



## Comprehensive Review of the Effects of Treated Vermicompost on Soil Health, Plant Growth, and Yield of Okra (*Abelmoschus esculentus* L.)

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### Declaration

#### Authors' Contribution

All authors equally contributed to the study and approved the final manuscript

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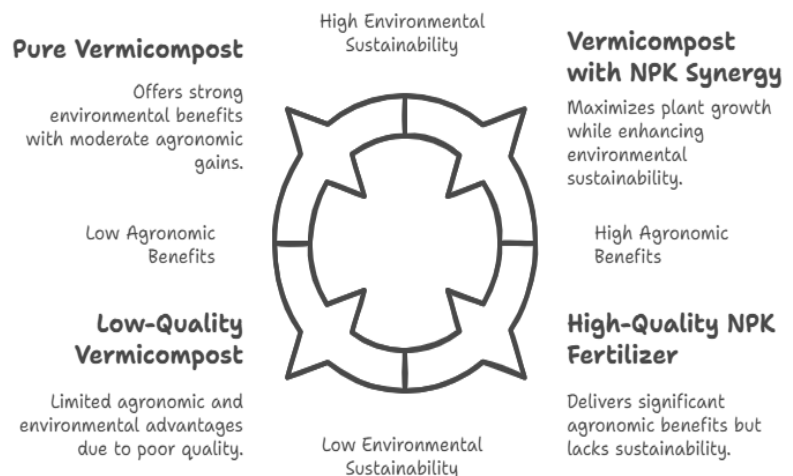
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### ABSTRACT

Vermicomposting is an environmentally sustainable method for restoring soil health, promoting plant development, and augmenting agricultural production. This study emphasizes its contribution to increasing okra (*Abelmoschus esculentus* L.) output by augmenting soil with vital nutrients (N, P, K) and fostering microbial activity, hence improving soil structure, water retention, and plant resistance. Research indicates that the use of vermicompost with NPK fertilizers markedly enhances okra growth, fruit output, and soil organic matter, while decreasing nutrient leaching. Moreover, vermicompost inhibits soil-borne pathogens, promotes root growth, and fosters sustained soil fertility. Notwithstanding its benefits, obstacles like nutritional fluctuation, protracted processing duration, and restricted farmer adoption remain. Advancements in vermiculture, microbial inoculants, and biofortified formulations provide ways to enhance its efficiency. Case studies demonstrate that vermicompost is an effective substitute for synthetic fertilizers, fostering sustainable agriculture and environmental preservation.



### INTRODUCTION

Okra (*Abelmoschus esculentus* L. Moench), sometimes referred to as lady's finger, is a warm-season vegetable grown in tropical and subtropical areas. It is thought to have originated in Africa, specifically Ethiopia, before disseminating to South Asia, the Middle East, and the Americas (Jha et al., 2018). Okra is a member of the Malvaceae family and is closely associated with crops such

as cotton, hibiscus, and cocoa. It is esteemed for its nutritional composition, serving as a substantial supply of vitamins A, C, and K, as well as minerals like calcium, magnesium, and potassium (Mehata et al., 2023). Okra's mucilaginous characteristics significantly contribute to digestive health, cholesterol modulation, and diabetes management (Selim, 2020). Studies indicate that it has antioxidant, anti-inflammatory, and cholesterol-lowering

properties, rendering it an essential element of balanced diets globally (Kumar et al., 2019).

India is the foremost producer of okra, yielding 6.18 million metric tons' year, succeeded by Nigeria and Sudan (FAOSTAT, 2020). The crop is mostly grown in Uttar Pradesh, Bihar, and West Bengal, where the climate is conducive to its cultivation. Okra is extensively utilized in curries and stews within Indian cuisine and is also significant in traditional medicine. Nonetheless, despite its worldwide importance, okra farming encounters several hurdles. Pest infestation continues to be a big problem, with fruit borers, aphids, and jassids adversely impacting production (MoALD, 2022). Moreover, nutritional deficits caused by the overuse of synthetic fertilizers have resulted in soil deterioration and decreased production (Verma et al., 2020). Climate variability, characterized by extreme heat and drought, adversely affects okra output by disrupting blooming and fruit development. Post-harvest losses resulting from inadequate handling exacerbate the economic challenges encountered by farmers. Confronting these difficulties necessitates sustainable agricultural solutions, with vermicomposting proving to be an efficacious technique for augmenting soil fertility and increasing production.

