit diameter (83%), protein (89%), fat (27.5%), fiber (12%), vitamin C (52%), calcium (54%), magnesium (117%), phosphorus (38%) and potassium (128%). In addition, significant improvements in different soil physicochemical properties were also pragmatic. The results suggest that vermicompost application with reduced doses of chemical fertilizers can be used to improve crop yield and soil physico-chemical properties.

**Keywords:** tomato; vermicompost; inorganic fertilizer; nutrients availability; yield; soil health

## 1. Introduction

Tomato (*Solanum lycopersicum* L.) is a highly valued vegetable crop in horticulture due to its nutritional value and versatile culinary applications [1]. Tomatoes are rich in essential vitamins and minerals, including vitamins A, C, and E; calcium; and niacin, which are linked to numerous human health benefits [2]. The global demand for tomatoes has increased significantly in recent years due to population increase, their widespread availability, and affordability [3]. However, traditional methods of tomato cultivation heavily depend on chemical fertilizers, which can have detrimental effects on soil health, the environment, and ultimately human health [4]. To address these issues, organic farming methods utilizing sustainable biofertilizers such as vermicompost have emerged as a viable alternative. This approach enhances the nutritional quality of fruits, making it an increasingly favored option for ensuring a sustainable crop supply [5].

Vermicompost is a nutrient-rich organic amendment produced through the breakdown of organic materials using earthworms and microbes [6], which produces a stable, peat-like material with a low carbon to nitrogen (C:N) ratio, enriched with essential nutrients, microbiologically active agents that increase porosity, and water-holding capacity (WHC) [7]. The application of vermicompost has several benefits: it reduces the application of chemical fertilizers, minimizes harm to soils and the environment, improves soil health, and provides better crop yields [8]. In addition, the application of vermicompost as a soil amendment can enhance the soil nutrient profile and promote soil health, leading to sustainable crop production [9]. Different field studies have shown that the integrated use of vermicompost with chemical fertilizers can significantly improve tomato growth and yield [10]. Mixed biofertilizer application has been reported to improve soil fertility, nutrient uptake, grain yield, and shoot biomass of many crops, including cowpea (*Vigna unguiculata* L.) [11], suggesting its potential to reduce chemical fertilizer usage and promote sustainable agriculture. The combined use of chemical fertilizers, biofertilizers, and compost enhanced the growth and yield of *Brassica compestris* [12]. Additionally, vermicompost application showed positive effects on root volume, fresh weight, and length in *Setaria* grass, *Lilium longiflorum*, pea, maize, and crossandra plants [3,13–15].

Vermicompost application increased shoot fresh weight and shoot dry weight in marigold (Tagetes) plants [14,16], as well as enhanced chlorophyll content, number of leaves, and leaf area in cucumber, pak choi, sorghum, and *Lilium* plants [15,17,18]. Moreover, it increased chlorophyll a and b content in *Andrographis paniculate* and cucumber, improved flowering and heading in African marigold, crossandra, *Chrysanthemum morifolium*, and *Matricaria chamomilla* plants [19–21], and increased fruit yield and length in strawberry, cucumber, eggplant, and garlic plants [14,20,22,23]. These findings suggest that vermicompost can enhance plant growth, nutrient uptake, and yield, making it a potential alternative to chemical fertilizers. It is hypothesized that organic matter and/or vermicompost application to soil could minimize the usage of chemical fertilizers and, subsequently, improve plant growth and reduce production costs. This study seeks to evaluate the effects of the sole and combined application of vermicompost and chemical fertilizers on the morpho-physiological responses of tomato plants, aiming to improve yield fruit quality, and soil health, and reduce the environmental risks associated with chemical fertilizer use.

## 2. Materials and Methods

### *2.1. Preparation and Collection of Vermicomposts*

For vermicompost 1 preparation, cattle dung was collected from the Agronomic Research Area, Sindh Agriculture University, Tandojam, Sindh, Pakistan. Earthworms (*Eisenia fetida*) were taken from Mian Dost Muhammad Farm Hyderabad, Sindh, Pakistan, and vermicomposting was performed at the same location in 6 pits (6 ft length $\times$ 4 ft width $\times$ 2 ft depth) in soil using the method of pre-composting described by Grag and Gupta [24]. After 20 days of pre-composting, the material was added to composting pits along with 8000 earthworms per composting pit at 25 $\pm$ 1 °C [25,26]. Water was sprinkled regularly in the composting pits and the final form of vermicompost (vermicast) was collected through sieves after 60 days [27]. Vermicompost 2 was obtained from the National Agricultural Research Centre (NARC), Islamabad, Pakistan, where the vermicompost that is commercially available to growers or researchers is prepared.

