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Substrate-Dependent Variations in Physicochemical Properties of Vermicompost from Agricultural Residues and Poultry Manure in Tropical Systems

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Abstract

The accumulation of agricultural residues represents a major environmental challenge in developing countries, particularly in tropical regions where inadequate waste management contributes to environmental degradation. Vermicomposting has emerged as a sustainable technology capable of transforming organic waste into nutrient-rich fertilizers through the combined activity of earthworms and microorganisms. This study evaluated the influence of different agricultural residues on the physicochemical properties of vermicompost under tropical conditions in Mozambique. The experiment was conducted at the experimental field of the Catholic University of Mozambique—Faculty of Engineering in Chimoio district, using three substrate types: leguminous residues (T1), cereal residues (T2), and horticulture residues (T3). Each treatment was combined with poultry manure in a 1:1 ratio. Vermicomposting was carried out using *Eisenia fetida*. Because treatments were not independently replicated, results are presented as descriptive physicochemical characterizations (means ± SD of analytical subsamples). All treatments produced vermicompost with physicochemical characteristics consistent with established maturity criteria: pH 8.03–9.07, moisture 50–76%, and electrical conductivity 527–939 µS/cm, C/N ratio ranged from 15.56 to 20.19, total nitrogen ranged from 1.2 to 1.8%, phosphorus from 0.6 to 0.9%, and potassium from 1.1 to 1.5%. T1 (leguminous residues + poultry manure) showed the highest nutrient concentrations and lowest C/N ratio. These descriptive findings suggest that vermicomposting represents a promising strategy for recycling agricultural residues into vermicompost with characteristics consistent with established maturity criteria, highlighting the importance of substrate selection. The findings suggest that vermicomposting is a promising strategy for sustainable waste management and soil fertility improvement in tropical smallholder systems.

Keywords: agricultural residues; organic waste recycling; *Eisenia fetida*; soil fertility; nutrient dynamics; sustainable agriculture

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1. Introduction

The rapid growth of the global population, coupled with agricultural intensification and urbanization, has led to a substantial increase in the generation of organic waste

worldwide [1]. The Agricultural sector produces millions of tonnes of residues annually, including crop residues, livestock manure, and agro-industrial by-products [2]. If improperly managed, these wastes may contribute to environmental degradation through soil contamination, water pollution, greenhouse gas emissions, and the proliferation of pathogens and pests [1,3]. Consequently, sustainable strategies for organic waste management have become an important component of modern environmental and agricultural policies [4].

Among various waste management technologies available, biological treatment methods such as composting and vermicomposting have gained increasing attention due to their environmental sustainability and potential for resource recovery [5–7]. Composting involves the aerobic microbial decomposition of organic materials under controlled conditions, resulting in a stabilized organic amendment suitable for soil application [7–9]. However, composting has the disadvantage of being a long-term process and frequent turning to maintain adequate aeration, which may lead to nutrient losses through volatilization and leaching [10]. Consequently, vermicomposting has emerged as an efficient alternative technology for the stabilization of organic waste [8,11]. This process involves the combined activity of earthworms and microorganisms such as bacteria and fungi, which accelerate the breakdown of organic matter and transform it into a nutrient-rich material known as vermicompost [3,12]. During the vermicomposting process, earthworms ingest organic residues and fragment them into smaller particles, thereby increasing the surface area available for microbial colonization and enzymatic activity [12,13]. The digestion process within the earthworm intestine further enhances microbial activity and facilitates the transformation of complex organic compounds into more stable humified substances [10].

The resulting vermicompost is widely recognized as a high-quality organic fertilizer [14–16] due to its balanced nutrient composition, high microbial activity, and presence of humic substances that improve soil structure and fertility [8,11]. Numerous studies have reported that vermicompost application enhances soil physicochemical properties, stimulates plant growth, and increases crop productivity [11–13]. In addition, vermicompost has been shown to improve soil microbial diversity and increase nutrient availability, particularly nitrogen, phosphorus, and potassium [14].

The efficiency of the vermicomposting process is influenced by several factors, including the type of organic substrate, moisture content, temperature, and earthworm species involved [15]. Among the various earthworm species used in vermicomposting systems, *Eisenia fetida* is considered one of the most suitable due to its high reproductive rate, rapid growth, and tolerance to a wide range of organic materials [17]. This epigeic species feeds primarily on organic matter present in the upper layers of the soil and is particularly effective in processing organic waste [9,18]. Substrate composition plays a critical role in determining both the efficiency of vermicomposting and the quality of the final product [19–21]. Agricultural residues vary considerably in their chemical composition [22,23], particularly in terms of carbon and nitrogen content [24,25]. Leguminous residues generally contain higher nitrogen levels and lower C/N ratios compared with cereal residues [23,26,27], which are typically rich in lignin and cellulose and therefore decompose more slowly [19], therefore influencing microbial activity, decomposition dynamics, and nutrient transformation during vermicomposting [22].

Recent studies have highlighted the importance of combining carbon-rich residues with nitrogen-rich materials such as animal manure to achieve an optimal C/N ratio for microbial [7,28,29]. Poultry manure is particularly suitable for vermicomposting because it contains high levels of nitrogen and essential nutrients that stimulate microbial growth and accelerate organic matter decomposition [30,31]. The addition of poultry manure can therefore enhance nutrient availability and improve the physicochemical properties of the resulting vermicompost [32].

