UNIVERSIDADE EDUARDO MONDLANE

Faculty of Agronomy and Forest Engineering

Department of Agricultural Economics and Rural Development

Master's Degree in Climate Change in Agricultural Systems

Climate Resilient Bio-Management of Agricultural Waste Through Vermicomposting to Produce Organic Fertilizer

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A Dissertation Submitted to the Department of Agricultural Economics and Rural Development in fulfillment of the Requirements for Master Degree in Climate Change in Agricultural Systems, Eduardo Mondlane University

Maputo, June 2026

DECLARATION AND RECOMMENDATION

Declaration

This thesis is my original work and has not been previously published or presented for the award of any degree in any University.

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Recommendation

This thesis has been submitted with our recommendation as University Supervisor

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Dedication

This thesis is dedicated to my mother, Mrs. Rosemary Mbuku and Prof. John Recha for their immeasurable support.

Acknowledgement

I thank the Almighty God for His protection, strength, and guidance throughout my studies at Eduardo Mondlane University.

I am sincerely grateful to the Centre of Excellence University under the World Bank for the scholarship support and to Eduardo Mondlane University for the opportunity to pursue my studies.

My heartfelt appreciation goes to my supervisor, **Prof. Doctor Rogerio Borguete Alves Rafael**, for his invaluable guidance and support throughout this research. I also thank **Prof. Doctor Nascimento Nhantumbo** (Opponent) and **Dra Sandra Chemane** (President) for their constructive comments and contributions to improving this work.

Finally, I thank all lecturers of the Faculty of Agronomy and Forest Engineering and everyone who contributed to the successful completion of this study.

Abstract

Sustainable management of agricultural waste and declining soil fertility remain major challenges for agriculture, particularly under increasing climate-induced stress. This study evaluated the effectiveness of vermicomposting using *Eisenia fetida* and molasses to convert combinations of cow dung, poultry waste, and vegetable waste into nutrient-rich organic fertilizer. A Completely Randomized Design (CRD) was used for decomposition assessment, while a Randomized Complete Block Design (RCBD) evaluated effects on soil health, crop yield, and drought resilience in lettuce.

Results showed that vermicomposting significantly accelerated decomposition compared to conventional composting. Earthworm activity enhanced microbial processes, waste fragmentation, and nutrient mineralization, while mixed substrates produced synergistic effects that improved nutrient availability. Vermicompost treatments demonstrated superior agronomic quality, indicating advanced maturity and reduced phytotoxicity. Nutrient analysis revealed increased macronutrient concentrations, particularly in mixed waste treatments, confirming enhanced mineralization and bioavailability.

Application of vermicompost improved soil fertility, structure, and microbial activity, creating favorable conditions for plant growth. Lettuce grown in vermicompost-amended soils exhibited higher fresh and dry biomass, improved yield, and greater drought resilience. These improvements were linked to enhanced soil moisture retention, improved root development, and slow-release nutrient availability. Additionally, molasses served as an energy source for microbial communities, accelerating decomposition and enhancing humification, resulting in stable, carbon-rich compost. Improved soil aggregation and water retention further supported plant performance under water stress, while enhanced root proliferation increased nutrient uptake efficiency and drought tolerance.These findings demonstrate that vermicomposting with *Eisenia fetida*, especially using mixed organic wastes, is a low-cost, climate-smart, and biologically efficient strategy for sustainable agricultural waste management and soil improvement.

Keywords: vermicomposting, sustainable agriculture, drought resilience, soil health, nutrient mineralization

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LIST OF ABBREVIATIONS AND ACRONYMS

ANOVA	Analysis of Variance
BA	Biomass Ash
BD	Bulk Density
Ca	Calcium
Cd	Cadmium
CEC	Cation Exchange Capacity
CRD	Completely Randomized Design
Cr	Chromium
CSB	Coconut Shell Biochar
Cu	Copper
Fe	Iron
GSPP	Gleditsia Sinensis Pod Powder
IPBES	Intergovernmental Science Policy on Biodiversity and Ecosystem Service
K	Potassium
N	Nitrogen
NPK	Nitrogen-Phosphorus-Potassium
P	Phosphorus
Pb	Lead
pH	Potential Hydrogen
RCBD	Randomized Complete Block Design
RHB	Rice Husk Biochar
SE	Standard Error

TOC	Total Organic Carbon
Tukey`s HSD	Tukey`s Honest Significant Difference
Zn	Zinc

1.0 Introduction

1.1 Background

Innovative approaches to managing agricultural waste and producing organic fertilizers are necessary to address climate change challenges in sustainable agriculture. By boosting adaptive capacity and fostering resistance to erratic and unpredictable weather patterns, this reduces greenhouse gas emissions and provides practical advantages (Srinivasa Rao et al., 2016). Methane gas emissions are a significant greenhouse gas that warms the planet more quickly than carbon dioxide. Crop residues, livestock manure, and landfills are examples of agricultural wastes that pose serious environmental risks. Additionally, nitrous oxide from nitrogenous fertilizers is 300 times more potent than carbon dioxide over a 100-year period, despite the fact that it greatly contributes to global warming. In Africa, particularly in Mozambique, where fertilizer application rates are still less than 10 kg per hectare, this problem is less severe (Zavale et al., 2020). By releasing stored carbon and changing surface reflectance (albedo), which affects local and regional temperatures, land use changes like deforestation and draining wetlands for agricultural purposes accelerate climate change (Salazar et al., 2015). In order to address these complex issues, resilient and sustainable farming methods that efficiently minimize waste and lessen the effects of climate change are crucial.

Traditional agricultural waste management techniques, such as burning and landfilling, are ineffective and harmful to the environment. According to Mahjoub et al. (2020), these actions raise health risks, environmental damage, and greenhouse gas emissions. By reducing the effects of air pollution, soil and water pollution, and climate change, effective waste management for sustainable agriculture enhances sustainable agricultural practices (Mahjoub et al., 2020). Inadequate waste processing capabilities have negative impacts on the environment, which emphasizes the need for innovative and workable solutions. As a result, soil fertility and structure are improved and environmental effects are decreased. Consequently, it is widely accepted that organic fertilizers are preferable to inorganic ones (Jain et al., 2024). Due to poor soil health caused by over cultivation and degradation, Mozambique needs alternative organic resources that can boost soil fertility. Particularly in areas like KaMubukwana, local perspectives draw attention to the expanding waste management problems that require sustainable solutions like vermicomposting. Employing earthworms enhances soil health, reduce waste volume, and reduce greenhouse gas emissions by breaking up, mixing, and increasing microbial activity in the organic waste matter (Thakur et al., 2021). Because they supply vital nutrients and alter the physical characteristics of soil by promoting long-term soil health, organic fertilizers are crucial for sustainable agriculture. Establishing effective waste management strategies is essential for reducing these effects and enhancing sustainable agriculture practices. Climate-resilient technologies that effectively manage agricultural waste, reduce greenhouse gas emissions, and enhance soil health are crucial. Therefore, vermicomposting stands out as an essential component suitable for sustainable waste management technologies that assist significant efforts to address these issues by converting waste into beneficial organic fertilizers and mitigating the climatic impact of agricultural operations.

The goal of current agricultural waste management techniques including composting, anaerobic digestion, and biofuel is to accelerate the reduction of solid waste (Alshehrei & Ameen, 2021). Even if these initiatives are in existence, their efficacy and climate resilience are generally constrained. Therefore, addressing the issues of waste management and climate change calls for a comprehensive and efficient solution. The efficacy of vermicomposting as a climate-resilient waste management system has not been extensively researched in Mozambique, despite considerable efforts. Given the growing amount of organic waste in places like KaMubukwana and the pressing need for climate-adaptive solutions, it's critical to look at the practical applications of vermicomposting. This study quantitatively investigated the efficacy of vermicomposting in managing agricultural waste and enhancing climate resilience in order to close this gap.

This study investigated vermicomposting as a climate-resilient method of managing agricultural waste in order to increase soil fertility and crop productivity. The conversion of organic waste into nutrient-rich organic fertilizer and its potential to improve soil health and agricultural resilience are given special consideration. Crop performance under varying soil fertility levels, resistance to climate-induced stress, waste decomposition dynamics, and nutrient enrichment in vermicompost (such as nitrogen, phosphorous, potassium, and organic carbon) are important factors to take into account. In order to comprehend soil functionality and long-term fertility restoration, the study also identified important indicators of soil health, including physicochemical characteristics like cation exchange capacity, water-holding capacity, and organic matter composition. However, the long-term sustainability and monitoring of vermicomposting procedures in agricultural settings may be impacted by variables such as climatic fluctuation, the availability of suitable decomposer species, research duration, and economic viability.

1.2 Problem statement and Justification

Mozambique's agriculture sector, as well as that of Sub-Saharan Africa faces challenges such as deteriorating soil health, rising climate variability, and mounting strain on food security. Due to unsustainable land management techniques, low organic matter content, and insufficient nutrient retention capacity, soil deterioration has grown to be a significant concern. Many Mozambican soils have poor cation exchange capacities (CEC), frequently less than 7.5 cmol(c) kg^{-1}, according to studies, which limits their capacity to hold onto vital nutrients and maintain agricultural output (Maria & Yost, 2006). These conditions reduce soil fertility and endanger the long-term sustainability of agricultural production systems.

To counteract declining soil fertility, chemical fertilizers are often advised to boost agricultural productivity. However, because they are expensive and difficult for smaller farmers to obtain, their use is still somewhat restricted in Mozambique. Current fertilizer usage rates are below less than 10 kg ha^{-1}, compared to the global average of approximately 133.2 kg ha^{-1} (Banerjee et al., 2023). This low adoption not only reduces agricultural productivity but also increases farming systems' vulnerability to climate-related stresses such as drought, erratic rainfall, and declining soil quality.

However, the continued use of synthetic fertilizers raises ecological problems. Long-term use of chemical fertilizers has been connected to nutrient leaching, salinization, soil acidification, and increased greenhouse gas emissions, all of which contribute to the gradual degradation of soil ecosystems (Singh & Kumar, 2017). The long-term sustainability of agricultural systems is threatened by these environmental impacts, which exacerbate soil health deterioration.

Mozambique produces a lot of agricultural waste, such as vegetable waste, maize husks, poultry manure, and animal manure, in addition to soil fertility problems. According to Pereira and Esteves da Silva (2024), these organic wastes are often poorly managed through landfilling, open burning, or unregulated disposal, which contaminates the soil, water, and air and misses the opportunity to recycle nutrients. As a result, inadequate waste management techniques contribute to both the underutilization of important organic resources that could aid in restoring soil fertility and the deterioration of the ecosystem.

The combination of declining soil fertility, limited fertilizer access, and poor agricultural waste management highlights a significant sustainability concern in Mozambique's agriculture sector. Since existing agricultural practices do not adequately integrate the recycling of organic waste into soil fertility management, there is a large gap in the development of climate-smart and sustainable agriculture practices (Silici et al., 2015). Particularly vulnerable to this mismatch are smallholder farmers, who make up the majority of the country's agricultural output yet often lack affordable and eco-friendly inputs.

Among the organic waste management methods that have been researched globally as potential alternatives for converting agricultural waste into advantageous soil nutrients are anaerobic digestion, traditional composting, and vermicomposting. Vermicomposting, which turns organic waste into nutrient-rich organic fertilizer using earthworms like *Eisenia fetida*, has garnered a lot of attention as an inexpensive and environmentally friendly technique. Vermicomposting has been shown to improve soil structure, stimulate microbial activity, promote plant development, and increase nutrient availability in a range of agricultural systems.

There is currently relatively little empirical research on the use of vermicomposting in Mozambican ecosystems, despite the fact that it has been demonstrated to be advantageous in many regions of the world. In particular, vermicomposting's capacity to transform easily accessible agricultural residues, such as vegetable waste, maize husks, and poultry manure into superior organic fertilizers that can improve soil fertility and support sustainable crop production is not well documented locally.

This knowledge gap is a challenge as well as an opportunity for Mozambique's agricultural development. In the absence of locally produced scientific data, farmers, cooperatives, and legislators lack the knowledge necessary to fully accept and promote vermicomposting as a viable waste-to-resource alternative. Such data must be produced in order to demonstrate how vermicomposting may simultaneously address waste management concerns, restore soil fertility, and support climate-resilient agricultural systems.

Therefore, this study investigated the effectiveness of vermicomposting in the KaMubukwana District in Maputo Province. The study used *Eisenia fetida* to evaluate how well different combinations of organic waste decompose. The resulting vermicompost's nutrient makeup was then analyzed to determine whether it may be used as an organic fertilizer to increase soil fertility. By providing empirical evidence on the transformation of locally accessible agricultural wastes into advantageous soil supplements, the study contributed valuable knowledge that can promote sustainable waste management, enhance soil productivity, and strengthen climate-resilient farming practices in Mozambique.

1.3 Objectives

1.3.1 General objectives

To assess the effectiveness of vermicomposting as a technology for converting agricultural waste into high-quality organic fertilizer under adverse climatic conditions

1.3.2 Specific objectives

1. To evaluate the efficiency of vermicomposting using *Eisenia fetida* in converting different types of agricultural waste into organic fertilizer.
2. To assess the effects of vermicomposting on the nutrient composition and quality of organic fertilizer derived from agricultural waste.
3. To determine the impact of vermicompost application on soil fertility indicators and crop performance under experimental conditions.

1.4 Hypothesis

2 The use of *Eisenia fetida* in vermicomposting significantly influences the decomposition rate of agricultural waste compared to systems without earthworms.

3 Different organic waste mixtures (vegetable waste, poultry manure, cow dung, and molasses) significantly affect the nutrient composition and quality of the resulting vermicompost.

4 Application of vermicompost significantly improved soil fertility indicators such as organic matter content, nutrient availability, and cation exchange capacity compared to conventional soil conditions.

1.5 Research questions

1. How do different vermicomposting strategies influence nutrient cycling, and what is their effectiveness in transforming agricultural waste into high-quality organic fertilizer?
2. How does vermicomposting affect soil health, particularly nutrient content, pH, cation exchange capacity, and soil moisture retention, in contrast to traditional composting techniques?
3. How does the use of organic fertilizers produced through vermicomposting contribute to improved crop yield, soil fertility, and resilience to climate-induced stress in smallholder agricultural systems?

2.0 LITERATURE REVIEW

2.1 Vermicompost and Soil Health

Soil health theory states that soil is a dynamic biological system whose productivity is determined by interactions between chemical, biological, and physical processes (Swami, 2020). Although this idea is widely accepted, there is still a lack of operationalization in degraded tropical soils where chemical dependence is predominant. In Sub-Saharan Africa, especially Mozambique, soil management practices still prioritize short-term nutrient correction over ecosystem restoration. This leads to the incompatibility between theory and practice. Soil health is therefore still more theoretical than practical in many farming methods.

When compared to artificial fertilizers, Olasekan et al. (2020) show that vermicompost increases soil organic carbon, microbial biomass, and aggregate stability. Their conclusions, however, are mostly based on controlled research, which limits their external validity in the face of field variability. This raises questions regarding the sustainability of observed soil improvements in tropical soils with low nitrogen levels and variable rainfall. Therefore, agronomic reliability is not always correlated with experimental strength. As a result, the literature overestimates outcome stability.

Vermicompost increases microbial populations, including phosphorus-solubilizing and nitrogen-fixing bacteria, according to Arancon et al. (2008). Although this validates claims of biological improvement, subsequent research reveals that microbial communities are extremely susceptible to environmental stress and feedstock composition. Vermicompost may not be biologically homogeneous based on this discrepancy. Rather than being innate, its microbiological function is conditional. As a result, extrapolations from one study to another lack scientific validity.

Vermicompost enhances soil aggregation and water retention capacity, according to Lazcano et al. (2013). They do not, however, sufficiently distinguish between long-term soil stability and short-term structural benefits. Aggregation effects may decrease after several cropping cycles, according to other research. This suggests that physical improvements to the soil can be temporary rather than long-lasting. As a result, assertions for long-term sustainability are still not fully supported.

The presumption that vermicompost is a standardized product is a major research restriction. In actuality, the type of waste and the conditions of decomposition greatly affect the nutrient makeup. However, the majority of research declare broad benefits while ignoring this diversity. The results' replications and comparability are diminished by this methodological reduction. As a result, the scientific agreement is not as strong as it seems.

Additionally, few research evaluates vermicompost made from various agricultural wastes under the same circumstances. This makes it difficult to determine which feedstocks maximize soil development. Recommendations are still too general in the absence of such comparable data. As a result, farmers receive general advice rather than evidence-based recommendations. Practical use in actual farming systems is weakened by this.

In Sub-Saharan Africa, soil degradation is intimately linked to continued farming and the loss of organic matter (Maria & Yost, 2006). Vermicompost is recommended as a treatment, however its localized effectiveness is unknown. Most global findings are unconfirmed under African soil conditions. This leads to a geographical bias in the literature on soil health. As a result, contextual adaptability remains a major deficit.

Despite vermicompost's consistent correlation with improved soil health indices, the literature generally lacks long-term field validation, substrate-specific comparisons, and contextual African evidence. These flaws limit its applicability to science and policy. The current work focuses on this empirical shortcoming. Specifically, it evaluates vermicompost under locally accessible trash combinations. This allows for a more accurate understanding of the transition in soil health.

2.2 Comparison between Vermicompost and Traditional Fertilizers

The argument between chemical fertilizers and vermicompost is essentially based on different approaches to managing soil fertility: one is productivity-driven and input-intensive, while the other is ecological and regenerative. Vermicompost is positioned by Atiyeh et al. (2002) as a soil-building amendment that improves soil structure, increases nutrient retention, and decreases nutrient leaching. Soil sustainability theory, which prioritizes long-term ecosystem functioning over immediate crop outputs, is consistent with this viewpoint. But in varied tropical agro-ecosystems, this framework frequently makes the assumption that soil systems react consistently across contexts, an assumption that is becoming more and more questioned. Chemical fertilizers, on the other hand, are assessed mostly based on their ability to quickly provide plant-available nutrients, which reflects a production-maximization rationale that puts short-term agronomic efficiency ahead of ecological stability.

Vermicompost is well known for its capacity to release nutrients gradually through microbial mineralization processes, increasing the efficiency of nutrient consumption from the standpoint of the nutrient cycle (Lazcano et al., 2013). This slow-release technique helps maintain soil fertility by gradually lowering nitrogen losses. However, field-specific climatic factors like temperature, moisture content, and substrate type have a significant impact on these advantages. Chemical fertilizers, on the other hand, provide instant plant absorption by delivering soluble nutrients straight to plants without the need for microbial mediation. However, this increases the danger of leaching, volatilization, and nutrient imbalance. As a result, the efficiency of absorption and the stability of nitrogen cycling in soil systems are fundamentally traded off.

According to Lal (2020), chemical fertilizers are still essential for solving the problems of global food security, especially on nutrient-depleted soils where quick production increases are needed. Empirical evidence from high-input agricultural systems, where synthetic fertilizers dramatically boost output, supports this claim. Nevertheless, long-term application's cumulative ecological costs—such as decreased microbial diversity, acidified soil, and greenhouse gas emissions—are disregarded. On the other hand, research endorsing vermicompost frequently highlights ecological restoration while minimizing nutrient concentration constraints and quick yield response. A wider epistemic gap between agronomic production and ecological sustainability is reflected in the literature's dual bias.

The different evaluation methods employed to gauge fertilizer performance represent a significant methodological shortcoming in comparison research. Vermicompost studies often concentrate on soil quality indicators including organic carbon, microbial biomass, and aggregate stability, as opposed to chemical fertilizers, which are usually evaluated in terms of yield response and nutrient efficiency. The absence of clear markers hinders effective cross-comparison and results in inconsistent conclusions. Temporal bias is also brought into the literature since many research use short-term experimental cycles that favor chemical fertilizers because of their quick reaction qualities. As a result, vermicompost's long-term effects on soil regeneration are frequently overlooked.

The inadequate treatment of environmental externalities in comparison assessments is another significant gap. When evaluating chemical fertilizers, their ecological effects—such as nitrous oxide emissions, groundwater contamination, and soil degradation processes—are frequently overlooked. On the other hand, vermicompost's production and scaling constraints are often overlooked in favor of its inherent environmental advantages. Because of this asymmetry, the evidence base is unbalanced and prioritizes normative environmental assumptions over a thorough scientific assessment. As a result, when applied to actual agricultural systems, policy suggestions drawn from such literature might not be as strong.

The integrated nutrient management (INM) approach developed by Lazcano et al. (2013) attempts to resolve these opposing perspectives by combining organic and inorganic nutrition sources. This hybrid approach is conceptually appealing because it seeks to achieve a balance between short-term productivity and long-term soil health maintenance. However, its practical applicability is limited by socioeconomic realities, particularly for smallholder farmers in Sub-Saharan Africa, where access to chemical fertilizers is often restricted due to supply chain and cost issues. This begs the question of whether INM is a universally applicable solution or a context-specific recommendation that benefits resource-rich agricultural systems.

