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Abstract: Chemical fertilizers are commonly used to meet the nutritional demands of the crops and boost their yield. However, their high costs and excessive application in soils increases 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 additional advantages of sustainable nutrient supply to crops and maintaining soil health. To evaluate the potential of two diverse vermicomposts, sole and combined application of these vermicomposts with reduced rates of chemical fertilizers were used for tomato cultivation in a field study. The results indicated that vermicompost produced from cow dung combined with chemical fertilizers proved to be more effective in improving tomatoes' growth, physiology, yield and nutritional attributes. Combined application of vermicompost and chemical fertilizer significantly improved 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%), and fruit diameter (83%) protein (89%), fat (27.5%), fiber (12%), vitamin C (52%), calcium (54%), magnesium (117%), phosphorus (38%), potassium (128%), as compared to control treatment (NP applied). In addition, significant improvements in different soil physico-chemical 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, 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, conventional tomato farming practices rely heavily on chemical fertilizers, which can negatively impact the soil health and environment, resulting in negative human health repercussions [4]. To address these issues, organic farming methods using sustainable biofertilizers, such as vermicompost, have gained popularity as an alternative to crop supply, reducing environmental pollution and improving fruit nutritional quality [5].

Vermicompost is a nutrient-rich organic amendment produced through the breakdown of organic materials using earthworms and microbes [6]. This process produces a stable, peat-like material with low carbon to nitrogen (C:N) ratio, increased porosity, and water-holding capacity (WHC). The material is also enriched with essential nutrients, microbiologically active agents, and organic matter [7]. Although the application of vermicompost to soils improves their health and crop productivity, it is a slow process as organic materials take time to decompose. So, the immediate benefits after the vermicomposts of other organic amendments application should not be expected. But combined application with reduced doses of chemical fertilizers can give an immediate response. This strategy has more than one benefit: it reduces the chemical fertilizers application, minimizes the harms to soils and environment, improves the soil health, and gives better crop yields [8]. Different field studies have shown that the integrated use of vermicompost with chemical fertilizers can significantly improve tomato growth and yield while reducing the need for chemical fertilizers [9]. 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 [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 [13–16].

Vermicompost application has increased shoot fresh weight and shoot dry weight in marigold (Tagetes) plants [15,17], as well as enhanced chlorophyll content, number of leaves, and leaf area in cucumber, pak choi, sorghum, and *Lilium* plants [16,18,19]. Moreover, it increased chlorophyll a and b content in *Andrographis paniculata* and cucumber, and improved flowering and heading in African marigold, crossandra, *Chrysanthemum morifolium*, and *Matricaria chamomilla* plants [20–22]. Vermicompost application also resulted in increased fruit yield and length in strawberry, cucumber, eggplant, and garlic plants [15,21,23,24]. These findings suggest that vermicompost can enhance plant growth, nutrient uptake, and yield, making it a potential alternative to chemical fertilizers. This study seeks to evaluate the effects of sole and combined application of vermicompost and chemical fertilizers on morpho-physiological responses of tomato plants, aiming to improve yield and fruit quality, soil health and reduce environmental risks associated with chemical fertilizer use. We hypothesized that organic fertilizers application to soils could minimize the usage of chemical fertilizers and, subsequently, can improve plant growth and reduce production costs.

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 also done in the same location in 6 pits (6 ft length × 4 ft width × 2 ft depth) in soil using the method of pre-composting described by Grag and Gupta [25]. After 20 days of pre-composting, the material was added to composting pits along with 8000 earthworms per composting pit having 25 ± 1°C temperature [26,27]. Water was sprinkled regularly in the composting pits and the final form of vermicompost (vermicast) was collected through sieves after 60 days [28]. The vermicompost 2 was obtained from National Agricultural Research Centre (NARC), Islamabad, Pakistan; the center prepares the vermicompost and commercially sells the product to the growers or researchers.