Vermicomposting, a time-honored organic agricultural technique, entails the breakdown of organic waste facilitated by earthworms and advantageous microbes (Dominguez & Edwards, 2004). Historical records demonstrate ancient civilizations like the Egyptians and Greeks acknowledged the significance of earthworms in the maintenance of soil fertility. Cleopatra (69–30 B.C.) regarded earthworms as sacred for their contribution to agricultural output in the Nile Valley, whereas Aristotle (384–322 B.C.) described them as “the intestines of the earth” in acknowledgment of their function in soil health (Barik et al., 2011). While traditional composting methods have been utilized for generations, contemporary vermicomposting techniques emerged in the 20th century, with scholars such as Dr. Thomas J. Barrett leading the investigation of earthworms in organic waste decomposition. Currently, vermicomposting is extensively utilized in sustainable agriculture, waste management, and organic agricultural efforts (Sundari & Gandhi, 2013).

Vermicompost, a nutrient-dense organic amendment, is generated via the biological decomposition of organic matter by earthworms and microorganisms. This method converts organic waste into a stable, humus-like substance with improved microbial diversity and nutrient accessibility. The increasing need for sustainable agricultural methods has enhanced the importance of vermicomposting as an environmentally benign substitute for artificial fertilizers (Nonthapa et al., 2024). Vermicompost is distinguished by its elevated organic matter content, enhanced soil structure, and the existence of advantageous microbial communities that promote plant development and inhibit diseases (Abad & Shafiqi, 2024). In contrast to traditional composting, which depends exclusively on microbial decomposition, vermicomposting enhances the breakdown of organic matter via the digestive processes of earthworms, hence

facilitating nutrient availability for plants (Suhani et al., 2023). Frequently utilized earthworm species are *Eisenia fetida* (red wigglers), *Perionyx excavatus*, and *Eudrilus eugeniae* (African nightcrawlers), all characterized by elevated reproduction rates and effective waste-processing capabilities (Nonthapa et al., 2024). The existence of these earthworms augments microbial activity, hence enhancing soil aeration, water retention, and nutrient cycling (Iqra Khalid et al., 2023).

**Table 1**  
*Earthworm waste decomposition efficiency*

Species	Reproduction rate	Optimal Temperature °C	Decomposition efficiency	Preferred waste type
<i>Eisenia fetida</i>	High	15-25°C	Fast	Organic waste
<i>Perionyx excavatus</i>	Medium	20-30°C	Moderate	Manure
<i>Eudrilus eugeniae</i>	High	25-30°C	Fast	Organic and manure mix

(Blouin et al., 2019)

A primary benefit of vermicomposting is its abundant nutritional content. Vermicompost comprises key macronutrients, including nitrogen (N), phosphorus (P), and potassium (K), as well as critical micronutrients such as calcium, magnesium, zinc, and iron (Mistry, 2015). Research demonstrates that vermicompost generally contains 9.15–17.88% organic carbon, 0.5–0.9% total nitrogen, 0.1–0.26% phosphorus, and 0.15–0.256% potassium, rendering it an exceptionally excellent soil amendment (Manyuchi et al., 2018). In contrast to conventional fertilizers, which frequently cause soil acidity and nutrient loss, vermicompost boosts soil structure, promotes microbial biodiversity, and elevates plant development hormones including auxins and cytokinins (Aslam et al., 2020). These characteristics render it especially advantageous for crops such as okra, which need balanced nutrient availability for maximum development and yield.

**Table 2**  
Physiochemical Characteristics of Maize feedstock and Vermicompost

Parameter	Feedstock	Vermicompost
Organic Carbon, OC (%)	8.39-8.68	5.21-5.25
Total Nitrogen, Tn (ppm)	2638.2-3125.7	4454.8-5331.7
Total Phosphorus, P (ppm)	419.4-423.5	796.3-838.1
Total Potassium, K (ppm)	1365.9-1587.2	1915.8-2384.7
Sodium, Na (ppm)	319.5-322.8	457.8-463.2
Calcium, Ca (ppm)	1679.9-1722.8	1897.9-1904.6
Magnesium, Mg (ppm)	398.9-423.8	543.7-546.8
pH	6.1-6.3	6.6-7.4
Moisture content (%)	50.5-60.5	52.5-53.5

Manyuchi, M., Mbohwa, C., & Muzenda, E. (2021).

The combined application of vermicompost and NPK fertilizers markedly enhances soil fertility, crop output, and general plant health in comparison to the use of either fertilizer independently. Vermicompost improves soil structure by enhancing aeration, water retention, and microbial activity, hence increasing nutrient retention and absorption efficiency for plants (Lakra et al., 2017).

Vermicompost, when used with NPK fertilizers, functions as a slow-release organic amendment, providing key macronutrients like nitrogen (N), phosphorous (P), and potassium (K) in a more prolonged way. Research indicates that the utilization of 50% NPK fertilizer combined with 100% vermicompost resulted in substantial enhancements in okra growth, evidenced by increased plant height (115.69 cm), a higher fruit yield per plant (20.71), and improved soil characteristics, including elevated organic carbon (0.84%) and available nitrogen (229.48 kg ha<sup>-1</sup>) (Lakra et al., 2017). The enhancement of soil health via vermicompost application diminishes nutrient leaching and increases microbial biomass, hence promoting long-term soil sustainability (Chowdhury et al., 2024).