Despite the growing interest in vermicomposting as a sustainable waste management strategy, relatively few studies have examined the comparative performance of different agricultural residues in vermicomposting systems under tropical environmental conditions. For instance, Masin et al. evaluated a sequential composting and vermicomposting process using poultry litter combined with vegetables residues, employing *Eisenia fetida*, and found that the combined process produced stabilized organic fertilizers with electrical conductivity values of 1.81–2.28 mS/cm within the range recommended for sensitive plant growth [33]. Similarly, Saba et al. evaluated the physicochemical characteristics of vermicompost mixtures derived from chicken manure combined with horse and cattle manures, concluding that mixtures containing chicken manure consistently yielded higher macronutrient concentrations including nitrogen, phosphorus, and potassium than mixtures without chicken manure, while also demonstrating that substrate composition exerted a significant effect on moisture content, C/N ratio, and earthworm growth and reproduction parameters [34]. Despite previous studies, none have simultaneously compared leguminous, cereal, and horticulture residues combined with poultry manure as the sole nitrogen-rich amendment under large-scale tropical field conditions. Furthermore, limited attention has been given to the physicochemical quality of the resulting vermicompost in relation to pre-settlement process validation parameters, representing an important knowledge gap for smallholder farming systems in Mozambique and similar sub-Saharan African agro-ecological regions where poultry manure and locally available crop residues constitute the most accessible inputs for low-cost organic fertilizer production. Tropical climates are characterized by higher temperatures and seasonal rainfall patterns that may influence microbial activity, earthworm survival, and organic matter decomposition [22]. Understanding how different organic substrates perform under these conditions is essential for optimizing vermicomposting practices and improving nutrient recycling in tropical agricultural systems.

Furthermore, the physicochemical characteristics of vermicompost, such as pH, electrical conductivity, organic carbon content, nutrient concentrations, and C/N ratio, are key indicators of compost maturity and agronomic quality [23], providing valuable information about the degree of organic matter stabilization and the potential of vermicompost to supply nutrients to crops [24].

Therefore, this study aimed to evaluate vermicompost production from different agricultural residues combined with poultry manure and to assess the influence of substrate type on the physicochemical characteristics of the final product under tropical conditions in Mozambique. The findings will support the development of sustainable organic waste management strategies and enhance soil fertility management in tropical agricultural systems.

2. Materials and Methods

2.1. Environmental Conditions

The experiment was conducted at the experimental field of the Faculty of Engineering of the Catholic University of Mozambique (UCM), located in Chimoio district, Manica Province (18°50′ latitude S; 33°15′ longitude E; altitude of 640 m), Mozambique. According to the Köppen–Geiger climate classification, the region has a warm temperate climate with a rainy summer season (Cwa) [35] The average annual rainfall ranges between 1000 and 1250 mm, with significantly lower precipitation occurring during the winter compared to the summer season [36].

The vermicomposting units were installed under a covered structure (Figure 1) to protect the substrate from direct sunlight and rainfall, ensuring stable environmental conditions during the experiment.



Figure 1. (**a**) Vermicompost Units (**b**) Plastic covering inside the Unit.

2.2. Methods

2.2.1. Vermicompost Production

Raw Materials and Substrate Preparation

Organic substrates consisted of agricultural residues collected from the experimental fields of the Faculty of Engineering. Three types of residues were evaluated: leguminous residues (common bean: *Phaseolus vulgaris*, soybean: *Glycine max*, and yellow acacia *Vachellia farnesiana*), cereal residues (maize: *Zea mays* stalks and spontaneous grasses), and horticulture residues (lettuce: *Lactuca sativa*, cabbage: *Brassica oleracea*, Kale: *Brassica oleracea acephala* and sunflower leaves: *Helianthus annuus*) (Figure 2). All plant materials were manually cut into fragments of approximately 2–5 cm to facilitate microbial decomposition and earthworm feeding. The residues were used in their fresh state without prior drying. Poultry manure obtained from a local poultry production unit was used as a nitrogen-rich amendment and was added directly to the substrates.

Experimental Design and Vermicomposting Process

The experiment comprised three treatments corresponding to different organic substrate types (Table 1). One vermicomposting unit was used per treatment (n = 1 per treatment; 3 units total). Physicochemical analyses were based on three analytical subsamples collected from different positions within each unit (front, centre, rear), providing within-unit analytical replication. Furthermore, the vermicomposting units were maintained under homogeneous environmental conditions, minimizing spatial variability among experimental units and supporting the suitability of the CRD [37].

Table 1. Composition of Treatments.

Treatments	Organic Substrate	Proportion
T1	Leguminous residues + poultry manure	50:50
T2	Cereal residues + poultry manure	50:50
T3	Horticulture residues + poultry manure	50:50

T, treatments.

The vermicomposting units consisted of wooden boxes measuring 1.60 m × 1.00 m × 0.80 m (length × width × height) (Figure 1a). Each unit was filled with alternating layers of 25 kg of crop residues and 25 kg of poultry manure until a total weight of 0.5 tons was reached. After substrate preparation, the earthworm species *Eisenia fetida* was introduced into each unit at a density of 1 kg of earthworms per composting unit. This species was selected due to its high reproductive rate, rapid growth, and strong adaptability to organic waste environments [38].



Figure 2. Vermicompost Units: (**a**) Leguminous residues (**b**) Cereals residues (**c**) horticulture residues (**d**) Unit covered during the vermicompost process.

2.2.2. Parameters Evaluated at Earthworm Settlement

The assessment of substrate temperature, leachate pH, and earthworm morphometric characteristics prior to settlement constitutes a critical pre-vermicomposting validation, ensuring that thermal, chemical, and biological conditions are simultaneously favorable for *Eisenia fetida* colonization, survival, and efficient organic matter processing.

Temperature

Prior to earthworm inoculation, substrate temperature was monitored daily with soil probe thermometer in triplicate (front, center, and rear) in each vermicomposting unit to ensure spatial representativeness of the thermal measurements across the unit. Ambient temperature was also recorded simultaneously as an external reference to confirm that the elevated thermophilic temperatures observed within the units were attributable to endogenous enzymatic and microbial metabolic activity rather than external climatic variation. Earthworm introduction was performed once substrate temperature at all three treatments declined and stabilized within the target mesophilic range of 25–30 °C, thereby minimizing thermal stress on *Eisenia fetida* and ensuring favorable conditions for successful colonization and organic matter processing.

