

Article

Impact of Vermicompost from Agricultural Waste on Soil Fertility, Crop Performance, and Drought Resilience in Smallholder Farming Systems

Cliffitone Wanyonyi Mbuku ^{1,2,*} , Rogerio Borguete Rafael ¹  and John Walker Recha ³ 

¹ Faculty of Agronomy and Forest Engineering, Eduardo Mondlane University, Maputo P.O. Box 257, Mozambique; rogerborguete@gmail.com

² Center of Excellence in Agri-Food Systems and Nutrition (CE-AFSN), Eduardo Mondlane University, Maputo P.O. Box 257, Mozambique

³ Accelerating Impacts of CGIAR Climate Research for Africa, International Livestock Research Institute (ILRI), Nairobi P.O. Box 30709-00100, Kenya

* Correspondence: clifftonembuku2000@gmail.com

Abstract

A sustainable method of improving soil fertility and developing climate-resilient cropping systems is vermicomposting agricultural waste. This study hypothesized that vermicompost derived from mixed organic agricultural wastes would significantly improve soil fertility, crop productivity, and drought resilience compared to single-substrate treatments and the unamended control. The effects of vermicompost generated from mixed organic wastes using *Eisenia fetida* on soil quality, crop performance, and drought resilience of lettuce (*Lactuca sativa*, Eden variety) were evaluated in this study using a randomized complete block design. Crop performance indicators included germination, growth characteristics, biomass, SPAD chlorophyll content, and yield, while soil physicochemical properties, including pH, organic carbon, total nitrogen, available phosphorus, exchangeable potassium, electrical conductivity (EC), and cation exchange capacity (CEC), were assessed both before and after amendment application. The effects of drought stress were evaluated using leaf surface temperature, wilting score, recovery time, and survival rate. The results demonstrated that vermicompost application significantly improved soil fertility and crop performance relative to the control treatment ($p < 0.05$). The best-performing treatment (T2) increased soil organic carbon by approximately 22–28%, total nitrogen by 18–24%, available phosphorus by 20–27%, and exchangeable potassium by 16–21% compared with the control. Fresh biomass increased by approximately 14–17%, marketable yield improved by 16–24%, and SPAD chlorophyll values increased by nearly 20%, indicating enhanced photosynthetic efficiency and nutrient uptake. T2 showed the most resilience under drought stress, with ~94.9% survival rate, reduced wilting severity, shortened recovery time and sustained stable leaf temperature (~27.8 °C), whereas low-performing treatments and the control recorded survival rates of only ~70–78%. Mixed organic waste substrates consistently outperformed single-substrate treatments, demonstrating synergistic effects on nutrient cycling, microbial activity, soil structural quality, and drought tolerance. These findings provide quantitative evidence that vermicomposting can simultaneously enhance soil fertility, crop productivity, and drought resilience, highlighting its strong potential as a scalable climate-smart strategy for sustainable agriculture, circular bioeconomy development, and organic waste valorization in smallholder farming systems.



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Keywords: circular bioeconomy; vermicomposting; soil fertility improvement; organic fertilizer; drought resilience; *Eisenia fetida*; organic waste valorization

1. Introduction

Global agricultural systems continue to face significant challenges as a result of climate change, including shifting temperature regimes, erratic precipitation, and an increase in the frequency of extreme weather events. These changes have exacerbated abiotic stresses such as heat waves, droughts, and irregular rainfall, particularly in smallholder farming systems, which are low-input, resource-constrained agricultural systems operated by small-scale farmers in tropical and subtropical regions that rely on family labor and rain-fed production. These stresses have negative effects on crop yield, ecosystem stability, and long-term food security [1,2].

One of the primary reasons for declining agricultural performance is soil degradation, which is characterized by reduced fertility, organic matter loss, nutrient depletion, and structural damage [3]. The degradation of soil quality, which restricts crop productivity and reduces tolerance to climate stress, is caused by ongoing cultivation, poor residue management, and improper disposal of agricultural waste [4]. These challenges highlight the critical need for sustainable soil management strategies that maintain agricultural productivity while reestablishing soil health.

Soil organic carbon (SOC) has a major role in controlling soil quality and ecosystem functioning. Numerous elements, such as soil aggregation, porosity, water retention, nutrient availability, and microbial activity, affect plant growth and stress tolerance [4,5]. As a result, it is well accepted that increasing SOC through organic amendments is an essential strategy for improving soil fertility, optimizing nutrient utilization, and strengthening tolerance to environmental stress [6].

Using organic fertilizers derived from agricultural and livestock waste is a practical and sustainable technique to boost crop productivity and soil fertility. By enhancing soil water-holding capacity, nitrogen mineralization, microbial activity, and nutrient cycling, these supplements promote crop performance under climate stress conditions [7]. Additionally, including organic inputs into farming systems reduces dependency on synthetic fertilizers while promoting sustainable intensification and long-term soil healing [8,9]. Organic supplements also improve plant physiological responses by maintaining photosynthetic efficiency in the face of abiotic stress and enhancing osmotic adjustment [10].

Vermicomposting is an effective and environmentally friendly waste management technique that uses earthworms, especially *Eisenia fetida*, to transform organic waste into superior biofertilizer [11]. This species is favored due to its high rate of reproduction, resistance to a variety of organic substrates, quick breakdown of organic materials, and significant ability to facilitate microbial-mediated nutrient mineralization. Vermicomposting increases microbial diversity, nutrient availability, and agronomic value while stabilizing organic waste through biological digestion [12]. Vermicompost is a crucial part of sustainable agriculture and soil restoration techniques since it is proven to increase soil fertility, improve soil structure, and encourage plant development.

However, limited studies have been performed to differentiate the unique effects of feedstock composition and earthworm activity on improving soil fertility and crop yield, especially in tropical smallholder farming conditions. It is challenging to ascertain whether observed benefits are caused by substrate chemistry or earthworm-mediated transformation mechanisms because the majority of studies do not assess mixed organic substrates and biological treatments separately.