Furthermore, several studies have shown that vermicompost and NPK fertilizers work well together, especially when it comes to improving the physical and chemical characteristics of soil, which has a direct impact on plant development and production. According to a research on okra growing, the maximum fruit yield (141.33 q ha<sup>-1</sup>) was obtained when vermicompost (5 t ha<sup>-1</sup>) and the required dosage of NPK fertilizers were applied together, as opposed to when chemical fertilizers were used alone (Chowdhury et al., 2024). Furthermore, soil treated with both amendments had greater levels of accessible nitrogen (292.33 kg ha<sup>-1</sup>), organic carbon content (0.52%), and pore space (48.83%), all of which improved nutrient availability and plant absorption efficiency (Chowdhury et al., 2024). Auxins and gibberellins, two hormones that promote plant growth, are also present in vermicompost. These hormones encourage root formation and general plant vigor, which increases agricultural output (Kumar et al., 2023). By lowering reliance on synthetic fertilizers and preserving high crop yield and soil health, this combination technique is regarded as a successful option for sustainable agriculture (Manyuchi et al., 2021).

### Mechanism of Vermicomposting

Vermicomposting is a sustainable waste management method that turns organic waste into nutrient-rich compost by using earthworms and microbes. By increasing the soil's microbial diversity, enzymatic activity, and nutrient availability, this procedure improves soil fertility and plant development (Abad & Shafiqi, 2024). Vermicomposting has become more well-known recently as an environmentally beneficial substitute for artificial fertilizers, providing a number of agronomic and environmental advantages.

### Role of Earthworms and Microbes in Composting

Vermicomposting is a biological process that utilizes the interaction between earthworms and microorganisms to decompose organic matter. Earthworms are essential for the fragmentation and aeration of organic waste, whereas microbes facilitate biochemical degradation and nutrient transformation (Dominguez & Edwards, 2004).

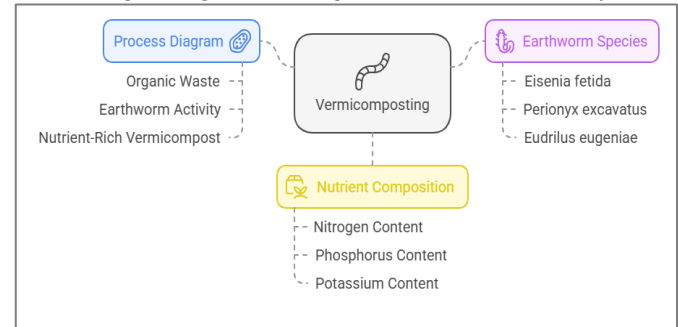
Earthworms, including *Eisenia fetida* and *Perionyx excavatus*, facilitate the decomposition process by consuming organic residues that are subsequently transformed by microbes within their digestive systems.

Earthworm castings contain high levels of humic substances, plant growth hormones, and essential nutrients, including nitrogen (N), phosphorus (P), potassium (K), and micronutrients (Abad & Shafiqi, 2024).

Microbial communities, comprising bacteria, fungi, and actinomycetes, enable the enzymatic degradation of complex organic compounds, including cellulose, lignin, and proteins (Nonthapa et al., 2024). Proteases, amylases, lipases, and cellulases persist in decomposing organic matter post-excretion by earthworms, thereby facilitating continuous nutrient release (Aslam et al., 2020).

**Figure 1**

*Vermicompositing: Process, Species and nutrient Benefits*



### Nutrient Cycling and Enrichment Process

The nutrient cycling process in vermicomposting encompasses the mineralization and humification of organic matter, resulting in the release of bioavailable nutrients. Nitrogen transformation is facilitated by microbial processes such as ammonification, nitrification, and nitrogen fixation, which improve soil fertility and enhance plant uptake efficiency (Blouin et al., 2019).

Research indicates that the application of vermicompost markedly enhances soil enzymatic activity, specifically increasing the activities of  $\beta$ -glucosidase, urease, and catalase, which facilitates organic matter decomposition and nutrient cycling (Ramazanoglu, 2024). Additionally, hormone-like substances including auxins, cytokinins, and gibberellins found in vermicompost enhance plant growth and stress tolerance (Dessai et al., 2023).

### Types of Vermicompost

Vermicompost can be classified based on the feedstock composition, which influences its nutrient content, microbial diversity, and decomposition efficiency. The selection of feedstock is crucial, as different raw materials yield varying nutrient profiles and soil amendments (Blouin et al., 2019).

### Importance of Feedstock Composition in Nutrient Availability

The availability of nutrients in vermicompost is primarily influenced by the type of feedstock utilized. Animal manure-based vermicompost typically exhibits higher levels of nitrogen and phosphorus, whereas crop residue-based vermicompost is characterized by increased organic carbon and lignin content, which decomposes at a slower rate (Iqra et al., 2023).