Empirical studies conducted in Sub-Saharan Africa further demonstrate that local agro-ecological elements, including as soil type, rainfall variability, and agricultural practices, significantly affect fertilizer performance. In these circumstances, the supposed benefit of chemical fertilizers in raising yields is often offset by poor soil structure and low organic matter content, which limit nutrient retention. Even while vermicompost releases nutrients more slowly, it may offer longer-term agronomic stability in damaged soils. However, because the research rarely evaluates both fertilizer types under the same stress conditions, it is difficult to draw context-sensitive conclusions regarding their relative efficacy.

A broader conceptual gap is reflected in the productivity-focused agronomy and the sustainability-focused soil science. The former encourages quick yield optimization to meet food security objectives, whereas the latter focuses more on long-term soil performance and ecosystem resilience. Chemical fertilizers dominate productivity-oriented rhetoric, while vermicompost is mostly linked to the sustainability paradigm. Because each system is evaluated using essentially distinct criteria, this separation has resulted in divergent interpretations of agricultural efficiency. This fragmentation hinders the development of integrated agricultural models that can simultaneously address yield and ecological problems.

In conclusion, there is some agreement in the literature about the productivity benefits of chemical fertilizers and the environmental benefits of vermicompost, but there is still significant disagreement regarding their long-term agronomic roles. The comparability of current findings is severely weakened by the lack of established evaluation frameworks, the scarcity of long-term field investigations, and the inadequate consideration of contextual variability. The application of integrated nutrient management models is further complicated by socioeconomic limitations in low-income agriculture systems. Therefore, a more context-specific and balanced paradigm is needed, one that unifies resource accessibility, sustainability, and productivity into a single analytical method. In order to produce evidence-based suggestions that are both practically applicable and scientifically sound for a variety of farming systems, especially in Sub-Saharan Africa, such a framework is crucial.

2.3 Vermicompost's Impact on Crop Productivity

Vermicompost has been demonstrated to improve crop germination, biomass accumulation, and overall yield performance, largely due to enhanced nutrient availability (Singh & Sinha, 2022). However, this prevalent conclusion is primarily the result of controlled experimental conditions that optimize moisture, temperature, and nutritional factors. Such controlled environments significantly lessen the complexity of farmer-managed fields, where there is a lot of variation in soil fertility, rainfall, and insect impact. These conclusions have limited external validity since they may not accurately reflect real agricultural systems. This raises concerns about the overgeneralization of vermicompost's benefits in applied agronomy.

According to Arancon et al. (2008), bioactive chemicals such as auxins, cytokinins, and humic molecules found in vermicompost stimulate plant growth. Despite the widespread acceptance of this biological explanation, further research shows that feedstock composition and breakdown circumstances have a significant impact on the concentration of these chemicals. This causes a great deal of variation in the plant responses that are seen in various investigations. Furthermore, many studies rely on indirect agronomic results rather than direct hormone content quantification. Therefore, rather than being empirically verified, the mechanical basis of plant growth promotion is still only partially understood.

Applying vermicompost considerably boosts agricultural yields in crops like tomatoes and maize, according to studies by Azarmi et al. (2009) and Gutiérrez-Miceli et al. (2017). However, most of these studies are conducted in controlled or semi-controlled settings using optimal management strategies. In these conditions, environmental pressures that typically impact crop production in real farming systems are lessened. Elements such as pest infestation, nutrition depletion, and irregular rainfall are often overlooked in experimental design. Performance estimates are exaggerated as a result of this methodological error and may not be applicable to smallholder agricultural scenarios.

The agronomic efficacy of vermicompost is more influenced by its quality than by its application rate, according to Luo et al. (2024). This represents a substantial shift in focus from quantity-based to composition-based evaluation of organic fertilizers. However, there is a dearth of comprehensive study in the literature regarding the effects of different mixes of agricultural waste on compost quality. As a result, the relationship between feedstock diversity and nutrient efficiency remains unknown. This gap hinders the development of optimal vermicompost formulations for specific crop requirements.

The absence of comparative studies across several crop species under consistent settings is a major research restriction. The majority of research focuses on certain crops, such as tomatoes or maize, which limits the findings' applicability to a variety of agricultural systems. It is challenging to create general agronomic advice that are applicable to mixed farming systems because of this crop-specific focus. As a result, little research has been done on the variations in plant response between species. As a result, studies on vermicompost have less overall predictive potential for agricultural planning.

The experimental designs' failure to account for abiotic stressors including salt, drought, and nutritional deprivation is another significant issue. Despite being major agricultural restrictions in Sub-Saharan Africa, these pressures are rarely included in vermicompost trials. Therefore, ideal growth conditions rather than actual environmental challenges are reflected in the majority of studies. As a result, there is a mismatch between field-level agricultural limitations and experimental results. Thus, the potential for stress resilience of vermicompost is unknown.

Additionally, many studies assume that microbial activity plays a significant role in enhancing plant growth without really evaluating microbial dynamics or functional pathways. Research often focuses observable agronomic outputs such as yield and biomass over basic biological mechanisms. This outcome-oriented approach limits the scientific understanding of how vermicompost interacts with physiological processes in plants. Because of this, it is yet unclear how applying vermicompost affects plant growth. This reduces the mechanical clarity of the text.

Overall, methodological shortcomings, simplicity of the environment, and a lack of mechanistic research limit the validity of these conclusions, even if the evidence now available consistently demonstrates that vermicompost has a positive impact on crop productivity. The paucity of multi-crop, stress-based, and feedstock-comparative studies significantly reduces the robustness of conclusions. This study solves these limitations by evaluating vermicompost efficacy under controlled conditions and different agricultural waste combinations. By further linking substrate composition to plant response dynamics, it offers a more thorough and context-sensitive agronomic perspective.

2.4 Vermicomposting and Sustainable Agricultural Systems

In the context of circular economy frameworks, IPBES (2019) envisions vermicomposting, in which organic waste is transformed into beneficial agricultural input rather than being discarded as an environmental burden. This framing is based on the existence of efficient garbage collection and segregation systems, notwithstanding its theoretical soundness. In many poor countries, particularly those in Sub-Saharan Africa, such infrastructure is either insufficient or unofficial. This gap between theory and practice substantially restricts operational viability. As a result, claims about the circular economy often remain normative rather than practical.

By highlighting the connections between soil, crops, microbes, and waste fluxes throughout agricultural ecosystems, Warwick (2008) improves systems theory. Nevertheless, this all-encompassing viewpoint is not operationalized in the majority of empirical vermicomposting investigations. Rather, they focus on specific characteristics like breakdown rate or nutritional content. Our comprehension of agricultural sustainability processes is disrupted by this reductionist perspective. As a result, research on the general behavior of agro-ecosystems is still lacking.

One recurring issue in the literature is the poor empirical evidence for vermicomposting as a climate-resilient method. Although soil fertility is thought to be adaptive to environmental stress, most research focuses on boosting soil fertility rather than resilience indices. Metrics like drought tolerance, carbon sequestration, or system stability are rarely included. Consequently, there is a gap between theoretical sustainability claims and measurable environmental outcomes. Because of this, resilience is currently primarily theoretical in the vermicomposting literature.

According to Silici et al. (2015), socioeconomic factors that hinder the adoption of sustainable agricultural technologies include smallholder farmers' lack of knowledge, labor shortages, and financial limitations. However, many studies on vermicomposting ignore these adoption dynamics in favor of focusing just on technical efficiency. As a result, there is a disconnect between the development of technology and its actual use. Therefore, vermicomposting is frequently presented as being universally applicable despite contextual restrictions. As a result, its policy importance is reduced.

The division of agronomic and environmental assessment systems in previous studies is another significant shortcoming. Vermicomposting is frequently evaluated in terms of improving soil or reducing garbage, but studies seldom combine the two. Its sustainability potential cannot be completely understood due to this disjointed approach. Productivity, environmental impact, and resource efficiency are rarely combined in integrated evaluation methods. As a result, existing assessments are still fragmented and lacking.

The majority of agricultural waste management systems in Sub-Saharan Africa are decentralized, informal, and resource-constrained. Despite this, controlled input availability and structured waste streams are assumed in the majority of vermicomposting investigations. A significant contextual bias is introduced into the literature by this assumption. It lessens the findings' relevance to actual farming systems where trash is inconsistently and heterogeneously accessible. As a result, contextual realism represents a major research gap.

Furthermore, without methodically assessing adaptation capacity, the research mostly makes the assumption that vermicomposting naturally improves climate resistance. There aren't many studies that evaluate performance in harsh weather circumstances like heat stress, flooding, or drought. The empirical foundation for resilience claims is weakened by this omission. Vermicomposting is hence frequently categorized as climate-smart without thorough verification. This is a conceptual overreach based on scant actual data.

Despite vermicomposting's theoretical framing as a sustainable, circular, and climate-resilient agricultural approach, empirical validation of the practice is still uneven and context-insensitive. The lack of integrated socio-ecological analysis, the little consideration of adoption limits, and the insufficient measurement of resilience indicators significantly reduce the robustness of existing results. Our work overcomes these limitations by evaluating vermicomposting in an actual agricultural waste system under controlled and context-relevant conditions. It integrates agronomic, environmental, and system-level perspectives to generate more trustworthy and locally relevant data.

2.5 Literature Gap and Study Justification

The majority of vermicomposting research, according to Kumar et al. (2023), focuses on single-substrate systems such food waste or animal manure. This approach allows for controlled testing while significantly reducing the complexity of real agricultural systems. In actuality, farmers deal with multiple waste streams simultaneously, including crop residues, animal excrement, and vegetable waste. This methodological reduction creates a gap between field reality and experimental design. Because of this, many findings have low external validity and poor contextual validity.

Mixed organic waste inputs interact concurrently during decomposition processes in agricultural settings, as acknowledged by Olasekan et al. (2020). Additionally, they highlight the fact that most studies do not examine the antagonistic or synergistic effects of these connected substrates. This exclusion has led to incomplete understanding of nutrient transformation routes and decomposition rates. If interaction effects are not considered, conclusions about vermicomposting efficiency are not complete. Substrate interaction consequently emerges as an important yet understudied scientific issue.

Nutrient mineralization and compost quality are significantly impacted by substrate composition, according to Bhat et al. (2020) and Gutiérrez-Miceli et al. (2017). However, without employing systematic frameworks for comparisons, their study primarily examines isolated or limited combinations. Because of this, it is impossible to determine with certainty which waste mixtures promote nutrient transformation. As a result, the majority of current research is still descriptive rather than explanatory. Therefore, limitations in experimental design reduce the predictive ability of present studies.

Vermicompost quality is influenced by both input material composition and process parameters, according to Dejene et al. (2024). Despite this, controllable process factors like temperature, moisture, and aeration receive disproportionate attention in most empirical research. Chemical heterogeneity and substrate variation are frequently regarded as secondary variables. Vermicomposting research suffers from a methodological imbalance as a result. As a result, determining how feedstock content affects the final quality of compost remains difficult.

There is a substantial geographic and contextual gap in the literature, particularly with regard to Mozambique and Sub-Saharan Africa. Asia, Europe, and Latin America have significantly distinct agro-ecological circumstances, and these regions account for much of the current study. Climate fluctuation, soil kinds, and waste content trends are some examples of these fluctuations. From a scientific perspective, the findings' direct relevance to Mozambican agricultural systems is therefore questionable. This highlights the critical need for regional empirical confirmation.

The lack of studies on the mechanisms of nutrient transformation in mixed-waste vermicomposting systems is another significant gap. Few studies monitor intermediate biochemical steps during breakdown, despite the fact that many document final nutrient concentrations. We find it more difficult to comprehend how nutrients are lost, stabilized, or mineralized as a result. Efficiency claims are still primarily outcome-based and mechanistically incorrect in the absence of process-level evidence. Very little is known about the internal dynamics of vermicomposting systems.

The predominance of small-scale, laboratory-based experiments further restricts the policy's applicability. Such scenarios do not adequately represent real-world agricultural variability, such as changes in the climate, farmer management practices, and resource constraints. The scalability of the results is therefore still unknown. As a result, recommendations for national agricultural planning and extension services are less relevant. Field-based validation is essential for the development of evidence-based policy.

In conclusion, there is a clear and persistent knowledge gap regarding the effects of mixed agricultural waste systems on vermicomposting efficiency, nutrient dynamics, and compost quality under real-world agro-ecological conditions. The current work instantly closes this gap by examining numerous locally accessible trash combinations in Mozambique under closely controlled experimental circumstances. It integrates substrate interaction, nutrient transformation, and agronomic performance into a unified analytical framework. This approach strengthens both theoretical understanding and practical implementation. In the end, it helps develop more evidence-based, context-specific sustainable agriculture strategies.

2.6 Conceptual Framework

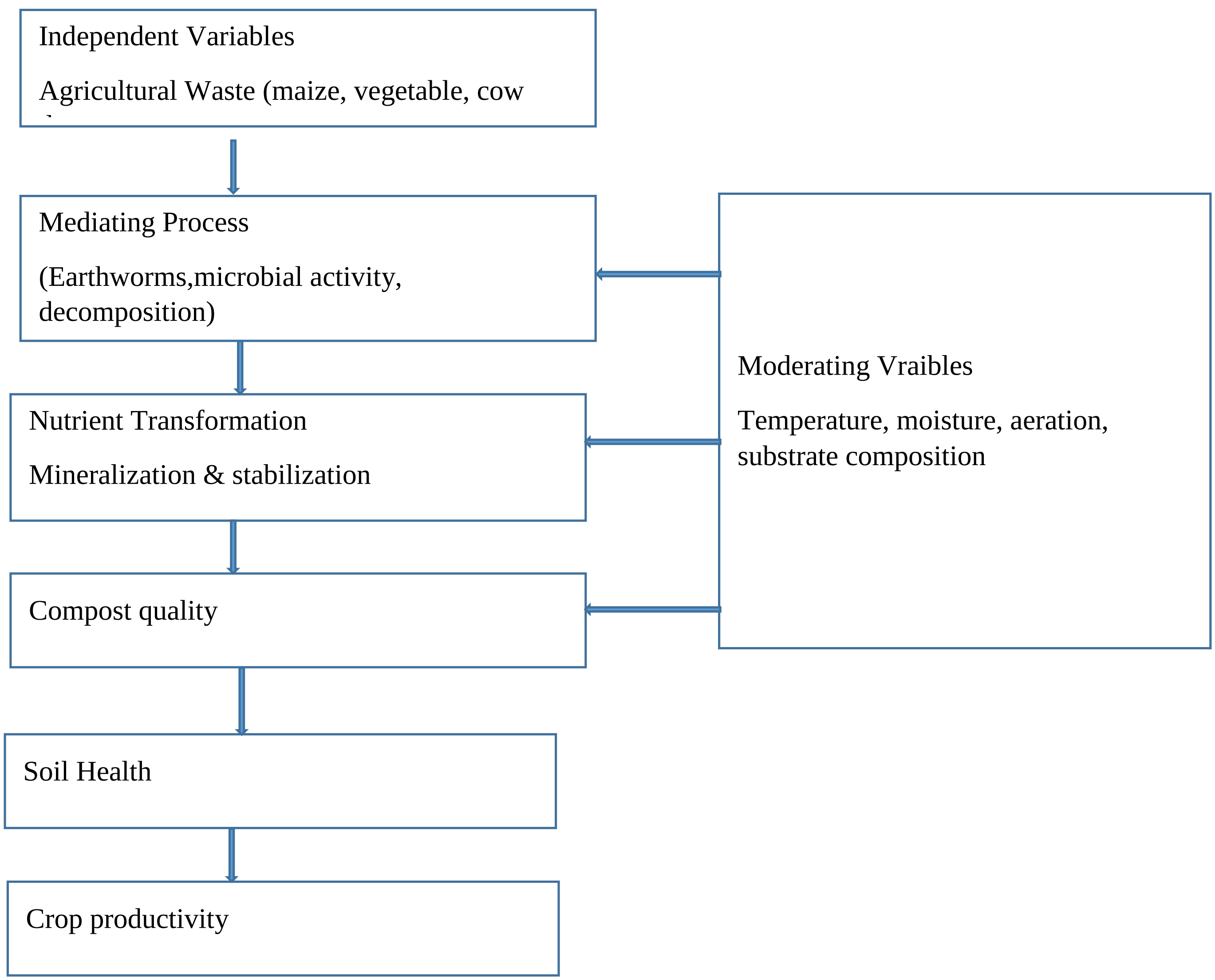
According to this study, vermicomposting is a dynamic, context-dependent process that uses biological and physicochemical interactions to convert agricultural waste into nutrients that plants can use (Bhat et al., 2020). Mixed substrates, vegetable waste, cow dung, and maize residues are just a few of the many types and combinations of agricultural waste inputs that form the basis of the framework. Decomposition pathways and nutritional potential are determined by the chemical composition and structural characteristics of these non-uniform inputs (Smith & Le, 2017). Therefore, it is thought that the main cause of the system's unpredictability is substrate variety. As a result, input-specific performance evaluation takes precedence over generalized composting results.

These inputs are altered by earthworm activity, especially *Eisenia fetida*, and microbial degradation (Mohite et al., 2024). Microorganisms promote nutrient mineralization and enzymatic breakdown, whereas earthworms promote fragmentation and aeration. Nevertheless, these processes are conditional and extremely sensitive to the properties of the substrate and the surrounding environment; they are not intrinsically stable. This challenges the notion that vermicomposting efficiency is consistent across systems. Therefore, rather than being fixed causes of results, biological mechanisms are viewed as interactive, variable-dependent processes.

The effectiveness of these processes is further influenced by moderating factors such as temperature, moisture, aeration, and substrate heterogeneity. These factors regulate microbial metabolism and earthworm activity, which impacts decomposition rates, nutrient release, and compost maturity. Changes in these criteria can have a significant impact on system performance, making them essential to understanding outcome variability. The interaction of inputs, processes, and moderating factors results in measurable dependent variables like crop yield, nutrient composition (N, P, and K), compost quality, and soil health indicators. These findings provide the empirical basis for evaluating vermicomposting's effectiveness.

The conceptual model of this study is illustrated in Figure 1, which presents vermicomposting as an integrated system where agricultural waste inputs are transformed through biological processes under environmental regulation to produce agronomic outputs. The figure shows a clear causal pathway from inputs to outputs, highlighting the role of moderating variables in regulating all stages of the system. It also demonstrates the closed-loop nutrient cycling system consistent with circular economy principles (IPBES, 2019; Warwick, 2008). Importantly, these relationships are non-linear and context-sensitive, meaning that similar inputs may produce different outcomes in different situations. By integrating inputs, mechanisms, agronomic outputs, and environmental controls, the framework provides a coherent and testable model that enhances both scientific understanding and practical application in Sub-Saharan African agricultural systems.

Figure 1: Conceptual Framework of Vermicomposting



3.0 MATERIALS AND METHODS

3.1 Experimental site

The study was conducted in the Maputo Province of Mozambique's KaMubukwana District, which is located at latitude -25.88° S and longitude 32.57° E. Part of the Maputo metropolitan area, it is a peri-urban area that links densely populated urban areas with rural agricultural territory. The National Institute of Statistics projects that the district had over 350,000 inhabitants by 2023, with a significant portion of them earning their living from subsistence and informal agriculture.

The area experiences different rainy and dry seasons due to its subtropical climate. The region normally has year-round temperatures between 20 and 32 degrees Celsius, with an average annual rainfall of 750–850 mm (INAM, 2022). The region regularly suffers extended dry spells and sporadic seasonal flooding, which can negatively impact soil fertility and water availability, even while these climate circumstances encourage the growth of short-cycle horticultural crops (Maulu et al., 2024).

Rapid population expansion and poor infrastructure design have made garbage disposal in KaMubukwana District more difficult. According to dos Muchangos et al. (2019), household-level agricultural operations, small-scale animal production, vegetable wastes, cow dung, and chicken manure from nearby markets account for the majority of the waste produced. Methane emissions, soil deterioration, and hazards to public health result from the routine disposal of these wastes in open areas or drainage systems (Alamgir et al., 2017).

The majority of the region's soils are sandy to sandy-loam, despite the fact that many sites have deteriorated due to erosion, nitrogen depletion, and low organic matter content brought on by unsustainable farming practices and inadequate use of organic fertilizer (Pereira & Esteves da Silva, 2024). The district's quick development has also increased competition for land usage, reducing the amount of arable land available and increasing the need for soil fertility management strategies that are efficient, reasonably priced, and climate resilient (De Albuquerque & Hobbs, 2016).

KaMubukwana District was selected for this study because it is an ideal place to look at decentralized organic waste valorization techniques. Given the region's availability of biodegradable waste, increasing soil degradation, community interest in sustainable agricultural methods, and proximity to metropolitan markets, vermicomposting can be evaluated as a sustainable means of managing organic waste and restoring soil fertility.

3.2 Vermicompost Production Using Different Strategies

3.2.1. Experimental design

In a completely randomized design (CRD), twelve identical halves of the 250L blue plastic vermicomposting bins were used (Nisar et al., 2025).

Fig 2. Experimental design and treatment layout

1.2.2 Treatment and replication

Four types of treatments were evaluated, each replicated three times as shown in the table.