2.2. Chemical Composition of Cattle Manure and Vermicomposts

The chemical properties of the 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) [29]. The gravimetric technique and titration with EDTA method were followed to determine the manures moisture status and total calcium (Ca) content, respectively [30]. Total nitrogen, available phosphorus, available potassium and organic carbon in the organic samples were determined by following the protocols of Bremner and Mulavaney [31], Watanabe & Olsen [32], Bansal & Kapoor 2000 [33] and Page & Page [34], respectively. The chemical composition of the manure and vermicomposts are given in Table 1.

Table 1. Physico-chemical properties of the cattle manure and vermicomposts used for the experiment. Values after ± represents 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
Phosphorus (P) %	0.26 ± 0.02	0.68 ± 0.02	0.81 ± 0.06
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 done using a soil auger. The samples were air-dried, ground, sieved through a 2 mm sieve, put in polyethene bags for storage in a cool and dry environment, and analyzed for physico-chemical properties [35]. The EC and pH were determined in 1:2.5 soil water extracts [36], and *EC and pH were recorded using EC* (Model Cyberscean Con11 standard portable series) *and pH meters* (Model SENSO Direct Lovibond pH 110*)*. Soil texture was assessed by the hydrometer method [37], while soil textural class was determined using the USDA triangle for soil texture determination. Nitrogen concentration in soil was determined by the Kjeldahl apparatus following the manual of Bremner et at. [31]. Similarly, extractable P and K were measured by AB-DTPA Method as described by Soltanpour et al. using Spectrophotometer and flame photometer [38], and organic matter content was determined by following the protocols of Walkely and Black [39,40], respectively. Physical and chemical characteristics of soil are presented in Table 2.

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Table 2. Physico-chemical properties of the soil before 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 at a farmer's field (Mian Dost Muhammad Farm Tando Jam, Sindh, Pakistan, during 2021 – 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 the 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 having four replications. Six treatments were used; 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}), 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 supplied as 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 each 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 contents, 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 contents (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 contents (RWC) and membrane stability index (MSI) were measured using the prescribed protocols [41–43].

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 Mg was determined by atomic absorption spectrophotometer. Total N was analyzed by 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 at. [45].

2.5. Statistical Analysis

After the experiment, the recorded data was subjected to variance analysis (ANOVA) using Statistix v8.1 and 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 two types of vermicomposts significantly ($p < 0.05$) enhanced tomato plants growth, yield, and physiological attributes. 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 the control treatment (NP, farmers practice). 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 their respective controls. 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 the respective controls. The results of tomato yield, fruit length and diameter are presented in Table 4. The application of T5 treatment yielded a significant yield, fruit length and diameter ($p < 0.05$) than the rest of the treatments. Maximum yield (13,778 ± 285 kg ha^{-1}) was obtained in T5. Also, 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 was increased 101% and 83% more than the control treatments, respectively.

Table 3. Effect of vermicomposts alone and in combination with conventional fertilizers on height, shoot and root attributes of tomato plant.

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

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 mean of four replicates ± standard errors, while means exhibiting same lettering are statistically non-significant at $P < 0.05$.

