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Vermicompost: Nature's Nutrient-Rich Organic Fertilizer

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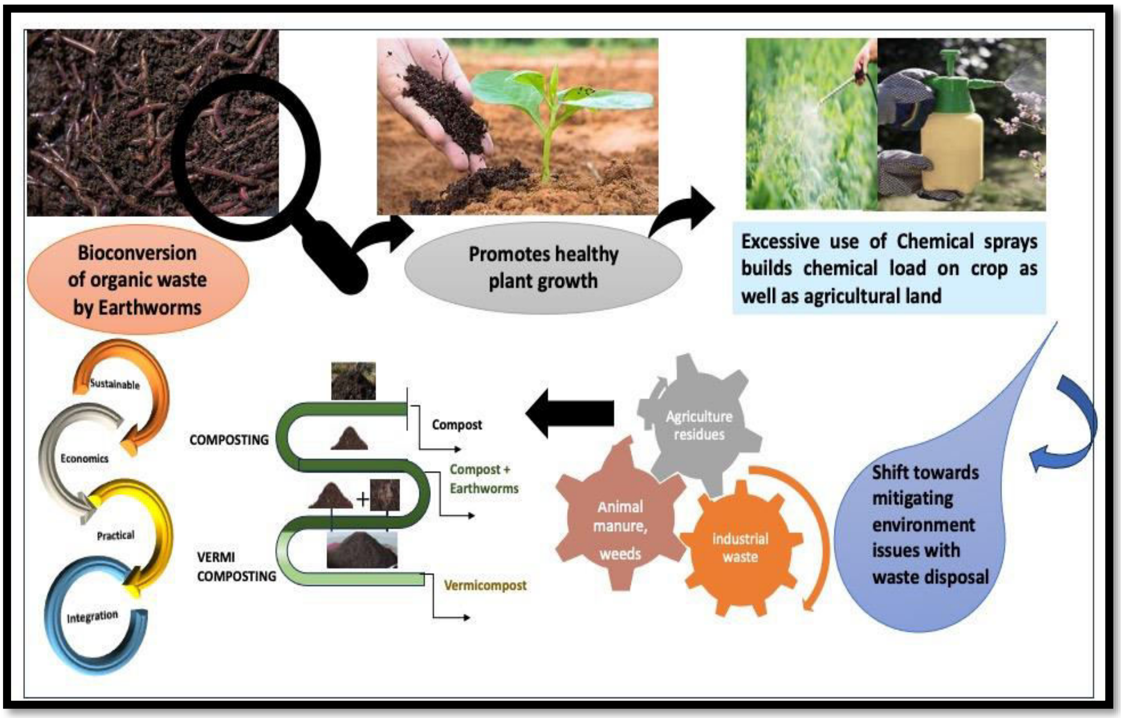
Abstract: In recent years, there has been an increasing concern regarding the environmental effects of conventional agricultural methods, especially the widespread application of chemical fertilizers and the environmentally unsustainable management of organic waste. These practices have led to soil deterioration, water pollution, and a decline in biodiversity, underscoring the necessity for more sustainable alternatives. Vermicomposting, the method of utilizing earthworms to transform organic waste into nutrient-dense compost, has become a promising approach to address these challenges. Vermicompost not only effectively recycles organic waste but also improves soil fertility and encourages vigorous plant development. The bioconversion of organic detritus via earthworms yields a product abundant in vital nutrients, advantageous microorganisms, and substances that promote growth. Unlike chemical fertilizers, vermicompost enhances soil structure, elevates its water retention capabilities, and diminishes the reliance on synthetic inputs. This study seeks to evaluate the efficacy of vermicompost as an environmentally sustainable fertilizer through an analysis of its effects on soil characteristics and plant growth. By examining the nutrient profile of vermicompost and its impact on diverse crops, this study aims to enhance the existing corpus of knowledge endorsing organic agricultural practices. Furthermore, it explores the potential of vermicompost to alleviate environmental challenges related to refuse management and intensive agricultural practices.