Table 1. Treatments, replications and description of substrates used in the study

Treatment code	Waste composition	Ratio (kg:kg)	Rational
T1	Poultry waste + fresh vegetable waste+ earthworms+molasses	1:1	Poultry manure provides high nitrogen while fresh vegetable waste improves C:N balance & moisture content for efficient vermicomposting
T2	Fresh Vegetable waste+cow dung+poultry waste+ earthworms+ molasses	1:1:1	Mixed substrates balances nutrients, pH, and microbial diversity
T3	Cow dung + Fresh vegetable waste+ earthworms+ molasses	1:1	Cow dung stabilizes temperature and enhances microbial activity
T4	Control: traditional compost	-	Serves as a baseline for comparing improvements due to vermicomposting.

1.2.3 Waste collection and pre-treatment

Fresh vegetables were collected in the Zimpeto market, and cow dung and poultry manure were acquired from local farmers. Cow and poultry dung were mixed with fresh vegetable waste that had been cut into small bits. The mixture was then pre-composted for ten days in bins. Pre-composting these fresh vegetable wastes increased microbial homogeneity, controlled ammonia toxicity, reduced heat stress, faster decomposition, and fewer infections (Amaral et al., 2025). The compost was checked daily using a Hannia compost thermometer. Vermicomposting occurred when the temperature fell below 30 °C.

Fig 3. Agricultural waste prepared for vermicomposting

3.2.4 Bin setup and Earthworm Inoculation

To enhance aeration, one kilogram of shredded cartons was added to each bin. A digital scale that had been calibrated was used to weigh the 55 kg of pre-composted waste that were placed in each bin. Following that, 4 kg of *Eisenia fetida* earthworms were added to each bin, for a total of 60 kg per bin (Sinha et al., 2010). To promote microbial growth and earthworm adaption, molasses solution was regularly given to all bins housing earthworms once a week at a ratio of 1:10 of water (one liter of molasses to ten liters of water) (Khattiyaphutthimet & Boonthai Iwai, 2019).

3.2.5 Environmental monitoring

Table 2. environmental conditions monitored during the vermicomposting process

Parameter	**Tool**	**Frequency**	**Target range**
Moisture content	Thermohygrometer	Every 2 days	50-70%
Temperature	Compost thermometer	Daily	<30°C
Ambient conditions	Shade and ventilation setup	continuous	Avoid extremes

3.2.6 Moisture control

A knapsack sprayer was used to apply clean water each time the moisture record dropped below 50%. The excess water was drained through a perforated bin base and collected as vermiliquid. Each bin was covered with dried grass to preserve humidity and encourage aeration.

Fig 4. Vermiwash collection during moisture control in vermicomposting bins

3.2.7 Turning and aeration

To maintain consistent decomposition and aerobic conditions, the compost was physically turned once a week. Farmers were the main participants in this effort to promote community capacity building and knowledge transfer.

3.2.8 Vermicompost Harvesting

After 60 days, mature vermicompost was collected. Earthworms were manually separated and then reassembled into a single reproductive unit. The weight of the harvested vermicompost in each bin was recorded.

3.2.9 Data analysis

R software was used for statistical data analysis in order to ascertain whether different organic waste treatments had a significant effect on the decomposition rate (%) of vermicomposted materials after 60 days. The analysis involved the following steps:

3.2.9.1 Determining the response variable

The following formula was used to calculate the response variable, decomposition rate (%), for each treatment unit:

$$\textbf{Decomposition Rate}\ (\%) = \left(\frac{\textbf{Initial Weight} - \textbf{Final Weigt}}{\textbf{Initial Weight}}\right)\ \textbf{x100}$$

Each bin was initially filled with 60 kg of the total weight. On the 60^{th} day of harvest, the final compost weight was measured in order to determine decomposition efficiency.

3.2.9.2 One-way ANOVA: Analyzing treatment effects

A one-way analysis of variance (ANOVA) was used to assess if the mean decomposition rates of the four treatments (T1-T4) differed significantly. In the ANOVA model, "treatment type" was the independent variable and decomposition rate was the dependent variable using the model:

$Y_{ij} = \mu + \tau_i + \epsilon_{ij}$

Where

The decomposition rate of replicate j in treatment I is denoted by Y_{ij}, the overall mean decomposition rate is denoted by μ, the treatment effect is denoted by τ_i, and the random error related to replication j in treatment I is denoted by ϵ_{ij}.

The following hypothesis were investigated:

(i) The null hypothesis (H_0) states that the mean decomposition rate did not significantly differ between treatments.

(ii) Alternative Hypothesis (H_1): The mean decomposition rate varied significantly in at least one treatment.

3.2.9.3 Post Hoc Analysis: Tukey`s Honest Significant Difference (HSD)

A Tukey's HSD post hoc test was used to identify whether treatment pairs varied significantly after the ANOVA findings were statistically significant ($p<0.05$). After adjusting for multiple comparisons, this test yielded:

(i) Differences in treatment means between pairs

(ii) Confidence intervals

(iii)Modified p-values

3.2.9.4 Treatment Effect Visualization

The decomposition rate statistics were graphically displayed using the following to aid in the interpretation:

(i) Box plots to examine how different treatments' decomposition rates are distributed.

(ii) Scatter points that are jittered to display separate replicate values.

(iii) Error bars (± SE) to show mean values with standard error margins.

R software's ggplot2 program was used for all of these visualizations.

3.2.9 5 Reporting and interpretation

Composting efficiency, treatment rankings, and statistical significance (p-values) were used to analyze the data. Implications for managing organic waste sustainably were examined, and the treatments with the best decomposition performance were highlighted.

3.2.9.6 Establishing Variable Management

All of the bins were housed in the same ventilated, shaded building to minimize external variability. Every bin had the same temperature, moisture content, and aeration techniques. To guarantee uniformity in size and biological activity, all earthworms were obtained from a single controlled breeding unit, and the organic waste were collected from the same spot on the same day and pre-composted under the same circumstances.

3.3 Nutrient Composition of Vermicompost from Agricultural Waste

After the 60-day composting period, compost samples were collected from each treatment bin and equally mixed from the top, middle, and bottom layers to account for geographical heterogeneity. Every sample collected in the lab was allowed to air dry in the kiln for two days. To ensure consistency, they were passed through a 5 mm mesh filter before laboratory testing.

3.3.1 Parameters and Laboratory Analysis

The physic-chemical parameters were analyzed using standardized methods to assess the compost's nutritional composition and quality. These included the parameters shown in the table that follows.

Table 3. physic-chemical parameters analyzed for vermicompost quality assessment

Parameter	**Relevance**	**Reference**
Total Nitrogen(N)	Indicates nitrogen composition	(Abrams et al., 2014)
Available Phosphorus(p)	Reflects plant-availability phosphorus	(Mustapha et al., 2022)
Available potassium(K)	Indicates plant available potassium essential for growth	(Gurav et al., 2018)
Organic Carbon (OC)	Estimates total organic matter	(Gelman et al., 2012)
C:N Ratio	Indicator of compost maturity and stability	(Loh et al., 2012)
pH	Affects nutrient solubility and microbial activity	(Vehniwal et al., 2020)
Electrical conductivity (EC)	Assesses salinity and potential phytotoxicity	(Kargas et al., 2018)
Bulk density	Affects nutrient composition per unit volume	(Mupambwa & Mnkeni, 2016)
Moisture content	Indicates water retention and storage quality	(Ileleji et al., 2010)

3.3.2 Data recording and statistical analysis

To determine whether the various organic waste treatments (T1–T4) produce statistically significant differences in important compost properties, all data were collected using Microsoft Excel and examined using R software.

3.3.2.1 ANOVA (One-Way Analysis of Variance) for Comparing Treatments

Every measured parameter, including total nitrogen, available phosphorus, organic carbon, C:N ratio, pH, EC, bulk density, and moisture content, was subjected to an ANOVA. Each compost quality or nutritional parameter (N, P, K, OC, pH, etc.) was the dependent variable, whereas treatment groups T1, T2, T3, and T4 were the independent variables.

The following hypotheses were examined:

(i) The Null Hypothesis (H_0) states that the mean value of the parameter did not differ significantly between the treatments.

(ii) The Alternative Hypothesis (H1) states that the mean parameter value of at least one treatment varied significantly.

3.3.2.2 Tukey's HSD, or post hoc analysis

Tukey's Honestly Significant Difference (HSD) test was used to identify which treatment pair varied significantly when the ANOVA findings were statistically significant ($p<0.05$). This tests included:

(i) The average variation between treatment pairs

(ii) Confidence intervals

(iii)Modified p-value to account for type I errors

3.3.2 **Visualization of Data**

The following R-generated graphics were used to support the results:

(i) Box plots for each nutrient to display treatment effects and distribution.

(ii) Bar charts that provide mean values with error bars (± standard error or standard deviation).

(iii) Grouped charts for comparing macronutrients, such as clustered bar graphs

Treatment labels (T1-T4), replicate variations, and potential significance marking were all included in the graphs.

3.3.3 Interpreting the findings

Vermicomposting had a favorable impact on compost nutrient enrichment and maturity, as evidenced by all parameters that showed significantly higher values in T1-T3 compared to T4 (control). These findings influenced future scaling and commercialization and validated suggestions for the application rates.

3.4 Effects of Vermicompost on Soil Health, Crop Yield and Climate Resilience

3.4.1 Experimental design

A Randomized Complete Block Design (RCBD) was employed in field settings to reduce geographic variability and improve statistical efficiency (Akinwale et al., 2021). The design included five treatments, each of which was replicated thrice to prevent treatment interference, resulting in fifteen 1.5 m × 1 m plots with 0.5 m between blocks and 0.3 m between plots (Garwa & Veerwal, 2024).

Table 4: Treatment Structure for Field Experiments

Code	**Treatment Type**	**Description**
T1	Vermicompost: Poultry waste + Vegetable waste	Nutrient-rich, high microbial activity
T2	Vermicompost: Cow dung+ Poultry waste + Vegetable waste	Synergistic nutrient and microbial diversity
T3	Vermicompost: Cow dung + Vegetable waste	Balanced decomposition and C:N ratio
T4 (Control 1)	Traditional compost	Baseline organic input control
T5 (Control 2)	NPK (12-24-12) inorganic fertilizer	Standard agronomic benchmark for chemical input comparisons

3.4.2 Soil and plot preparation

A sample of 0.5 kg of surface soil was taken at a depth of 0–20 cm for laboratory analysis. Pre-planting analysis was performed using standard soil analysis techniques to ascertain the pH, organic carbon, nitrogen, phosphorus, and potassium content of the soil (Adekiya et al., 2020). Eight days prior to sowing, the land was prepared by manually removing the field, leveling the plots uniformly, and adding organic treatments down to a depth of fifteen centimeters.

3.4.3 Application of treatments

The topsoil was manually mixed with organic fertilizers (T1–T4) at a rate of 20 t ha^{-1}, or 4 kilograms per plot (1.5 m^2). In order to improve microbial activity, nutrient uptake, and plant performance, vermiliquid made from the vermicomposting process was additionally sprayed on the leaves seven days after planting and then once a week after that. 200 kg ha^{-1} (0.5 kg per plot) of NPK (12:24:12) fertilizer was used for the inorganic fertilizer treatment (T5).

3.4.4 Crop management

The Eden variety of lettuce (*Lactuca sativa*) was selected because it is ideal for evaluating treatment effects due to its short growth cycle and sensitivity to soil and water conditions. Direct seedling was applied to each plot in rows that were 20 cm apart. After being sowed on October 1st, 2025, and growing for 45 days, the lettuce was harvested on November 15, 2025. Irrigation was carried out in accordance with the regular schedule until the beginning of the drought simulation to assess the ability of organic and inorganic fertilizers to enhance crop resilience under water stress. Weeding and thinning were done by hand in each plot to ensure uniform crop management.

Fig 5. Manual irrigation of lettuce

3.4.5 **Stress Simulation Associate Climate Change**

In order to evaluate lettuce tolerance under water constraint, all plots had a consistent seven-day irrigation withholding throughout the middle development stage (days 25–31) to mimic typical dry-season stress in KaMubukwana (Owusu et al., 2024). To monitor heat stress, the midday leaf surface temperature was measured daily between 12:00 and 14:00 using a calibrated infrared thermometer (Assiri et al., 2024). Plant withering and recovery were observed during the drought and after rewatering in order to assess physiological responses and stress recovery.

Fig 6. Wilting symptoms in lettuce (Lactuca sativa) during the drought simulation period

3.4.6. Data collection parameter

- **3.4.6.1 Soil Fertility (Pre-and Post-Harvest)**

Parameter	Reference
Soil pH	(Aziz Alaie & Gupta, 2019)
Organic Carbon	(Ahmad et al., 2024)
Total Nitrogen	(Abrams et al., 2014)
Available Phosphorus	(Mustapha et al., 2022)
Available potassium	(Gurav et al., 2018)
Cation exchange capacity	(Garau et al., 2022)

3.6.6.2 Crop Performance

- Germination (%)
- Leaf count per plant
- Plant height (cm)
- Fresh and dry biomass (g/plant)
- Marketable yield per plot (kg)
- Chlorophyll content (Using SPAD meter)

3.6.6.3 Resilience to Stress

- Leaf surface temperature(°C)
- Wilting score (1=none, 5=severe)
- Days to recovery post-drought
- Survival rate after stress (%)

3.4.7 Statistical analysis

All data were evaluated using R software to see whether different fertilizer treatments (T1-T5) significantly change crop performance, soil fertility, and stress resilience under drought simulation circumstances.

3.4.7.1 One-Way ANOVA for Treatment Effects

For each outcome variable, a one-way Analysis of Variance (ANOVA) was carried out separately to see whether there were statistically significant differences between the five treatment groups. The fertilizer treatment (T1–T5) was the independent variable, while the following were the dependent variables:

(i) Soil fertility indicators (pH, OC, N, P, and K for pre- and post-harvest).

(ii) Crop performance parameters, such as SPAD chlorophyll index, germination percentage, biomass yield, and plant height.

(iii) Stress resilience indicators (leaf temperature, recovery days, survival rate, and wilting score).

The form of each ANOVA model was $Yij=\mu+\tau i+\beta j+\epsilon ij$.

Where:

Yij is the variable's observed value in treatment I and block j.

μ is the general mean, and τi is the treatment's fixed effect (T1-T5).

βj is the block j's random effects (to account for spatial variance).

ϵij is the random error considered to have a constant variance and a normal distribution.

3.4.7.2 Post Hoc Test: Tukey`s Honest Significant Difference (HSD)

Tukey's HSD test was used for pairwise comparison of treatment means following the significance of the ANOVA results ($p<0.05$). After adjusting for multiple comparisons, this test found:
(i) Which treatment groups were substantially different from one another?

(iii) Adjusted p-values and confidence intervals.

3.4.7.3 Regression analysis

The relationships between crop performance indicators (such as marketable yield and plant height) and soil fertility parameters (N, P, K, and OC) were investigated using simple and multiple linear regression models. Additionally, predictive trends between soil quality improvement and plant resilience indicators (such as recovery days and the SPAD index) were evaluated.

An example of the model:

$$Yield = \beta 0 + \beta 1 \text{ (Total N)} + \beta 2 \text{ (Available P)} + \epsilon$$

The model's performance was evaluated using R-squared, F-statistics, and P-values of coefficients.

3.4.8 Data visualization

The following treatment effect data visualizations were produced using ggplot2 in R:

(i) Bar chart with error bars (±SE) for treatment comparisons of yield, biomass, SPAD reading, etc.

(ii) Box plot for soil nutrient variability and drought response traits.

(iii) Leaf temperature and wilting score time-series plot during stress simulation

(iv) Regression plots to show how soil fertility and yield or stress metrics are related.

RESULTS

4.1 Vermicompost Production Using Different Strategies

Significant differences in the rates of decomposition were observed across the different combinations of organic waste during the 60-day vermicomposting period. Vermicomposting treatments demonstrated higher rates of decomposition than the traditional composting control.

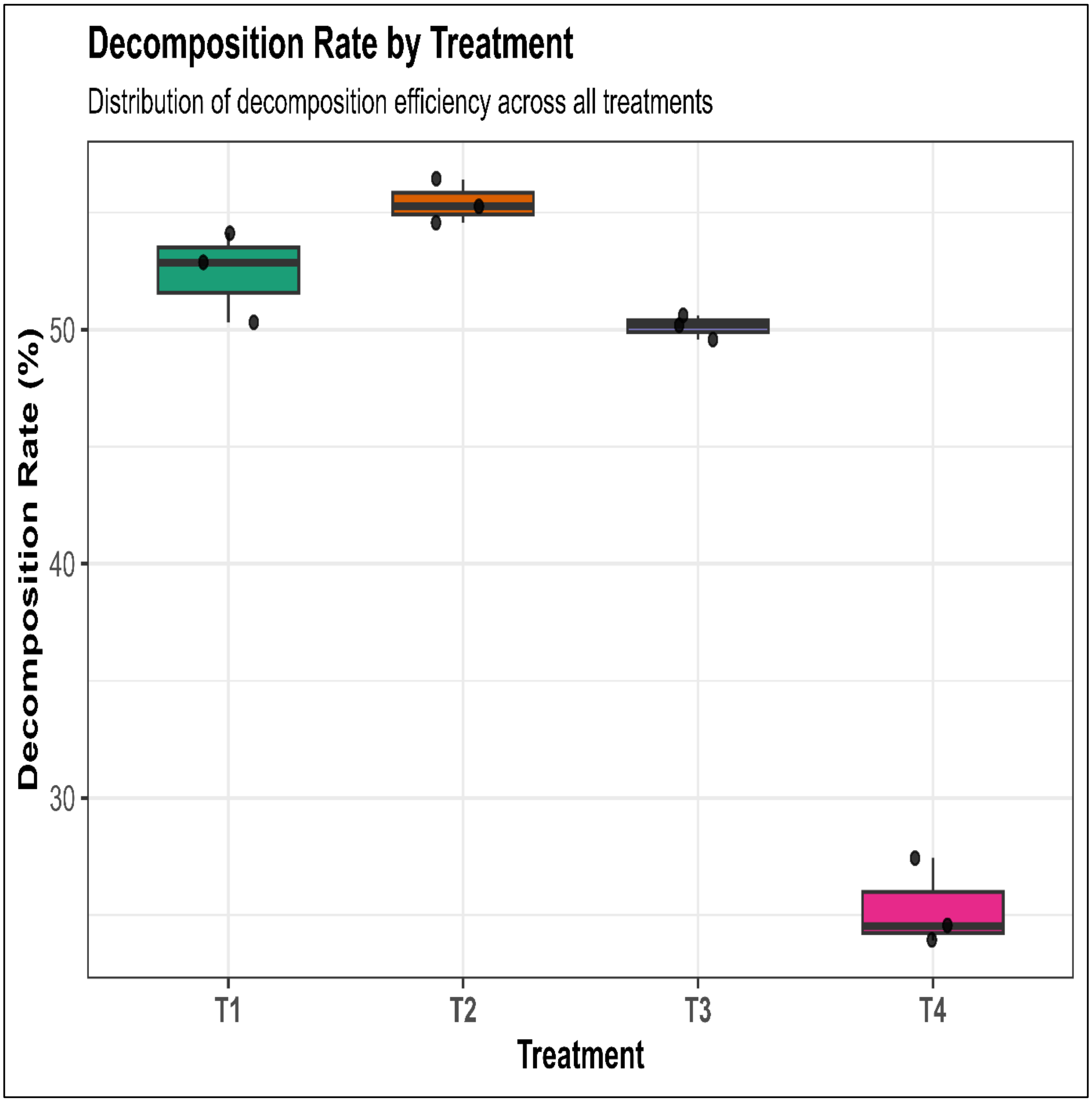
One-way analysis of variance (ANOVA) revealed that treatment type had a substantial impact on decomposition rate ($F (3, df) = 270.4$, $p < 0.001$). The decomposition rate was highest when vegetable waste, cow dung, and poultry manure were treated together (55.4 ± 0.54%), followed by cow dung and vegetable waste (50.1 ± 0.30%) and poultry manure and vegetable waste (52.4 ± 1.13%). At 25.3 ± 1.09%, the control treatment had the lowest decomposition rate.

Every vermicomposting treatment was statistically different from the control ($p < 0.001$), according to Tukey's HSD test post-hoc comparisons. The combination treatment of vegetable waste, cow dung, and chicken manure showed a significantly higher decomposition rate than the cow dung and vegetable waste treatment ($p = 0.009$). However, there was no significant difference between the poultry manure and vegetable waste treatment and the cow dung and vegetable waste treatment ($p = 0.288$). Similarly, the triple-substrate treatment and the poultry manure and vegetable waste treatment did not vary statistically significantly ($p = 0.134$). The treatment effect accounted for almost 99% of the variance in decomposition rate ($\eta^2 = 0.99$).

4.1.1 Distribution of Decomposition Rates by Treatment

The distribution of decomposition rates among treatments is displayed in Figure 7. The boxplot clearly shows the differences between the vermicomposting and control treatments. Compared to the control treatment, which had the lowest median decomposition rate, all vermicomposting treatments had substantially higher median values. Among the vermicomposting treatments, the mixture of vegetable waste, cow dung and poultry waste combinations exhibited the highest median decomposition rate and a relatively small interquartile range, indicating consistent decomposition performance across replicates.