The carbon-to-nitrogen (C:N) ratio is a crucial determinant of vermicomposting efficiency. A C:N ratio of

20:1 to 30:1 promotes balanced microbial activity and nutrient release (Mbohwa et al., 2017).

### General Classification of Vermicompost Based on Feedstock

The primary classification of vermicompost includes:

- **Dung-Based Vermicompost** (e.g., cow dung, poultry manure) (Iqra et al., 2023).
- **Crop Residue-Based Vermicompost** (e.g., wheat straw, maize straw, sugarcane bagasse) (Mbohwa et al., 2017).
- **Organic Waste-Based Vermicompost** (e.g., vegetable waste, fruit peels, leaf litter) (Abad & Shafiqi, 2024).
- **Industrial Waste-Based Vermicompost** (e.g., food processing waste, agro-industrial residues) (Nonthapa et al., 2024).

Each type of vermicompost has unique characteristics that impact soil fertility and plant growth.

#### Dung-Based Vermicompost

##### Nutrient Profile and Impact on Soil:

Dung-based vermicompost, originating from cow, poultry, or goat manure, contains high levels of nitrogen (N), phosphorus (P), and potassium (K). It increases microbial activity and enhances soil porosity, aeration, and moisture retention (Iqra et al., 2023). Research indicates that vermicompost derived from cow dung markedly enhances crop yield and plant biomass, attributed to its elevated nutrient levels and well-balanced microbial composition (Khalid et al., 2023). Dung-based vermicompost also enhances rhizobium nodulation in leguminous crops, thereby improving nitrogen fixation and soil fertility (Dessai et al., 2023).

#### Wheat Straw-Based Vermicompost

##### Organic Matter and Microbial Activity:

Vermicompost made from wheat straw is a great source of organic carbon that enhances soil structure and microbial diversity (Ramazanoglu, 2024). For crops like vegetables and grains that need a high organic matter content, this kind of vermicompost is very helpful. The breakdown process is accelerated and the availability of secondary metabolites that support plant development is increased when cellulose-degrading bacteria and fungi are present in wheat straw compost (Nonthapa et al., 2024).

#### Maize Straw-Based Vermicompost

##### Microbial Diversity and Decomposition Efficiency:

Vermicompost derived from maize straw enhances microbial activity, especially among actinomycetes and fungi, which are essential for the degradation of organic matter and the process of humification (Mbohwa et al., 2017). Studies demonstrate that maize straw compost improves root growth and increases water retention in sandy soils, positioning it as a beneficial amendment for arid and semi-arid areas (Dessai et al., 2023).

#### Sugarcane Straw-Based Vermicompost

Sugarcane straw-based vermicompost contains high levels of polysaccharides and organic acids, enhancing soil microbial interactions and nutrient solubilization (Abad & Shafiqi, 2024). Its high potassium content makes it

especially advantageous for potassium-demanding crops, including bananas and sugarcane.

### Impact on Crop Growth

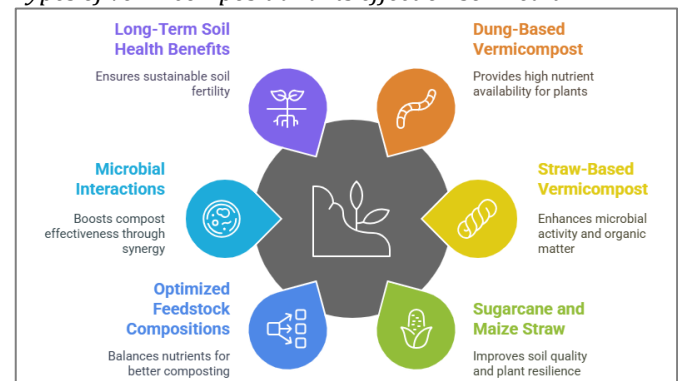
- Improves **potassium solubilization** for enhanced fruit quality.
- Enhances **soil microbial biomass** and organic matter stability.
- Reduces **disease incidence** by promoting beneficial microbial communities (Nonthapa et al., 2024).

By converting organic waste into nutrient-rich compost, vermicomposting is a biologically driven process that improves soil fertility and plant development. For agriculture to be sustainable, microorganisms and earthworms play a critical role in the cycling of nutrients. Vermicomposting's nutritional content, microbial diversity, and agronomic advantages depend on the kind of feedstock employed.

While straw-based vermicompost improves microbial activity and organic matter enrichment, dung-based vermicompost offers high nutritional availability among the various forms of vermicompost. Vermicompost made from sugarcane and maize straw enhances soil quality and increases plant resistance to environmental stresses. As vermicomposting research develops, more study should concentrate on microbial interactions, optimal feedstock compositions, and long-term soil health advantages.