### 2.2. Chemical Composition of Cattle Manure and Vermicomposts

The chemical properties of cattle manure and vermicompost 1 and 2 were analyzed. The EC and pH were recorded using EC (Model Cyberscean Con11 standard portable series) and pH meters (Model SENS Direct Lovibond pH 110) [28]. The gravimetric technique and titration with the EDTA method were followed to determine the manure's moisture status and total calcium (Ca) content, respectively [29]. Total nitrogen, available phosphorus, available potassium, and organic carbon in the organic samples were determined by following the protocols of Bremner and Mulavaney [30], Watanabe and Olsen [31], Bansal and Kapoor [32], and Page and Page [33], respectively. The chemical compositions of the manure and vermicompost are given in Table 1.

**Table 1.** Physico-chemical properties of the cattle manure and vermicompost used for the experiment. Values after ± represent standard error.

| Properties | Cattle Manure | Vermicompost 1 | Vermicompost 2 |
|---|---|---|---|
| Color | Dark Brown | Dark Brown to Black | Dark Brown to Black |
| Odor | Odor | Odorless | Odorless |
| Particles size | 4 mm | 4 mm | 4 mm |
| Moisture % | - | 24.28 ± 0.20 | 21.29 ± 0.14 |
| pH | 8.6 ± 0.03 | 7.74 ± 0.05 | 8.07 ± 0.05 |
| Electrical conductivity (dS $m^{-1}$) | 0.66 ± 0.04 | 3.56 ± 0.07 | 4.26 ± 0.07 |
| Organic Carbon (OC) % | 0.65 ± 0.03 | 18.13 ± 0.05 | 16.70 ± 0.04 |
| Nitrogen (N) % | 0.86 ± 0.04 | 1.85 ± 0.03 | 1.75 ± 0.03 |
| Available Phosphorus (P) % | 0.26 ± 0.02 | 0.68 ± 0.02 | 0.81 ± 0.06 |
| Available Potassium (K) % | 0.60 ± 0.03 | 0.93 ± 0.02 | 0.83 ± 0.03 |
| Calcium (Ca) % | 1.10 ± 0.02 | 1.29 ± 0.05 | 1.47 ± 0.04 |

### 2.3. Soil Sampling and Preparation

Pre-and post-experiment soil sampling (0–30 cm) was performed using a soil auger. The samples were air-dried, ground, sieved through a 2 mm sieve, placed in polyethylene bags for storage in a cool and dry environment, and analyzed for physico-chemical properties [34]. The EC and pH were determined in 1:2.5 soil water extracts [35], and EC and pH were recorded using EC (Model Cyberscean Con11 standard portable series, Lovibond, Amesbury, UK) and pH meters (Model SENSO Direct Lovibond pH 110). Soil texture was assessed using the hydrometer method [36], whereas the soil textural class was determined using the USDA triangle for soil texture determination. Nitrogen concentration in the soil was determined using the Kjeldahl apparatus following the manual of Bremner et al. [30]. Similarly, extractable P and K were measured by the AB-DTPA method as described by Soltanpour et al. [37] using a spectrophotometer and flame photometer, and the organic matter content was determined by following the protocols of Walkely and Black [38,39]. The physical and chemical characteristics of soil are presented in Table 2.

**Table 2.** Physico-chemical properties of the soil before the experiment.

| Soil Properties | Values |
|---|---|
| a. Sand (%) | 32.40% |
| b. Silt (%) | 27.30% |
| c. Clay (%) | 40.30% |
| Textural class | Clay |
| pH (1:2.5 soil water extract) | 8.43 ± 0.05 |
| Electrical conductivity (dS $m^{-1}$) | 0.66 ± 0.03 |
| Soil organic matter (%) | 1.60 ± 0.11 |
| Nitrogen (%) | 0.08 ± 0.01 |
| Phosphorus (mg $kg^{-1}$) | 1.63 ± 0.23 |
| Potassium (mg $kg^{-1}$) | 82.25 ± 2.66 |

### *2.4. Crop Husbandry and Experimental Design*

The experiment was conducted in a farmer's field (Mian Dost Muhammad Farm Tando Jam, Sindh, Pakistan) from 2021 to 2022. The soil was prepared by performing two cross-ploughings, each followed by planking with the help of a tractor-drawn tine-cultivator to achieve a normal seedbed. Tomato crop was used as a test crop whose certified seeds (Sultan F1 Hybrid) were purchased from a private company (Millan Agro Seed, Pakistan). A randomized complete block design (RCBD) was used to arrange the treatments with four replicates. Six treatments were used as follows: $T_1$ = N:P (100:50 kg ha$^{-1}$, common practice of tomato growers),$T_2$ = N:P:K (100:50:50 kg ha$^{-1}$), $T_3$ = Vermicompost 1 (2 t ha$^{-1}$), $T_4$ = Vermicompost 2 (2 t ha$^{-1}$), $T_5$ = N:P:K + Vermicompost 1 (50:25:25 kg ha$^{-1}$ + 1.5 t ha$^{-1}$), and $T_6$ = N:P:K + Vermicompost 2 (50:25:25 kg ha$^{-1}$ + 1.5 t ha$^{-1}$). The required amount of chemical fertilizer was urea, diammonium phosphate (DAP), and muriate of potash (MOP).