Earthworm Morphometric

To characterize the physiological condition and biological processing capacity of the inoculated population, morphometric measurements were performed with nine repetitions per treatment, each randomly selecting three samples at a time from successive 100 g portions of *Eisenia fetida* (Figure 3a) until nine repetitions were fully characterized. Body length was measured from the prostomium to the pygidium using a caliper (Figure 3b). Mid-body diameter was determined with a caliper (Figure 3c), and individual fresh weight was recorded on an analytical balance (±0.001 g precision) (Figure 3d).



Figure 3. Earthworms sample (**a**); Length measurement (**b**); Diameter measurement (**c**); and weighing of earthworm sample (**d**).

This sequential random selection procedure ensured that the morphometric sample was spatially and statistically representative of the entire earthworm population designated for inoculation, providing a standardized biological baseline across experimental units and ensuring that observed differences in vermicompost quality were attributable to substrate composition rather than to variation in the physiological condition or metabolic capacity of the introduced populations.

Leachate pH

The pH is an indicator of the chemical stability and degree of organic matter pre-stabilization within each vermicomposting unit. Leachate samples were collected in triplicate (n = 3) from the base drainage point of each composting unit and analyzed. Measurements were performed using a calibrated digital pH meter, and the mean pH value per treatment was calculated from three independent readings.

2.2.3. Vermicomposting Management

The vermicomposting process lasted 120 days, which was necessary due to the size of the composting units and the quantity of organic material used. Prior to the introduction of the earthworms, the temperature of the substrate was monitored to ensure that it had decreased to levels suitable for earthworm survival, which is recommended to between 20–30 °C [39]. After the introduction of *Eisenia fetida*, moisture content was maintained between 60–80% [40], levels favorable for earthworm survival, microbial activity support, reproduction and multiplication, through periodic watering when necessary, based on visual and tactile moisture assessment. Unlike conventional composting systems, the plant material was not turned during the vermicomposting process to avoid disturbing the earthworm population and to maintain stable conditions within the composting units.

2.2.4. Physicochemical Analysis of Vermicompost

Sampling

Vermicompost sampling was conducted following a simple spatial sampling scheme to obtain representative samples from each vermicomposting unit. Three subsamples were collected from the upper layer of the vermicompost at a depth of 4 cm. The sampling points were located at three positions within the vermicomposting bed: the front, the center, and the rear sections. The collected samples were stored in labeled polyethylene bags and transported to the laboratory for subsequent physicochemical characterization.

Physicochemical Analysis

All physicochemical analyses were performed in triplicate (n = 3) to ensure analytical reliability and reproducibility. Eight physicochemical parameters were analyzed following the methodology described by [41]: Moisture content was determined using a moisture balance based on weight loss during drying, providing rapid and accurate estimation of water content, which is essential for evaluating compost stability and microbial activity. pH was measured in a 1:2.5 vermicompost–water suspension using a digital pH meter, a method commonly used for compost characterization as it reflects substrate acidity or alkalinity, affecting nutrient availability and microbial processes. Electrical conductivity (EC) was determined using a conductivity meter, indicating the concentration of soluble salts and providing information about potential salinity when applied to soils. Organic carbon (OC) was determined using the Walkley–Black dichromate oxidation method, a widely accepted procedure for estimating organic carbon content in organic amendments and soils. Total nitrogen (TN) was measured using the Kjeldahl digestion method, which quantifies total nitrogen in organic materials, providing an estimate of nitrogen availability. Available phosphorus (P) was determined using the Olsen extraction method, commonly applied to evaluate plant-available phosphorus in organic substrates and soils. Exchangeable potassium (K) was determined by flame photometry following extraction. Finally, the C/N ratio was calculated from the measured organic carbon and total nitrogen values, serving as an indicator of organic matter stabilization and compost maturity.

2.3. Experimental Procedure and Statistical Analysis

The vermicomposting process was monitored in two sequential phases: (i) thermophilic pre-composting and (ii) earthworm settlement and vermicompost stabilization. At the end of the vermicomposting cycle, mature vermicompost samples were collected and analyzed for moisture content, pH, electrical conductivity (EC), total organic carbon (TOC), total nitrogen (TN), available phosphorus (P), exchangeable potassium (K), and C/N ratio using standard laboratory procedures. Each physicochemical parameter was determined from three within-unit analytical subsamples per treatment. All reported values represent

means ± SD of these analytical subsamples. The eight parameters were selected on the basis that they constitute the most widely accepted and analytically robust set of indicators for simultaneously assessing vermicompost maturity, organic matter stabilization, nutrient mineralization efficiency, and agronomic quality for tropical soil applications [42,43].

All physicochemical data are presented as descriptive characterisation based on within-unit analytical subsamples (n = 3 per treatment). Descriptive statistics were expressed as mean ± standard deviation. Statistical analyses were conducted using JMP 7.Ink statistical software [44].

The study was conducted using a single vermicomposting unit per treatment. Consequently, the observed differences among treatments should be interpreted as descriptive observations rather than statistically validated treatment effects.

3. Results

3.1. Parameters Influenced Earthworm Settlement

3.1.1. Temperature Evolution Prior to Earthworm Settlement

The evolution of substrate temperature prior to earthworm settlement revealed three distinct phases across treatments: an initial thermophilic heating phase, a transitional phase, and a progressive cooling toward mesophilic conditions (Figure 4). Ambient temperature remained stable throughout the monitoring period, ranging from 19.0 to 26.0 °C, confirming that thermal dynamics within the substrates were driven exclusively by internal biological activity rather than external climatic variation. In T1 and T2, substrate temperatures rose rapidly during the first days, reaching peak values of 53.0 °C on day 5 and 52.0 °C on day 8, respectively, characteristic of intense microbial oxidation of readily available organic compounds. Following the thermophilic peak, both T1 and T2 entered a well-defined cooling phase and converged to 26 °C and 24 °C by day 22, indicating full dissipation of microbial metabolic heat and completion of the pre-stabilization phase. The T3 exhibited a markedly different and accelerated thermal pattern. Temperature peaked at only 42.0 °C on day 2 and declined below 35 °C by day 6, ten days earlier than T1 and twelve days earlier than T2.