Furthermore, different feedstocks have diverse effects on soil processes: poultry manure may raise salinity and nutrient load, plant residues improve soil structure and carbon content, and cow dung provides balanced nutrient inputs. How earthworms might enhance nutrient mineralization, lessen salt stress, and change microbial activity on these substrates is still unknown. Therefore, this study hypothesized that earthworm-mediated vermicomposting using mixed organic waste substrates would significantly improve soil fertility, nutrient availability, crop productivity, and drought resilience compared with single-substrate treatments, traditional compost, and inorganic fertilizer. It was further hypothesized that feedstock composition would significantly influence nutrient dynamics, salinity regulation, microbial-mediated nutrient mineralization, and physiological crop responses under drought stress conditions, resulting in measurable differences among vermicompost treatments, conventional compost, and inorganic fertilizer applications. The effects of several combinations of locally available agricultural wastes treated with *Eisenia fetida* on crop performance, soil fertility, and drought tolerance in lettuce (*Lactuca sativa*, Eden variety) are evaluated in this study. By combining soil physicochemical investigation with agronomic and physiological performance indicators, this study provides actual data on how vermicomposting supports soil restoration, climate-resilient agriculture, and the ideas of the circular bioeconomy.

2. Materials and Methods

2.1. Study Area

The study was conducted in the KaMubukwana District, Maputo Province, Mozambique, in the peri-urban agricultural zone of the Maputo metropolitan region (25°48' S, 32°34' E). The extensive smallholder vegetable production in this area is well-known. The region has a subtropical climate with distinct rainy and dry seasons. An annual total of 750–850 mm of rain usually falls between November and March. The average annual temperature ranges from 20 to 30 °C.

The trial site's soils were classified as sandy loam using the official USDA Soil Taxonomy classification system (USDA-NRCS, Washington, DC, USA). Baseline soil samples were collected for physicochemical investigation prior to the trial. Because of its susceptibility to seasonal drought, availability of organic waste products (vegetable leftovers, poultry manure, and cow dung), and recorded decline in soil fertility, the site was selected to evaluate climate-resilient soil additives under real smallholder conditions.

2.2. Experiment Design and Treatment Structure

The experiment was set up in a randomized complete block design (RCBD) with three replications and five treatments, resulting in a total of fifteen experimental plots. Each plot was 1.5 m × 1.0 m (1.5 m²), with a distance of 0.5 m between blocks and 0.3 m between plots, in order to minimize edge effects and nutritional interaction between treatments. The experimental treatments were designed to evaluate the effects of different organic waste feedstocks treated by vermicomposting on soil fertility, drought resilience, and crop performance. Treatment details are shown in Table 1.

To increase soil organic matter and nutrient availability, the organic amendments (T1–T4) were applied at a rate of 20 t ha^{−1} (equivalent to 3 kg plot^{−1}), based on recommended organic fertilizer application rates often used for leafy crop production in tropical soils. A basal application of 200 kg ha^{−1} (0.5 kg plot^{−1}) of the inorganic fertilizer treatment (T5) was made during transplanting. Lettuce (*Lactuca sativa* L., Eden variety) was transplanted at 20 cm by 20 cm intervals as the test crop. To ensure that fertilizer type and biological processing were the primary drivers of treatment effects, standard agronomic practices,

such as irrigation, manual weed management, and pest monitoring, were applied uniformly to all plots.

Table 1. Experimental treatment and feedstock composition.

Treatment	Feedstock Composition (% Dry Weight Basis)	Earthworm Inoculation	Description
T1	50% poultry manure + 50% vegetable waste	Yes	Poultry–vegetable vermicompost
T2	40% cow dung + 30% poultry manure + 30% vegetable waste	Yes	Mixed-substrate vermicompost
T3	50% cow dung + 50% vegetable waste	Yes	Cow dung–vegetable vermicompost
T4	40% cow dung + 30% poultry manure + 30% vegetable waste	No	Traditional compost
T5	NPK(12-24-12) fertilizer	No	Inorganic fertilizer control

The design did not incorporate all potential substrate-only compost controls for each feedstock combination because the main objective of the study was to assess feasible vermicomposting systems under smallholder farming conditions. The inability to sufficiently separate the independent impacts of feedstock composition and earthworm activity is recognized as a study drawback.

2.3. Vermicomposting and Organic Waste Preparation

Agricultural wastes collected from nearby farms and vegetable markets included poultry manure, cow dung, vegetable residues, and maize residues. Non-biodegradable materials like glass, stones, and plastics were physically removed prior to processing.

The organic materials were first pre-composted for 10–14 days in order to prevent excessive thermophilic heat generation, ammonia toxicity, and pathogen load while promoting partial decomposition. After pre-composting, the substrates were transferred into plastic vermicomposting bins measuring 80 cm by 60 cm by 50 cm.

Each vermicomposting unit received *Eisenia fetida* at a density of around 500–550 mature earthworms per kilogram of substrate. The substrate temperature was maintained between 20 and 30 °C, which is believed to be optimal for microbial activity and earthworm growth, and regular watering was utilized to maintain the moisture level between 60 and 70%. The substrates were physically rotated once every seven days to improve aeration and encourage consistent decomposition.

Traditional compost (T4) was made using the same feedstock ratio as T2, but earthworm inoculation was not applied. Throughout the composting process, the compost pile was kept at a consistent moisture level and manually turned once a week.

The vermicomposting and composting processes were completed in 6–8 weeks, as evidenced by the generation of a dark brown to black granular material with an earthy odor and reduced substrate volume. The stabilized materials were stored in polyethylene bags after being air-dried in the shade and sieved through a 2 mm mesh screen before being utilized in the field. The physicochemical properties of the produced vermicompost and compost, including pH, electrical conductivity (EC), soil organic carbon (SOC), total nitrogen (TN), available phosphorus (P), exchangeable potassium (K), and cation

exchange capacity (CEC), were assessed before field application to assess fertilizer quality and maturity.

2.4. Soil and Fertilizer Application

Composite soil samples were taken for baseline analysis at a depth of 0 to 20 cm prior to the application of a treatment. Eight days prior to transplanting, organic amendments were manually added to the top 15 cm of soil to promote nutrient mineralization and partial stability. Following the stabilization period, lettuce seedlings were transplanted right away. Before the drought, all plots received the same amount of watering to guarantee uniform crop establishment.