#### 2.4.1. Plant Growth, Physiology and Yield Attributes

After four weeks of transplanting, a random sample of 3 tomato plants per experimental sub-plot was taken. Plants were carefully shoveled out of the soil, and excess soil around the roots was carefully removed. After that, the roots were washed using tap water to remove the rest of the adhered soil. Then, the harvested plants were transferred to the laboratory for physiological measurements (chlorophyll SPAD and 'a and b' contents, photosynthetic rate, carotenoids, relative water content, and membrane stability index), along with growth and yield attributes, i.e., root length, root and shoot fresh and dry weight, and plant height. Moreover, plant height was recorded during the last picking of tomato fruit. Moreover, fruit quality and yield attributes, such as size, weight, and overall yields, were also calculated upon harvest.

The chlorophyll content (SPAD) values were taken using a portable chlorophyll meter (SPAD-502 Plus, Konica Minolta Sensing, Inc., Osaka, Japan). Furthermore, the photosynthetic rate was measured before flowering using a portable photosynthesis 'Combined infra-red analyzing' system (CIRAS) using its automatic light source in 1800 µmol m$^{-2}$ s$^{-1}$ photon flux density. Chlorophyll 'a', 'b', carotenoids, relative water content (RWC), and membrane stability index (MSI) were measured using the prescribed protocols [40–42].

#### 2.4.2. Nutritional Quality of the Tomato

Tomato fruit samples were randomly taken from each experimental sub-plot, oven-dried at 70 ± 5 °C until constant weight, and ground in a stainless-steel grinder. Total P was determined by the Vanado-molybdate method, K and Ca were determined by flame photometry, and the sample for Mg was determined by atomic absorption spectrophotometer following the method described by Shehzad et al. [43]. Total N was analyzed using the micro-Kjeldahl procedure as described, and crude protein was obtained by multiplying the total N by a factor of 6.25 [44]. Concentrations of nutrients were expressed based on the percentage of dry fruit material as described by Chapman et al. [45].

### *2.5. Statistical Analysis*

After the experiment, the recorded data were subjected to variance analysis (ANOVA) using Statistix v8.1 (Analytical Software, Tallahassee, FL, USA), and the least significant difference (LSD) test was applied for multiple comparisons at a *p* value of 0.05.

## 3. Results

### *3.1. Plant Growth, Yield and Physiological Attributes*

The application of recommended NPK levels alone and reduced doses of NPK in combination with the two types of vermicompost significantly ($p < 0.05$) enhanced tomato plant growth, yield, and physiological attributes. The maximum plant height (184 ± 2.93 cm) was recorded in T5, where vermicompost 1 was applied in combination with reduced doses of NPK (Table 3). The increase was 168% more than that of the control treatment (NP, farmers' practice). The maximum shoot fresh weight (10.52 ± 0.09 g) and shoot dry weight

(1.04 ± 0.014 g) were recorded in the same treatment, which was 39 and 44% more than that of their respective controls. The maximum root length (11.50 ± 0.15 cm) was recorded in T5 with a 22% increase, while root fresh (3.11 ± 0.09 g) and dry weight (0.38 ± 0.009 g) were also found in the same treatment with 45 and 46% more than that of the respective controls. The results of tomato yield, fruit length, and diameter are presented in Table 3. The application of the T5 treatment yielded a significant yield, fruit length, and diameter ($p < 0.05$) than the rest of the treatments. The maximum yield (13,778 ± 285 kg $ha^{-1}$) was obtained in T5. Additionally, the maximum fruit length (8.51 ± 0.12 cm) and fruit diameter (5.85 ± 0.10 cm) were observed in the plants under the T5 treatment, which increased by 101% and 83% more than the control treatments, respectively (Table 4).

**Table 3.** Effect of vermicompost alone and in combination with conventional fertilizers on the height, shoot, and root attributes of tomato plants.

| Treatments | Plant Height (cm) | Shoot Fresh Weight (g) | Shoot Dry Weight (g) | Root Length (cm) | Root Fresh Weight (g) | Root Dry Weight (g) |
|---|---|---|---|---|---|---|
| T1 | 68.7 ± 2.40 e | 7.57 ± 0.06 d | 0.72 ± 0.018 d | 9.46 ± 0.20 d | 2.14 ± 0.06 c | 0.26 ± 0.005 e |
| T2 | 133.8 ± 1.24 c | 10.22 ± 0.13 a | 0.86 ± 0.016 c | 10.84 ± 0.22 bc | 2.93 ± 0.13 ab | 0.35 ± 0.002 bc |
| T3 | 120.3 ± 0.50 d | 9.31 ± 0.09 b | 0.82 ± 0.012 c | 10.69 ± 0.13 bc | 2.62 ± 0.09 b | 0.32 ± 0.002 cd |
| T4 | 111.3 ± 0.91 d | 8.78 ± 0.12 c | 0.75 ± 0.003 d | 10.15 ± 0.07 cd | 2.58 ± 0.10 bc | 0.31 ± 0.003 d |
| T5 | 184.0 ± 2.93 a | 10.52 ± 0.09 a | 1.04 ± 0.014 a | 11.50 ± 0.15 a | 3.11 ± 0.09 a | 0.38 ± 0.009 a |
| T6 | 159.8 ± 2.78 b | 10.35 ± 0.16 a | 0.94 ± 0.016 b | 11.20 ± 0.10 ab | 2.94 ± 0.10 ab | 0.36 ± 0.008 ab |