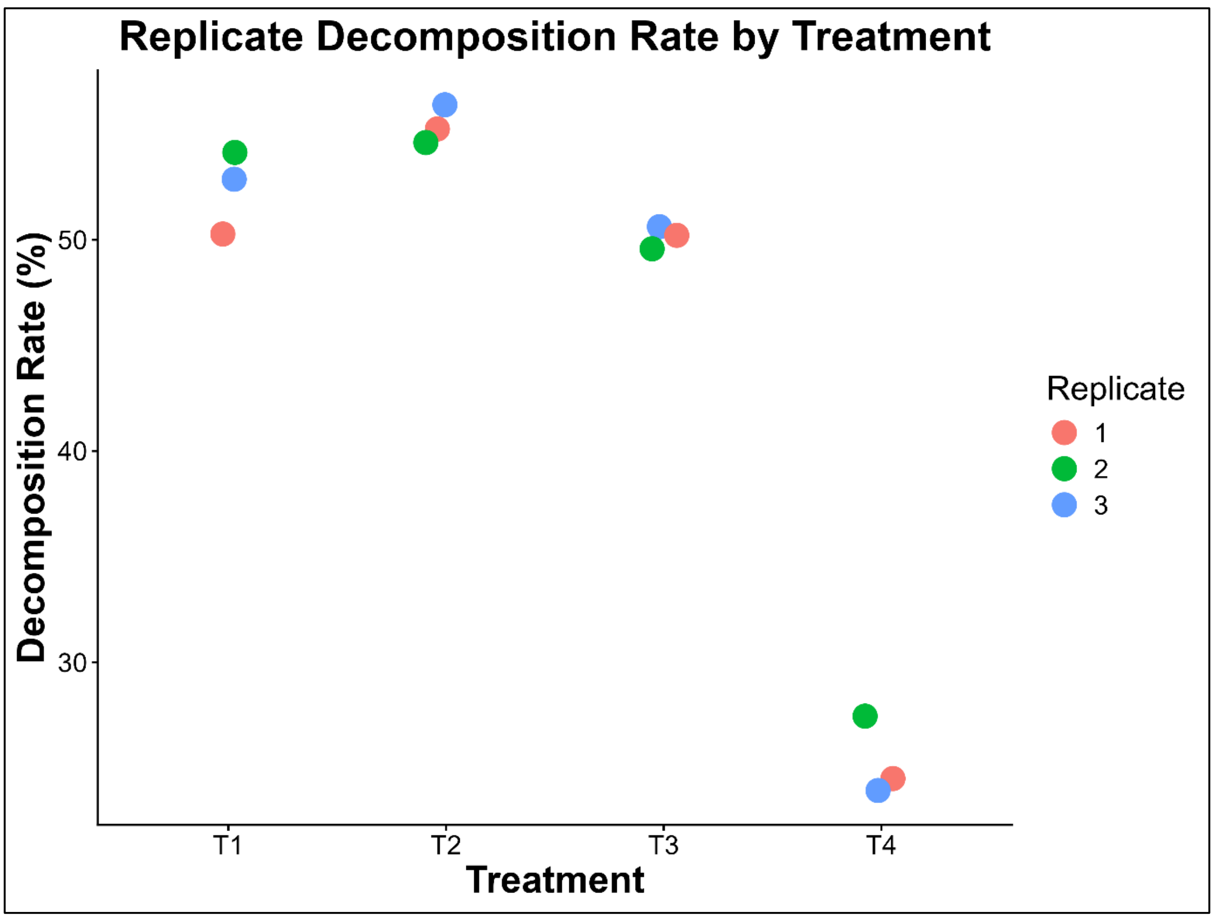
Fig 7. A boxplot showing the differences in decomposition rates between different treatment



4.1.2 Decomposition Rate Variability at the Replicate Level

Each treatment's unique replicate data is displayed in Figure 8 using a jittered scatter plot. The control and vermicomposting treatments are distinct from each other, and replicate values within treatments are clearly clustered in the plot. Replicates of the vermicomposting treatments consistently produced higher rates of decomposition as compared to the control treatment. The clustering pattern, which demonstrates relatively low variability among replicates within each treatment, confirms the consistency of the reported treatment effects.

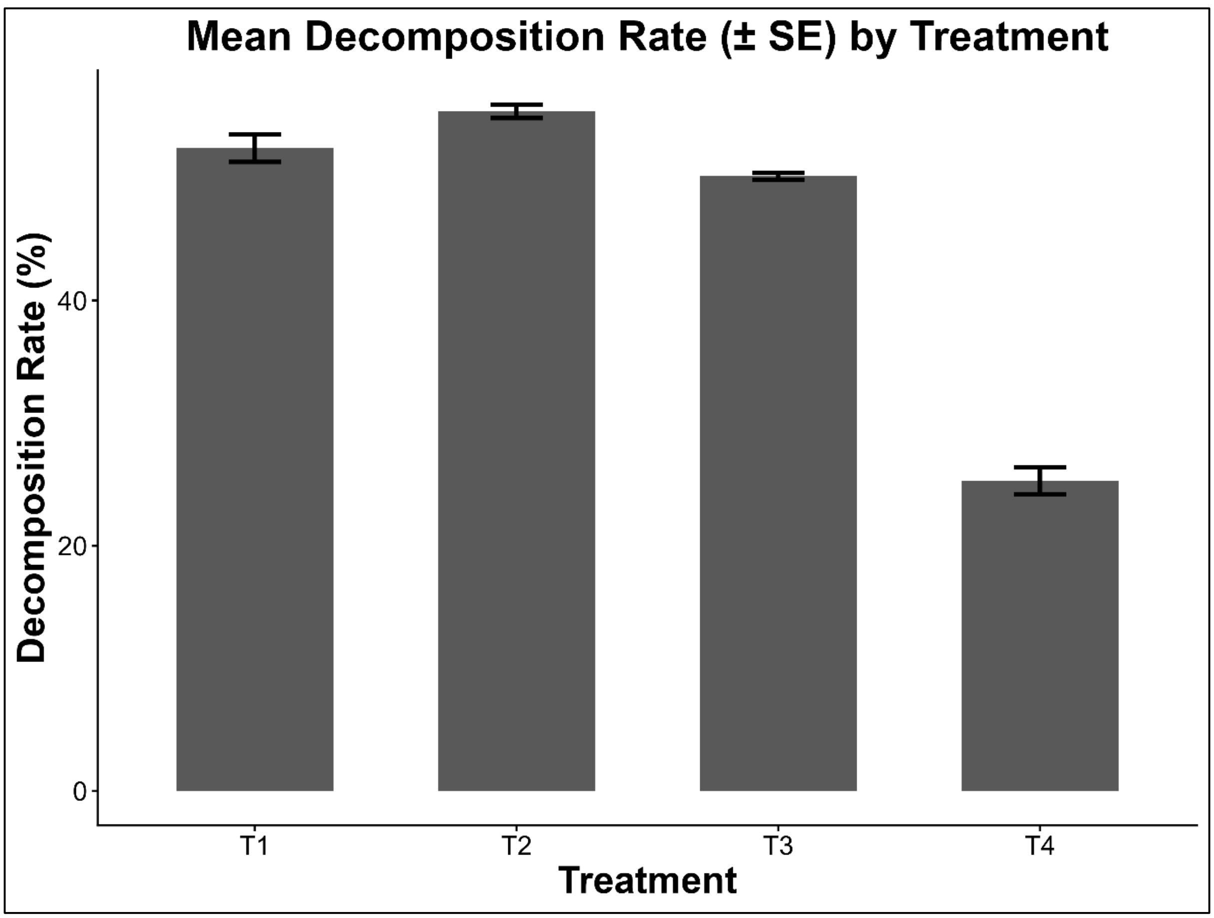
Fig 8. A jittered scatter plot showing the variation in treatment breakdown rates at the duplicate level



4.1.3 Average Decomposition Performance for Each Treatment

The average decomposition rates and associated standard errors are shown in Figure 9. The bar graph shows that all vermicomposting treatments performed better than the control treatment in terms of mean decomposition rates. The mixture of poultry manure and vegetable waste treatment, and that of treatment mixture of cow dung and vegetable waste, and the vegetable waste, cow dung and poultry waste mixture had the highest mean decomposition rates. In contrast, the conventional composting control exhibited the lowest mean rate of decomposition.

Fig 9. Shows the average decomposition rates (± standard error) for each treatment.



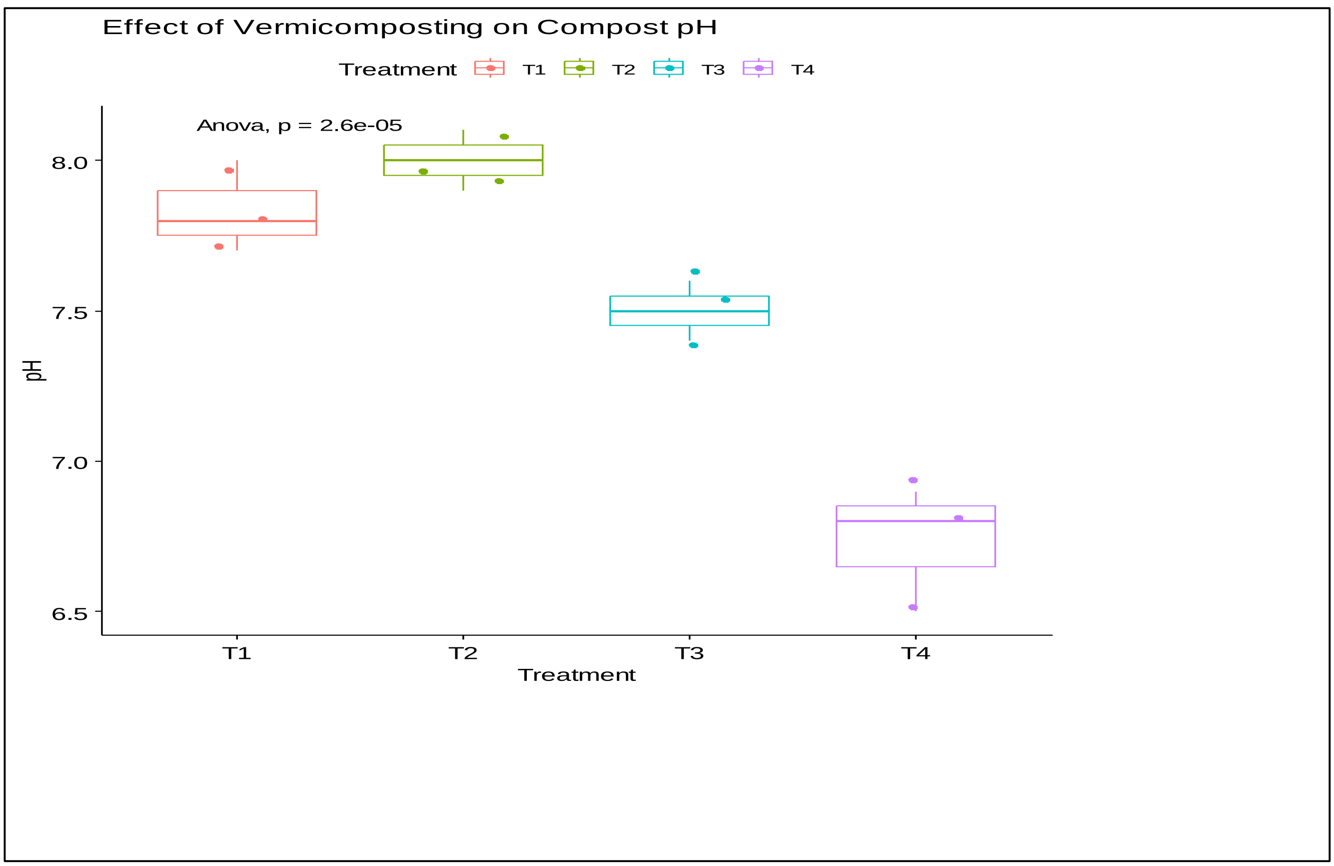
4.2 Nutrient Composition of Vermicompost from Agricultural Waste

4.2.1 pH

The pH of the matured compost differed significantly between treatments after 60 days. Vermicomposting treatments (T1–T3) produced neutral to slightly alkaline compost with mean pH values ranging from 7.50 to 8.00, whereas the control (T4) remained lower at 6.73. The pH of T2 was the highest (8.00), followed by T1 (7.83) and T3 (7.50). All vermicomposting treatments had pH values that were significantly higher than the control ($p < 0.005$).

Figure 10 displays the distribution of pH values across treatments, with the control showing greater variability and the vermicomposting treatments showing rather stable values.

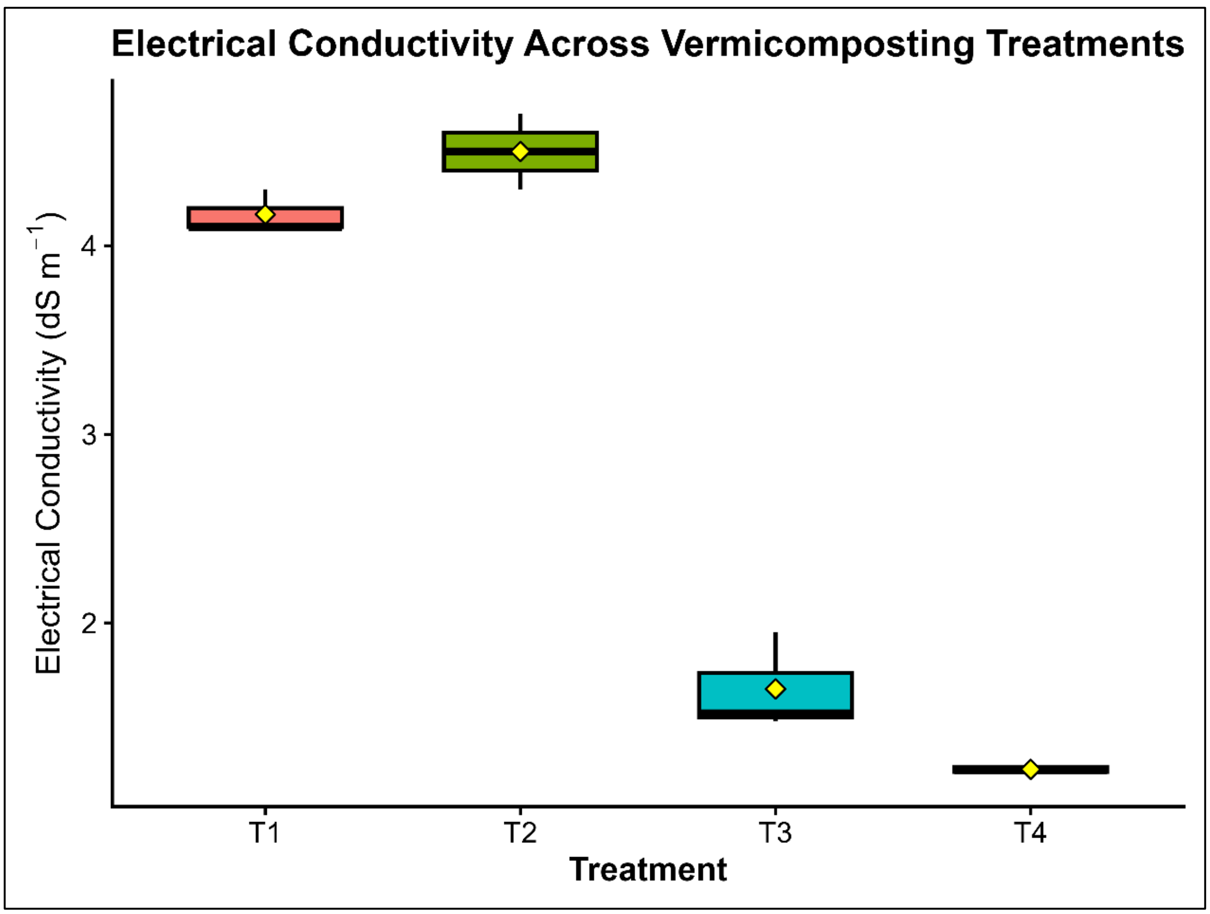
Fig 10: Distribution of vermicompost pH by treatment



4.2.2 Electrical conductivity (EC)

Treatments varied in electrical conductivity, with vermicomposting treatments showing greater values than the control. The control had the lowest EC (1.0 mS/cm), while T2 had the highest (4.5 mS/cm), followed by T1 (4.2 mS/cm) and T3 (2.0 mS/cm). Every value stayed within permissible agronomic bounds. With comparatively constant observations among treatments, Figure 11 illustrates the difference in EC across treatments.

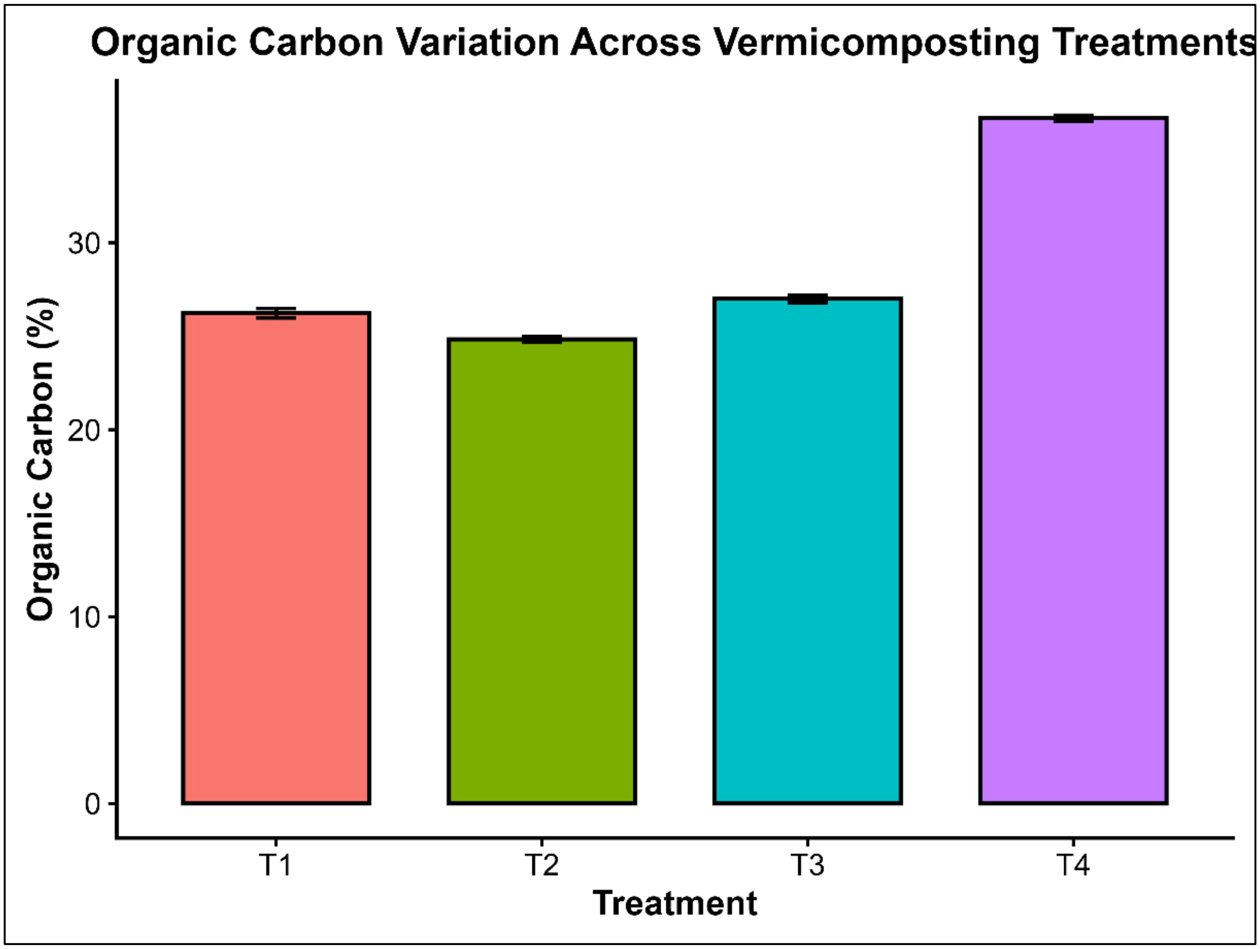
Figure 11 shows the variation in EC between treatments with relatively constant observations.



4.2.3 Organic Carbon

The amount of organic carbon (OC) in each treatment varied significantly, with vermicomposting treatments (T1–T3) showing lower values than the control (T4). T2 had the lowest OC (24.83%), followed by T1 (26.23%) and T3 (27.00%). The highest OC content (36.66%) was found in the control treatment. In comparison to the control, vermicomposting treatments consistently shown a decrease in OC. There was little variation within treatments, suggesting consistency between replicates. The distribution of OC across treatments is shown in Figure 12.

Figure 12: Vermicompost organic carbon variation by treatment (mean ± SE).