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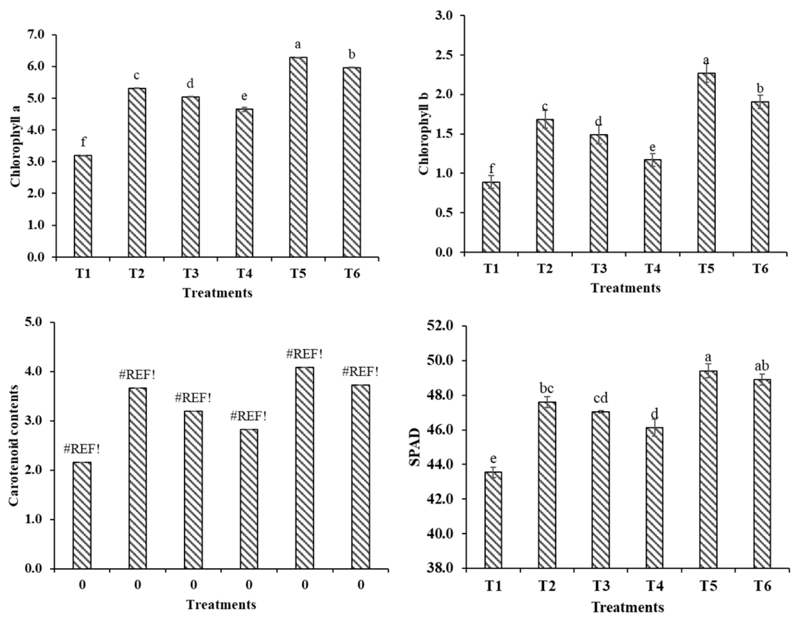
Table 4. Effect of different types of vermicompost alone and in combination with conventional fertilizers on yield, fruit length and fruit diameter of tomato.

Treatments	Yield (kg ha^{-1})	Fruit length (cm)	Fruit diameter (cm)
T1	7,310 ± 250d	4.40 ± 0.12e	3.33 ± 0.15f
T2	11,827 ± 310b	7.17 ± 0.10c	4.43 ± 0.19c
T3	10,742 ± 270c	6.45 ± 0.15d	4.15 ± 0.16d
T4	10,612 ± 258c	5.62 ± 0.14f	3.76 ± 0.10e
T5	13,778 ± 285a	8.51 ± 0.12a	5.85 ± 0.10a
T6	12,515 ± 264b	7.94 ± 0.13b	5.45 ± 0.14b

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 mean of four replicates ± standard errors, while means exhibiting same lettering are statistically non-significant at P < 0.05.

The application of reduced doses of NPK in combination with two types of vermicomposts significantly ($p < 0.05$) enhanced the tomato plants physiological attributes. 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 maximum (8.5 ±0.36 mg g^{-1}) in T5, with an 109% increase over the control treatment. The same treatment showed the highest response of relative water contents (RWC), membrane stability index (MSI) and photosynthetic was also found to be maximum in T5, having maximum values of 91.4± % and 88±1.22 % and 26 μmol m^{-2} s^{-1} ± 0.77, which was percent increase 17%,16% and 150% more than the control treatments, respectively (Figure 1b).



(a)