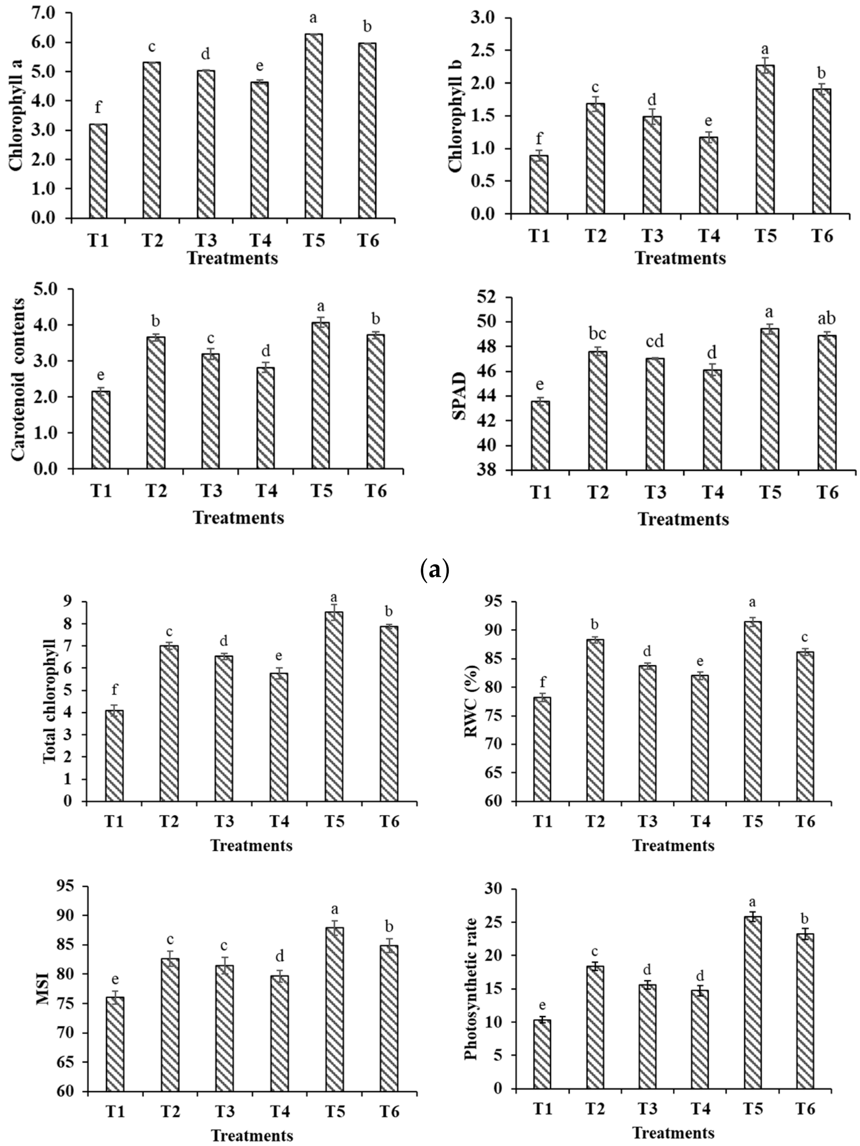
T1 = N:P (100:50 kg $ha^{-1}$); T2 = N:P:K (100:50:50 kg $ha^{-1}$); T3 = $Vermicompost_1$ (2 t $ha^{-1}$); T4 = $Vermicompost_2$ (2 t $ha^{-1}$); T5 = N:P:K + $Vermicompost_1$ (50:25:25 kg $ha^{-1}$ + 1.5 t $ha^{-1}$); T6 = N:P:K + $Vermicompost_2$ (50:25:25 kg $ha^{-1}$ + 1.5 t $ha^{-1}$). Values are the mean of four replicates ± standard errors, while means exhibiting the same lettering are statistically non-significant at $p < 0.05$.