4.2.4 The carbon to nitrogen ratio (C: N)

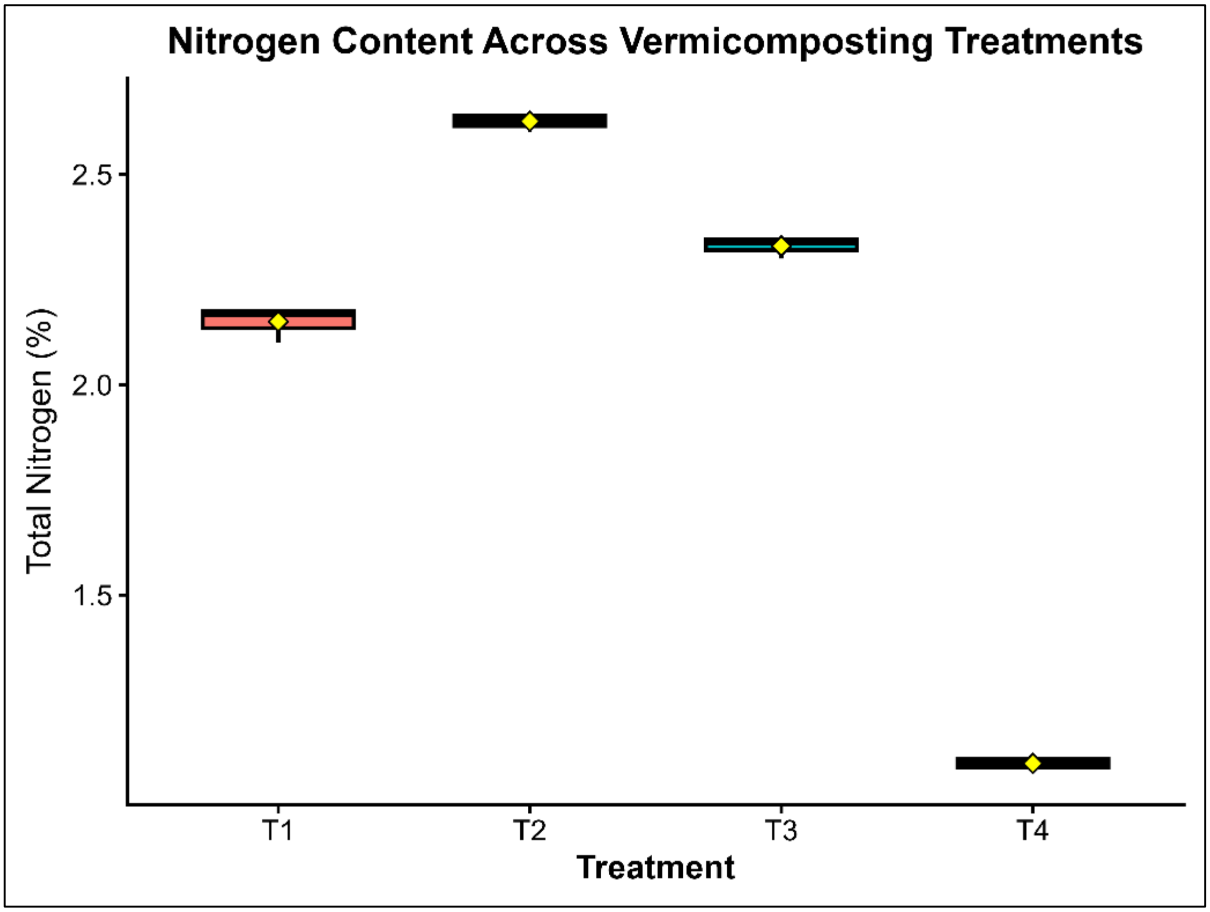
The carbon-to-nitrogen (C: N) ratio varied significantly between treatments; vermicomposting treatments (T1–T3) exhibited lower values than the control (T4). The lowest C: N ratio was found in T2 (12.23), followed by T1 (13.23) and T3 (14.00). The C: N ratio was highest in the control treatment (26.43). C: N ratios were consistently lower in all vermicomposting treatments than in the control. Each assessment clearly showed the variations between treatments. Because there was little variation within treatments, replicates seemed to be consistent. When compared to the control, the vermicomposting treatments showed values that were tightly grouped. Overall, the vermicomposting and control treatments were clearly different.

4.2.5 Macro-Nutrients

4.2.5.1 Total Nitrogen (N)

The total nitrogen (N) content of the treatments varied significantly, with vermicomposting treatments (T1–T3) showing higher values than the control (T4). T2 had the greatest nitrogen level (2.63 ± 0.11%), followed by T3 (2.34 ± 0.09%) and T1 (2.15 ± 0.08%). At 1.10 ± 0.05%, the nitrogen concentration was lowest in the control treatment. The nitrogen levels in each vermicomposting treatment were consistently higher than the control. All indicators showed significant differences between treatments. Because there was little variation within treatments, replicates seemed to be consistent. When compared to the control, the vermicomposting treatments showed findings that were closely clustered. The difference in total nitrogen between treatments is shown in Figure 13.

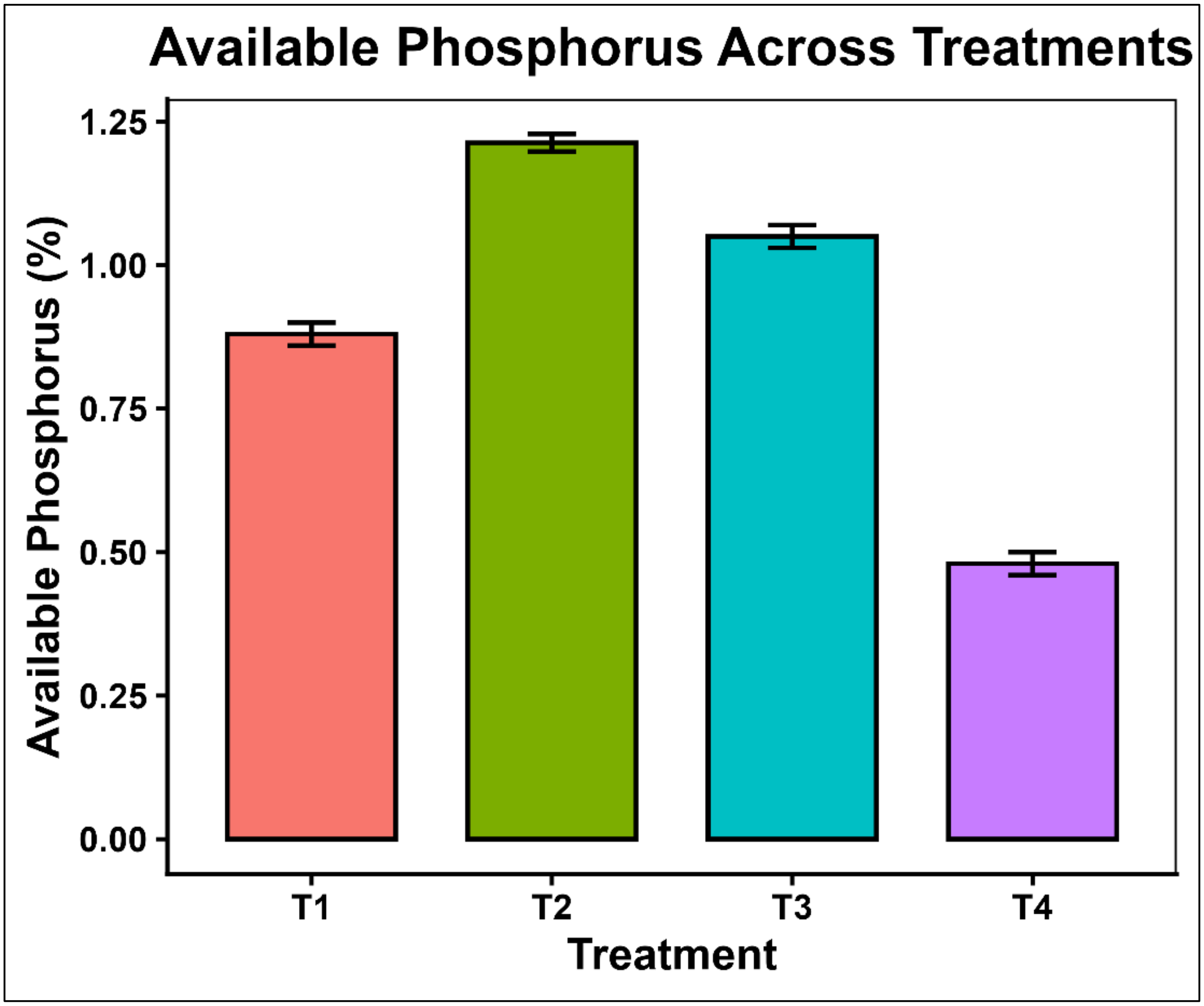
Fig. 13. Total Nitrogen (N) Content in Different Vermicomposting Techniques



4.2.5.2 Available Phosphorus (P)

The amount of available phosphorus (P) varied significantly between treatments; vermicomposting treatments showed higher values than the control. T2 had the highest phosphorus concentration (1.21 ± 0.06%), followed by T3 (1.05 ± 0.05%) and T1 (0.88 ± 0.04%). The lowest phosphorus concentration (0.48 ± 0.03%) was found in the control treatment. Phosphorus was available in the following order across treatments: T2 > T3 > T1 > T4. Phosphorus levels were consistently higher in all vermicomposting treatments than in the control. There was little variation within treatments, suggesting that replicates were consistent. All metrics showed considerable differences between treatments. The difference in phosphorus between treatments is depicted in Figure 14.

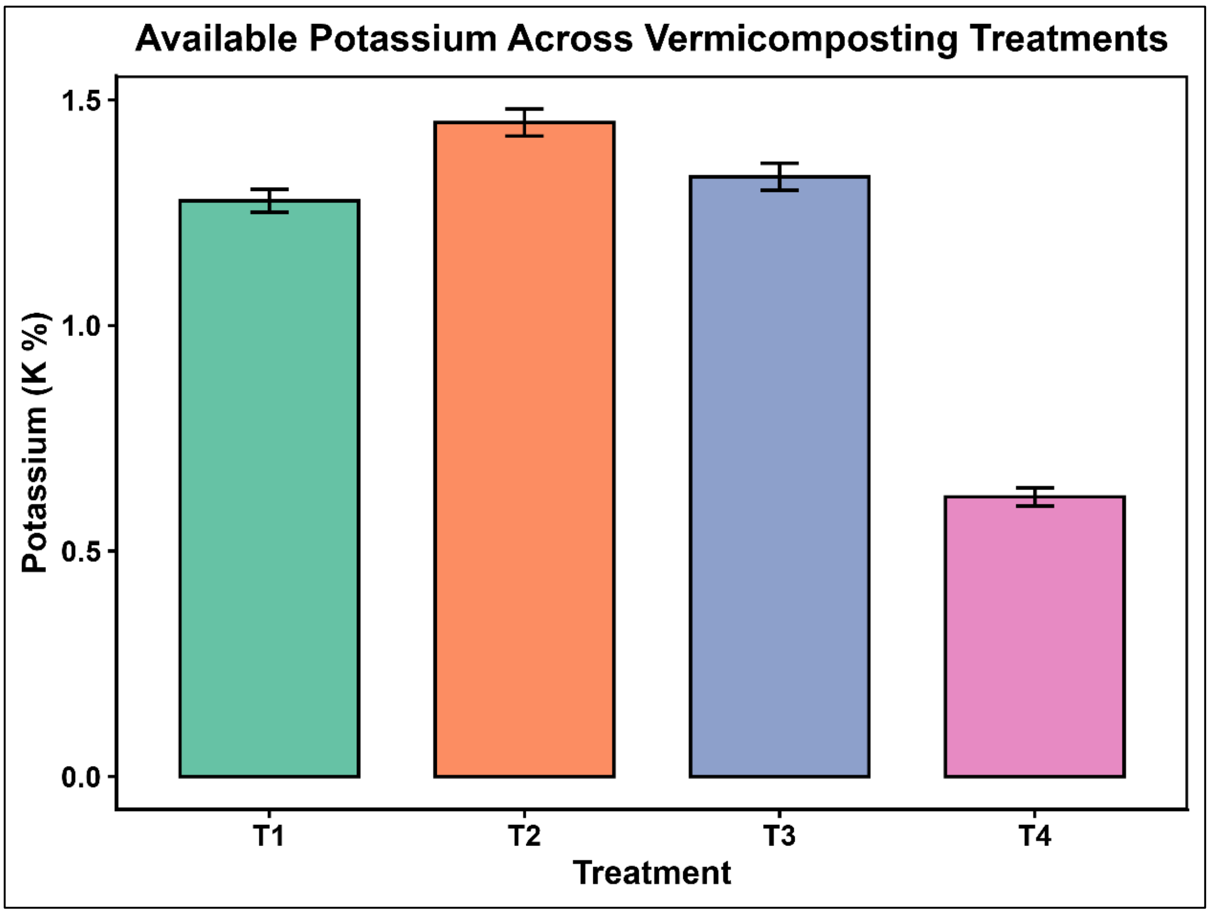
Fig 14. Comparative available phosphorus levels in vermicompost made from different combinations of agricultural waste



4.2.5.3 Available Potassium (K)

There were significant differences in the available potassium (K) content between the treatments; vermicomposting treatments had greater values than the control. The potassium concentration was highest in T2 (1.45 ± 0.08%), followed by T3 (1.33 ± 0.06%) and T1 (1.28 ± 0.07%). The control treatment had the lowest potassium concentration (0.62 ± 0.04%). Every vermicomposting treatment had consistently greater potassium levels than the control. Significant variations between treatments were evident in all parameters. Replicates appeared to be consistent because there was minimal variance within treatments. The vermicomposting treatments displayed results that were closely clustered when compared to the control. Figure 15 illustrates the difference in potassium between treatments.

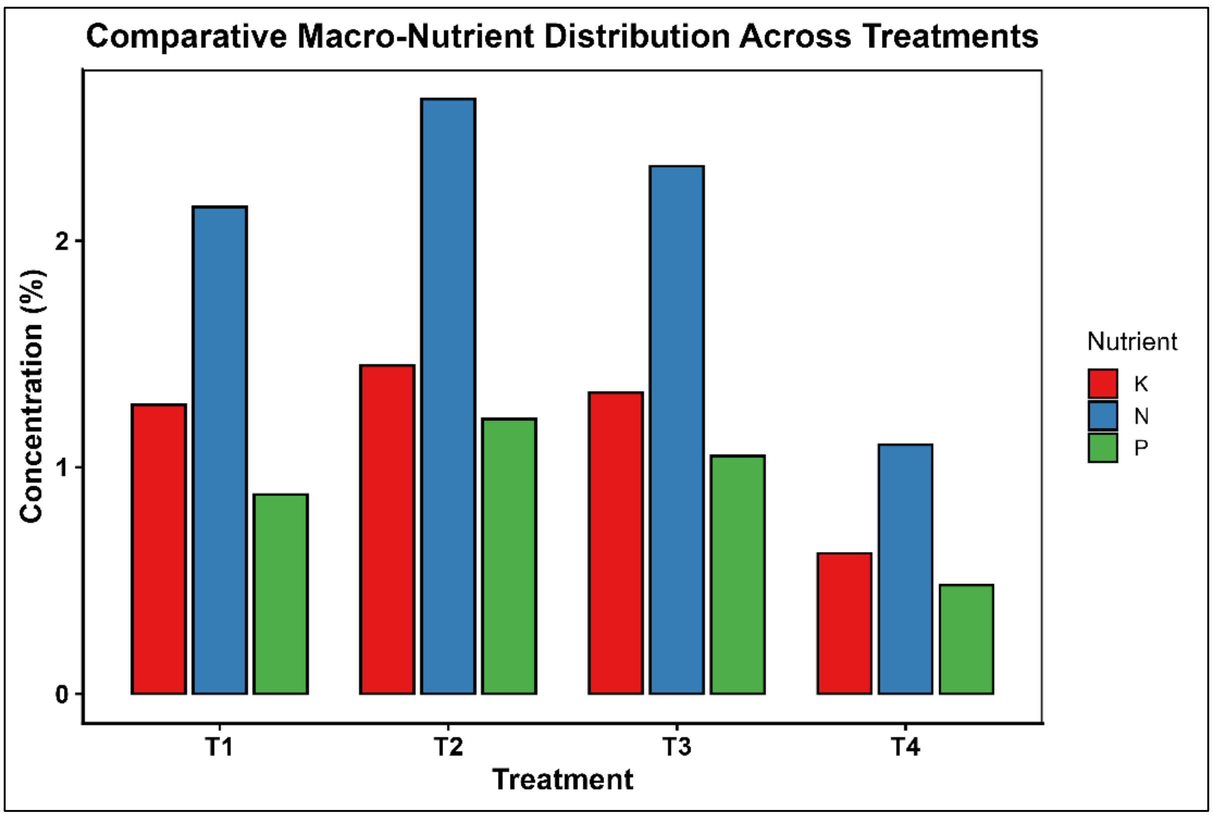
Fig 15. Comparative available potassium levels in vermicompost made from different combinations of agricultural waste



4.2.5.4 The Total Macronutrient Profile of All Treatments

Vermicomposting treatments (T1–T3) demonstrated higher values than the control (T4) in the composite macronutrient profile (N, P, and K). T2 consistently had the highest levels of nitrogen (2.63 ± 0.11%), phosphorus (1.21 ± 0.06%), and potassium (1.45 ± 0.08%). T3 showed intermediate values for each macronutrient, whereas T1 came in second. The control treatment had the lowest levels of potassium (0.62 ± 0.04%), phosphorus (0.48 ± 0.03%), and nitrogen (1.10 ± 0.05%). All vermicomposting treatments consistently displayed higher levels of macronutrients than the control. There were clear changes between treatments for every nutrient that was assessed. Replicates appeared to be consistent because there was minimal variance within treatments. Figure 16 displays the comparative macronutrient composition for each treatment.

Fig 16. Grouped plots such as clustered bar graphs for macro-nutrient comparisons



4.2.6 Bulky Density and Moisture level

Bulk density (BD) varied among treatments, with vermicomposting treatments (T1–T3) exhibiting lower values than the control (T4). T2 had the lowest BD (0.68 g cm^{-3}), followed by T1 (0.71 g cm^{-3}) and T3 (0.73 g cm^{-3}). The control treatment had the highest BD (0.84 g cm^{-3}). In every vermicomposting treatment, BD was continuously lower than the control. Significant differences between treatments were evident in all parameters. Replicates appeared to be consistent because there was minimal variance within treatments. The results of the vermicomposting treatments were closely clustered when compared to the control. Overall, there were noticeable differences between the vermicomposting and control treatments.

4.4 Effects of Vermicompost on Soil Health, Crop Yield and Climate Resilience

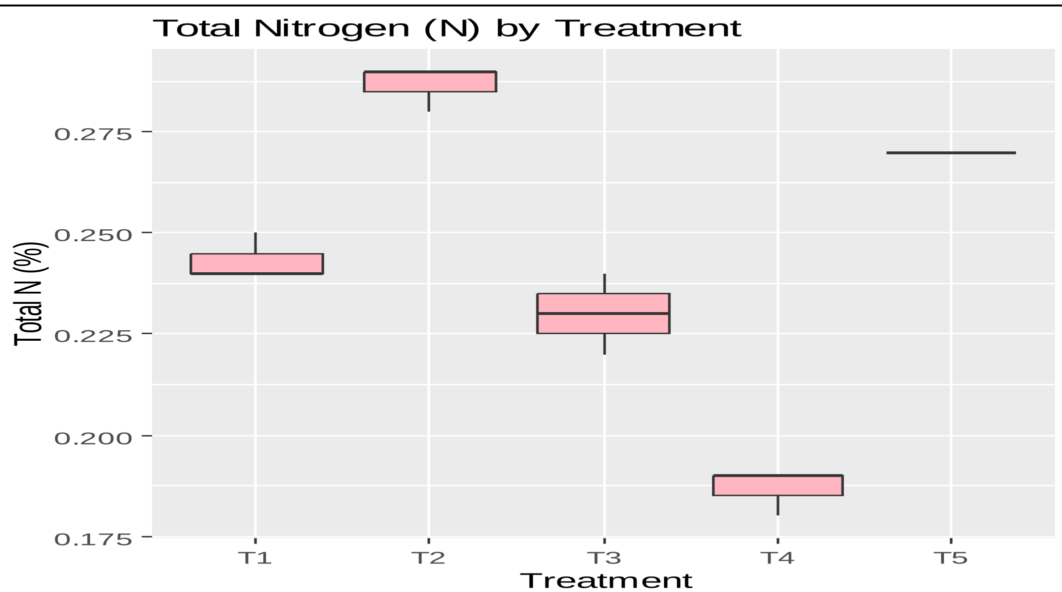
All of the experimental data was analyzed using R software (version 4.3.2). A one-way ANOVA was used to evaluate the effects of fertilizer treatments (T1–T5) on soil fertility indices, crop performance, and plant resistance during drought simulation.

4.4.1 Soil Fertility and Nutrient Indicators

4.4.1.1 Total Nitrogen (N)

The total nitrogen (N) content varied significantly between treatments ($p < 0.001$). The original soil nitrogen levels in the plots were rather constant, ranging from 0.1733% to 0.1767%. After treatment application, the nitrogen content increased across all treatments, but to varying degrees. The highest nitrogen content was found in T2 (0.2867%), followed by T5 (0.2700%), T1 (0.2433%), and T3 (0.2300%). The control compost treatment (T4) showed a smaller increase of 0.1867%. All vermicompost treatments had higher nitrogen levels than the control. Replicates variations were low across treatments. Figure 17 displays the distribution of soil total nitrogen by treatment.