Key words: agricultural systems, beneficial microbes, organic waste, environmental issues, vermicompost

Graphical Abstract



1 Introduction

1.1 Definition and Overview

Vermicomposting harnesses the benefit of earthworms, mainly Eisenia foetida and Perionyx excavates, to degrade organic wastes into highly stable and nutritious levels of vermicompost. Literature on the contents of total nitrogen in vermicompost has varied between approximately 1.03 to 1.87 percent, phosphorus level at up to approximately 2.17 percent, and potassium at approximately 1.93 percent depending on the feedstock composition and the worm species utilized (Zhu et al., 2024). On diverse backgrounds less coarse substrates (such as kitchen scraps, agro-residues, paper mill sludge, and textile wastes), nitrogen, phosphorus and potassium concentrations increased significantly (up to 56-fold in the case of nitrogen and 1.4 to 6.5-fold in the case of readily available phosphorus) and total organic carbon and the C:N ratio decreased during the vermicomposting phase (Suthar, 2005). Vermicompost also becomes abundant in micronutrients like copper, zinc, manganese, and iron and possesses increased microbial and enzymatic activity related to nutrient cycling and growth regulators like auxins, gibberellins, cytokinin's, and humic acids (Singh et al., 2018). Moreover, the use of vermicompost to enrich the soil has been demonstrated to enhance chemical, biochemical, and biological soil health- such as phosphorus-transformation enzyme activities, nitrogen-binding microbe colonies, and phytopathogen suppression, like Fusarium-further contributing to its dietary application in a sustainable soil health regime (Arancon et al., 2020).

Vermicomposting may be done in a variety of structures like bins, pits or beds, and usually includes a process of layering organic matter with bedding material, made of straw or shredded paper. Earthworms flourish in a wet, open air condition, where they hasten the decay of organic materials by their digestive system (Kaur & Kaur, 2017).The resulting products are a homogeneous, fine-textured product called vermicompost, which is nutrient-rich and helpful to plant growth (Edwards &Arancon, 2004; Dominguez & Edwards, 2011).

1.2 Importance of vermicomposting

Vermicompost is acknowledged for its elevated nutrient composition and plethora of advantageous microorganisms. It markedly strengthens soil structure, improves aeration, and boosts water retention capacity, rendering it an efficient organic fertilizer and soil conditioner (Aira et al., 2002; Lazcano& Domínguez, 2011). Vermicompost has superior microbial activity relative to typical compost, resulting in enhanced nutrient cycling, elevated enzyme activity, and improved plant growth and agricultural yields (Arancon et al., 2006). Furthermore, vermicomposting is vital in sustainable waste management by repurposing organic elements that might otherwise augment landfill accumulation. Vermicomposting mitigates greenhouse gas emissions by decreasing methane and nitrous oxide released from decomposing organic waste (Edwards et al., 2011). Consequently, it provides an eco-friendly substitute for chemical fertilizers and promotes sustainable farming methods. Vermicompost, generated by the biological decomposition of organic materials by earthworms, is now recognized for its diverse advantages in agricultural and environmental sustainability. The significance can be classified into numerous essential domains, including enhancement of soil health, reduction of waste, and the advancement of low-impact agricultural systems.

1.3 Plant Growth and Productivity

1. **Enhanced Growth:** Research indicates that vermicompost stimulates plant growth, improves seed germination, and increases crop yield compared to conventional fertilizers. It acts as a growth regulator due to the presence of hormones and beneficial microbe (Table 1).

Table 1: Depicting vermicompost application rates, methods, and reported agronomic benefits for different crop types