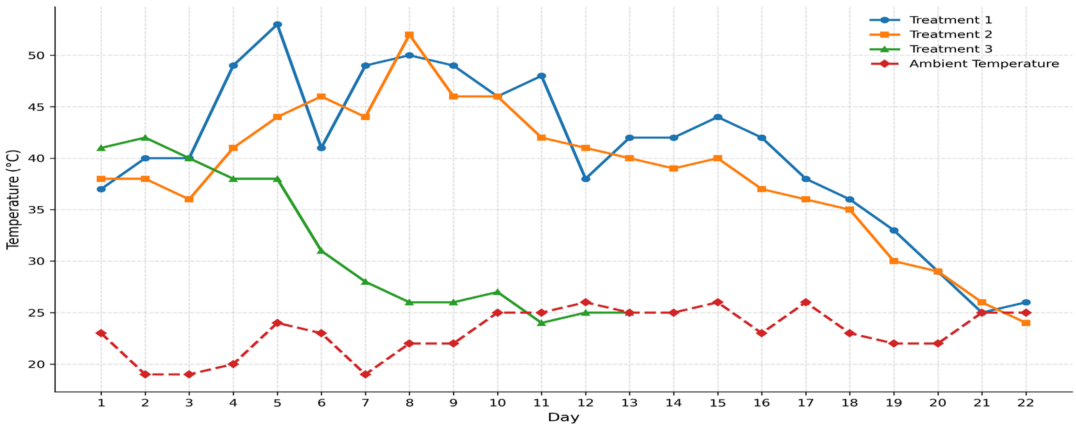


Figure 4. Temperature evolution prior to earthworm settlement.

T3 exhibited a markedly attenuated thermophilic response, reaching a peak temperature of 42 °C on day 2, approximately 10 °C below the maxima recorded for T1 (53 °C, day 5) and T2 (52 °C, day 8) and returning to mesophilic conditions by day 6, some 16 days earlier than the T1 and T2 (Figure 4). The physicochemical characteristics of horticulture residues: readily biodegradable, high moisture content and limited structural complexity, lacking the cellulose and lignin-rich fractions that sustain prolonged microbial thermogenesis can contribute to this variation. Earthworm settlement was consequently advanced to day

13 for T3. These contrasting thermal profiles reflect differential microbial metabolic capacity between substrate types; however, given the absence of independent biological replication, formal inferential analysis was not applicable.

The convergence of T1 and T2 temperatures to approximately 24 °C by day 22 well below the 35 °C threshold critical for *Eisenia fetida* survival confirms that both substrates completed the pre-stabilization phase required for safe earthworm introduction, minimizing thermal stress and providing favorable conditions for colonization and subsequent vermicomposting.

3.1.2. Earthworm Morphometric

The morphometric characteristics of *Eisenia fetida* introduced into the vermicomposting units are summarized in Table 2. Body weight, length, and diameter were measured to assess the physiological condition of the earthworms at the beginning of the experiment, as these parameters are closely related to feeding capacity and substrate processing efficiency.

Table 2. Morphometric Characteristics of Earthworms.

Measure	T1	T2	T3
Weigh (g)	0.7 ± 0.1	0.6 ± 0.3	0.6 ± 0.2
Length (cm)	7.5 ± 1.1	6.8 ± 1.3	7.3 ± 1.1
Diameter (mm)	4.3 ± 0.9	4.3 ± 0.9	3.4 ± 0.6

T (Treatment), T1: Leguminous residues + poultry manure, T2: Cereal residues + poultry manure, T3: Horticulture residues + poultry manure.

The results of earthworm body weight, lengths and diameters, in T1 indicate the presence of predominantly sub-adult to mature individuals. T2 suggests a mixed population including fully mature worms. In contrast, T3 presented slightly smaller individuals, indicating a higher proportion of juvenile worms. Descriptively, the three morphometric parameters showed overlapping means and standard deviations across treatments (Table 2), suggesting comparable physiological condition of the inoculated populations regardless of the substrate unit.

The presence of both juvenile and mature individuals is advantageous for vermicomposting, as larger worms enhance organic matter fragmentation while smaller individuals contribute to population growth and system stability. Therefore, the earthworm populations introduced in this study were within the optimal size range for efficient substrate colonization and organic matter decomposition.

3.1.3. Leachate pH at Settlement

The leachate pH measured at the time of earthworm settlement is presented in Table 3. The values vary from 8.31 (T2) to 8.63 (T1), showing a very low variability among replicates (SD = 0.01), indicating stable chemical conditions in the substrates prior to the introduction of *Eisenia fetida*.

Table 3. pH of leachate prior settlement.

pH	T1	T2	T3
Mean	8.63 ± 0.01	8.31 ± 0.01	8.46 ± 0.01

n = 3, T1: Leguminous residues + poultry manure, T2: Cereal residues + poultry manure, T3: Horticulture residues + poultry manure.

Overall, the leachate exhibited slightly alkaline conditions, which are characteristic of substrates that have progressed beyond the initial acidic phase of organic matter decomposition. During compost maturation, the degradation of organic acids and the mineralization

of nitrogen compounds typically lead to a gradual increase in pH toward neutral or mild alkaline levels. These conditions are generally considered suitable for the introduction of epigeic earthworms such as *Eisenia fetida*, which tolerate a broad pH range but perform optimally in near-neutral to slightly alkaline environments.

The consistent near-neutral to slightly alkaline range indicates that leachate pH was unlikely to have constituted a confounding factor between treatments, and that the pre-stabilization period was sufficient for all substrate types and for maintaining balanced microbial communities that support organic matter transformation during the vermicomposting process.