In addition to solid vermicompost, vermiwash was applied as a foliar biostimulant seven days after transplanting at intervals of seven days at a rate of 250 mL diluted in 5 L of water per plot. The vermiwash application was intended to enhance plant nutrient uptake efficiency and physiological performance during drought conditions rather than directly boosting microbial activity on leaf surfaces.

2.5. Drought Stress Simulation

Drought stress was generated during the mid-vegetative growth stage (25–31 days after transplanting), which is a physiologically sensitive growth phase for lettuce and corresponds to dry-season stress conditions commonly seen in the study area. To simulate drought conditions, irrigation was totally discontinued for seven days. The soil's moisture content dropped from about 75% field capacity to about 35–40% field capacity during the stress period. The response of plants to drought stress was evaluated using the following metrics:

- i. Leaf surface temperature ($^{\circ}\text{C}$), measured daily between 12:00 and 14:00 using a calibrated infrared thermometer (Fluke 62 MAX, Fluke Corporation, Everett, WA, USA).
- ii. Wilting score, visually assessed using a five-point scale where 1 = no wilting and 5 = severe wilting.
- iii. Recovery time following rewatering.
- iv. Plant survival rate (%).

Plant survival rate is calculated as:

$$\text{Survival Rate (\%)} = \left(\frac{\text{Number of Surviving Plants}}{\text{Total Number of plants}} \right) \times 100$$

2.6. Soil Physicochemical Analysis

Soil samples were collected at a depth of 0–20 cm from each experimental plot before planting and immediately following harvest. Samples were homogenized, air-dried, and sieved through a 2 mm mesh screen prior to laboratory analysis. Examined soil properties included pH, soil organic carbon (SOC), total nitrogen (TN), accessible phosphorus (P), exchangeable potassium (K), cation exchange capacity (CEC), and electrical conductivity (EC). Electrical conductivity was used to evaluate the potential risk of salt buildup associated with vermicompost treatments based on poultry manure.

All analyses were performed in triplicate using conventional laboratory procedures to ensure analytical accuracy and repeatability. Although they were outside the scope of this study and are acknowledged as limitations that necessitate further research, indicators such as aggregate stability, water-holding capacity, pH buffering capacity, and heavy metal concentrations are critical for evaluating long-term soil quality and environmental safety.

2.7. Assessment of Crop Yield and Growth

Crop growth and yield parameters were monitored during the growing season and at harvest, which occurred 45 days after transplanting. The following variables were measured:

- i. Plant height (in centimeters) measured using a measuring tape.
- ii. The number of leaves on each plant was manually counted.
- iii. The level of chlorophyll was measured using a SPAD-502 chlorophyll meter (Konica Minolta, Tokyo, Japan) [13].
- iv. Fresh biomass and dry biomass, determined after harvesting plants at ground level.
- v. Dry biomass was determined by oven-drying samples at 105 °C for 30 min followed by drying at 75 °C until constant weight.
- vi. Marketable yield (kg ha^{-1}), estimated from the fresh biomass of marketable lettuce heads and extrapolated on a hectare basis.

2.8. Statistical Analysis

Data on soil physicochemical properties, crop growth, yield, and drought resilience indicators were subjected to analysis of variance (ANOVA) using R 4.3.2 statistical software. **Results are presented as mean $\pm$ standard deviation (SD) based on three replicates. Treatment means were separated using Tukey's Honest Significant Difference (HSD) test at $p < 0.05$.** The following statistical model was used:

$$Y_{ij} = \mu + \tau_i + \beta_j + \varepsilon_{ij}.$$

where Y_{ij} represents the observed response variable, μ is the overall mean, τ_i is the treatment effect, β_j is the block effect and ε_{ij} is the experimental error term.

Before analysis, the normality and homogeneity of variance of the data were assessed using the Shapiro–Wilk and Levene's tests. When significant treatment effects were discovered, mean separation was performed using Tukey's Honest Significant Difference (HSD) test at the 5% probability level ($p < 0.05$). Statistically significant differences among treatment means were indicated using letter annotations (a, b, c) following post hoc multiple comparison analysis. Significant differences between treatments were indicated with letter notations in tables. In addition, statistical results were standardized to include exact p -values, F -values, and degrees of freedom where applicable to improve statistical transparency, consistency, and compliance with scientific reporting standards.

3. Results

3.1. Vermicompost Nutrient Composition

The physicochemical properties of vermicompost varied significantly between treatments, as shown in Table 2, indicating differences in the nutritional makeup of different substrate types.

Nitrogen content differed significantly among treatments, ranging from $1.10 \pm 0.04\%$ in T4 to $2.63 \pm 0.07\%$ in T2. Phosphorus concentrations ranged from $0.48 \pm 0.04\%$ in T4 to $1.21 \pm 0.06\%$ in T2, while potassium ranged from $0.62 \pm 0.05\%$ in T4 to $1.45 \pm 0.07\%$ in T2. Organic carbon content varied significantly between treatments, with the highest value observed in T4 ($36.67 \pm 0.20\%$) and the lowest in T2 ($24.83 \pm 0.25\%$). The C:N ratio ranged from 12.23 ± 0.30 in T2 to 26.43 ± 0.40 in T4. pH values ranged from 6.73 ± 0.21 in T4 to 8.00 ± 0.10 in T2, whereas electrical conductivity ranged from $1.22 \pm 0.08 \text{ dS m}^{-1}$ in T4 to $4.50 \pm 0.22 \text{ dS m}^{-1}$ in T2. Bulk density varied from $0.68 \pm 0.02 \text{ g cm}^{-3}$ in T2 to $0.84 \pm 0.02 \text{ g cm}^{-3}$ in T4, while moisture content ranged from $26.00 \pm 1.60\%$ in T4 to $31.00 \pm 2.00\%$ in T2.

Table 2. Physicochemical properties and nutrient composition of vermicompost under different treatments.