Crop Type	Recommended Vermicompost Dose	Method of Application	Reported Effects on Growth & Yield
Cereals (e.g., wheat, rice, maize)	2–5 t/ha (partially replacing chemical fertilizers)	Basal application before sowing	Improved seed germination, increased tillering, higher grain yield
Pulses (e.g., chickpea, lentil, mungbean)	1.5–3 t/ha	Mixed with soil or applied in rows	Enhanced nodulation, higher biomass, improved protein content
Vegetables (e.g.,	2–4 t/ha **or** 500–1000	As basal dose +	Faster growth, early

tomato, brinjal, chili, okra)	g per plant	side dressing during growth	flowering, higher fruit yield and quality
Fruit crops (e.g., banana, papaya, guava, citrus)	3–5 kg per plant annually	Around root zone (ring method)	Improved flowering, fruit size, sugar content, and shelf life
Ornamental & flowering plants	250–500 g per pot	Mixed in potting mixture or as top-dressing	Increased flower number, size, and longevity
Field vegetables (leafy greens, spinach, lettuce)	2–3 t/ha	Mixed into soil before sowing	Faster leaf growth, higher chlorophyll, better market quality
Plantation crops (tea, coffee, sugarcane)	2–5 t/ha	Applied in furrows or near root zone	Increased shoot growth, yield, and resistance to pests/diseases

2. Disease Resistance: The beneficial microorganisms in vermicompost can help protect plants against diseases by outcompeting pathogens for resources and space. This natural defence mechanism contributes to healthier crops (Table 2).

Table2: Vermicompost's effect on disease suppression in major crops: recommended doses, key pathogens controlled, and improvements in plant health and yield

Crop	Major Disease Controlled	Pathogen	Vermicompost Dose Applied	Reported Effect
Tomato	Wilt	Fusarium oxysporum	2–4 t/haor 500 g/plant	Reduced wilt incidence, increased survival rate
Brinjal (Eggplant)	Root-knot nematode	Meloidogyne incognita	2–3 t/ha	Decreased gall formation, improved root growth
Chilli	Damping-off	Pythium spp.	1.5–2 t/ha	Lower seedling mortality, healthier seedlings
Potato	Early blight	Alternaria solani	3–4 t/ha	Reduced lesion formation, improved tuber yield

Cabbage & Cauliflower	Clubroot	Plasmodiophorabrassicae	2–5 t/ha	Suppressed pathogen load, stronger root system
Wheat	Root rot	Rhizoctonia solani	2 t/ha	Lower disease incidence, higher tiller number
Banana	Panama wilt	Fusarium oxysporum sp. cubense	3–5 kg/plant/year	Reduced wilt, better plant vigor
Tea/Coffee	Root diseases & collar rot	Phytophthora spp.	2–3 t/ha	Lower infection rate, improved plant stand
Beans/Pulses	Anthracnose	Colletotrichum lindemuthianum	2 t/ha	Reduced leaf spots, better pod yield
Ornamental plants	Leaf spot & blight	Helminthosporium spp.	250–500 g/pot	Improved leaf health, fewer lesions

1.4Environmental Benefits

1. **Waste Management:** Vermicomposting effectively recycles organic waste, such as kitchen scraps and agricultural residues, reducing landfill use and promoting sustainable waste management practices. Vermicomposting sends organic waste—including food scraps, yard trimmings, and paper products—from landfills away from their disposal. In addition to lowering trash volume, this lessens the generation of dangerous greenhouse gasses such as methane from the anaerobic breakdown of organic materials in landfills (Table 3 and 4).

Table 3: Represents categories of organic waste appropriate for vermicomposting and their major environmental advantages

Waste Type	Examples	Benefits
Kitchen Waste	Veg/fruit peels, tea, coffee, eggshells	Reduces household waste, rich compost
Agricultural Waste	Crop residues, straw, bagasse	Prevents stubble burning, improves soil
Garden Waste	Leaves, grass, flowers	Converts bulky biomass into compost
Animal Waste	Cow dung, poultry litter, pig manure	Recycles manure, lowers odour& pathogens
Industrial Waste	Fruit pulp, press mud, brewery waste	Utilizes agro-industry by-products

Paper Waste	Shredded paper, cardboard	Diverts biodegradable paper from landfills
Sewage Sludge	Treated municipal biosolids	Safe recycling, reduces toxicity
Food Industry Waste	Dairy, bakery, vegetable market waste	Reduces landfill load, eco-friendly
Biodegradable Packaging	Starch-based bioplastics, fibre packaging	Eco-friendly disposal

2. **Sustainable Agriculture**: As a natural fertilizer, vermicompost supports organic farming practices, reducing reliance on chemical fertilizers that can harm the environment. It is particularly beneficial for small-scale farmers by providing a low-cost, sustainable alternative. Vermicomposting recycles nutrients back into the soil by turning organic waste into beneficial compost, therefore completing the cycle in the nutrient count. In agriculture, this technique lessens the necessity for outside inputs and lessens the environmental impact of waste disposal.