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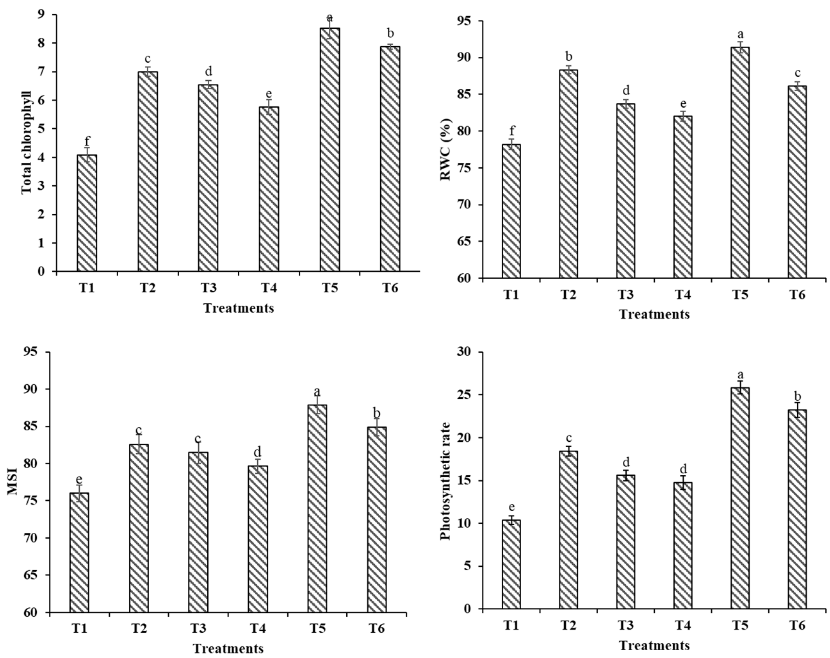
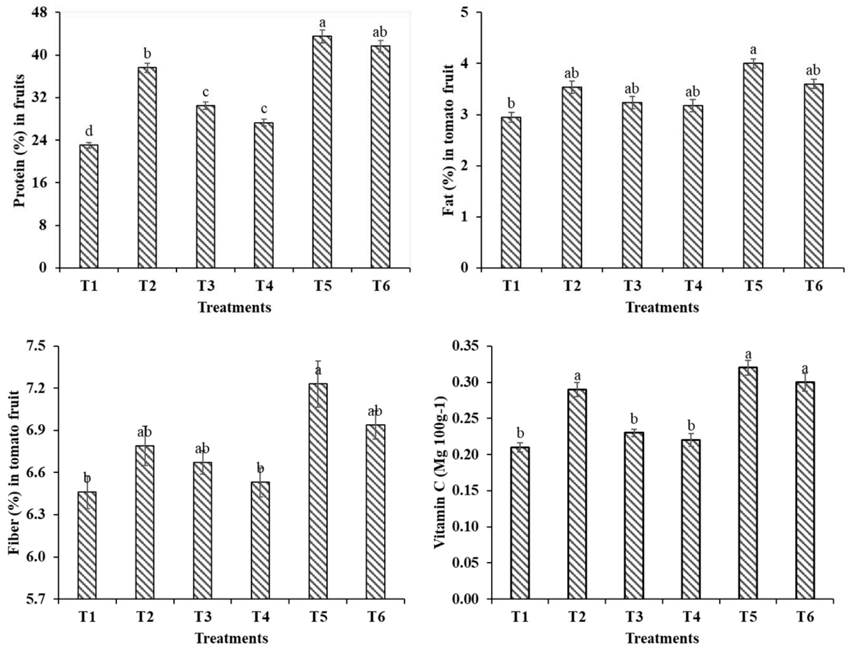


(**b**)

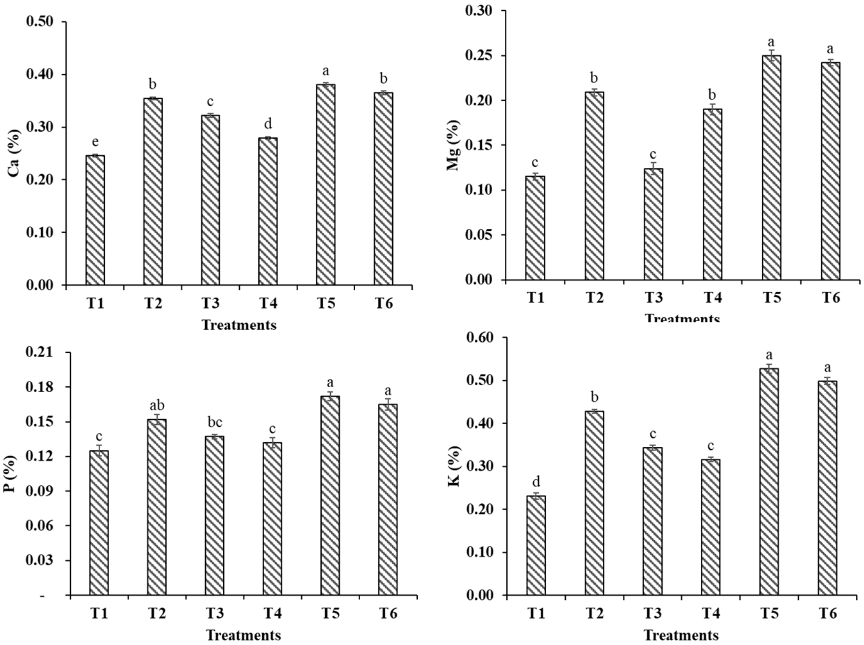
Figure 1. (**a**): Effect of vermicomposts alone and in combination with conventional fertilizers on tomato physiological attributes. T1 = N:P (100:50 kg ha-1),T2 = N:P:K (100:50:50 kg ha-1), T3 = $Vermicompost_1$ (2 t ha-1),T4 = $Vermicompost_2$ (2 t ha-1), T5 = N:P:K + $Vermicompost_1$ (50:25:25 kg 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 same letters are statistically non-significant at $P < 0.05$. (**b**): Effect of vermicomposts alone and in combination with conventional fertilizers on tomato physiological attributes. Bars exhibiting same letters are statistically non-significant at $P < 0.05$.