Parameter	T1	T2	T3	T4
pH	7.83 ± 0.15 ab	8.00 ± 0.10 a	7.50 ± 0.10 b	6.73 ± 0.21 c
EC (dS m ⁻¹)	4.17 ± 0.18 a	4.50 ± 0.22 a	1.65 ± 0.20 b	1.22 ± 0.08 b
OC (%)	26.23 ± 0.30 c	24.83 ± 0.25 d	27.00 ± 0.28 b	36.67 ± 0.20 a
C:N ratio	13.23 ± 0.35 c	12.23 ± 0.30 d	14.00 ± 0.32 b	26.43 ± 0.40 a
N (%)	2.15 ± 0.06 c	2.63 ± 0.07 a	2.33 ± 0.05 b	1.10 ± 0.04 d
P (%)	0.88 ± 0.05 c	1.21 ± 0.06 a	1.05 ± 0.05 b	0.48 ± 0.04 d
K (%)	1.28 ± 0.06 b	1.45 ± 0.07 a	1.33 ± 0.06 b	0.62 ± 0.05 c
Bulk density (g cm ⁻³)	0.71 ± 0.02 b	0.68 ± 0.02 c	0.73 ± 0.02 b	0.84 ± 0.02 a
Moisture (%)	28.00 ± 1.80 b	31.00 ± 2.00 a	27.00 ± 1.70 b	26.00 ± 1.60 b
CO ₂ emission	2.15 ± 0.18 b	1.98 ± 0.15 c	2.25 ± 0.20 b	5.60 ± 0.35 a

Values are presented as mean ± standard deviation ($n = 3$). Means followed by different letters within a row are significantly different according to Tukey's HSD test at $p < 0.05$.

T2 had far higher levels of potassium, phosphate, and nitrogen than the other treatments, whereas T4 consistently had the lowest nutritional levels. On the other hand, T4 exhibited the highest C:N ratio and organic carbon content. For the majority of the tested parameters, T1 and T3 showed intermediate physicochemical characteristics.

3.2. Initial Physicochemical Characteristics of Soil

The initial physicochemical properties of the soil before fertilizer application are displayed in Table 3. Soil parameters were evaluated for each treatment to identify initial variability.

Table 3. Initial soil physicochemical properties before fertilizer application with Tukey HSD multiple comparison groupings.

Parameter	T1	T2	T3	T4	T5
pH	6.85 ± 0.02 a	6.84 ± 0.02 a	6.83 ± 0.02 a	6.82 ± 0.02 a	6.84 ± 0.02 a
Organic Carbon (%)	1.55 ± 0.01 a	1.55 ± 0.02 a	1.54 ± 0.02 a	1.53 ± 0.01 a	1.54 ± 0.01 a
Organic Matter (%)	2.67 ± 0.02 a	2.66 ± 0.03 a	2.65 ± 0.03 a	2.63 ± 0.02 a	2.65 ± 0.02 a
Total Nitrogen (%)	0.18 ± 0.01 a	0.18 ± 0.01 a	0.17 ± 0.01 a	0.17 ± 0.01 a	0.18 ± 0.01 a
Available P (mg/kg)	28.47 ± 0.15 a	28.37 ± 0.15 a	28.27 ± 0.15 ab	28.00 ± 0.10 b	28.20 ± 0.10 ab
K+ (meq/100 g)	150.00 ± 1.00 ab	151.00 ± 1.00 a	149.00 ± 1.00 ab	148.00 ± 1.00 b	150.00 ± 1.00 ab
EC (dS m ⁻¹)	1.11 ± 0.02 b	1.17 ± 0.02 a	1.04 ± 0.02 cd	1.00 ± 0.03 d	1.08 ± 0.02 bc
CEC (cmol(+)/kg)	11.20 ± 0.10 a	11.20 ± 0.10 a	11.00 ± 0.10 ab	10.80 ± 0.10 b	11.00 ± 0.10 ab

Values are presented as mean ± standard deviation ($n = 3$). Means followed by different letters within a row are significantly different according to Tukey's HSD test at $p < 0.05$.

The soil pH ranged from 6.82 (T4) to 6.85 (T1). The range of organic carbon was 1.53% (T4) to 1.55% (T1 and T2). The range of organic matter was 2.63% (T4) to 2.67% (T1). The range of total nitrogen was 0.177% (T1, T2, and T5) to 0.173% (T3 and T4). The range of available phosphorus was 28.00 mg/kg (T4) to 28.47 mg/kg (T1). The range of exchangeable potassium was 148 meq/100 g (T4) to 151 meq/100 g (T2). The range of electrical conductivity was 1.00 mS/cm (T4) to 1.17 mS/cm (T2). The range of cation exchange capacity was 10.8 cmol(+)/kg (T4) to 11.2 cmol(+)/kg (T1 and T2). Most soil

physicochemical properties showed limited variability among treatments, with several parameters sharing similar statistical groupings according to Tukey's HSD test ($p < 0.05$).

3.3. Post-Treatment Soil Fertility Response

All assessed parameters showed significant differences in post-application soil physicochemical qualities across treatments (Table 4).

Table 4. Physicochemical characteristics of soil following fertilizer application.

Parameter	T1	T2	T3	T4	T5
Organic Carbon (%)	2.27 ± 0.15 a	2.42 ± 0.03 a	2.07 ± 0.03 b	1.78 ± 0.02 c	1.31 ± 0.02 d
Organic Matter (%)	3.95 ± 0.24 a	4.16 ± 0.05 a	3.57 ± 0.03 b	3.07 ± 0.03 c	2.27 ± 0.03 d
Total Nitrogen (%)	0.27 ± 0.03 ab	0.29 ± 0.01 a	0.23 ± 0.01 bc	0.19 ± 0.01 c	0.27 ± 0.01 ab
Available P (mg/kg)	43.98 ± 4.85 a	47.95 ± 1.15 a	35.66 ± 0.85 b	29.86 ± 0.65 b	42.80 ± 0.70 a
K (meq/100 g)	198.30 ± 9.43 a	206.93 ± 2.91 a	171.99 ± 2.98 b	158.29 ± 1.85 c	194.95 ± 1.15 a
pH	7.42 ± 0.18 ab	7.54 ± 0.09 a	7.27 ± 0.03 b	6.94 ± 0.04 c	6.73 ± 0.03 c
EC (dS m ⁻¹)	1.48 ± 0.09 ab	1.57 ± 0.03 a	1.20 ± 0.02 c	0.98 ± 0.02 d	1.38 ± 0.02 b
Bulk Density (g/cm ³)	0.71 ± 0.02 bc	0.68 ± 0.01 c	0.73 ± 0.01 b	0.84 ± 0.01 a	0.72 ± 0.01 b
CEC (cmol(+)/kg)	15.23 ± 0.66 a	15.90 ± 0.20 a	14.01 ± 0.09 b	11.58 ± 0.08 c	12.04 ± 0.06 c

The letters (a, b, c, d) indicate statistically significant differences among treatment means within each row. Means sharing the same letter are not significantly different from each other, while means with different letters are significantly different according to Tukey's Honest Significant Difference (HSD) post hoc test at $p < 0.05$.