2 Key Earthworm Species Used

Naturally found in decaying organic waste including leaf litter, manure piles, and compost heaps, essential earthworm species employed in vermicomposting:

1. Eisenia fetida (Red Wigglers or Red Worms) little, reddish-brown worms with a strong appetite called red wigglers. They flourish in a wide spectrum of temperatures and are therefore quite flexible in different surroundings, usually between 15 and 25°C (59–77°F). Their high reproduction rate, great capacity to consume daily organic waste, and ability to transform it into nutrient-rich vermicompost help in better composting efficiency which is perfect for fertilizing plants, their castings—worm manure—rich in nitrogen, phosphorous, and potassium. Eisenia fetida is the most often used species in commercial and domestic vermicomposting systems since of its versatility and efficiency in processing waste.

2. Lumbricusrubellus, the Red Earthworm, usually found in rich, organic soils and leaf litter, likes cooler, damp conditions. These worms have a reddish-brown appearance and are rather bigger than red wigglers. Their well-known deep digging activity helps to aerate the ground. Lumbricusrubellus breaks down organic materials rather well, however, its processing speed is rather slower than that of Eisenia fetida. Their resilience and capacity to withstand a variety of environmental conditions, however, continue to be factors of popularity.

3. Eisenia hortensis (European Nightcrawler or Dendrobaenaveneta) lives in top layers of soil rich in organic materials. Larger than red wigglers, European nightcrawlers have a bluish or pinkish colour. Their low-temperature tolerance qualifies them for composting in cooler areas. Although they do not digest organic matter as quickly as Eisenia fetida, they are nonetheless effective decomposers and are sometimes combined with red wigglers to build a stronger composting system. Apart from their part in vermicomposting, their bigger size and capacity to flourish in cooler surroundings make them a popular choice for fisherman as bait.

4. Perionyx excavates (Blue worms), sometimes known as Indian blue - Native to tropical and subtropical areas, flourish in warm, humid surroundings, usually found in rotting

plant matter. Particularly under light, blue worms are small, thin, with a bluish hue. Their fast rates of reproduction and growth are well-known, and under the correct conditions this can result in quite effective composting. Blue worms are ideal for vermicomposting in warm settings since they break down organic material quite quickly. They might not do well in colder surroundings, though, and they can be sensitive to temperature fluctuations. Perfect for tropical environments, they may greatly hasten the composting process under appropriate conditions.

Table 4: Summarizing the types of organic waste suitable for vermicomposting

Sr. No.	Category	Type of waste	Note
1.	Kitchen Scraps	Coffee Grounds and Filters- Tea Bags (without staples)- Eggshells (Crushed) – Bread and Grains-	Rich in nitrogen; worms are attracted to them and they can even digest the filters Most tea bags can be composted if they don't contain plastic Crushed eggshells add calcium and help balance pH Small amounts of stale bread, rice, pasta, and cereals
2.	Yard Waste	Leaves- Grass Clippings- Non-woody Plant Material- Weeds (without seeds)-	Especially dried leaves, which break down easily. In small amounts, as too much can create a slimy mess Soft stems, flowers, and other green waste If the weeds haven't gone to seed, they can be used
3.	Paper Products	Cardboard (Shredded)- Office Paper (Shredded)-	Brown cardboard and egg cartons, free from plastic and staples Non-glossy paper without a lot of ink
4.	Other Suitable Organic Waste	Hair and Fur- Cotton and Wool Scraps- Vacuum Dust (from natural fibers)	Pet fur and human hair, though these take a while to decompose Natural fibers only, without synthetic blends If it's free from synthetic materials