**Table 4.** Effect of different types of vermicompost alone and in combination with conventional fertilizers on the yield, fruit length, and fruit diameter of tomato.

| Treatments | Yield (kg $ha^{-1}$) | Fruit Length (cm) | Fruit Diameter (cm) |
|---|---|---|---|
| T1 | 7310 ± 250 d | 4.40 ± 0.12 e | 3.33 ± 0.15 f |
| T2 | 11,827 ± 310 b | 7.17 ± 0.10 c | 4.43 ± 0.19 c |
| T3 | 10,742 ± 270 c | 6.45 ± 0.15 d | 4.15 ± 0.16 d |
| T4 | 10,612 ± 258 c | 5.62 ± 0.14 f | 3.76 ± 0.10 e |
| T5 | 13,778 ± 285 a | 8.51 ± 0.12 a | 5.85 ± 0.10 a |
| T6 | 12,515 ± 264 b | 7.94 ± 0.13 b | 5.45 ± 0.14 b |

T1 = N:P (100:50 kg $ha^{-1}$); T2 = N:P:K (100:50:50 kg $ha^{-1}$); T3 = $Vermicompost_1$ (2 t $ha^{-1}$); T4 = $Vermicompost_2$ (2 t $ha^{-1}$); T5 = N:P:K + $Vermicompost_1$ (50:25:25 kg $ha^{-1}$ + 1.5 t $ha^{-1}$); T6 = N:P:K + $Vermicompost_2$ (50:25:25 kg $ha^{-1}$ + 1.5 t $ha^{-1}$). Values are the mean of four replicates ± standard errors, while means exhibiting the same lettering are statistically non-significant at $p < 0.05$.

The application of reduced doses of NPK in combination with the two types of vermicompost significantly ($p < 0.05$) enhanced the physiological attributes of tomato plants. The maximum chlorophyll a, b, carotenoid and chlorophyll (SPAD) readings were found to be 6.3 ± 0.02 mg $g^{-1}$, 2.27 ± 0.11 mg $g^{-1}$, 4.08 ± 0.43 mg $g^{-1,}$ and 49.41 ± 3.21 in T5, with 96%, 155%, 89%, and 13.5% increases over their respective controls (Figure 1a). Total chlorophyll contents were recorded as maximum (8.5 ± 0.36 mg $g^{-1}$) in T5, with a 109% increase over the control treatment. The same treatment showed the highest response of relative water content (RWC), membrane stability index (MSI), and photosynthesis was also found to be maximum in T5, with maximum values of 91.4 ± 0.78%, 88 ± 1.22%, and 26 μmol $m^{-2}$ $s^{-1}$ ± 0.77, which was were 17%, 16%, and 150% more than the control treatments, respectively (Figure 1b).




(**a**)

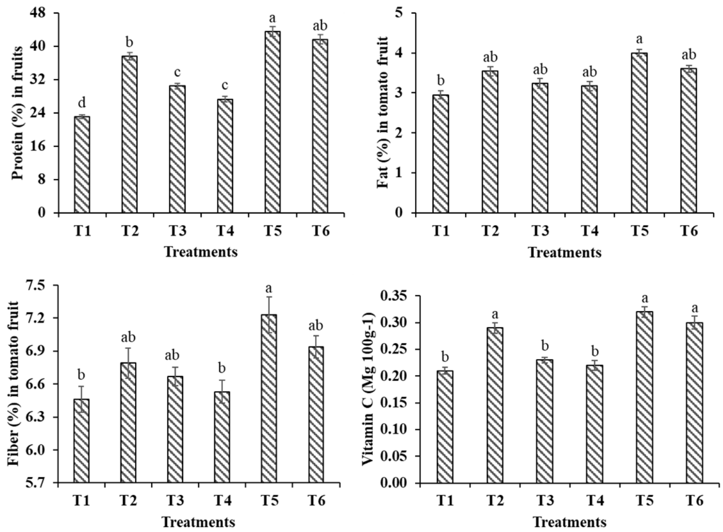
(**b**)

**Figure 1.** (**a**): Effect of vermicompost alone and in combination with conventional fertilizers on tomato physiological attributes. T1 = N:P (100:50 kg ha$^{-1}$); T2 = N:P:K (100:50:50 kg ha$^{-1}$); T3 = Vermicompost$_1$ (2 t ha$^{-1}$); T4 = Vermicompost$_2$ (2 t ha$^{-1}$); T5 = N:P:K + Vermicompost$_1$ (50:25:25 kg ha$^{-1}$ + 1.5 t ha$^{-1}$); T6 = N:P:K + Vermicompost$_2$ (50:25:25 kg ha$^{-1}$ + 1.5 t ha$^{-1}$). Bars exhibiting the same letters are statistically non-significant at $p < 0.05$. (**b**): Effect of vermicompost alone and in combination with conventional fertilizers on the tomato physiological attributes. Bars exhibiting the same letters are statistically non-significant at $p < 0.05$.