**Figure 2**

*Types of vermicompost and its effect on soil health*



### Comparative Case Studies

#### Global Case Studies: Evaluating Growth, Yield, and Soil Health

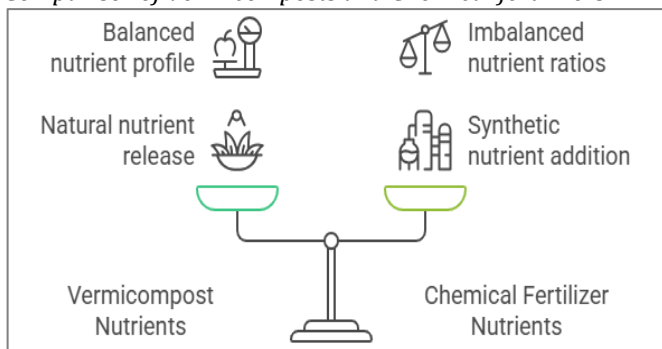
##### Case Study 1: Vermicompost as an Alternative to Inorganic Fertilizers in Côte d'Ivoire

A field research in Côte d'Ivoire investigated the efficacy of vermicompost as a substitute for inorganic fertilizers to enhance okra yield. Over three growing seasons, researchers evaluated the impact of vermicompost-treated plots against those treated with standard chemical fertilizers on plant growth and yield (Coulibaly et al., 2021). The research indicated that plants treated with vermicompost displayed markedly enhanced germination rates, increased height, greater leaf count, and higher fruit output, underscoring its viability as a sustainable option. The tallest plants, measuring 1.88 m, were recorded with inorganic fertilizer treatments, whereas okra plants cultivated with vermicompost reached 1.78 m, demonstrating similar vegetative growth ability. Furthermore, blooming transpired almost 14 days sooner

in plots treated with vermicompost, indicating improved nutritional bioavailability and hormonal activity. With terms of fruit yield, the average number of fruits per plant was 34.5, closely resembling the 34.2 seen with inorganic fertilizer treatments. The overall okra production in plots treated with vermicompost was  $8.7 \text{ t ha}^{-1}$ , which was comparable to the  $8.85 \text{ t ha}^{-1}$  seen in chemically fertilized plots. Vermicompost shown enhanced impacts on soil health by maintaining pH levels at 6.8, therefore mitigating soil acidification commonly linked to the overuse of chemical fertilizers. Furthermore, microbial biomass carbon rose by 45%, enhancing soil microbial activity and the breakdown of organic materials. These findings highlight that vermicompost may efficiently substitute synthetic fertilizers, promoting plant growth and preserving soil health while diminishing reliance on chemical inputs.

**Figure 3**

*Comparator of Vermicomposts and Chemical fertilizers*



### Case Studies on Specific Crops and Vermicompost Efficiency

#### Case Study 2: Effect of Vermicompost on Wheat in Pakistan

A field experiment in Pakistan examined the effects of crop residue-based vermicompost on wheat yield, specifically under drought stress circumstances (Ahmad et al., 2022). The research contrasted wheat planted using vermicompost against that produced with synthetic fertilizers, examining factors such as plant height, biomass buildup, soil moisture retention, and grain production. Results indicated that wheat plants treated with vermicompost exhibited a 10% increase in height compared to those receiving conventional fertilizers, reflecting enhanced root stability and nutrient uptake. The research indicated a 35% rise in grain production in soils supplemented with vermicompost, due to improved water retention and increased microbial activity. Dry matter accumulation was significant, with root and shoot biomass rising by 27–40%, indicating enhanced physiological development under organic nutrition control. The use of vermicompost markedly enhanced soil structure, augmenting water retention capacity by 30%, a crucial element for crop resilience in arid climates. Moreover, soil infiltration rates enhanced by 15%, mitigating compaction and facilitating greater root penetration. The findings demonstrate that vermicompost promotes wheat growth and production while alleviating water stress by improving soil moisture retention and microbial enrichment, rendering it an excellent soil supplement for semi-arid and drought-prone areas.

#### Case Study 3: Vermicompost and NPK in Okra Cultivation – A Meta-Analysis

A comprehensive meta-analysis of 68 independent experiments aggregated data on the impact of vermicompost treatment in okra production, offering quantitative evidence of its impacts on plant development, yield, and soil characteristics (Blouin et al., 2019). The investigation indicated that vermicompost enhanced plant height by an average of 26%, illustrating its efficacy in fostering robust vegetative development. Furthermore, shoot biomass grew by 78%, while root biomass exhibited a 57% enhancement, underscoring the significance of vermicompost in promoting root proliferation and nutrient absorption efficiency. The total commercial output rose by 126%, demonstrating that vermicompost substantially enhances plant production. The study assessed soil physical characteristics, observing a 15% decrease in soil bulk density, which enhanced porosity and root penetration. Furthermore, the content of soil organic matter rose by 9.2–17.9%, hence enhancing long-term soil fertility. This meta-analysis demonstrated compelling evidence that vermicompost serves as a feasible substitute for synthetic fertilizers while also improving plant health, soil structure, and sustainable agricultural yield.