3 Factors Influencing Vermicomposting- Temperature, moisture, pH levels, and aeration

3.1 Moisture

The fragmentation, mineralization, and bioconversion of organic matter in vermicomposting depend on moisture (Palsania et al., 2008). Moisture helps earthworms maintain a thin water coating for gas exchange (Águila Juarez et al., 2011). Earthworms, which are 75–90% water, need ideal moisture levels for survival, motility, and biological activity. Earthworms leak a lot of water to survive in dry conditions, limiting their activity (Palsania et al., 2008). Earthworm proliferation is directly related to moisture level since they lack a protective layer. Most earthworms need 60–85% moisture to absorb enough to compensate for evaporation (Amaravathi and Mallikarjuna Reddy, 2015).

Earthworms lower CH_4 emissions by increasing anaerobic respiration in the latter stages of vermicomposting (Lv et al., 2016). Due to red worm gut digestive enzyme activity, cattle dung vermicomposting at 70% moisture content degrades crude fiber and increases crude protein content through mineralization (Hossen et al., 2022). Growing bacterial variety at 70% moisture improves garden waste breakdown and stability (Li et al., 2021). Vermicompost made from vegetable market solid waste at 70–80% moisture improves worm growth and breakdown, reducing organic carbon and C/N ratio (Suthar, 2005). Moisture content affects worm growth, with 70-80% favoring adult growth and 60-70% favoring juvenile growth (Águila Juarez et al., 2011). Ambient moisture keeps worms' skin wet during breathing. Composting involves temperature and moisture. Vermicomposting worm growth and activity are best at 65–75% moisture and 15–25 °C (Rostami et al., 2010). Earthworms' tolerance of temperatures outside their optimum range depends on substrate wetness. Worm growth and activity are better in mild conditions than in heat (Amaravathi and Mallikarjuna Reddy, 2015).

3.2 Temperature

Temperature impacts earthworm growth, respiration, metabolism, and reproduction. For bioconversion, they need 10–35 °C, however species preferences and tolerance vary (Garg and Gupta, 2011). Worms grow faster at 30 °C but may postpone sexual maturity. At 25 °C, reproduction rates peak. Worms travel to the top and sides of the compost bin when the temperature exceeds the ideal range, leaving unprocessed substrate in the centre (Singh et al., 2018). High temperatures promote microbial activity in the substrate, which competes for oxygen and depletes earthworms. Earthworms may hibernate in deeper soil layers under high temperatures, stopping growth at 4 °C (Domfnguez, 2004). After 16 weeks of composting, worms increase weight at 20 °C and lose weight at 5 °C (Águila Juarez et al., 2011).

During pig manure composting, Eisenia fetida has the highest antioxidant enzyme activity and reduces total organic carbon, humification index, and C/N ratio at 30 °C. Due to temperature-dependence at 19.7 °C and 0.039 mg/g in cow dung coupled with sugarcane bagasse at 25 °C (MahboubKhomami et al., 2016). Eudriluseugeniae thrives around 25–30 °C, but temperatures above 30 °C kill it (Utekar and Deshmukh, 2016). Earthworm development and bacterial diversity increase at 25°C during dewatered sludge vermicomposting, improving mineralization, breakdown, and stabilization (Zhang et al., 2020). Eisenia fetidavermicompost household trash more actively, grows faster, and reproduces in winter than summer. Winter vermicompost has more N, P, and K than summer compost (Garg and Gupta, 2011). Drawidasulcata survives and grows better at 26.5–29.5 °C during poultry litter decomposition (Yuvaraj et al., 2018).