3.1.1. Fruit Quality and Nutritional Analysis

The fruit nutritional and quality attributes were also assessed and compared with the mean using ANOVA. It was revealed that fruit nutritional and quality parameters were positively affected by the applied treatments. Maximum tomato fruit protein contents (43.47%), fat and fiber contents were also 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 T5 treatment application. Vitamin C was found to be 0.32 mg100 g^{-1}, which was 52% more than the control treatment (Figure 2a). 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) recorded in T5, which were percent increase 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 fruit quality and nutritional analysis of tomato fruit. Bars exhibiting 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 fruit quality and nutritional analysis of tomato fruit. Bars exhibiting same letters are statistically non-significant at $P < 0.05$

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

The soil physico-chemical properties were assessed after the experiment to check the effectiveness of applied treatments in improving soil physico-chemical properties. In our results, we observed that different treatments led to a considerable improvement in the physico-chemical

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parameters of the post-harvest soil. The individual and combined application of different vermicomposts 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 vermicomposts yielded more significant outcomes than conventional fertilizers and their combined treatments for improving soil characteristics. The changes in the soil's physico-chemical properties are represented in Table 5.

Table 5. Post-harvest physico-chemical properties of the soil.

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

Values are Mean ± standard error of 4 replications. 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 application of both types of vermicomposts, especially cow dung vermicompost, in combination with a reduced dose of NPK fertilization enhanced various growth (plant height, root and shoot length and weight) as compared to individual application of vermicompost or synthetic sources of soil fertilization. The increase in these properties could be due to the high moisture content and balance between its organic and inorganic nutrients, which enhances plant growth and yield upon its application [46]. Various researchers have reported similar results that application of vermicompost as an amendment to soil enhances plant growth, productivity, and soil health [47,48]. The application of vermicompost supplies various micro- and macro-nutrients to the soils, which the plant ultimately takes up. Furthermore, vermicompost, on account of the regulation of its own natural phytohormones such as auxins, gibberellin and cytokinin, mineralizes the organic matter in the soil, improves soil pH and hence, enhances the soluble form of different nutrients and also augments the uptake of these nutrients by plant roots [18,49]. Similar results were also reported by [50,51]; furthermore, it has been reported 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 by following 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 depletion from soil [52]. In a study, [53] checked the effects of the combined application of vermicompost and NPK fertilizers in improving the growth and yield of spinach (*Amaranthus tricolor* L.). They reported that the application of NPK fertilizers along with vermicompost improved the length of spinach leaves due to the high NPK contents of inorganic fertilizer as well as increased nutritional attributes of vermicompost, which stimulated metabolic activities in plants and increased its growth. Vermicompost-mediated improvement in soil properties and uptake of essential nutrients has also been reported in potato tubers by [54]. Furthermore, increased fruit length, diameter and number of fruits in vermicompost-amended soils along with NPK fertilization may be correlated with increased water holding capacity, aeration, drainage, high surface area and porous nature of vermicompost, which permits increased elemental absorption as well as retention and seem to retain more essential nutrients for an increased time period to be used by the plants [52].