#### Case study in India

##### Case Study 1: Okra Growth and Yield Under Vermicompost and NPK in India

A comparative analysis in Uttar Pradesh, India, investigated the synergistic impact of vermicompost and NPK fertilizers on the growth, yield, and soil health of okra. Researchers conducted a factorial experiment to evaluate the effects of several fertilizer combinations, including full dosages of NPK, vermicompost, and farmyard manure (FYM), on crop performance (Lakra et al., 2017). The research indicated that the administration of 100% vermicompost led to plants attaining a height of 115.69 cm, exceeding the growth recorded in plants treated solely with NPK fertilizers. Okra plants grown on vermicompost-enriched soil demonstrated the highest branch proliferation (48.5 branches per plant), which directly associated with increased canopy expansion and fruiting capacity. Flowering commenced sooner in plants treated with vermicompost, whereas dry matter accumulation peaked at  $199.21 \text{ q ha}^{-1}$ , signifying improved biomass output and higher soil fertility. The quantity of harvests per season was markedly higher in plants treated with vermicompost, extending the harvesting cycle and enhancing total crop yield. The cumulative okra yield with the vermicompost + NPK treatment attained  $199.21 \text{ q ha}^{-1}$ , markedly surpassing yields from NPK-only treatments. Besides enhancing production, vermicompost strongly influenced soil biological activity, microbial respiration, and enzymatic processes, notably increasing dehydrogenase and phosphatase activity in comparison to control plots. The soil cation exchange capacity (CEC) improved, resulting in enhanced nutrient retention and less nutrient leaching. The research determined that the use of vermicompost with traditional fertilizers maximizes nutrient utilization efficiency, increases crop productivity, and boosts long-term soil vitality, rendering it a feasible approach for sustainable agriculture.

### Economic Viability of Vermicompost Application

In addition to its agronomic benefits, vermicompost has been recognized as an economical alternative for farmers, providing financial advantages in conjunction with enhanced soil health. A research in Nepal assessed the economic viability of vermicompost application, determining a Benefit-Cost Ratio (B:C) of 1.59, indicating that for each unit of cost invested, farmers received 1.59 times their investment in returns (Acharya et al., 2024). This study indicated that the use of vermicompost decreased fertilizer expenses by 30%, rendering it a viable alternative for resource-constrained farmers aiming to minimize production costs. Furthermore, productivity enhancements resulting from vermicompost resulted in a 25% rise in farm profitability, illustrating its potential as a financially feasible and environmentally friendly substitute for synthetic fertilizers. Vermicompost provides a sustainable economic benefit for farmers shifting to organic or integrated farming systems by improving crop production, lowering input expenses, and fostering soil sustainability.

### Advantages of Vermicompost in Agriculture

#### Soil Fertility Improvement

Vermicompost improves soil structure and nutrient availability, which raises soil fertility. Because vermicompost contains humic compounds, it helps retain vital nutrients, limiting nutrient loss and encouraging soil aggregation. Applications of vermicompost have been found to improve soil microbial biomass, organic carbon levels, and enzyme activity, all of which are linked to improved plant health and increased fertility (Suhani et al., 2023). Vermicompost is a useful supplement for soils that are prone to acidification since it also increases the soil's ability to buffer pH (Choudhary et al., 2024). Additionally, it increases the availability of micronutrients that are essential for plant metabolism, such as manganese (Mn), iron (Fe), and zinc (Zn).

#### Enhancement of Plant Growth and Yield

Vermicomposting has been shown to improve root development and nutrient absorption efficiency, which in turn increases plant growth and agricultural productivity (Kalika-Singh et al., 2022). Vermicompost has been shown in several experiments to improve germination rates, biomass buildup, and fruit output in crops including wheat (*Triticum aestivum* L.), tomatoes (*Solanum lycopersicum*), and okra (*Abelmoschus esculentus* L.) (Kumar et al., 2024). According to Choudhary et al. (2024), using vermicompost in conjunction with NPK fertilizers increased okra yields and plant height, confirming its significance in agricultural production. Vermicompost also promotes shoot growth and root elongation, which results in stronger, more durable plants.

#### Microbial and Enzymatic Activity Stimulation

Vermicompost promotes a vibrant microbial community that improves disease prevention and soil nutrient cycling. According to Nonthapa et al. (2024), it contains mycorrhizal fungi, phosphate-solubilizing microorganisms, and nitrogen-fixing bacteria that enhance soil fertility and plant resistance to diseases. Protease, cellulase, and chitinase enzymatic activities aid in the breakdown of organic materials, increasing the bioavailability of nutrients for plants (Suhani et al., 2023).