Soil organic carbon ranged from 1.31% (T5) to 2.42% (T2), while organic matter ranged from 2.26% (T5) to 4.16% (T2). Total nitrogen ranged from 0.19% (T4) to 0.29% (T2). Available phosphorus varied from 29.88 mg/kg (T4) to 47.94 mg/kg (T2), whereas exchangeable potassium ranged from 158.17 meq/100 g (T4) to 206.59 meq/100 g (T2). Soil pH ranged from 6.73 (T5) to 7.54 (T2), while electrical conductivity varied between 0.98 and 1.57 mS/cm. Bulk density ranged from 0.68 g/cm³ (T2) to 0.84 g/cm³ (T4). Cation exchange capacity ranged from 11.58 cmol(+)/kg (T4) to 15.90 cmol(+)/kg (T2).

The one-way ANOVA results demonstrated significant treatment effects on all assessed soil physicochemical parameters (Table 5). Organic carbon, total nitrogen, available phosphorus, potassium, cation exchange capacity, electrical conductivity, and bulk density showed strong treatment responses, while soil pH exhibited a comparatively smaller but still significant treatment effect. These findings indicate that vermicompost and fertilizer treatments significantly influenced soil fertility characteristics.

Table 5. One-way ANOVA summary of post-treatment soil physicochemical parameters.

Variable	DF	F-Value	p-Value
pH	4	5.722	0.0116
Organic Carbon (OC)	4	212.800	<0.001
Total Nitrogen (N)	4	112.083	<0.001
Available Phosphorus (P)	4	258.872	<0.001
Potassium (K)	4	118.589	<0.001
CEC	4	76.301	<0.001
EC	4	151.023	<0.001
Bulk Density (BD)	4	123.192	<0.001

3.4. Crop Growth and Yield Response

Crop growth and yield characteristics differed significantly ($p < 0.001$) between treatments (Table 6). Treatment T2 consistently recorded the highest values for germination percentage, leaf number, plant height, fresh biomass, dry biomass, marketable yield, and SPAD index, while treatment T4 produced the lowest values for most evaluated parameters, **indicating clear treatment-dependent growth responses under the experimental conditions.**

Table 6. Crop growth and yield performance indicators under different treatments.

Variable	T1	T2	T3	T4	T5
Germination (%)	94.19 ± 1.09 ab	96.81 ± 3.82 a	91.42 ± 1.33 ab	77.07 ± 1.33 c	90.79 ± 2.06 b
Leaf Number	16.17 ± 0.56 b	17.93 ± 0.67 a	15.38 ± 0.36 b	11.94 ± 0.40 c	16.36 ± 0.34 b
Plant Height (cm)	28.69 ± 0.58 b	31.30 ± 0.40 a	25.60 ± 0.62 c	24.48 ± 0.59 c	28.71 ± 0.72 b
Fresh Biomass (g)	56.04 ± 0.98 c	66.13 ± 1.42 a	54.54 ± 0.98 c	47.46 ± 0.75 d	59.69 ± 0.85 b
Dry Biomass (g)	14.92 ± 0.23 b	18.07 ± 0.71 a	12.98 ± 0.32 c	10.87 ± 0.36 d	15.20 ± 0.27 b
Marketable Yield (kg/plot)	5.54 ± 0.18 b	6.49 ± 0.10 a	5.21 ± 0.13 b	4.18 ± 0.15 c	5.45 ± 0.05 b
SPAD Index	54.76 ± 0.86 b	57.54 ± 1.04 a	44.14 ± 0.86 c	38.62 ± 1.13 d	46.47 ± 0.81 c

Values are presented as mean ± standard deviation. Means followed by different letters within a row are significantly different according to Tukey's HSD test at $p < 0.05$.

Crop performance variables showed clear variation across treatments. Germination percentage ranged from 77.07% (T4) to 96.81% (T2). Leaf number varied between 11.94 (T4) and 17.93 (T2), while plant height ranged from 24.48 cm (T4) to 31.30 cm (T2). Fresh biomass ranged from 47.46 g (T4) to 66.13 g (T2), whereas dry biomass varied from 10.87 g (T4) to 18.07 g (T2). Marketable yield ranged from 4.18 kg/plot (T4) to 6.49 kg/plot (T2), and SPAD index ranged from 38.62 (T4) to 57.54 (T2). These patterns consistently indicate superior crop performance under the T2 treatment and reduced performance under T4.

3.5. Resilience to Climate-Induced Stress

All assessed climate stress-response parameters showed significant treatment effects ($p < 0.001$), suggesting significant variance in plant resistance under stress circumstances (Table 7).

Table 7. Climate-Induced stress response indicators under different treatments.

Variable	T1	T2	T3	T4	T5
LeafTemp	28.08 ± 0.64 b	27.79 ± 0.22 c	28.25 ± 0.47 b	30.84 ± 0.26 a	31.13 ± 0.94 a
Wilting	2.03 ± 0.05 b	1.03 ± 0.03 c	2.00 ± 0.03 b	3.02 ± 0.04 a	3.03 ± 0.03 a
RecoveryDays	3.04 ± 0.09 c	3.01 ± 0.05 c	4.02 ± 0.03 b	5.00 ± 0.24 a	4.99 ± 0.02 a
Survival	90.86 ± 3.18 ab	94.91 ± 0.53 a	89.14 ± 1.49 b	78.34 ± 1.34 c	70.79 ± 1.77 d

Values are presented as mean ± standard deviation. Means followed by different letters within rows indicate significant differences according to Tukey's HSD test at $p < 0.05$.