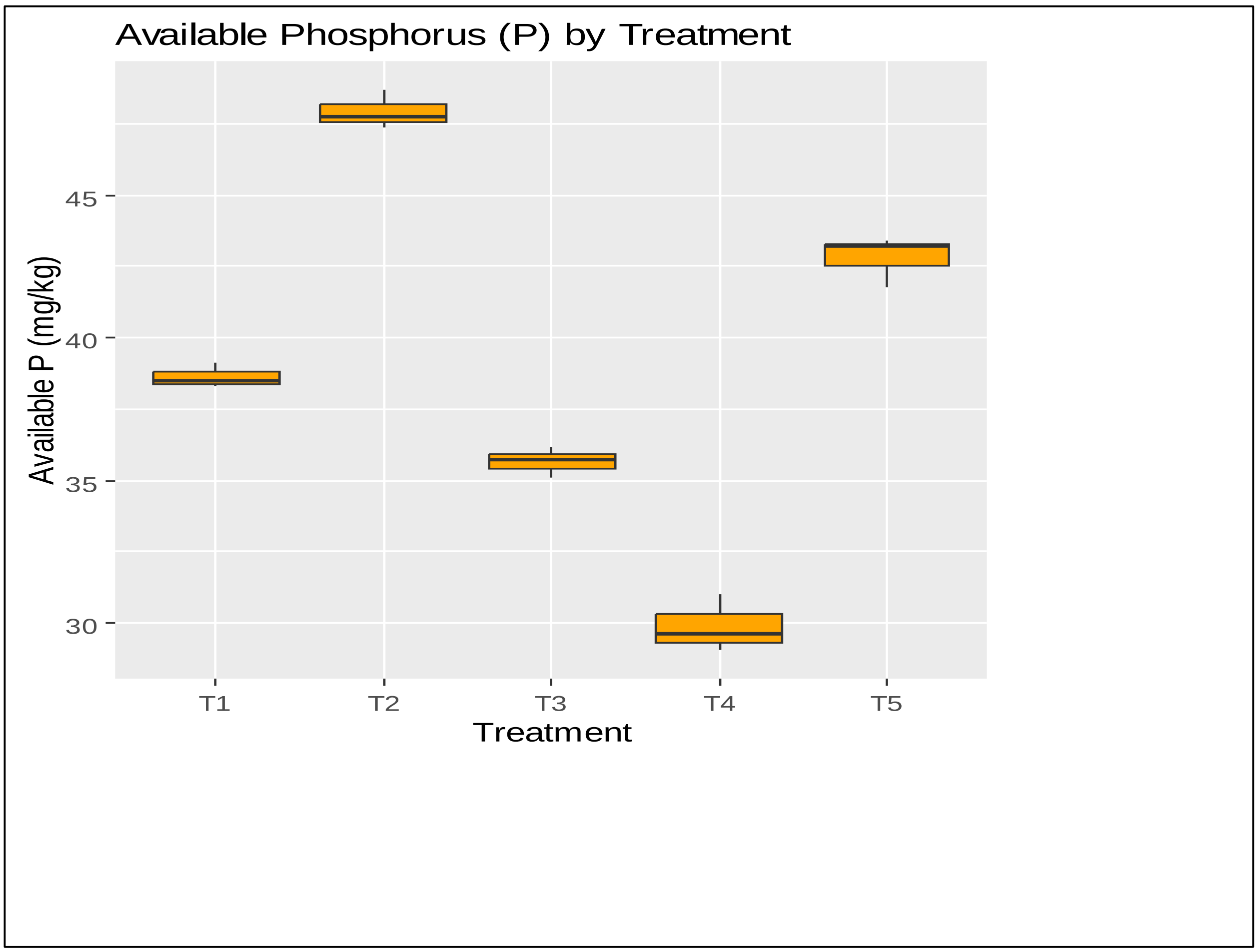
Fig 17. The distribution of soil total nitrogen (N) among the several fertilizer treatments



4.4.1.2 Available phosphorus (p)

There was a significant difference in the amount of available phosphorus (P) across treatments **(**F (df_1, df_2) = 212.23, $p < 0.001$**).** The initial phosphorus levels in all plots were quite constant, averaging around 28 mg/kg. Following treatment application, the phosphorus content increased in all treatments. The highest value was observed in T2 (47.94 mg/kg), followed by T5 (42.80 mg/kg), T1 (38.63 mg/kg), and T3 (35.67 mg/kg). The control compost treatment (T4) showed the least increase, at 29.88 mg/kg. All vermicomposting treatments had higher phosphorus levels than the control. Replicate variation was low across treatments. Figure 18 illustrates how available phosphorus is distributed among treatments.

Fig 18. The distribution and variability of accessible soil phosphorus (P) among fertilizer



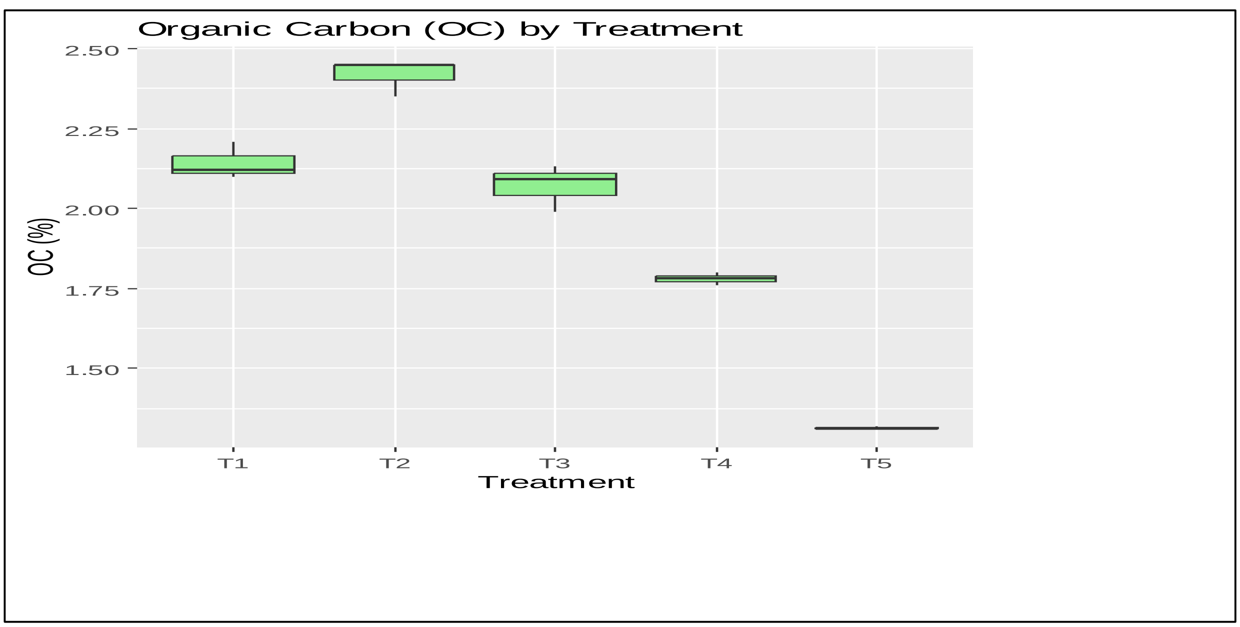
4.4.1.3 Exchangeable Potassium(K)

There was a significant difference in exchangeable potassium (K) levels across treatments ($p < 0.001$). The plots' starting potassium levels, which ranged from 148 to 151 mg/kg, were quite comparable. Following the application of fertilizers, potassium levels rose in each treatment. T2 had the highest value (206.59 mg/kg), followed by T5 (194.95 mg/kg), T1 (188.41 mg/kg), and T3 (171.48 mg/kg). At 158.17 mg/kg, the control treatment (T4) had the least increase. Potassium levels were higher in all vermicomposting treatments than in the control. There was little variation between replicates for any treatment.

4.4.1.4 Organic Carbon (OC)

The soil's organic carbon (OC) content differed significantly between treatments ($p < 0.001$). The initial OC levels of the plots were similar, ranging from 1.53% to 1.55%. OC increased after fertilizer application in most treatments. The highest OC was found in T2 (2.4167%), followed by T1 (2.1433%) and T3 (2.07%). The control compost, T4, experienced a 1.78% increase. The inorganic fertilizer treatment (T5) decreased to 1.313%. Vermicomposting treatments consistently showed higher OC as compared to other treatments. Figure 19 illustrates how soil organic carbon is distributed among treatments.

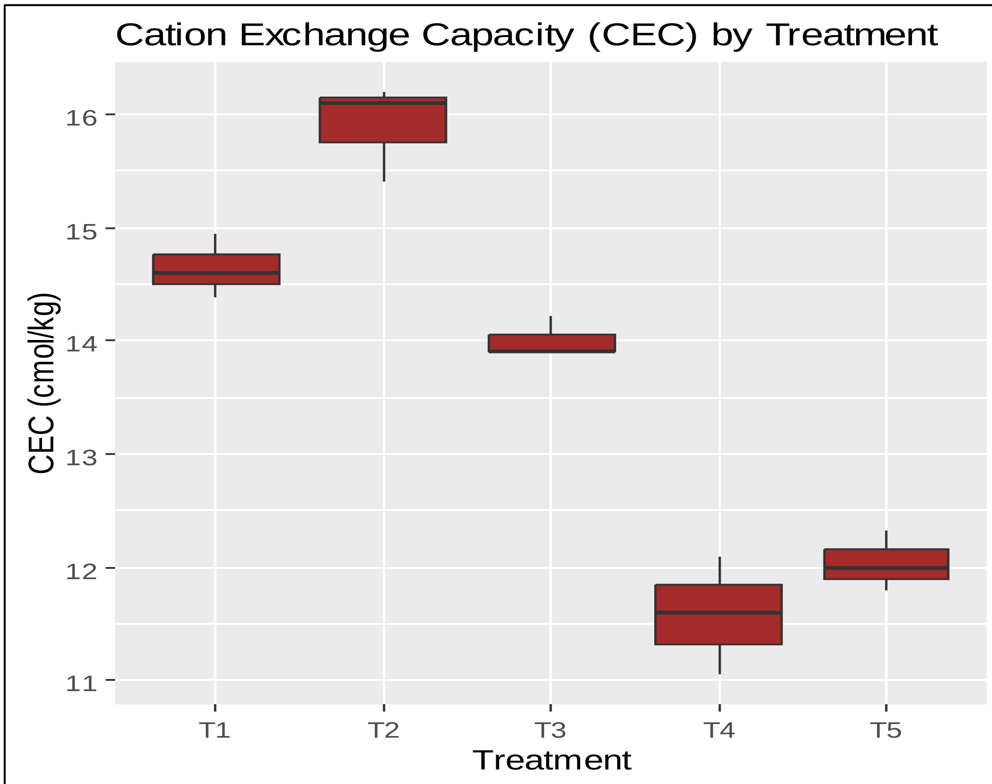
Fig 19: Comparative organic carbon levels in soils amended with various fertilizer and vermicompost treatments



4.4.1.5 Cation Exchange Capacity (CEC)

Soil cation exchange capacity (CEC) varied significantly among fertilizer treatments. The initial CEC values varied from 11.0 to 11.2 cmol (+) kg^{-1} plot-wise. Except for the control, which exhibited minimal change, all treatments had an increase in CEC after treatment application. The maximum CEC was found in T2 (15.90 cmol (+) kg^{-1}), followed by T1 (14.64 cmol (+) kg^{-1}) and T3 (14.01 cmol (+) kg^{-1}). 12.04 cmol (+) kg^{-1} was attained by the inorganic fertilizer application (T5). The control compost (T4) showed the least increase, at 11.58 cmol (+) kg^{-1}. Vermicomposting treatments consistently had higher CEC values than other treatments. Figure 20 displays the distribution of soil CEC among treatments.

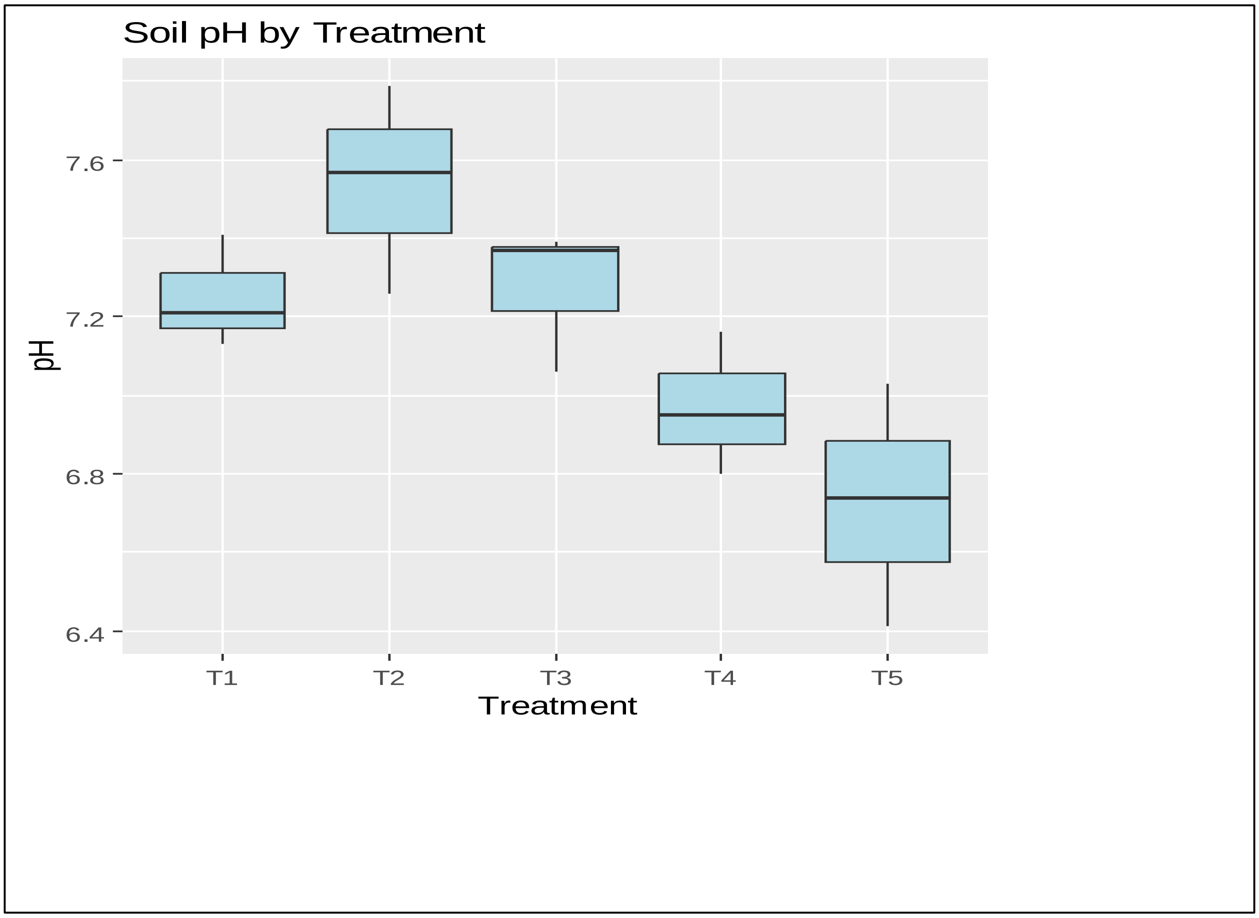
Fig 20: Variations in soil cation exchange capacity among fertilizer and vermicompost treatments



4.4.1.6 Soil pH

The pH of the soil varied significantly between fertilizer treatments. The plots' starting pH values, which ranged from 6.82 to 6.85, were quite close. The vermicomposting treatments and the control showed a minor increase in pH after treatment application, but the inorganic fertilizer treatment showed a reduction. The pH was highest in T2 (6.84 to 7.54), followed by T1 (6.85 to 7.25) and T3 (6.83 to 7.27). From 6.82 to 6.97, the control (T4) recorded a slight increase. There was a drop from 6.84 to 6.73 for the inorganic fertilizer treatment (T5). The pH values of vermicomposting treatments were consistently higher than those of other treatments. The variation of soil pH between treatments is shown in Figure 21.

Fig 21: Variations in soil pH under vermicompost and fertiliser treatments



4.4.2 Crop growth and yield indicators

4.4.2.1 Germination Rate

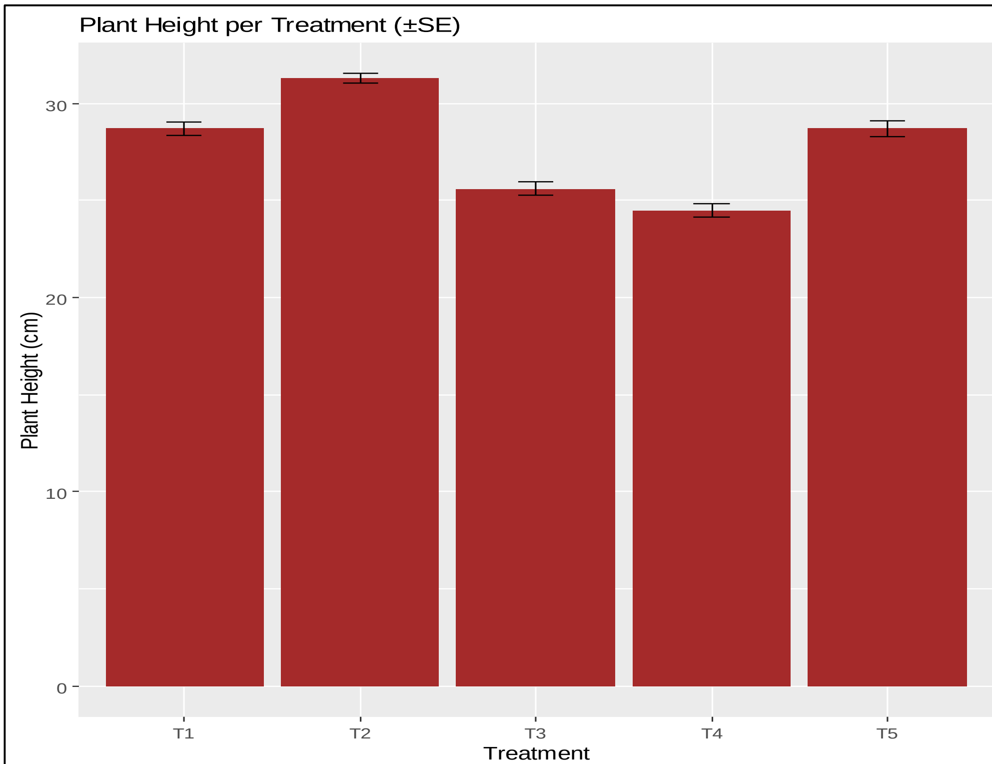
The rate of germination varied significantly between treatments ($p < 0.01$). T2 had the highest germination rate (96.81%), followed by T1 (94.19%) and T5 (90.79%). T4 had the lowest germination rate (77.07%), while T3 had a lower rate than T2 and T1. In comparison to the control, all vermicomposting treatments displayed increased germination rates. All metrics showed considerable differences between treatments. There was little variation between replicates for any treatment. Higher germination performance was consistently shown by vermicomposting treatments. The difference in germination rate across treatments is shown in Figure 22.

Fig 22. lettuce (Eden variety) germination under different fertilizer treatments

4.4.2.2 The plant's height

There was a significant difference in lettuce plant height between treatments ($p < 0.05$). The tallest plant was T2 (31.3 cm), followed by T1 (28.69 cm) and T5 (28.71 cm). T3 had a lower plant height of 25.60 cm, while T4 had the lowest figure (24.48 cm). All vermicomposting treatments showed higher plant heights than the control. Significant variations between treatments were evident in all parameters. For every treatment, there was minimal variance between replicates. T2 consistently exhibits the strongest growth performance. Figure 23 shows the variation in plant height between treatments.