Furthermore, the application of vermicompost has been associated with elevated dehydrogenase activity, a sign of better soil health and microbial respiration (Kumar et al., 2024). Additionally, vermicompost adds gibberellins and auxins, which are plant growth regulators that improve plant vigor and production.

#### Pest and Disease Suppression

Vermicompost is well-known for its capacity to inhibit pests and soil-borne pathogens, lowering the prevalence of illnesses such as Fusarium wilt and damping-off (Kalika-Singh et al., 2022). Vermicompost's beneficial microorganisms encourage natural biocontrol systems that prevent the growth of dangerous bacteria and fungi, hence lowering the need for artificial pesticides.

#### Environmental Sustainability and Reduced Chemical Dependency

Vermicompost helps reduce waste, save soil, and cut greenhouse gas emissions as a sustainable substitute for synthetic fertilizers (Kalika-Singh et al., 2022). It increases long-term soil production while reducing contamination of the soil and water by substituting artificial fertilizers. According to studies, using vermicompost in the production of wheat and vegetables lowers reliance on artificial inputs while preserving or even increasing crop yields (Ahmad et al., 2022). Furthermore, it is a crucial instrument in climate-resilient farming due to its capacity to trap carbon (Abad & Shafiqi, 2024). By increasing the amount of organic matter and microbial diversity in deteriorated soils, vermicomposting also helps to restore them.

#### Limitations and Challenges of Using Vermicompost

**Nutrient Variability and Inconsistency**  
A notable constraint of vermicompost is its variable nutritional content, influenced by feedstock type, earthworm species, and composting conditions (Choudhary et al., 2024). In contrast to artificial fertilizers that offer certain nutritional compositions, the nutrient content of vermicompost may vary, resulting in difficulties in ensuring consistent crop nutrition. This unpredictability requires meticulous monitoring and testing to improve application rates (Nonthapa et al., 2024). The gradual nutrient release in vermicompost may not consistently satisfy the immediate requirements of high-yielding crops, necessitating the use of additional fertilizers.

#### Time-Consuming Production Process

When compared to conventional composting or the creation of synthetic fertilizer, vermicomposting takes a processing time that is substantially longer. According to Abad and Shafiqi (2024), the natural decomposition of organic waste by earthworms and microorganisms can take anywhere from a few weeks to several months, and it is necessary to maintain continual monitoring of temperature, moisture, and aeration. According to Kalika-Singh et al. (2022), the scalability of vermicomposting for large-scale agricultural operations is limited due to the fact that it requires a significant amount of time. The procedure is further complicated by the fact that particular earthworm species, such as *Eisenia fetida*, are required for it to be successful.

#### Storage and Handling Issues

It is essential to store and handle vermicompost in the

appropriate manner in order to preserve the microbial activity and nutritional integrity of the compost. According to Nonthapa et al. (2024), vermicompost, because of its hygroscopic nature, has the ability to absorb moisture from the surrounding environment. This can result in microbial imbalances and the loss of nutrients if it is not stored under regulated circumstances. Furthermore, the storage and delivery of organic fertilizer on a wide scale offer logistical issues, particularly in places that lack the necessary infrastructure for the distribution of organic fertilizer (Choudhary et al., 2024). An further cause for worry is the possibility of disease development in the event that vermicompost is not treated appropriately, which calls for severe quality control procedures to be implemented.

### Market Challenges and Farmer Adoption

For a variety of reasons, including high production costs, a lack of awareness, and inadequate market infrastructure, vermicompost adoption among farmers continues to be restricted, despite the fact that it offers several benefits (Ahmad et al., 2022). Small-scale farmers are discouraged from broad adoption of vermicomposting products due to the initial investment necessary for vermicomposting units and the labor-intensive processing involved. In addition, the lack of established quality control procedures and certification systems is another factor that inhibits commercialization and the confidence of farmers (Kalika-Singh et al., 2022). It is necessary for the government to provide financial incentives, policy support, and enhanced extension services in order to boost the level of vermicompost adoption in conventional agriculture. In addition, the market demand is restricted since consumers have a limited understanding of the benefits of vermicompost in comparison to the characteristics of chemical fertilizers.

### Future Directions of Vermicomposting

A substantial amount of progress is being made in the field of vermicomposting, which has the potential to significantly enhance soil health, reduce dependency on chemical fertilizers, and contribute to sustainable agriculture. It is anticipated that the future of this industry will be shaped by technological advancements, the development of markets, and the backing of policymakers. The integration of Internet of Things (IoT) and Artificial Intelligence (AI) in vermiculture is one of the most significant breakthroughs. This connection is helping to optimize factors like as temperature, moisture, and aeration in order to increase the efficiency of composting. Vermicomposting is becoming more accessible and scalable as a result of the development of automated systems by Amin (2023). These systems are being developed to improve worm control and compost quality. Improvements in the decomposition process are also being driven by research into microbial inoculants and enzyme treatments. These advancements are leading to improved nutrient retention and increased soil fertility. Another promising trend is the creation of biofortified vermicompost, which is filled with beneficial bacteria and trace minerals. This approach ensures increased crop yields while simultaneously lowering reliance on synthetic fertilizers.