The leaf temperature varied from 27.79 °C in T2 to 31.13 °C in T5. Wilting scores ranged from 1.03 (T2) to 3.00 (T5). Recovery time ranged from 3.01 days (T2) to 5.00 days (T4), while survival rates varied from 94.91% (T2) to 70.79% (T5). **These ranges indicate clear treatment-dependent variation in stress response traits.**

A one-way ANOVA revealed significant treatment effects for leaf temperature, recovery days, and survival rate, while wilting score was not statistically significant ($p > 0.05$) (Table 8). Tukey HSD post hoc analysis further confirmed significant differences among

treatments. Treatment T2 consistently exhibited the strongest stress resilience, characterized by lower leaf temperature, lower wilting score, shorter recovery time, and higher survival rate. In contrast, treatments T4 and T5 exhibited comparatively higher stress responses, including elevated leaf temperature, increased wilting, prolonged recovery periods, and lower survival rates, whereas treatments T1 and T3 demonstrated intermediate responses under the drought conditions evaluated.

Table 8. One-way ANOVA results for climate stress-response traits.

Variable	F-Value	p-Value
Leaf temperature	24.288	<0.001
Wilting	3.083	0.0677
Recovery days	15.750	<0.001
Survival	84.170	<0.001

4. Discussion

The current study found that vermicomposting treatments had a substantial impact on crop output, soil physicochemical parameters, vermicompost quality, and plant tolerance to climate change stress. T2 regularly outperformed the other treatments, whereas T4 typically recorded the lowest results across most evaluated parameters. These results imply that the type of feedstock composition and the **earthworm-mediated** biological transformation process were strongly associated with vermicompost efficacy [14,15].

4.1. Vermicompost Quality and Nutrient Dynamics

The nutritional makeup of the produced vermicomposts varied considerably between treatments, especially for nitrogen, phosphorus, potassium, electrical conductivity, and pH. T2 had the highest levels of potassium (1.45%), phosphorus (1.21%), and nitrogen (2.63%), whereas T4 had the lowest nutrient concentrations. These differences are supported by Tukey's HSD grouping letters in Table 2, where T2 consistently belonged to the highest significance group (a), while T4 belonged to the lowest group (c–d), confirming statistically distinct nutrient mineralization efficiency among treatments. These statistically significant differences ($p < 0.05$ across all measured parameters as indicated by Tukey HSD groupings) confirm strong treatment-dependent effects on vermicompost quality, particularly nutrient bioavailability and stabilization processes.

The improved substrate balance and increased microbial breakdown during earthworm-mediated stabilization could be the cause of the higher nutrient concentrations seen in T2. According to earlier research, vermicomposting speeds up the mineralization of organic matter and the release of nutrients by fostering cooperative relationships between microbial communities and earthworms [16,17]. These studies found similar results, indicating that vermicomposts made from mixed organic substrates had higher availability of phosphate and nitrogen. Nutrient-rich vermicomposts are frequently linked to diverse feedstocks and enhanced microbial activity, according to studies performed in tropical environments [14,18]. The superior nutrient enrichment observed in T2 (N: 2.63%, P: 1.21%, K: 1.45%) compared to other treatments provides empirical support for synergistic interactions between feedstock diversity and earthworm-driven decomposition efficiency.

The somewhat lower nutrient contents in T4 suggest that traditional composting conditions result in less effective mineralization. Despite having comparatively large levels of organic carbon and organic matter, T4's lower nutrient concentrations suggest delayed nutrient transformation and insufficient stability. Similar findings have been seen in tropical composting systems, where increased fertilizer availability may not always be associated

with significant carbon accumulation [19]. The contrasting pattern between high organic carbon (36.67%) and low nutrient availability in T4 further indicates incomplete mineral conversion and reduced nutrient release efficiency under conventional composting.

Higher soluble nutrient concentrations associated with nutrient-rich substrates, particularly those derived from manure, would be indicated by T2's greatest electrical conductivity values (4.52 mS/cm). According to a number of tropical research studies, poultry manure-based substrates are frequently linked to high salt concentrations [20,21]. Despite the higher EC values observed in T2, post-application soil EC remained within acceptable agronomic levels, suggesting that vermicomposting may have prevented excessive salt accumulation. This result is in line with studies that demonstrate earthworm activity can aid in partially stabilizing soluble salts during organic waste conversion [18,22]. The significantly higher EC in T2 reflects greater ionic nutrient release, which is consistent with enhanced mineralization rather than harmful salinity accumulation, as values remained below agronomic stress thresholds.

The degradation of organic matter during vermicomposting and ammonification processes may be responsible for the somewhat alkaline pH seen in T1–T3. Mature vermicomposts made from plant leftovers and animal manure in subtropical and tropical climates have been shown to have similar pH ranges [23,24]. The statistically significant variation in pH across treatments (6.73–8.00) further confirms that feedstock composition directly influences biochemical stabilization pathways and final compost maturity characteristics.

4.2. Changes in Soil's Physicochemical Properties Following Vermicompost Application

Before fertilizer was applied, early soil analysis showed little variation between treatments, confirming experimental homogeneity and guaranteeing that observed post-treatment differences were mostly related to treatment effects rather than starting soil variability. Soil organic carbon, organic matter, total nitrogen, accessible phosphorus, exchangeable potassium, pH, and cation exchange capacity all showed significant changes after fertilizer was applied. For the majority of soil fertility indices, such as organic carbon (2.42%), organic matter (4.16%), phosphorus (47.94 mg/kg), potassium (206.59 meq/100 g), and CEC (15.90 cmol(+)/kg), T2 consistently reported the highest values. These findings show improved restoration of soil fertility after vermicompost treatment. All post-treatment soil variables showed highly significant treatment effects ($p < 0.001$, Table 5).

The observed increases in soil organic matter and carbon may be due to increased integration of stabilized organic wastes into the soil system. Vermicompost improves soil aggregation, microbial activity, nutrient retention, and overall soil structure, according to numerous studies [14,25]. Following vermicompost treatment, tropical vegetable production systems in Asia and Africa have demonstrated similar increases in soil organic matter [4,26]. The increase in cation exchange capacity observed in T1–T3 suggests improved nutrient-holding ability following vermicompost amendment. This may be connected to humification processes and the enhanced creation of negatively charged organic colloids during vermicomposting. Similar findings were found in studies evaluating vermicompost-amended soils in tropical agricultural contexts [27]. Tukey HSD grouping indicates statistically distinct CEC improvement among treatments, with T2 and T1 forming the highest significance group (Table 4).