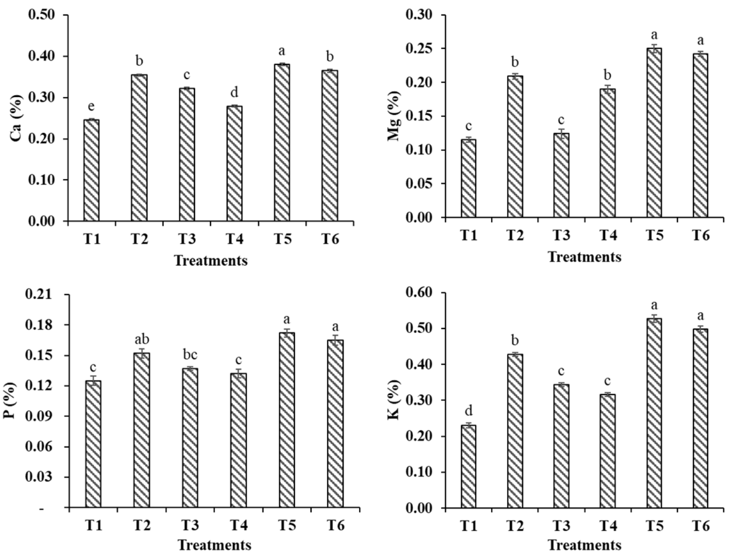
Fruit Quality and Nutritional Analysis

The nutritional and quality attributes of the fruits were also assessed and compared with the mean using ANOVA. It was revealed that the nutritional and quality parameters of the fruits were positively affected by the applied treatments. The maximum tomato fruit protein contents (43.47%) and fat and fiber contents were recorded at 43.47% ± 1.17, 4% ± 0.09, and 7.23% ± 0.12 in T5. In the same treatment, Vitamin C contents also show the same response after the T5 treatment application. Vitamin C was found to be 0.32 mg 100 g$^{-1}$, which was 52% more than the control treatment (Figure 2a). The maximum tomato fruit calcium, magnesium, phosphorus, and potassium contents were found to be

0.380% ± 0.004, 0.250% ± 0.006, 0.172% ± 0.004, and 0.527% ± 0.010 in T5, which were 54%, 117%, 38%, and 128% more than the respective controls, respectively (Figure 2b).




(**a**)




(**b**)

**Figure 2.** (**a**) Effect of different types of vermicompost alone and in combination with conventional fertilizers on the quality of tomato fruit. Bars exhibiting the same letters are statistically non-significant at $p < 0.05$. T1 = N:P (100:50 kg ha$^{-1}$); T2 = N:P:K (100:50:50 kg ha$^{-1}$); T3 = Vermicompost$_1$ (2 t ha$^{-1}$); T4 = Vermicompost$_2$ (2 t ha$^{-1}$); T5 = N:P:K + Vermicompost$_1$ (50:25:25 kg ha$^{-1}$ + 1.5 t ha$^{-1}$); T6 = N:P:K + Vermicompost$_2$ (50:25:25 kg ha$^{-1}$ + 1.5 t ha$^{-1}$). (**b**) Effect of different types of vermicompost alone and in combination with conventional fertilizers on the nutritional attributes of tomato fruit. Bars exhibiting the same letters are statistically non-significant at $p < 0.05$.

### *3.2. Post-Harvest Variation in Soil Physico-Chemical Properties*

The physico-chemical properties of the soil were assessed after the experiment to check the effectiveness of the applied treatments in improving the soil's physico-chemical properties. In our results, we observed that different treatments led to a considerable improvement in the physico-chemical parameters of the post-harvest soil. The individual and combined application of different vermicompost and NPK fertilization significantly improved soil properties such as organic matter content, total N, available P, and exchangeable K contents after crop harvest. It was concluded that the sole application of vermicompost yielded more significant outcomes than conventional fertilizers and their combined treatments in improving soil characteristics. The changes in the soil's physico-chemical properties are presented in Table 5.

**Table 5.** Post-harvest physico-chemical properties of the soil. Values after ± show standard error of four replicates of each treatment, while different letters show the level of significance at $p \leq 0.05$.

| Soil Properties | T1 | T2 | T3 | T4 | T5 | T6 |
|---|---|---|---|---|---|---|
| pH (1:2.5 soil water extract) | 8.6 ± 0.02 a | 8.5 ± 0.07 ab | 8.1 ± 0.04 de | 8.0 ± 0.07 e | 8.2 ± 0.07 cd | 8.4 ± 0.07 bc |
| EC (dS $m^{-1}$) | 0.56 ± 0.02 d | 0.62 ± 0.01 e | 0.90 ± 0.02 a | 0.86 ± 0.03 a | 0.75 ± 0.02 b | 0.64 ± 0.03 c |
| Soil organic matter (SOM, %) | 1.2 ± 0.05 c | 1.3 ± 0.11 c | 2.2 ± 0.11 a | 1.6 ± 0.07 b | 1.7 ± 0.07 b | 1.6 ± 0.04 b |
| Nitrogen (N, %) | 0.069 ± 0.01 b | 0.080 ± 0.01 b | 0.147 ± 0.01 a | 0.129 ± 0.01 a | 0.128 ± 0.01 a | 0.117 ± 0.01 a |
| Available Phosphorus (P, mg $kg^{-1}$) | 1.60 ± 0.08 d | 1.88 ± 0.07 c | 2.50 ± 0.07 a | 2.20 ± 0.07 b | 2.15 ± 0.04 b | 2.03 ± 0.05 bc |
| Extractable Potassium (K, mg $kg^{-1}$) | 78.1 ± 0.93 c | 80.3 ± 1.11 d | 98.3 ± 0.57 a | 94.1 ± 0.95 b | 89.6 ± 0.64 c | 87.7 ± 0.83 c |

T1 = N:P (100:50 kg $ha^{-1}$); T2 = N:P:K (100:50:50 kg $ha^{-1}$); T3 = $Vermicompost_1$ (2 t $ha^{-1}$); T4 = $Vermicompost_2$ (2 t $ha^{-1}$); T5 = N:P:K + $Vermicompost_1$ (50:25:25 kg $ha^{-1}$ + 1.5 t $ha^{-1}$); T6 = N:P:K + $Vermicompost_2$ (50:25:25 kg $ha^{-1}$ + 1.5 t $ha^{-1}$).