3.2. Physicochemical Parameters of Vermicompost

The physicochemical parameters of the vermicompost produced from the different substrates are summarized in Table 4. The analyzed parameters included pH, moisture content, electrical conductivity (EC), organic carbon (OC), C/N ratio, total nitrogen (TN), phosphorus (P), and potassium (K), providing therefore, important information regarding organic matter stabilization, nutrient status, and the physicochemical characteristics of the final vermicompost product.

Table 4. Physicochemical parameters of vermicompost from different substrate.

Parameters	T1 (Mean ± SD)	T2 (Mean ± SD)	T3 (Mean ± SD)
pH	9.07 ± 0.06	8.47 ± 0.06	8.03 ± 0.06
Moisture (%)	67.00 ± 0.00	76.00 ± 0.00	50.00 ± 0.00
EC (µS/cm)	938.7 ± 0.58	594.7 ± 0.58	527.7 ± 0.58
Organic Carbon (%)	28.00 ± 0.00	24.23 ± 0.21	26.10 ± 0.10
C/N ratio	15.56 ± 0.00	20.19 ± 0.17	17.40 ± 0.07
Total Nitrogen (%)	1.80 ± 0.00	1.20 ± 0.00	1.50 ± 0.00
Phosphorus (%)	0.87 ± 0.06	0.60 ± 0.00	0.77 ± 0.06
Potassium (%)	1.47 ± 0.06	1.13 ± 0.06	1.27 ± 0.06

EC (Electrical conductivity), T1: Leguminous residues + poultry manure; T2: Cereal residues + poultry manure; T3: Horticulture residues + poultry manure.

The results of physicochemical parameters are summarized in Table 4. T1 (leguminous residues + poultry manure) recorded the highest values for pH, electrical conductivity, organic carbon, total nitrogen, phosphorus, and potassium, and the lowest C/N ratio. T2 (cereal residues + poultry manure) showed the highest moisture content but the lowest electrical conductivity, total nitrogen, and nutrient concentrations. T3 (horticulture residues + poultry manure) showed intermediate values for most parameters. For phosphorus, T1 and T3 recorded similar values while T2 was lower; for potassium, T1 was highest while T2 and T3 showed comparable values. Differences among treatments were observed; however, the absence of independent replication precludes statistical inference.

3.2.1. pH and Moisture Content

The final vermicompost exhibited a pH range of 8.03 to 9.07, reflecting a moderately alkaline profile for T2 and T3, whereas T1 demonstrated a strong alkaline character (see Table 4). The pH showed a clear gradient: T1 (9.07 ± 0.06) > T2 (8.47 ± 0.06) > T3 (8.03 ± 0.06). The higher pH in T1 attributable to the greater nitrogen content of leguminous residues, which sustains elevated ammonification rates during decomposition and the consequent release of ammonium ions that drive alkalinization of the substrate especially when combined with poultry manure indicating a more intense mineralization process and possible accumulation of basic cations.

Moisture content followed a treatment dependent gradient T2 (76%) > T1 (67%) > T3 (50%) consistent with the higher water retention characteristic of leguminous and cereal-based mate-

rials relative to horticulture residues. The moisture levels observed in T1 and T2 fall within the range of 60–80% widely recognized as optimal for *Eisenia fetida* activity, microbial decomposition, and earthworm metabolism, while the lower moisture content of T3 suggests that the structural collapse of horticulture residues during decomposition reduced water retention capacity.

3.2.2. Electrical Conductivity and Organic Carbon

The EC was highest in T1 (938.7 μS/cm), intermediate in T2 (594.7 μS/cm), and lowest in T3 (527.7 μS/cm). The markedly higher EC in T1 reflects the greater release of soluble ionic species—principally NH_4^+, NO_3^-, $H_2PO_4^-$, and K^+ resulting from the more intensive mineralization of leguminous residues combined with poultry manure, while all values remained well below the phytotoxicity threshold of 4000 μS/cm, indicating that none of the treatments produced vermicompost with salinity levels likely to impair plant growth or soil biological activity upon field application.

The organic carbon was highest in T1 (28.00%), intermediate in T3 (26.10%), and lowest in T2 (24.23%). The highest value observed in T1 reflects high biomass input and partial conversion of carbon despite rapid decomposition, indicating formation of stable humic substances while under T2 suggests a greater C loss probably as CO_2 due to slower but prolonged decomposition of high C/N (20.19) cereal residues. The progressive reduction in organic carbon relative to the initial substrate composition is a well-established consequence of earthworm-mediated decomposition, during which carbon rich compounds are oxidized through microbial respiration and incorporated into stable humified organic matter, with the more pronounced carbon retention in T1 reflecting the formation of recalcitrant humic substances associated with the advanced mineralization of nitrogen-rich leguminous residues.

3.2.3. Nutrient Content (N, P, and K)

Total nitrogen was highest in T1 (1.80%), intermediate in T3 (1.50%), and lowest in T2 (1.20%). These patterns are consistent with the higher nitrogen content of leguminous residues (T1) and the high C/N ratio of cereal residues (T2), which can promote nitrogen immobilization during organic matter decomposition.

Phosphorus was highest in T1 (0.87%), intermediate in T3 (0.77%), and lowest in T2 (0.60%). The comparable values of T1 and T3 suggest that poultry manure, present equally across treatments, may be the primary phosphorus source, with residue type playing a secondary role. For potassium, T1 showed the highest value (1.47%), while T2 (1.13%) and T3 (1.27%) showed comparable lower values, suggesting similar potassium release dynamics from cereal and horticulture residues under the conditions of this study.

The consistently superior macronutrient concentrations recorded in T1 across all three parameters reflect the biochemical complementarity between leguminous residues characterized by higher protein-bound and structural nitrogen and the broad-spectrum nutrient profile of poultry manure, which together optimized microbial metabolic activity, earthworm feeding efficiency, and the mineralization of organic nitrogen, phosphorus, and potassium into plant-available forms throughout the vermicomposting process.