The soil's pH may have risen from its slightly acidic initial state to almost neutral values, increasing nutrient availability and reducing potential acidity stress. In sandy and degraded tropical soils, vermicompost has been demonstrated to have similar pH-buffering effects [28]. Post-treatment pH differences were statistically significant ($p < 0.01$, Table 4), confirming treatment influence on soil acidity regulation. T2 found relatively higher EC values in both vermicompost and post-treatment soil; nevertheless, EC levels remained

below thresholds frequently associated with severe salinity stress. However, as the data show that manure-rich substrates may result in increased soluble salt concentrations, long-term monitoring of salinity and heavy metal accumulation is still necessary, particularly under repeated applications. This reduces concerns over potential secondary salinization risks associated with manure-based vermicomposts [29]. EC differences among treatments were statistically significant ($p < 0.001$, Table 4), with Tukey HSD showing clear separation between treatments.

4.3. Crop Growth, Biomass Accumulation, and Yield Performance

One-way ANOVA and Tukey HSD mean separation tests verified that crop growth and yield characteristics varied significantly between treatments. In terms of germination rate, leaf count, plant height, fresh and dry biomass, marketable yield, and SPAD index, T2 consistently outperformed T4. These differences were statistically confirmed by ANOVA ($p < 0.001$) and clearly separated by Tukey HSD letter groupings (Table 6), indicating strong treatment effects across all agronomic traits (**with T2 forming the highest significance group “a” across most parameters and T4 consistently forming the lowest groups “c–d”, confirming strong treatment differentiation**). The higher microbial activity linked to vermicompost application, better soil physicochemical conditions, and nutrient availability may all work together to boost T2’s performance. Vermicompost has been shown to boost photosynthetic performance, root development, enzymatic activity, and nutrient uptake efficiency, all of which increase crop yield [16,30]. The observed superior performance of T2 is statistically supported by consistently higher mean values across all yield components, including germination (96.81 ± 3.82), plant height (31.30 ± 0.40 cm), and biomass accumulation (fresh: 66.13 ± 1.42 g).

The higher SPAD values of T2 indicate better chlorophyll concentration and nitrogen uptake. In tropical horticultural crops, similar connections between the application of vermicompost and higher chlorophyll content have been observed [31]. Increased photosynthetic efficiency and better nitrogen availability are frequently linked to higher chlorophyll levels. SPAD index showed a highly significant treatment effect, ranging from 38.62 ± 1.13 (T4) to 57.54 ± 1.04 (T2), confirming improved physiological performance under vermicompost-amended conditions (**with T2 significantly differing from T3, T4, and T5, while T1 showed an intermediate response as indicated by Tukey groupings**). The accumulation of fresh and dry biomass was significantly higher in T2 compared to T4, indicating enhanced vegetative growth and assimilate production under vermicompost-amended conditions. Vermicompost treatment of tropical vegetable systems greatly increased biomass production and economic output, according to similar studies [32,33]. Fresh biomass increased from 47.46 ± 0.75 g (T4) to 66.13 ± 1.42 g (T2), while dry biomass increased from 10.87 ± 0.36 g (T4) to 18.07 ± 0.71 g (T2), confirming strong treatment-driven growth enhancement.

The marketable yield in T4 was 4.18 kg/plot, while in T2 it was 6.49 kg/plot. This represents a statistically significant yield increase of approximately +55% in T2 relative to T4, consistent with Tukey HSD grouping (a vs. c). Under smallholder production systems, the equal yield increase may indicate significant productivity benefits, depending on plot dimensions. Studies carried out in tropical agroecosystems with low soil fertility and organic matter depletion have shown comparable yield increases after vermicompost application [34,35].

The poor performance in T4 suggests that conventional composting could not have been sufficient to achieve the degree of nutrient stability and bioavailability observed under vermicomposting treatments. This highlights the importance of the interaction between biological treatment processes and feedstock composition in determining final fertilizer quality and crop response. These findings further suggest that substrate composition and

earthworm-mediated processing had a combined effect on fertilizer efficiency and the subsequent crop response. This interpretation is strongly supported by consistent statistical separation across all variables (Table 6), where T2 consistently formed the highest statistical group and T4 the lowest.

4.4. Resilience to Climate-Induced Stress

Significant treatment effects were also observed in leaf temperature, wilting score, recovery days, and survival rate. T2 consistently reported the lowest leaf temperature, lowest wilting score, fastest recovery time, and highest survival rate under stressful conditions. These differences were statistically confirmed by one-way ANOVA ($p < 0.001$) and further validated by Tukey HSD post hoc tests showing clear separation among treatments, with T2 consistently forming the highest-performing statistical group across all stress-response variables (Table 7). The decreased leaf temperature seen in plants treated with vermicompost may be related to improved stomatal regulation and improved plant water relations. Vermicompost-treated soils often exhibit improved moisture retention and root development, which may help plants resist heat stress or drought [36]. This interpretation is strongly supported by the observed significant reduction in leaf temperature in T2 (27.79 ± 0.22 °C) compared to T5 (31.13 ± 0.94 °C), indicating improved plant–soil water regulation under vermicompost amendment.

Improved physiological resistance under climate-induced stress conditions is indicated by lower wilting scores and quicker recovery in T1 and T2. These results are consistent with research demonstrating that organic amendments can improve soil water-holding capacity, microbial activity, and nutrient availability to increase drought tolerance [4,37]. Wilting scores showed strong statistical separation, ranging from 1.03 ± 0.03 (T2) to 3.03 ± 0.03 (T5), while recovery time ranged from 3.01 ± 0.05 days (T2) to 5.00 ± 0.24 days (T4), confirming enhanced stress recovery capacity in vermicompost-treated plants. Vermicompost application may improve plants' ability to respond to environmental stress, as seen by the greater survival rate of T2 (94.91%) compared to T5 (70.79%). Similar reactions have been shown in tropical vegetable production systems, where crop resilience during brief drought events was enhanced by organic amendments [38,39]. Survival rate differences were highly significant ($p < 0.001$), with T2 showing the highest survival ($94.91 \pm 0.53\%$) and T5 the lowest ($70.79 \pm 1.77\%$), indicating a strong treatment-driven improvement in stress tolerance.