3.3pH

Earthworms and gut microorganisms depend on substrate pH (Amaravathi and Mallikarjuna Reddy, 2015). Acidic environments diminish nutrient availability, limiting earthworm quantity, growth, and spread (Utekar and Deshmukh, 2016). Vermicomposting works best at 6.5–7.5 pH. Lower pH levels restrict bacterial activity, interrupting earthworm-microbe symbiosis and killing earthworms (Rostami et al., 2010). At pH 5.1, earthworms die 100% in municipal solid waste vermicomposting. Due to the unpleasant acidity of organic waste, Perionyx excavatus decomposed it slower at 4.3–4.8 substrate pH (Khare et al., 2005). High pH of 7.63 in cow dung and Mikania micrantha substrate mix impairs feeding activity due to excess soluble salts (Debnath and Chaudhuri, 2020). Most earthworms prefer a neutral pH, and cow dung, kitchen trash, and sugarcane straw with a pH of 7.2 produce high-nutrient vermicompost due to the worms' maximum activity (Jawaher, 2020). Alkaline cow dung (pH 8.52) helps Eisenia fetida grow and survive, unlike acidic poultry manure (pH 5.88), which kills worms (Vodounnou et al., 2016). An initial substrate pH of 7.92 (cow dung and leaf litter) helps Eudriluseugeniae decomposes (Viji and Neelanarayanan, 2015). High-acid substrate mixes like palm oil mill effluent and palm pressed fiber kill earthworms (Rupani et al., 2022). Vermicomposting wasted drilling fluid kills earthworms due to its high pH tolerance limit of 9.5 (Wang et al., 2021).

3.4 Aeration

Without respiratory organs, earthworms get oxygen and exhale CO2 by diffusion (Domfnguez, 2004). They are highly sensitive to anaerobic environments, which can significantly reduce their respiration rate when oxygen is low. Earthworms decompose best on porous, aerated organic substrates (Kaur, 2020). Insufficient aeration causes anaerobic conditions, whereas excessive aeration slows composting due to water loss (Xiong et al., 2017). Vermi-beds can become anaerobic due to poor aeration, moisture, or fat. Due to oxygen shortage and poisonous chemicals and gases generated by anaerobic bacteria, such as ammonia (NH_3), CH_4, and CO_2, earthworms might die (Munroe, 2007).

The substrate particle size should be around 5 cm for optimal aeration and decomposition, allowing for a wider surface area for microbial and earthworm activity (Águila Juárez et al., 2011). Aeration for 2 h during vegetable waste vermicomposting kills earthworms due to anaerobic conditions, while 6–10 h causes moisture loss and temperature rise. Worm growth improves with 4–6 h of aeration. Compacted 100% water hyacinth substrate generates anaerobic conditions and releases NH_3, killing earthworms (Zirbes et al., 2011).

4 Harvesting and Processing Vermicompost- Methods for separating worms and compost.- Preparation for use in soil.

Vermicompost harvesting and processing are crucial for its quality, nutritional availability, and utility in agricultural systems (Sani, 2025). After the active vermicomposting phase, characterized by a black, grainy texture and lack of organic matter, a 2 to 4week maturation period stabilizes microbial activity and humification processes (Dominguez & Edwards, 2004). Remove earthworms from the compost afterward. Manual light exposure allows worms to travel lower and eventually eliminate the upper layers of compost piles (Edwards & Bohlen, 1996). Large-scale processes benefit from mechanical screening and horizontal or vertical mobility.

To minimize moisture and preserve beneficial microbial populations, compost is air-dried in shady, ventilated places after separation (Suthar, 2007). A consistent product is achieved by sieving through fine mesh (2–4 mm) to eliminate undecomposed debris and cocoons (Atiyeh et al., 2000). Preventing anaerobic breakdown and nutrient loss requires cool, dry storage in permeable containers such jute sacks (Arancon et al., 2003).

Vermicompost can be blended into potting media or applied straight to soil. Another frequent product is vermicompost tea, an aqueous extract used as a foliar spray or soil drench to improve nutrient availability and rhizosphere microbial colonization (Singh et al., 2008). These processing and application methods greatly affect vermicompost's agronomic efficacy, soil health, and plant yield (Figure 1) .