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 pragmatic when vermicompost was applied to radish along with conventional inorganic fertilizers [55]. Vermicompost and chemical fertilizers increase soil organic matter, i.e., humic acid elements, and thereby affect nutrient addition to the soil, providing media for uptaking nutrients by the plants and encouraging its growth by enhancing chlorophyll contents [51]. Similarly, our results in terms of carotenoid contents and photosynthetic rate in tomato leaves were further confirmed by those who reported the increased attributes upon the application of vermicompost. Vermicompost has ample diversity and microbial populations, particularly actinomycetes and fungi. Sufficient numbers of plant growth promoting rhizobacteria (PGPR) directly improve plant productivity via biological nitrogen fixation (BNF), nutrient solubilization and production of different growth hormones. These growth promoters, as well as regulators, enhance plant growth, development and physiology, such as carotenoid contents as well as gas exchange attributes such as photosynthetic rate etc. [52].

Rekha et al. 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 [56]. Our results in terms of the effect of vermicompost on the photosynthetic attributes of the plant were also confirmed by [57]; 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 as compared to chemical fertilizers yielded more significant outcomes in terms of photosynthetic attributes of the plant. Similarly, another study [58] assessed the potential of vermicompost application in improving soil fertility and plant growth (*Zeya mays* L.). They also reported that the application of vermicompost increased chlorophyll contents in maize leaves, indicating enhanced photosynthetic activity. Khosropour et al. reported better photosynthetic rates and increased plant biomass due to vermicompost mediated improved soil properties such as nutrient and water retention capacities [59]. Furthermore, they observed increased chlorophyll 'a' and 'b' contents in maize leaves, which were referred to increased activities of mycorrhizal fungi in vermicompost, which symbiosis with plant roots and improved chlorophyll contents as well as photosynthetic rates [60]. Also, 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. [61]. The increase in the chlorophyll contents was attributed to more nitrogen availability from vermicompost. As nitrogen is a key component of chlorophyll molecules, adequate nitrogen supply can stimulate the production of chlorophyll. Moreover, reduced chlorosis due to improved nitrogen supply also helped in more chlorophyll synthesis and activity and its production. Relative water contents (RWC) is a significant contributor to explaining the water relations plant physiology. Amendments of soil with both types of vermicompost significantly enhanced relative water contents in tomato leaves alone and were associated with NPK fertilization. Similar results were reported by [62], who reported that the application of vermicompost to wheat plants under drought stress enhanced plants' relative water contents (RWC). Synergistic application of vermicompost and NPK fertilizers enhanced available water contents in soil and hence maintained turgor pressure under stressed conditions. It was explained that the application of vermicompost enhanced the bulk density as well as field capacity of the soil, leading to an increase in available soil water and, subsequently the RW contents in plants and at the same time, increased photosynthetic rate owing to increased chlorophyll contents and gaseous exchange and plant nutrient uptake. Vermicompost also uplifts soil properties, ultimately leading to improved physiological attributes of plants and resultant nutrient uptake [63,64]. Hafez et al. also observed an increase in the relative water contents of the wheat plant after the combined application of biochar and vermicompost [65].

Furthermore, [66] evaluated the response of the lettuce plant to vermicompost application and reported significant differences between RWC. It was attributed to a balance in water loss and ionic uptake after vermicompost application. Vermicompost is very efficient in maintaining the hydraulic attributes of soil and its aeration, and hence, more nutrients and water uptake from the rhizosphere is ensured [67]. In another study, [68] reported that the application of vermicompost enhanced relative water contents under salinity stress by supplying N fertilizer [69]. Similar outcomes were observed by [70], who observed that vermicompost supplementation to soil mitigated the effect of drought stress on rapeseed by increasing the RWC in its leaves. Vermicompost mediated improvement in physical properties of soil, such as water holding capacity, organic matter increases as well as nutrient holding capacity and creation of suitable photosynthetic conditions, are the prime causes of its beneficial impacts on plant growth and physiology [71].