## 4. Discussion

### *4.1. Plant Growth, Yield, Physiology and Nutritional Quality Attributes of Tomato Plant*

In the current study, we observed that the application of both types of vermicompost, especially cow dung vermicompost, in combination with a reduced dose of NPK fertilization, enhanced various growth parameters compared to the individual application of vermicompost or chemical fertilization. The increase in these properties could be due to the high moisture content and balance between its organic and inorganic nutrients, which enhance plant growth and yield upon its application [46]. Various researchers have reported similar results that the application of vermicompost as an amendment to soil enhances plant growth, productivity, and soil health [47,48]. Similar results have also been reported by [49,50] that vermicompost application improves growth attributes and, hence, enhances overall plant productivity. In addition, the presence of an increased number of N-fixing bacteria and mycorrhizal fungi in vermicompost promotes plant growth via different mechanisms of growth promotion. Vermicompost also encompasses different enzymes such as chitinases, amylases, lipases, and cellulases, which are very helpful in organic matter degradation and the release of various nutrients, making them available to plant roots for their uptake even after soil depletion [51]. Reference [52] observed the effects of the combined application of vermicompost and NPK fertilizers in improving the growth and yield of spinach (*Amaranthus tricolor* L.) due to the high NPK contents of inorganic fertilizer as well as the increased nutritional attributes of vermicompost. Vermicompost-mediated improvement in soil properties and uptake of essential nutrients has also been reported in potato tubers by Afandi et al. [53].

We also noted a significant positive effect of the combined application of vermicompost and NPK fertilizers in improving different physiological attributes, such as chlorophyll and carotenoid contents and SPAD value in tomato leaves. Identical results were observed when vermicompost was applied to radish along with conventional inorganic fertilizers [54]. Similarly, our results, in terms of carotenoid contents and photosynthetic rate in tomato leaves, were further confirmed by those who reported increased attributes upon the application of vermicompost. Vermicompost has a diversity of plant growth-promoting rhizobacteria (PGPR) that directly improve plant productivity via biological nitrogen fixation (BNF), nutrient solubilization, and production of different growth hormones that enhance plant growth, development, and physiology, such as carotenoid contents, as well as gas exchange attributes, such as photosynthetic rate [51].

Rekha et al. [55] reported that vermicompost supports a wide range of essential nutrients, the uptake of which leads to a substantial increment in plant growth, photosynthesis as well as chlorophyll contents by exerting positive impacts on plant nutrition. Our results, in terms of the effect of vermicompost on the photosynthetic attributes of the plant, were also confirmed by Mahmoud et al. [56]; they observed that the application of different levels of vermicompost significantly improved the chlorophyll contents of bean plant (*Phaseolus vulgaris* L.) and they also observed that increasing the dose of vermicompost compared to chemical fertilizers yielded more significant outcomes in terms of photosynthetic attributes of the plant. Khosropour et al. [57] reported better photosynthetic rates and increased plant biomass due to the vermicompost-mediated improved soil properties, such as nutrient and water retention capacities. Additionally, due to its high nutrient-supplying capacities, vermicompost can act as a plant growth promoter by facilitating chlorophyll contents. Similar results were also reported by Wang et al. [1] and Arancon et al. [58]. The increase in the chlorophyll contents was attributed to increased nitrogen availability from vermicompost. As nitrogen is a key component of chlorophyll molecules, an adequate nitrogen supply can stimulate the production of chlorophyll. Moreover, reduced chlorosis due to improved nitrogen supply also helped increase chlorophyll synthesis, activity, and production. Relative water content (RWC) is a significant contributor to the relationship between water and plant physiology. Amendments of soil with both types of vermicompost significantly enhanced RWC in tomato leaves alone and were associated with NPK fertilization. Similar results were reported by [59], who found that the application of vermicompost to wheat plants under drought stress enhanced the RWC of plants. Vermicompost also uplifts soil properties, ultimately leading to improved physiological attributes of plants and resultant nutrient uptake [60,61]. Hafez et al. also observed an increase in the relative water content of the wheat plant after the combined application of biochar and vermicompost [62].