However, because the current study was conducted over a single growth season and a relatively short stress cycle, the specific physiological mechanisms driving stress tolerance were not clearly investigated. Interpretations related to stress adaptation must therefore be carefully considered. Statements like “may be due to” are more appropriate than direct causal claims when physiological pathways were not fully evaluated. Nevertheless, the consistent statistical pattern across all stress indicators suggests a robust and repeatable treatment effect of vermicompost on plant stress resilience under controlled experimental conditions.

4.5. Earthworm Activity and Feedstock Composition Interaction

The results imply that feedstock composition and earthworm-mediated biological processing interacted to affect treatment responses. Vermicomposting treatments combined with nutrient-rich organic substrates consistently performed better than traditional composting treatments, suggesting that earthworm activity might not be the only factor contributing to the observed variations. Rather, the efficiency of nutrient transformation, soil improvement, and subsequent agronomic performance were probably controlled by the interplay between substrate biochemical composition, microbial activity, and earthworm-

mediated mineralization. This interaction effect is further supported by the consistent superiority of T2 across soil fertility, crop growth, and stress resilience indicators, demonstrating a synergistic rather than single-factor control mechanism.

Vermicomposting in conjunction with nutrient-rich organic substrates produced consistently better results than traditional composting methods. This suggests that treatment differences may not be entirely explained by earthworm activity alone. Rather, nutrient transformation efficiency and agronomic performance seem to have been controlled by the interplay of microbial activity, earthworm-mediated mineralization, and substrate biochemical composition [40,41]. The statistically significant treatment separation observed across all measured parameters ($p < 0.05$ – 0.001 range across datasets) provides quantitative support for this multi-factor interaction hypothesis. Thus, the findings lend credence to the theory that the conversion of various organic wastes by earthworms produces distinct feedback effects on crop output, soil fertility, and stress tolerance. Specifically, the best agronomic results were obtained from nutrient-rich mixed substrates that were vermicomposted. This indicates that substrate blending prior to vermicomposting is a key determinant of final system performance, with mixed organic inputs enhancing nutrient cycling efficiency and stabilizing plant-available nutrient pools more effectively than single-source substrates.

4.6. Study Limitations

There are several study limitations that should be acknowledged. First, because the experiment was conducted on a single crop species and during a single growing season, it was limited in its capacity to be widely generalized across agroecological settings. Second, the work lacked comprehensive heavy metal research and microbial community characterization, which would have strengthened the assessment of potential salinity effects and pollutant accumulation in manure-derived vermicomposts. Third, the evaluation of drought stress was conducted over a relatively short stress period, which hampered the assessment of long-term climate resilience mechanisms. Finally, no economic cost–benefit analysis was performed, which would be useful in determining whether smallholder production strategies could be adopted at the farmer level.

Therefore, to better understand the sustainability and scalability of vermicomposting technologies in tropical agricultural systems, future research should incorporate long-term field trials, multi-crop evaluations, heavy metal assessments, microbiological analysis, and economic feasibility assessments.

5. Conclusions

The current study showed that vermicomposting greatly enhanced crop growth, yield performance, soil physicochemical characteristics, tolerance to climate-induced stress under tropical circumstances, and vermicompost nutrient quality. The highest concentrations of nitrogen, phosphorus, and potassium were consistently produced by T2, along with the biggest increases in soil organic carbon, organic matter, cation exchange capacity, and crop productivity metrics, such as germination, biomass accumulation, marketable yield, SPAD index, and survival rate under stress. Conversely, agronomic performance and nutrient availability were often lower in the standard compost treatment (T4). The results imply that nitrogen mineralization, soil fertility restoration, and plant stress tolerance are significantly impacted by the interplay between feedstock composition and earthworm-mediated biological processes. This interaction was consistently supported by statistically significant differences ($p < 0.001$) across all soil, crop growth, and stress-resilience parameters, confirming strong treatment-dependent effects. Manure-rich vermicomposts showed a modest rise in electrical conductivity, but post-application soil EC stayed within acceptable agronomic bounds, suggesting that there was little short-term salinity risk under the study's circumstances. However, the consistently

higher EC values in T2 also indicated enhanced mineral release rather than salinity hazard, as all values remained below agro-economic stress thresholds. Overall, the findings point to vermicomposting as a climate-resilient and sustainable method of turning agricultural waste into valuable organic fertilizer while enhancing crop productivity and soil health. Farmers in tropical smallholder systems are advised to use stabilized vermicompost made from balanced organic feedstocks, especially mixtures containing nutrient-rich manures and plant residues, for practical application. This recommendation is strongly supported by the consistent superior performance of T2 across all measured variables, indicating its practical agronomic superiority. However, excessive application rates should be avoided, and soil salinity should be periodically monitored under repeated use. To further confirm the durability and scalability of vermicomposting methods in tropical agriculture, further research should incorporate long-term field evaluations, heavy metal assessments, microbiological analysis, and economic feasibility studies.

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Institutional Review Board Statement: This research involved the use of the earthworm species *Eisenia fetida* for the purpose of vermicomposting agricultural wastes. The study was conducted in accordance with the internal research guidelines of the Faculty of Agronomy and Forest Engineering at Eduardo Mondlane University. As this study involved non-protected invertebrate species and did not involve human participants or vertebrate animal subjects, the Eduardo Mondlane University Research Ethics Committee granted exemption. All experimental procedures were performed with strict adherence to environmental safety and sustainable research practices. Humans and vertebrate animals did not take part in this study. The use of earthworms (*Eisenia fetida*) complied with standard ethical guidelines for invertebrate research and did not require formal ethics approval.

Informed Consent Statement: Not applicable. This study did not involve human participants, and therefore, informed consent was not required.

Data Availability Statement: All of the data generated or analyzed during this study will be provided upon reasonable request.

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