Fig 23: The effects of fertilizer and vermicompost on lettuce plant height



4.4.2.3 The number of leaves

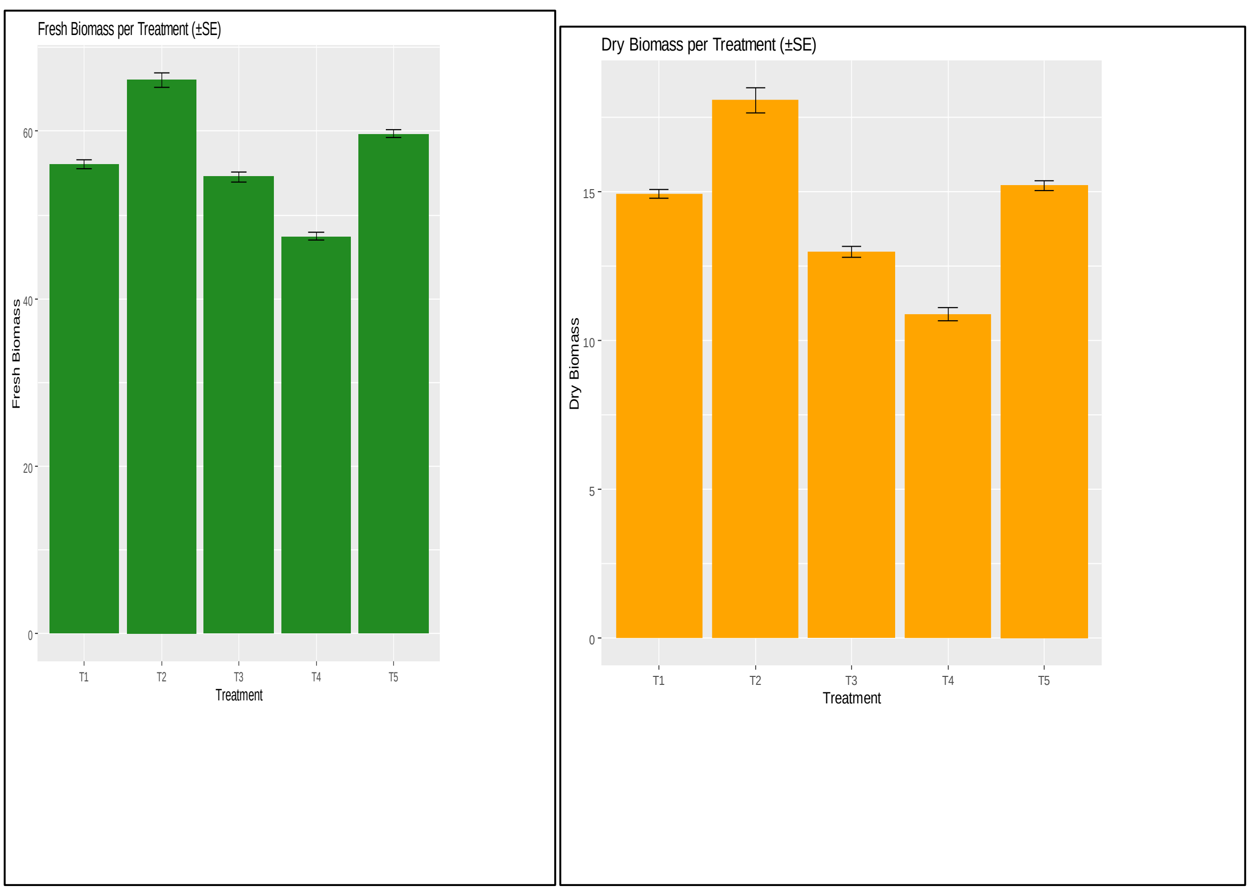
There was a significant difference ($p < 0.05$) in the number of leaves per plant across treatments. T2 had the highest mean number of leaves (17.93), followed by T1 (16.17) and T5 (16.36). T4 had the fewest leaves (11.94), whereas T3 had a reasonable value of 15.38. In comparison to the control, all vermicomposting treatments displayed more leaves. All metrics showed considerable differences between treatments. There was little variation between replicates for any treatment. The best vegetative performance was continuously recorded by T2. The variation in leaf number between treatments is seen in Figure 24.

Fig 24. Lettuce leaf development under different fertilizer treatments

4.4.2.4 Fresh and dry biomass

Fresh and dry biomass varied significantly between treatments ($p < 0.001$). The highest biomass was found in T2 (66.13 g fresh, 18.07 g dry), followed by T1 (61.04 g, 16.92 g) and T5 (59.69 g, 15.20 g). While T3 had lower values (54.54 g fresh and 12.98 g dry), T4 had the lowest biomass levels (47.46 g fresh and 10.87 g dry). All vermicomposting treatments showed higher biomass than the control. Significant variations between treatments were evident in all parameters. For every treatment, there was minimal variance between replicates. T2 consistently recorded the highest biomass production. Figure 25 illustrates the variations in fresh and dry biomass among treatments.

Fig 25 a &b: Lettuce biomass after various fertilizer treatments.



(a) (b)

4.4.2.5 Marketable yield

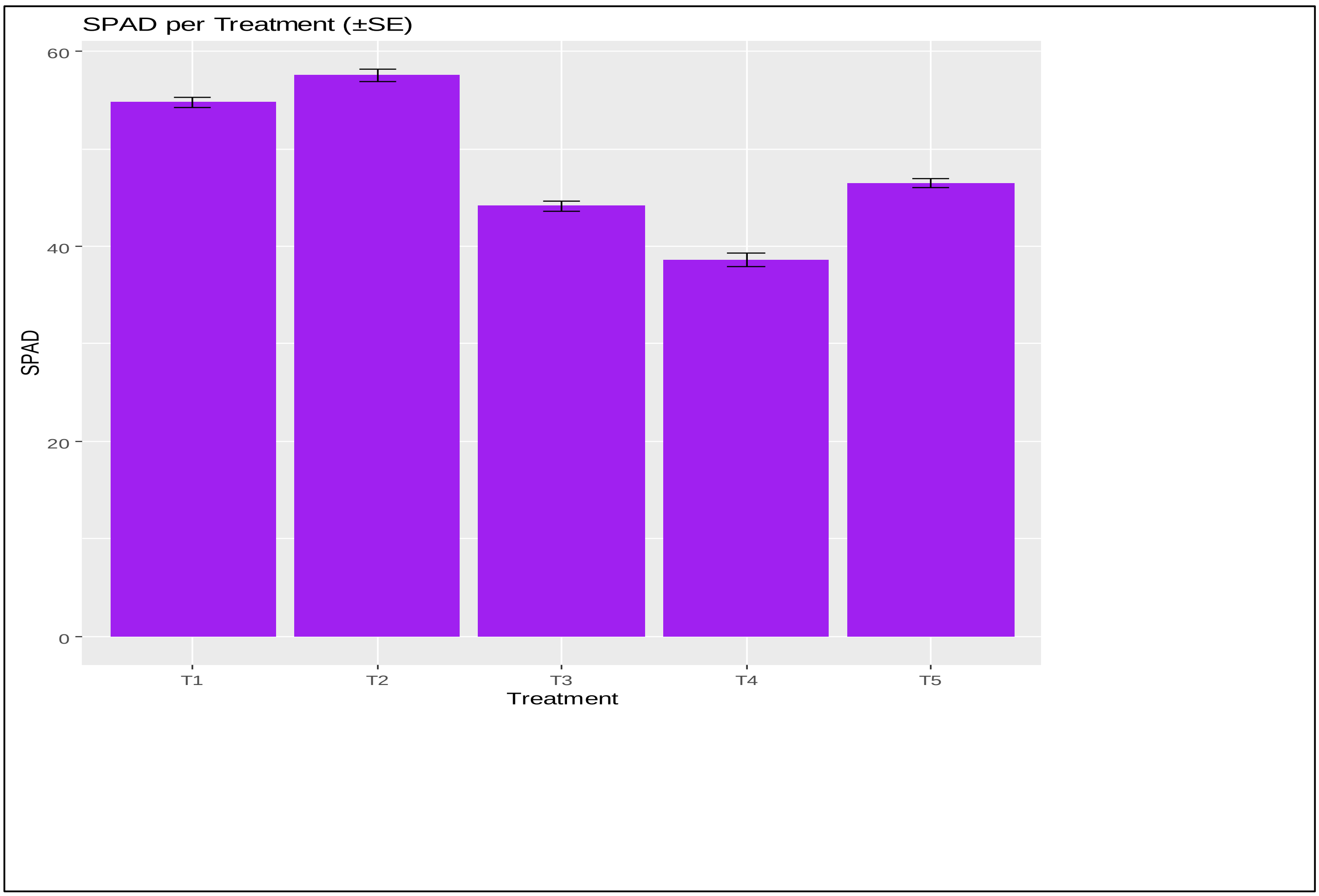
Marketable yield varied significantly between treatments ($p < 0.001$). T2 produced the most (6.49 kg/plot), followed by T1 (5.74 kg/plot) and T5 (5.63 kg/plot). T3 produced an intermediate yield of 5.20 kg/plot, while T4 had the lowest yield of 4.18 kg/plot. In terms of yield, all vermicomposting treatments performed better than the control. Significant variations between treatments were evident in all parameters. For every treatment, there was minimal variance between replicates. T2 was always the most productive. Figure 26 illustrates the variation in marketable yield between treatments.

Fig 26. Lettuce plants ready for harvest under different soil amendment conditions

4.4.2.6 SPAD's chlorophyll content

The concentration of SPAD chlorophyll varied significantly between treatments ($p < 0.001$). T2 (57.54) had the highest SPAD value, followed by T1 (54.76) and T5 (46.47). T3 had a lower score of 44.14, while T4 had the lowest value. All vermicomposting treatments had higher levels of chlorophyll than the control. Significant variations between treatments were evident in all parameters. For every treatment, there was minimal variance between replicates. T2 consistently had higher levels of chlorophyll accumulation. Figure 27 shows the variation in SPAD chlorophyll content between treatments.

Fig 27. Effect of vermicompost and fertilizer treatments on lettuce chlorophyll content (SPAD Index)

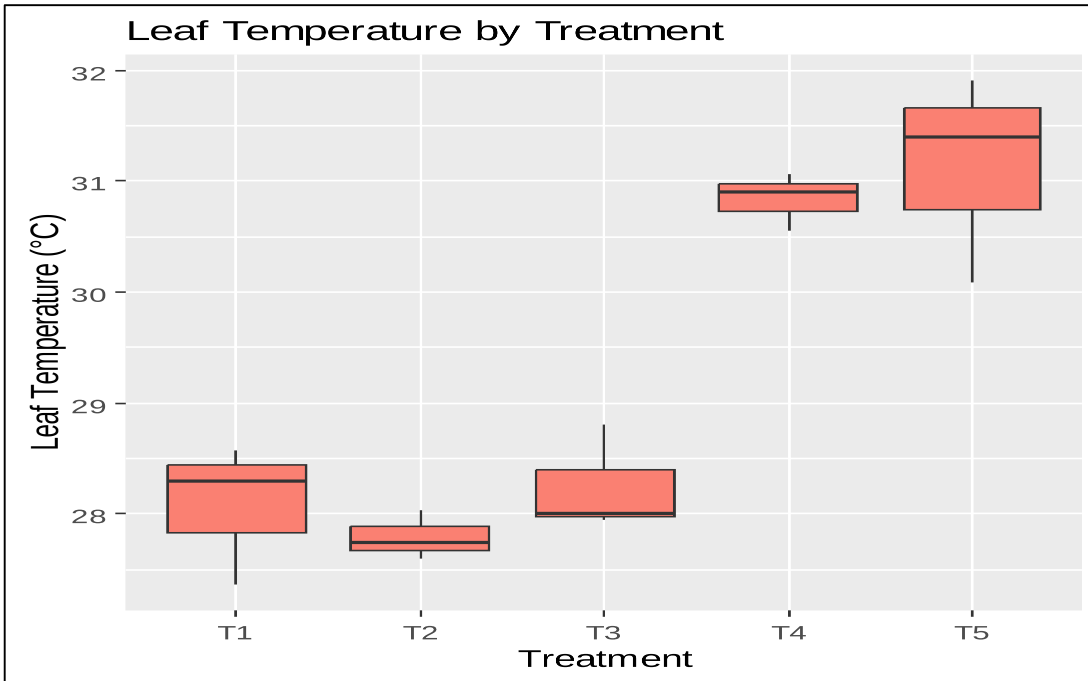


4.4.3 Resilience to climate-induced stress

4.4.3.1 Leaf Surface Temperature

The leaf surface temperature varied significantly between treatments ($p < 0.01$). The lowest temperature was recorded by T2 (27.79 °C), which was followed by T1 (28.08 °C) and T3 (28.25 °C). T4 had a higher temperature of 30.84 °C, while T5 had the highest temperature (31.13 °C). All vermicomposting treatments showed lower leaf surface temperatures than the control and inorganic fertilizer treatments. Significant variations between treatments were evident in all parameters. For every treatment, there was minimal variance between replicates. T2 consistently had the lowest canopy temperature. Figure 28 shows the variation in leaf surface temperature between treatments.

Fig 28. Illustrates how the surface temperature of lettuce leaves is impacted by various fertilizer applications.



4.4.3.2 Wilting score

Between treatments, wilting scores differed significantly. T2 had the lowest wilting score (1.33), followed by T1 (2.00) and T3 (2.33). T4 had a higher wilting score of 2.67, whereas T5 had the highest value (3.00). All vermicomposting treatments showed reduced wilting ratings in comparison to the control and inorganic fertilizer treatments. Significant variations between treatments were evident in all parameters. For every treatment, there was minimal variance between replicates. T2 consistently had the least amount of wilting under demanding conditions. Figure 29 shows the variation in wilting ratings between treatments.

Fig 29. Wilting response of lettuce plants under different fertilizer treatments

4.4.3.3 Days of Recovery

Different treatments demonstrated varying post-stress recovery durations after drought stress. T2 and T1 recovered the fastest (3 days), followed by T3 (4 days). The control treatments T4 and T5 had the longest recovery durations, averaging five days. All vermicomposting treatments showed faster recovery than the control and inorganic fertilizer treatments. Significant differences between treatments were evident in all parameters. For every treatment, there was minimal variance between replicates. T2 consistently showed the fastest recovery response following stress. Figure 30 illustrates the variation in post-stress recovery duration between treatments.

Fig 30. Post-drought recovery response of lettuce plants under different fertilizer treatments

4.4.3.4 Survival Rate

There was a significant difference in survival rates between treatments ($p < 0.05$). T2 had the best survival rate (94.91%), followed by T1 (90.86%) and T3 (89.14%). T4 had the lowest survival rate (78.34%), whereas T5 had a lower rate. In comparison to the control and inorganic fertilizer treatments, all vermicomposting treatments demonstrated greater survival rates. All metrics showed considerable differences between treatments. There was little variation between replicates for any treatment. The best survival performance was continuously obtained by T2. The difference in survival rate across treatments is shown in Figure 31.

Fig 31. Survival response of lettuce under different fertilizer treatments

4.4.3.5 Time Series Analysis

Throughout the stress simulation session, time-series analysis revealed differences in leaf temperature and wilting score between treatments. Throughout the monitoring period, vermicomposting treatments—especially T2—consistently reported lower leaf temperatures than T4 and T5. Over time, vermicomposting treatments maintained reduced wilting ratings. Treatment variations persisted across all time periods. Throughout the stress phase, T4 and T5 showed higher values for both measurements. Throughout the simulation, treatment differences remained unchanged. There was little variation between replicates for any treatment. The wilting score and leaf temperature time patterns are shown in Figure 32.

Fig 32 a. Time-series plot for surface leaf temperature trends during stress simulation

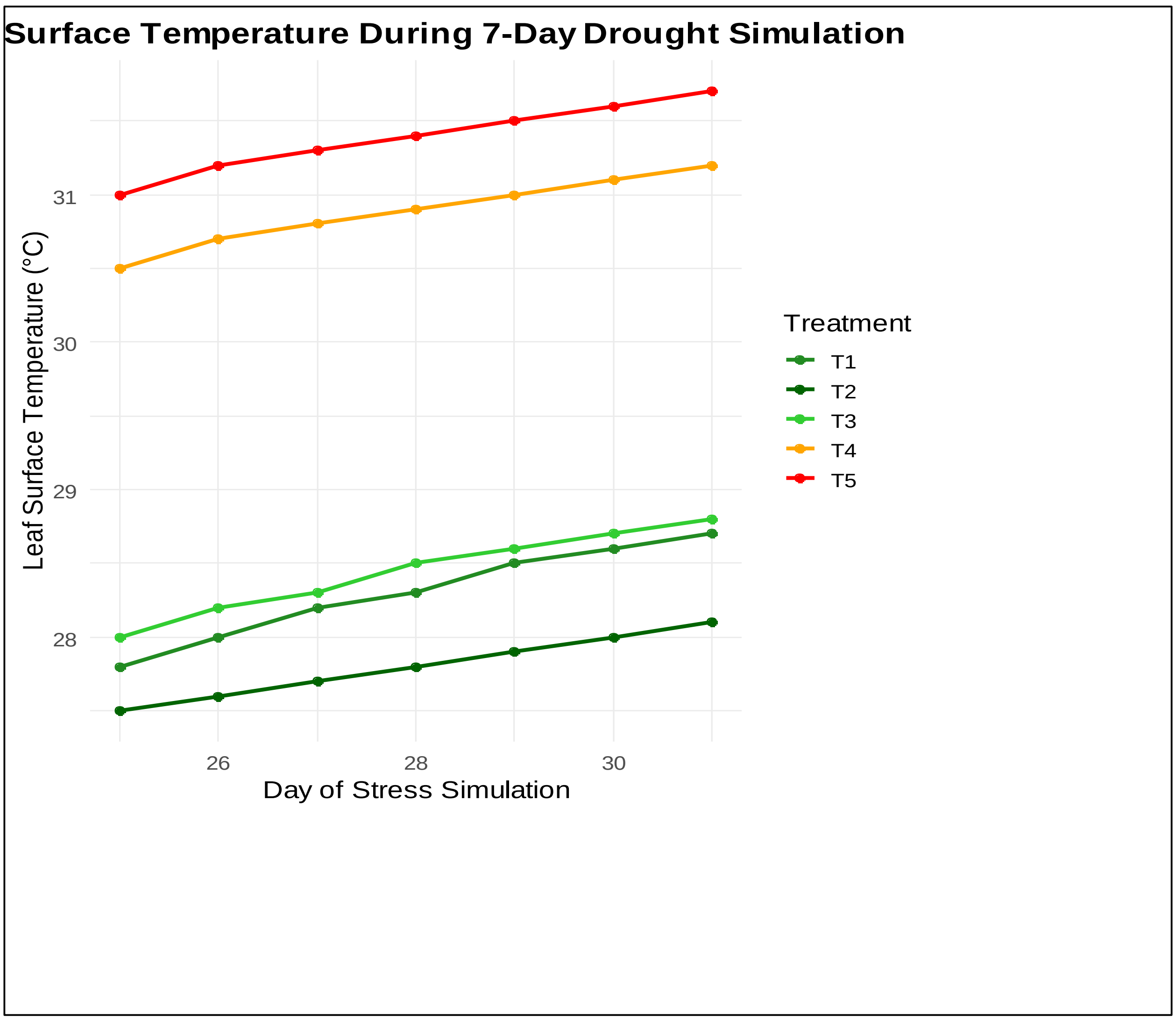
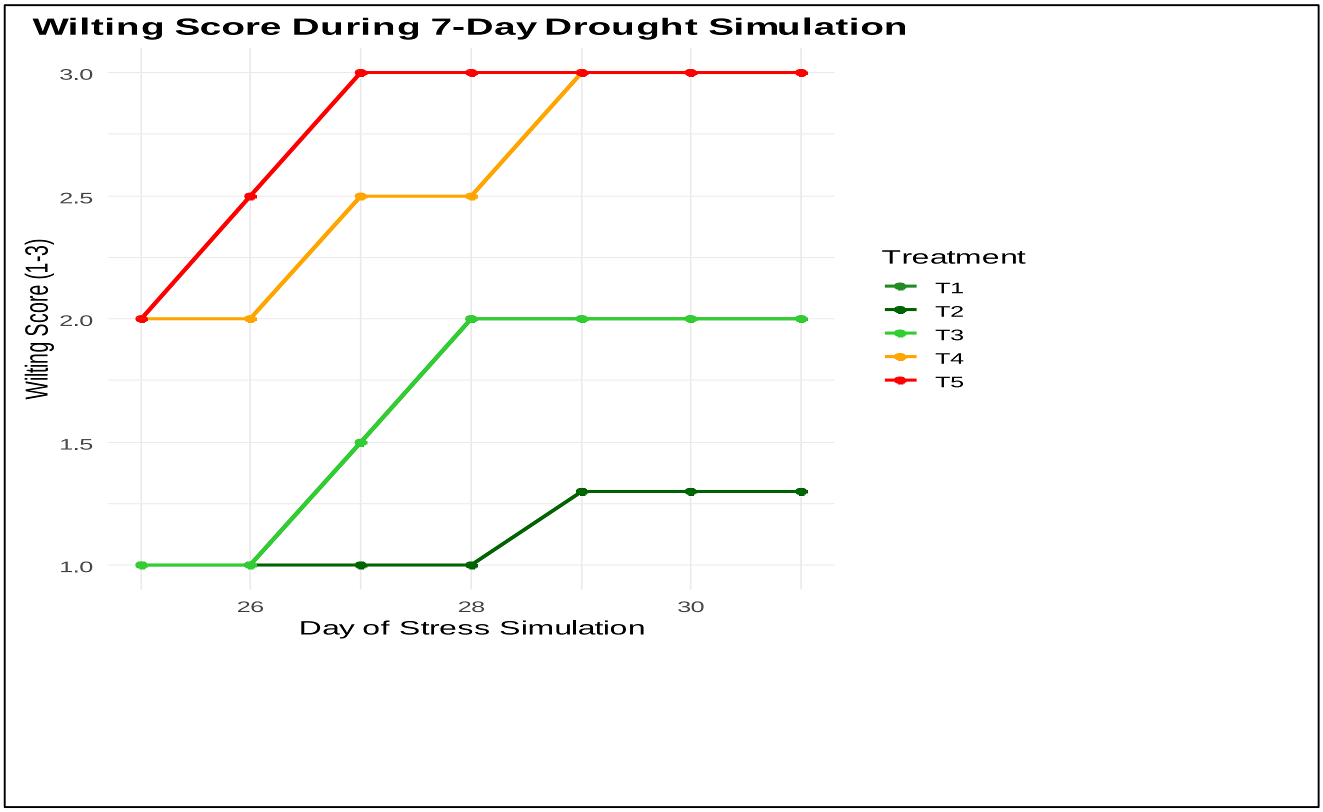


Fig 32 b. Time-series plot for wilting score trends during stress simulation



4.4.3.6 Regression Analysis

To evaluate the connections between plant performance characteristics and soil fertility indicators, regression analysis was used. There were correlations found between yield-related indicators and the chemical characteristics of the soil. Wilting response and soil fertility indicators were shown to be correlated. Relationship strength variation was noted between treatments. Across treatments, yield demonstrated correlations with CEC. Wilting response also demonstrated correlations with measures of soil fertility. Measurable trends between variables were shown in all regression models. The regression correlations between yield, wilting response, and soil fertility indicators are shown in Figures 33a and 33b.