The current experiment indicated a significant increase in the membrane stability index of tomato plants owing to the single and combined applications of vermicompost and NPK fertilizer. Similar results were pragmatic in the findings of [72], who checked the effect of vermicompost application in alleviating the salinity stress in 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, [73] reported that the application of vermicompost to potatoes significantly increased MSI and RWC, which reflected increased membrane damage under salinity stress. However, vermicompost application ameliorated its adverse effects on cell membranes and increased their stability under stressed conditions. In another experiment, [71] stated that 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 prevention of plasma membrane damage [74]. Aslam et al. 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 [75].

We also observed that the application of both types of vermicompost combined with reduced NPK fertilization enhanced various yield (fruit length, diameter, and overall yield) attributes of tomatoes compared to individual applications of NPK. Results of the current study are in line with the following of earlier studies that reported that the application of vermicompost enhanced not only different vegetative attributes of tomatoes but also increased dry matter contents as well as flowering traits [76–78] in addition to fruit and seed yields. The increase in plant yield and related attributes were because macronutrients contained in vermicomposts and NPK fertilizers play an important role in crop yield based on their role in activating enzymes for chlorophyll synthesis, growth, fruit ripening and maintenance of the plant's enzyme system [24]. Thus, a high nutrient or hormone status of soil with vermicompost may improve the speed of tomato growth found in plants treated with vermicompost treatment. Therefore, the use of vermicompost constitutes an important alternative source of fertilizer that has environmental benefits, productivity and crop quality compared to inorganic fertilizer.

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 [79], who checked the potential of vermicomposting of different organic wastes in improving growth and yield and also performed the proximate analysis of the cucumber plant. They stated that the application of vermicompost positively impacted 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 [15]. Moreover, Adekiye et al. 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

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substantial quantity of crude protein contents in okra [80]. An increase in these mineral elements upon the application of vermicompost is assumed to be correlated with the high nutritional content of vermicompost [81] Similar results were obtained by Joshi et al., who reported enhanced crude fiber and fat contents with an increase in the vermicompost application level. An ample supply of essential nutrients to plants leads to higher fat and fiber content in plants [15]. In another study, Rahman et al. 2021. reported an increase in the protein contents of sunflower upon the application of vermicompost in the soil, and values were found to be positively correlated with the increase in the vermicompost levels [82]. Furthermore, an increment in the protein contents after the application of vermicompost has already been reported by several researchers [83,84].

4.2. Effect of Vermicompost on Physicochemical Properties of Post-Harvest Soil

The application of various rates of vermicompost showed statistically significant positive effects on the Physiochemical properties of postharvest soil. [85]. 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 increases various soil parameters, including total porosity, bulk density, hydraulic conductivity, field capacity, and accessible water holding capacity [86]. Raising soil aggregates stability is indicative of improving soil quality and health, and this trend appears to be driven primarily by organic matter in the soil [87]. In this study, vermicompost treatments significantly altered the soil aggregate and structural stability indexes [88]. 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 was associated with higher soil organic matter levels [89]. It has also been observed that the soil's content of organic carbon (C) increases with increasing doses of vermicompost, followed by organic waste [90]. It is also reported that vermicompost has valuable source of readily accessible nutrients, It was revealed that the vermicompost had 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 [91]. 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 humic acid's beneficial effects on soil microbes, the production of organic acids increases, hence improving soil quality [92]. 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, acidic pH, and organic matter [93]. Vermicompost improves plant nutrition intake and conveniently delivers all nutrients [94]. The EC of Vermicompost was related to the ion concentration of the starting materials [86]. Similarly, soil EC values for both acidic and alkaline soils increased after being treated with organic fertilizers [95]. Soil Mg and Ca exchangeable concentrations were dramatically increased after VC treatments. Higher VC-treatment doses increased Mg and Ca exchangeable contents [96]. Using vermicompost improves the soil in both a nutritional and physical sense.

5. Conclusions

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

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