3.2.4. C/N Ratio

The C/N ratio showed the pattern T2 (20.19) > T3 (17.40) > T1 (15.56). The lowest C/N ratio recorded in T1 reflects the combined effect of its higher initial nitrogen content and the accelerated mineralization of leguminous carbon substrates, which are structurally less complex than cereal or horticulture residues and therefore more readily metabolized by the earthworm-associated microbial community, resulting in greater carbon oxidation relative to nitrogen conservation.

Conversely, the highest C/N ratio in T2—while remaining within the accepted maturity threshold of ≤20—indicates that the structural complexity of cereal residues, characterized by higher proportions of lignin and cellulose, partially constrained carbon mineralization relative to the other substrates. All three treatments attained C/N ratios equal or below 20, the threshold widely recognized as indicative of advanced organic matter stabilization and vermicompost maturity suitable for direct soil application, confirming that the 120-day vermicomposting period was sufficient to achieve a fully stabilized end-product regardless of substrate type, while the significantly lower C/N ratio of T1 further suggests that leguminous residue-based vermicompost would favor net nitrogen mineralization rather than nitrogen immobilization upon incorporation into tropical agricultural soils.

4. Discussion

The study was conducted using a single vermicomposting unit per treatment. Consequently, the observed differences among treatments in this section should be interpreted as descriptive observations rather than statistically validated treatment effects. Additional studies employing replicated experimental units are required to confirm these findings.

4.1. Parameters for Prior Settlement of Earthworms

4.1.1. Temperature Evolution

The thermal dynamics recorded across the three vermicomposting treatments are best understood not merely as environmental monitoring data, but as biochemical evidence of the differential microbial metabolic capacity of the three substrate types and by extension, as a determinant of the quality of conditions presented to *Eisenia fetida* at inoculation. The prolonged thermophilic phase sustained by T1 and T2 reflects the greater availability of readily degradable organic compounds in leguminous and cereal residues combined with poultry manure, which collectively provided a richer and more sustained energy substrate for pioneer thermophilic microbial communities than the vegetable-based T3 [45,46]. Environmental conditions particularly temperature play a decisive role in earthworm activities during vermicomposting, with temperature tolerances varying considerably among *epigeic* species [47–49]; *Eisenia fetida* exhibits optimal physiological performance at 30 °C [50,51], with antioxidant stress responses evidenced by elevated peroxidase, superoxide dismutase, and malondialdehyde levels activating progressively above this threshold and intensifying sharply beyond 35 °C [52,53].

What is particularly significant in the context of this study is not the magnitude of the thermophilic peak itself, but the biological meaning of the cooling trajectory that followed it. The linear cooling rates of approximately 1.75 °C day^{-1} observed in T1 and T2 represent the progressive depletion of labile organic carbon fractions that had sustained thermophilic microbial respiration a process that simultaneously pre-conditioned the substrate by partially hydrolyzing structural biopolymers, reducing phytotoxic compound concentrations, and suppressing pathogenic microorganisms, all of which are prerequisites for successful earthworm colonization [54]. Vermicomposting is inherently a mesophilic process requiring substrate temperatures below 35 °C to prevent earthworm mortality [49,50]; however, an initial thermophilic pre-stabilization phase during which temperatures reach 55–70 °C is recognized as beneficial for pathogen suppression and partial degradation of structurally complex organic compounds [55], provided earthworms are introduced only after the substrate has fully transitioned to mesophilic conditions [48,56]. The absence of significant correlation between ambient and substrate temperatures in T1 and T2 throughout the monitoring period constitutes a critical methodological validation: it confirms that the thermophilic dynamics were entirely driven by endogenous microbial metabolic activity rather than by the tropical climate of Chimoio, a distinction that strengthens the

biological interpretability of the temperature data and rules out confounding by external thermal variation.

The substantially shorter thermophilic phase of T3, with its rapid descent to mesophilic temperatures by day 6, reflects the intrinsic lability of horticulture residues rich in easily fermentable carbohydrates but poor in the lignocellulose structural polymers that sustain prolonged microbial thermogenesis [2,57]. While this accelerated transition superficially appears advantageous for earthworm introduction, it may in fact signal incomplete pre-stabilization [2]: the brief thermophilic exposure of T3 is unlikely to have achieved the degree of pathogen suppression and structural organic matter pre-degradation attained in T1 and T2, potentially compromising the biochemical accessibility of the substrate for *Eisenia fetida* during subsequent vermicomposting a hypothesis consistent with the lower nutrient concentrations and EC values ultimately recorded in T3. Temperature directly governs microbial community succession, diversity, and metabolic activity during vermicomposting [46], with higher substrate temperatures within the mesophilic range accelerating organic matter decomposition, mineralization and nitrification [58,59], demonstrating that the thermal history of a substrate prior to earthworm inoculation shapes the biological and chemical quality of the vermicompost ultimately produced.

4.1.2. Earthworm Morphometric Characteristics

The morphometric characterization of *Eisenia fetida* at inoculation serves a purpose that extends well beyond descriptive documentation of the earthworm population: it functions as a quantitative biological baseline against which the efficiency of organic matter processing can be mechanistically interpreted [60,61], and as an experimental control variable whose standardization is essential for attributing differences in final vermicompost quality to substrate composition rather than to heterogeneity in the inoculated populations. Vermicomposting is a bio oxidative mesophilic process in which *epigeic* earthworm species interact synergistically with microorganisms to accelerate organic matter stabilization [62–64]; among *epigeic* species, *Eisenia fetida* is the most widely used worldwide owing to its high metabolic rates, broad environmental tolerance, and rapid reproduction characteristics that are directly expressed in and predicted by its morphometric condition at inoculation [65,66].