Fig 33 a. Regression plots to visualize relationships between yield and CEC

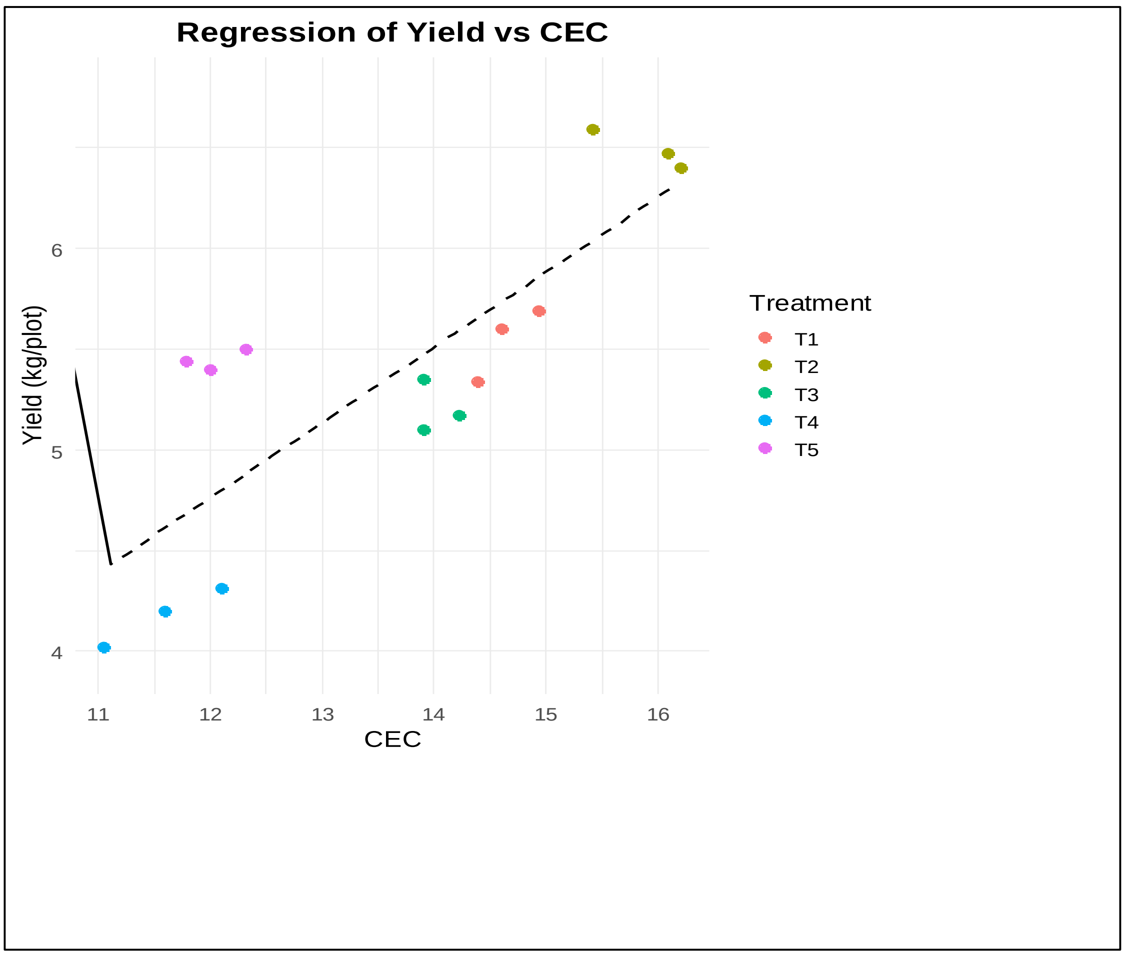


Fig 33 b. Regression plots to visualize relationships between yield and wilting

DISCUSSION

5.1 Vermicompost Production Using Different Strategies

When compared to traditional composting techniques, the current study shows that vermicomposting significantly improves the decomposition of agricultural waste. The decomposition rates of all vermicomposting treatments are much higher than those of the control, indicating that *Eisenia fetida*-mediated systems are effective in speeding up the breakdown of organic matter. The substantial relationship between earthworm activity and waste type in affecting decomposition efficiency is highlighted by the very large effect size ($\eta^2 = 0.99$), which further suggests that substrate composition was the primary factor controlling breakdown kinetics. These results are in line with recent research showing that in organic waste systems, earthworm activity speeds up microbial growth, fragmentation, and nutrient mineralization (Villegas-Cornelio & Laines, 2017; Yadav et al., 2013).

The combination of cow dung, poultry manure, and vegetable waste (T2) showed the quickest rate of decomposition out of all the treatments, demonstrating the potent synergistic effect of mixed organic substrates (Qinfei et al., 2024). The complimentary nature of the substrates—cow dung provides a stable carbon matrix that supports microbial activity over time, while poultry manure offers easily accessible nitrogen for microbial development—explains this enhanced performance (Khatua et al., 2018; Turp et al., 2021). Singh and Suthar (2012) discovered similar outcomes, pointing out that balanced C: N ratios improve microbial efficiency and decomposition rate in mixed waste systems. The findings demonstrate that substrate diversity is essential for optimizing interactions between microorganisms and earthworms during vermicomposting.

The performance of T1 (vegetable and chicken waste) and T3 (cow dung and vegetable waste) was somewhat reduced but comparable, suggesting that single animal-based waste combinations can still maintain good decomposition, but less successfully than mixed substrates. This is consistent with research by Manyuchi and Whingiri (2014), who found that while different kinds of organic waste can help with decomposition, they do not exhibit the increased microbial synergy found in mixed systems. More evidence that overall nutritional balance influences decomposition efficiency more than any particular substrate type comes from the lack of discernible differences between different vermicomposting treatments.

The limits of passive decomposition systems were confirmed by the fact that the typical composting treatment consistently recorded the lowest decomposition rate. The slower decomposition shown in the control is in line with research by Lim et al. (2016), who found that because earthworm-mediated aeration and fragmentation are absent in typical composting systems, microbial activity is lower and organic matter transformation is slower. This emphasizes how crucial biological agents are for improving nutrient cycle and decomposition efficiency.

The findings clearly demonstrate that vermicomposting is a highly successful biological process for converting agricultural waste into stable organic compounds. Although the significant treatment effects highlight the need of substrate optimization, the consistency seen between duplicates confirms the reliability of the method. These results strongly support previous research demonstrating that earthworm activity combined with integrated organic waste mixtures provides an effective and sustainable way to manage organic waste and produce high-quality compost suitable for agricultural use (Lim et al., 2016; Dominguez & Edwards, 2010).

5.2 Nutrient Composition of Vermicompost from Agricultural Waste

When compared to traditional composting, vermicomposting greatly improved the nutritional content, stability, and maturity of organic fertilizers made from agricultural waste. The combination of molasses and *Eisenia fetida* produced ideal conditions for better nutrient mineralization, increased humification, and faster decomposition. All of these procedures demonstrate that vermicomposting is a physiologically effective method of converting diverse agricultural waste into stable, nutrient-rich organic fertilizer. Similar findings that earthworm activity improves microbial diversity, enzymatic breakdown, and organic matter stability during composting have been extensively documented (Kumar et al., 2023; Prajapati et al., 2023).

The pH of vermicompost (T1–T3) varied from 7.5 to 8.0, indicating a shift toward neutral to slightly alkaline conditions, in contrast to the control (6.73) (Xu et al., 2023). Increased ammonification, buffering capacity, and organic acid degradation under earthworm-mediated decomposition are the causes of this increase(Pereira et al., 2023; Varma et al., 2015). The greatest pH values in poultry-based treatments (T1 and T2) are caused by higher nitrogen availability and enhanced microbial activity, which speed up the breakdown of organic waste. These findings are in line with past studies showing vermicomposting enhances soil chemical stability and increases nutrient availability, particularly nitrogen, phosphate, and potassium (Gusain & Suthar, 2020). Conversely, the lower pH of the control suggests limited microbial metabolism and incomplete degradation, which may restrict the availability of nutrients.

Electrical conductivity (EC) was also significantly influenced by substrate composition, with higher values observed in vermicomposting treatments, particularly T1 and T2. Increased mineralization and soluble ion release during decomposition are the causes of this increase(Zhang et al., 2020). Importantly, fertilizer enrichment did not raise the danger of salinity because all EC values remained below agronomically safe ranges (<8 mS/cm). These findings are consistent with research showing vermicomposting improves nutrient solubilization while maintaining soil safety criteria for agricultural application (Arachis, 2024; Srivastava et al., 2020b). The control's relatively lower EC further confirms reduced mineral release under conventional composting systems.

The reduction in organic carbon and carbon-to-nitrogen (C: N) ratio over vermicomposting treatments (T1–T3) indicates advanced decomposition and compost maturity. It is widely accepted that the reported C: N range (about 12–15:1) indicates stable compost with minimal phytotoxic risk that is suitable for use in agriculture (Yadav et al., 2013b). T2's lowest C: N ratio illustrates the synergistic effect of mixed waste substrates, where nitrogen-rich chicken manure increases microbial activity and carbon-rich materials provide structural stability. This supports a study by Molavi et al. (2020) that discovered balanced carbon–nitrogen interactions significantly boost microbial efficiency and nutrient bioavailability during composting.

The superiority of vermicomposting systems, especially T2, which continuously recorded the greatest nutrient contents across all parameters, is further supported by macronutrient enrichment (N, P, and K). Enhanced microbial mineralization, enzymatic activity, and earthworm-driven nutrient cycling are responsible for this improvement. Vermicomposting dramatically increases plant-available nutrients through rapid organic matter transformation and humification processes, according to similar findings (Piya et al., 2018; Sumathi et al., 2015). The system's stability and dependability are further supported by the consistency shown among replicates.

The reduction in bulk density (BD) in vermicomposting treatments demonstrates improved soil structure, porosity, and aggregation (Miito et al., 2021). T2's lowest BD reflects the formation of solid organic aggregates and enhanced decomposition made possible by earthworm activity. Root penetration, aeration, and water retention—all of which increase soil fertility—all depend on this augmentation. These findings are consistent with past studies that demonstrate vermicompost improves soil physical quality by increasing pore space formation and organic matter stability (Ceylan et al., 2025).

These results demonstrate that vermicomposting not only increases nutrient availability but also enhances the physical and chemical quality of organic additions. The combined effects of earthworm activity and substrate diversity produce a stable, nutrient-rich, and agronomically superior compost. This shows that vermicomposting is an extremely effective and sustainable way to convert agricultural waste into useful soil additives suitable for climate-smart and sustainable farming systems.

5.3 Effects of Vermicompost on Soil Health, Crop Yield and Climate Resilience

Vermicompost significantly improved crop production, plant resistance, nutrient content, and soil biochemical quality under drought stress. Across all evaluated variables, vermicomposting treatments consistently outperformed single-substrate vermicomposts and the control treatments, particularly the mixed substrate system (T2: cow dung, poultry manure, and vegetable waste). This demonstrates how substrate heterogeneity promotes efficient nutrient cycling, accelerates the decomposition of organic matter, and boosts microbial activity—all of which lead to a more stable and agronomically advantageous soil amendment. These findings are in line with earlier studies that demonstrate how earthworm-mediated systems improve microbial diversity, humification, and nutrient digestion in organic waste systems (Goswami et al., 2021; Liu et al., 2024).

The use of vermicompost significantly improved the soil's pH, electrical conductivity, organic carbon, and nutrient availability. Because of enhanced ammonification, reduced organic acid accumulation, and greater microbial turnover, the pH of vermicompost-amended soils changes from neutral to slightly alkaline (Lim et al., 2015). The slightly higher pH observed in poultry-based treatments (T1 and T2) is explained by rapid nitrogen mineralization and enhanced buffering capacity, which is consistent with previous research demonstrating that nitrogen-rich organic amendments speed decomposition and stabilize soil chemical conditions (Pramanik et al., 2016). Conversely, the higher acidity of the control soil indicates incomplete breakdown and less microbial transformation, which limits the availability of nutrients and soil biological activity.

Electrical conductivity results provided additional evidence for improved nutrient solubilization in vermicomposting systems, particularly in T1 and T2. The elevated EC values indicate the increased release of soluble ions such as potassium, phosphate, and nitrate due to increased microbial and earthworm activity (Yuvaraj et al., 2021). Importantly, all EC values were within safe agronomic bounds, indicating that nutrient enrichment did not cause salt stress. This supports previous studies that demonstrate vermicomposting increases nutrient availability without compromising soil quality or plant safety (Srivastava et al., 2020b). The lower EC of the control treatment further emphasizes its decreased mineralization efficiency.

Reductions in organic carbon and carbon-to-nitrogen (C: N) ratios across vermicompost treatments indicate advanced decomposition and compost maturity. It is well recognized that the observed C: N range (about 12–15:1) indicates stable, mature compost with good agronomic value and low phytotoxic risk (Yadav et al., 2013b). The lowest C: N ratio in T2 denotes the best synchronization between nitrogen mineralization and carbon degradation due to the synergistic microbial activity in mixed organic substrates. This is in line with study by Molavi et al. (2020), who discovered that microbial efficiency and compost stabilization are enhanced by balanced carbon and nitrogen inputs.

Macronutrient enrichment (N, P, and K) was consistently highest in T2, and it was significantly higher in vermicomposting treatments. This enhancement is caused by earthworm-driven fragmentation, enzymatic digestion, and microbial mineralization processes that enhance nutrient release and transformation. While rising nitrogen levels suggest faster proteolytic and ammonification processes, rising phosphorus availability is linked to phosphatase activity and microbial solubilization of insoluble phosphate molecules. In a similar way, potassium enrichment results from better mineral release through vermi-fragmentation and physical breakdown of organic waste. These findings are consistent with studies that demonstrate vermicomposting significantly boosts plant-available nutrients through biological transformation processes (Villegas-Cornelio & Laines, 2017; Molavi et al., 2020b).

The structural advantages of vermicomposting are further illustrated by improvements in the physical characteristics of the soil, especially decreased bulk density. Improved soil porosity, aeration, and aggregate stability—all crucial for root penetration and water retention—are shown by lower bulk density in T2. The development of stable humified organic matter and earthworm activity are closely related to these physical advantages. Due to its porous organic matrix, vermicompost has been shown to improve soil structure and moisture retention capacity (Pandya et al., 2023).

Increased soil fertility was directly linked to improved crop growth, yield, and physiological performance. Vermicompost-treated plants demonstrated improved germination, plant height, leaf production, biomass accumulation, and marketable yield in comparison to control treatments.

Better nutrient availability, more root development, and enhanced microbial interactions in the rhizosphere all contribute to this. T2's superior performance is a result of the combined impacts of balanced nutrient release and microbial stimulation, which enhance photosynthetic efficiency and control plant development. These findings are consistent with recent research showing vermicompost improves plant development by boosting nutrient absorption efficiency and phytohormone stimulation (Vig et al., 2022).

Vermicompost also significantly improved a plant's ability to withstand drought-induced stress. Treated plants exhibited lower leaf surface temperatures, lower wilting scores, faster recovery periods, and higher survival rates as compared to control and inorganic fertilizer treatments. Stronger root-soil-water interactions, better aggregation, and enhanced soil moisture retention—all made possible by organic matter stability—are linked to these improvements (Bagali et al., 2021; Piya et al., 2018). Vermicompost also increases antioxidant enzyme activity, stabilizes chlorophyll, and enhances osmotic control in conditions of water stress (Ceylan et al., 2025). The superior performance of T2 highlights the importance of humified, microbial-rich organic amendments in boosting physiological resilience to stress brought on by climate change.

Time-series analysis further demonstrated the temporal stability of vermicompost-induced stress tolerance. Compared to control and inorganic fertilizer treatments, vermicompost-treated plants—especially T2—consistently maintained lower leaf surface temperatures over the stress period, suggesting stable stomatal regulation and sustained transpiration efficiency (Lv et al., 2024). Significantly, as the length of the drought increased, these variations were more noticeable, indicating that vermicompost not only enhances the initial physiological status of plants but also reduces the rate of stress-induced decline(Iqbal et al., 2024). Wilting progression curves also revealed that, in contrast to control treatments, which showed rapid physiological deterioration, T2 maintained much slower wilting intensity over time and postponed the onset of obvious stress signs. Vermicompost improves resilience through ongoing soil-plant-water regulation rather than transient physiological buffering, as this temporal behavior confirms.

Regression analysis confirmed the strong connections between crop performance measurements and soil fertility indicators, demonstrating that improvements in soil chemical quality directly increase yield and stress tolerance(Turp et al., 2023). The connections between CEC, nutrient availability, and plant productivity show how crucial physiologically driven nutrient cycling is for regulating plant growth responses. These links demonstrate how vermicomposting enhances soil chemically and functionally, affecting plant physiological stability under both ideal and stressed conditions.

These findings all point to vermicomposting as a highly effective method of managing soil that strengthens plant resistance to environmental stress, improves crop output, and increases soil fertility. Integrating heterogeneous organic waste streams has a synergistic effect that optimizes microbial efficiency, nutrient cycling, and soil structure improvement. In the context of increasing environmental stress, vermicomposting is presented as a climate-smart, sustainable agricultural technique with significant potential to improve food production systems.

6.0 CONCLUSION AND RECOMMENDATIONS

This study demonstrates that vermicomposting is a highly efficient, biologically driven process that converts a range of agricultural wastes into stable, nutrient-rich organic fertilizer while also improving soil quality, crop productivity, and drought resilience. In terms of plant performance, nutrient enrichment, and decomposition efficiency, *Eisenia fetida's* integration with mixed organic substrates (vegetable waste, cow dung, and poultry manure) consistently produced better results, highlighting the critical role that earthworm–microbial interactions play in accelerating the transformation of organic matter. Substrate diversification was found to have a substantial impact on vermicompost quality, with the mixed system (T2) consistently outperforming single-substrate treatments because of improved microbial activity, balanced C: N ratios, and greater humification processes.

Compared to traditional composting, vermicomposting yielded a more developed and agronomically superior product with better pH management, higher cation exchange capacity, enhanced availability of N, P, and K, and lower C: N ratios, indicating advanced decomposition and greater fertilizer stability. There was a direct correlation between increased crop performance and improvements in germination, vegetative development, biomass accumulation, and marketable production. T2's consistent superiority shows that balanced nutrient release and microbial stimulation are essential for maintaining efficient soil biological activity and sustained plant productivity under both normal and stressful conditions.

Vermicompost also significantly boosted drought stress tolerance by enhancing soil moisture retention, reducing bulk density, strengthening soil aggregate stability, and encouraging more stable plant physiological regulation. Lower leaf surface temperatures, less intense withering, faster recovery, and higher survival rates were indicative of improved soil-plant-water interactions under stress conditions. Time-series and regression studies show that vermicompost strengthens the relationship between soil fertility and plant performance and stabilizes physiological responses over time. Future studies should focus on long-term field validation across different agro-ecological zones to confirm vermicomposting's consistency, scalability, and use in real agricultural situations.

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APPENDICES

Appendix 1: 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 $p < 0.05$.

Appendix 2: 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 $p < 0.05$.

Appendix 3: Physicochemical characteristics of soil after 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

Values are mean ± SD. Different letters indicate significant differences ($p < 0.05$), while the same letter means no significant difference.

Appendix 4: 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

All parameters showed significant differences ($p < 0.05$); pH ($p = 0.0116$), others ($p < 0.001$)

Appendix 5: 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

Means within a row followed by different letters (a–d) differ significantly at $p < 0.05$ according to Tukey's Honest Significant Difference (HSD) test. Values sharing the same letter are not significantly different. Data are presented as mean ± standard error (SE).

Appendix 6: Climate-Induced stress response indicators under different treatments.

Variable	T1	T2	T3	T4	T5
Leaf temp	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
Recovery Days	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 error (SE). Means within a row followed by different letters (a, b, c, d) are significantly different at $p < 0.05$ according to Tukey's Honest Significant Difference (HSD) test. Means sharing at least one letter are not significantly different.

Appendix 7: 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

Significant: p<0.001, not significant: p=0.0677