The current study indicated a significant increase in the membrane stability index of tomato plants due to the single and combined applications of vermicompost and NPK fertilizer. Similar results were observed in the findings by Beyk-Khormizi et al. [63], who checked the effect of vermicompost application in alleviating the salinity stress of Foeniculum vulgare. They reported that under salinity stress, a substantial decline in the MSI was observed with a simultaneous increment in the tomato plant. In another study, Ezzat et al. [64] reported that the application of vermicompost to potatoes significantly increased the MSI and RWC, which reflected increased membrane damage under salinity stress. However, vermicompost application ameliorated the adverse effects on cell membranes and increased their stability under stressed conditions. In another experiment, Ref. [65] stated that the simultaneous application of compost and vermicompost enhanced the MSI under salinity stress and attributed this increase to the regulation of membrane integrity, as well as the prevention of plasma membrane damage [66]. Aslam et al. [67] also reported similar results where they explained that the application of vermicompost increased membrane stability in tomatoes, as evidenced by increased MSI percentage in the treated plants.

Our outcomes regarding different vitamins and biochemical attributes, such as protein, fiber, and fat contents, revealed their strong correlation with vermicompost application. Similar outcomes were observed by [68], who checked the potential of vermicomposting of different organic wastes in improving growth and yield and performed a proximate analysis of cucumber plants. They stated that the application of vermicompost positively affected the proximate analysis of cucumbers, such as fat, protein, fiber, and other nutritional contents. In addition, Joshi observed that adding vermicompost to soil increased wheat protein, fat, fiber, and carbohydrate contents compared to the control treatment [14]. Moreover, Adekiye et al. [69] reported that increased N input to the soil upon the application of vermicompost enhanced the total protein contents since N is a crucial component of protein and different enzymes, as well as chlorophyll; hence, they observed a substantial quantity of crude protein contents in okra. An increase in these mineral elements upon the application of vermicompost is assumed to be correlated with the high nutritional content of vermicompost [70]. Similar results were obtained by Joshi et al., who reported enhanced crude fiber and fat contents with an increase in the vermicompost application level. In another study, Rahman et al. [71] reported an increase in the protein contents of sunflowers upon the application of vermicompost in the soil, and the values were found to be positively correlated with the increase in the vermicompost levels. Furthermore, an increase in the protein contents after the application of vermicompost has been reported by several researchers [72,73].

### *4.2. Effect of Vermicompost on Physico-Chemical Properties of Post-Harvest Soil*

The application of various rates of vermicompost showed statistically significant positive effects on the physico-chemical properties of postharvest soil. [74]. In general, the physical characteristics of sandy clay loam soil were improved by vermicompost treatments under water-limiting and water-replete conditions. The application rate of vermicompost at 5% effectively increased various soil parameters, including total porosity, bulk density, hydraulic conductivity, field capacity, and accessible water holding capacity [75]. Raising soil aggregate stability is indicative of improving soil quality and health, and this trend appears to be driven primarily by organic matter in the soil [76]. In this study, vermicompost treatments significantly altered the soil aggregate and structural stability indexes [77]. Organic matter plays an important role in soils because of its increased water-holding capacity (WHC), cation exchange capacity (CEC), and chelation ability. According to the literature, more vermicompost is associated with higher soil organic matter levels [78]. It has also been observed that the soil's content of organic carbon (C) increases with increasing doses of vermicompost, followed by organic waste [79]. It is reported that vermicompost has a valuable source of readily accessible nutrients. It is also revealed that vermicompost has a high concentration of humic acid. Because of the humic acid's positive effects on soil microbes, organic acid production has increased, improving the soil's overall quality [80]. Vermicompost contains a rather high level of humic acid, which contributes to its reputation as a useful source of easily absorbable nutrients. As a result of the beneficial effects of humic acid on soil microbes, the production of organic acids increases, thereby improving soil quality [81]. Vermicompost treatments have also been linked to an increase in soil phosphorus content. A sizable fraction of total N is readily available to plants due to adequate moisture, low pH, and organic matter [82]. Vermicompost improves plant nutritional intake and conveniently delivers all nutrients [83]. The EC of vermicompost is related to the ion concentration of the starting materials [75]. Similarly, soil EC values for both acidic and alkaline soils increased after treatment with organic fertilizers [84]. Exchangeable Soil Mg and Ca concentrations dramatically increased after VC treatments. Higher VC treatment doses increased the exchangeable Mg and Ca contents [85]. Using vermicompost improves the soil in both a nutritional and physical sense.

## 5. Conclusions

The application of inorganic chemical fertilizers can be minimized by supplementing them with organic fertilization sources such as vermicompost, which not only improves the physico-chemical properties of the soil but also facilitates nutrient transfer to plants, leading to increased growth and yield. In the current study, a similar concept was used, and the results suggested that vermicompost combined with half of the recommended doses of NPK enhanced tomato growth, yield, physiology, nutrient uptake, and proximate nutrient concentrations. Furthermore, a significant improvement in different physico-chemical attributes of post-harvest soil was also observed under the sole and combined application of vermicompost. It was concluded that vermicompost, along with reduced NPK fertilization, can be used as an ideal agent for improving soil properties, followed by an improvement in plant growth and fruit quality.

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