Body weight, length, and diameter are not independent traits but integrative physiological indicators that reflect the nutritional history, reproductive maturity, and metabolic capacity of the earthworm population at the time of settlement [67,68]. Heavier, longer individuals consume and process proportionally greater quantities of organic material per unit time since feeding rate in *Eisenia fetida* scales with body mass while clitella adults contribute simultaneously to organic matter fragmentation and reproductive output, sustaining population density throughout the vermicomposting period [69]. Morphometric studies of *Eisenia fetida* grown across diverse organic substrates have demonstrated that substrate-induced changes in earthworm body dimensions and integumentary thickness including cuticle and epidermis morphology [70], reflect adaptive physiological responses to substrate-specific biochemical and physical conditions of vermicomposting [69]. The presence of both juvenile and sub-adult individuals across all three treatment populations at settlement is agronomically advantageous: while mature individuals drive initial organic matter fragmentation and substrate aeration, juveniles ensure progressive population recruitment into the reproducing adult cohort, sustaining processing capacity across the full 120-day vermicomposting period [48,65,67].

Critically, the standardization of morphometric profiles across experimental units achieved through the randomized sequential selection protocol from 100 g subsamples minimized the biological variability among inoculated populations, thereby satisfying a

fundamental assumption of the completely randomized design: that observed differences in vermicompost quality among treatments are attributable to substrate composition rather than to differential earthworm population capacity. Without this morphometric standardization, inter-treatment differences in processing efficiency could not be unambiguously attributed to substrate biochemistry, fundamentally undermining the causal interpretability of the physicochemical results.

4.1.3. Leachate pH

The between-treatment differences in leachate pH, in turn, reflect the differential biochemical maturity of the three substrate types at the moment of earthworm introduction: the higher pH of T1, driven by the more intensive ammonification of leguminous residue nitrogen, indicates a more advanced degree of organic acid neutralization and therefore a greater biochemical readiness for earthworm colonization relative to T2 and T3 [71]. The pH influence on the composition and activity of earthworm-associated microbial communities, as well as on earthworm physiology directly [72]; *Eisenia fetida* tolerates a broad pH range but performs optimally near neutrality, with slightly alkaline conditions generally associated with the dominance of ammonifying and nitrifying bacterial communities that sustain the nitrogen mineralization processes central to vermicompost nutrient enrichment [59,73,74].

The narrow pH range across treatments (8.31–8.63) also implies that all three substrate types had reached comparable degrees of fermentation-phase completion despite their biochemical differences [75], suggesting that the 22-day pre-stabilization period was sufficient across all substrate types to drive the transition from acidic fermentation to ammonification-dominated chemistry. This convergence is of methodological importance: it means that leachate pH at settlement did not constitute a confounding variable between treatments, and that the physicochemical differences observed in the final vermicompost can be attributed to substrate composition and its influence on *Eisenia fetida* processing efficiency, rather than to differential starting chemical conditions at inoculation. Earthworms introduced to substrates with stable, near-neutral to slightly alkaline pH exhibit elevated reproduction rates and enhanced detoxifying capacity relative to individuals introduced to chemically unstable or acidic substrates, confirming that leachate pH at settlement is not merely a descriptive parameter but a functional predictor of the biological performance of the earthworm population throughout the subsequent vermicomposting process [59,74].

4.2. Physicochemical Parameters of Vermicompost

4.2.1. pH

The pH of the final vermicompost ranged from 8.03 (T3) to 9.07 (T1) similar results was found in [59,73,74], showing the descriptive pattern T1 > T2 > T3, consistent with the known influence of substrate nitrogen content on alkalization dynamics during vermicomposting [76]. The presence of animal manure in the substrates may also contribute to higher pH values due to ammonification processes during nitrogen mineralization [77].

The significantly higher pH recorded in T1 (leguminous residues + poultry manure) relative to T2 and T3 is mechanistically attributable to the greater nitrogen content of leguminous substrates, which sustains higher rates of ammonification and releases ammonium ions (NH_4^+) that elevate interstitial pH during organic matter decomposition [78]. Vermicomposting studies have consistently demonstrated that the physicochemical composition of the substrate particularly its nitrogen content and carbon-to-nitrogen ratio is the primary determinant of pH dynamics, with nitrogen-rich substrates generating more pronounced alkalization through ammonification-driven proton consumption [74]. The slightly lower pH in T3 (horticulture residues) likely reflects the faster depletion of labile

nitrogen compounds in vegetable substrates and the comparatively lower ammonification potential of horticulture residues relative to leguminous materials [59].

All final pH values fall within the range reported as agronomically acceptable for vermicompost soil application [79], and remain compatible with the physiological tolerances of *Eisenia fetida* [80].

4.2.2. Moisture Content

Descriptively, moisture content followed the pattern T2 > T1 > T3, ranging from 50% (T3) to 76% (T2). The higher moisture retention in T2 (cereal residues) is attributable to the greater hygroscopic capacity and structural porosity of cereal straw materials particularly maize stalks which retain water within their cellulose and hemicellulose matrices [49,81]. Conversely, the lower moisture in T3 (horticulture residues) reflects the faster structural collapse of vegetable materials during decomposition, reducing water retention capacity and increasing evaporative losses from the composting bed [82]. Maintaining moisture content within the range of 60–70% is widely recommended for vermicomposting systems, as this range supports optimal microbial activity and earthworm physiology without inducing anaerobic conditions [83]. While T1 (67%) and T2 (76%) broadly satisfy this criterion, T3 (50%) falls below the optimal threshold, suggesting that horticulture residue may require supplementary moisture management under tropical conditions, where evapotranspiration rates are elevated [82].