One of the reasons for the rapid growth of the vermicompost industry throughout the world is the growing awareness of organic farming and the importance of sustainability. In the period between 2022 and 2030, the vermicompost business is anticipated to expand at a compound annual growth rate (CAGR) of 15.56%, as stated by Zion Market Research. This growth is expected to be driven by the increasing demand for organic food and environmentally friendly farming techniques. Regulatory frameworks in countries such as North America, Europe, and Asia-Pacific are encouraging the use of organic fertilizers, which is leading to an increase in the demand for vermicompost of a high grade. Vermicomposting, which converts organic waste into a nutrient-rich soil supplement, reduces the amount of garbage that is sent to landfills, and minimizes greenhouse gas emissions, is gaining popularity as an effective waste management option. This is in line with existing global sustainability targets and makes a contribution to the reduction of climate change.

### Vermicomposting in India

Vermicomposting is undergoing substantial development in India, notably in terms of its potential to serve as a tool for the promotion of youth agripreneurship and rural employment of young people. Vermicomposting is being marketed as a sustainable and self-employment option, particularly in rural and peri-urban regions, in light of the fact that the unemployment rate among young people is roughly 27 percent. Vermicompost producers are receiving help from the government through programs such as the Paramparagat Krishi Vikas Yojana (PKVY) and the National Project on Organic Farming (NPOF), which together offer financial aid and training programs to boost organic farming techniques (Bordoloi, 2023). In addition, the government is providing financial assistance and other incentives to farmers who use vermicomposting, which helps them become less reliant on artificial fertilizers while simultaneously enhancing the health of the soil.

In addition, India has become a significant exporter of vermicompost, which it uses to sell organic fertilizers to markets in Southeast Asia and the Middle East. Vermicompost manufacturers in India have been motivated to enhance the product's quality, packaging, and branding qualities in response to the increased demand for certified organic products on a worldwide scale. Agricultural cooperatives, self-help groups (SHGs), and farmer-producer organizations (FPOs) are also being utilized to foster the growth of companies that are based on vermicompost. These programs are assisting small-scale farmers and agripreneurs in establishing a presence in the market while also guaranteeing that they can maintain sustainable livelihoods. The implementation of vermicomposting on a large scale has the potential to make a big contribution to India's objective of expanding organic farming and cultivating sustainable agriculture.

### CONCLUSION

The outcomes of this study indicate the considerable influence that treated vermicompost kinds and vermicompost mixed with NPK fertilizers have on the health of the soil, the growth of plants, and the production of okra (*Abelmoschus esculentus L.*). The findings suggest

that vermicomposting increases the amount of microbial activity, the amount of organic matter present, and the availability of nutrients in the soil, which ultimately leads to an increase in soil fertility. The use of vermicompost, either on its own or in conjunction with NPK fertilizers, has been demonstrated to result in enhanced crop yields, improved root development, and higher growth rates when compared to the use of standard chemical fertilizers. Furthermore, the application of vermicompost over an extended period of time adds to the improvement of soil structure, the retention of moisture, and a reduced reliance on synthetic fertilizers, which makes it a viable solution for sustainable farming as well.

There is a significant amount of potential for vermicomposting to be used in sustainable agriculture. It provides an environmentally benign alternative to synthetic fertilizers while simultaneously enhancing soil fertility and production. The utilization of vermicomposting as a means of decreasing reliance on chemical fertilizers has the potential to ultimately result in improved soil health and a reduction in environmental deterioration. The economic potential that are involved with the production of vermicompost, particularly for small-scale farmers and rural businesses, are another

reason why this agricultural innovation is appealing. The rise of the vermicompost market throughout the world further increases its economic viability, which in turn ensures the financial sustainability of organic farmers and agripreneurs. It is vital for nations like India to have policy interventions and government assistance in order to enable the widespread adoption of vermicomposting. This support can be provided in the form of subsidies, training programs, and market connections.

In addition to its economic benefits, vermicomposting acts as a significant contributor to the mitigation of climate change. It does this by lowering emissions of greenhouse gases, decreasing problems associated with waste disposal, and supporting ecologically friendly farming practices. Through ongoing research and technical improvements, its potential will be further unlocked, therefore establishing it as an essential component of the sustainability of agriculture on a worldwide scale. Vermicomposting is a viable option for a more sustainable and resilient agricultural future, particularly in light of the growing concerns regarding the deterioration of soil environments, the preservation of the environment, and the preservation of food supplies.

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