4.2.3. Electrical Conductivity

Descriptively, EC showed the pattern T1 > T2 > T3, with values of 938.7, 594.7, and 527.7 μS/cm, respectively. The markedly higher EC in T1 reflects the greater mineralization of leguminous residues combined with poultry manure, which releases higher concentrations of soluble ionic species principally NH_4^+, NO_3^-, $H_2PO_4^-$, and K^+ into the interstitial soil solution during organic matter decomposition [84,85]. All EC values recorded in this study remain well below the phytotoxicity threshold of 4000 μS/cm widely cited in the literature, indicating that none of the treatments produced vermicompost with salinity levels likely to inhibit plant growth or soil microbial activity upon field application [86–88]. Usually for good quality vermicompost EC ranges from 500–1500 μS/cm which is low to moderate EC range and shows absence of salinity risk, suitable for direct soil application and effective regulation of salts by earthworm activity [89]. Vermicompost generated under optimal conditions exhibits elevated concentrations of macronutrients including nitrogen, phosphorus, and potassium, reflected in correspondingly higher EC values, without reaching levels that impose osmotic stress on the rhizosphere [80]. The role of *Eisenia fetida* in EC dynamics is important due to its contribution to stabilization of soluble salts though ingestion and casting as well as enhancement of microbial transformation for example nitrification [90]. The substantially higher EC of T1 relative to T2 and T3 further corroborates the superior nutrient mineralization efficiency of leguminous residue-based substrates under tropical vermicomposting conditions [85].

4.2.4. Organic Carbon and C/N Ratio

Descriptively, organic carbon ranged from 24.23% (T2) to 28.00% (T1), with T1 > T3 > T2. The C/N ratio showed the inverse pattern (T2 > T3 > T1), with values of 20.19, 17.40, and 15.56, respectively. The lower C/N ratio in T1 reflects the combined effect of its higher initial nitrogen content and the accelerated mineralization of leguminous carbon substrates, which are structurally less complex than cereal or horticulture residues and therefore more readily metabolized by the earthworm-associated microbial community [91,92]. C/N ratios decrease progressively during vermicomposting as carbon-rich compounds are oxidized and nitrogen is conserved or mineralized, with studies reporting reductions of 37.5–54.4%

depending on substrate composition [63,93,94]; final C/N ratios of 15.5–20.0 are consistent with advanced organic matter stabilization and compost maturity [95,96]. The lowest C/N ratio in T1 (15.56) is particularly noteworthy, as values below 16 are associated with net nitrogen mineralization rather than nitrogen immobilization upon soil application, maximizing the short-term agronomic nitrogen supply to crops [97]. The highest C/N ratio in T2 (20.19), while still within the accepted maturity threshold of <20, suggests that the structural complexity of cereal residues characterized by higher lignin and cellulose fractions partially limited carbon mineralization relative to the other substrates [92,98]. The C/N values recorded across all three treatments in the present study, confirming that the 120-day vermicomposting period was sufficient to achieve mature, stabilized vermicompost regardless of substrate type.

4.2.5. Total Nitrogen, Phosphorus, and Potassium

Descriptively, total nitrogen followed T1 (1.80%) > T3 (1.50%) > T2 (1.20%). For phosphorus, T1 (0.87%) and T3 (0.77%) showed similar values while T2 (0.60%) was lower, suggesting poultry manure as the primary phosphorus driver. For potassium, T1 (1.47%) was highest, while T2 (1.13%) and T3 (1.27%) showed comparable values.

The superior nitrogen content of T1 is consistent with the biochemical composition of leguminous residues, which carry higher concentrations of protein-bound and structural nitrogen relative to cereal or vegetable materials, providing a larger pool of mineralizable nitrogen for microbial transformation during vermicomposting [83,99]. Increased nitrogen levels in vermicompost are primarily driven by the mineralization of organic compounds containing protein and ammonia-nitrogen to nitrates [24], a process mediated by the digestive activity of earthworms and the nitrogen-fixing and nitrifying microbial communities associated with their gut and casting microbiome [100,101]. The partial overlap in phosphorus concentrations between T1 and T3 despite their divergent nitrogen and carbon dynamics suggests that poultry manure, present in equal proportions across all treatments, was the principal driver of phosphorus enrichment [102], a pattern consistent with poultry manure as the primary phosphorus source given its equal proportion across all treatments. Similarly, the comparable potassium values in T2 and T3 suggest similar release dynamics from cereal and horticulture materials at 120 days, while T1's higher value is consistent with the potassium-rich biochemistry of leguminous tissues [6].

Descriptively, T1 (leguminous residues + poultry manure) consistently showed the highest nutrient concentrations across nitrogen, phosphorus, and potassium, making it the most chemically enriched substrate combination among the three evaluated. Field-scale validation and germination bioassays are necessary before agronomic recommendations can be made with confidence.

5. Conclusions

This exploratory, descriptive study conducted provides baseline characterization data on how substrate composition influences vermicompost physicochemical properties under tropical conditions in Chimoio, Mozambique. Pre-settlement monitoring confirmed that all substrates successfully completed the thermophilic pre-stabilization phase driven by microbial activity, while leachate pH and earthworm morphometric data were descriptively consistent with chemical and biological suitability of the substrates for Eisenia fetida inoculation.

Among the evaluated treatments, leguminous residues combined with poultry manure descriptively produced vermicompost with the highest concentrations of nitrogen, phosphorus, potassium, and organic carbon, and the lowest C/N ratio among the three substrate types evaluated. These results highlight the biochemical complementarity between nitrogen-rich leguminous materials and poultry manure, which enhances nutrient

mineralization and organic matter stabilization. All treatments achieved C/N ratios below the maturity threshold of 20 and electrical conductivity values within safe limits, confirming that the 120-day vermicomposting process produced stable and agronomically suitable organic fertilizers.

Overall, the descriptive results suggest that vermicomposting is a promising low-input strategy for recycling agricultural residues in tropical smallholder systems. Among the three substrate types evaluated, leguminous residues combined with poultry manure produced vermicompost with the most favourable chemical characteristics. However, given the absence of independent experimental replication, these findings should be treated as hypothesis-generating rather than confirmatory. Future research priorities include: (i) replicating the experiment with a minimum of three independent units per treatment; (ii) including initial substrate characterisation and an earthworm-free composting control; (iii) measuring earthworm performance metrics (survival, final biomass, reproduction); and (iv) conducting germination bioassays and field-scale trials to validate agronomic potential.

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