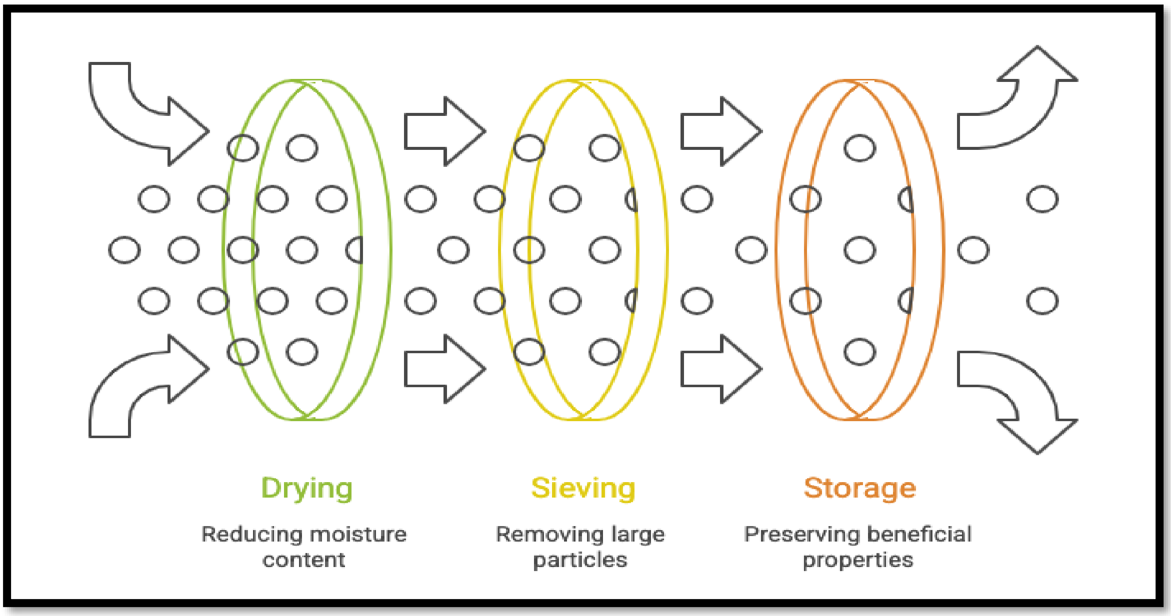


Figure 1: Representing the preparation process of vermicompost

Table 5: Nutrient Content and Soil Benefits - Nutrient Profile of Vermicompost

Nutrient	**Concentration Range**	**Role in Soil/Plant Health**	**Reference**
Nitrogen (N)	0.5% – 1.5%	Promotes leafy growth and chlorophyll production	Edwards &Arancon, 2004
Phosphorus (P)	0.1% – 0.3%	Supports root development and flower/fruit production	Atiyeh et al., 2000
Potassium (K)	0.15% – 0.6%	Enhances disease resistance and water regulation	Domínguez & Edwards, 2004
Calcium (Ca)	0.5% – 1.0%	Strengthens cell walls and aids root and leaf development	Arancon et al., 2003
Magnesium (Mg)	0.2% – 0.4%	Vital for photosynthesis and enzyme activation	Atiyeh et al., 2001
Iron (Fe)	0.01% – 0.05%	Essential for chlorophyll synthesis and respiration	Suthar, 2009
Zinc (Zn)	Trace amounts	Stimulates growth hormones and enzyme systems	Yadav & Garg, 2009
Copper (Cu)	Trace amounts	Helps in photosynthesis and respiration	Singh et al., 2010
Manganese (Mn)	Trace amounts	Assists in chloroplast formation and nitrogen metabolism	Hartenstein & Hartenstein, 1981
Organic Matter	9% – 17%	Improves soil texture, aeration, and moisture retention	Edwards & Fletcher, 1988

4.1 Impact on Soil Structure and Fertility- Improved soil texture, aeration, and water retention

4.1.1 Impact on Soil Structure and Fertility

Vermicompost improves soil structure and fertility, promoting sustainable soil management and crop productivity (Tadasse, 2025). Increased stable soil aggregates from vermicompost improve soil texture, aeration, and root penetration (Edwards &Arancon, 2004). Vermicompost's high organic matter content boosts soil water-holding capacity, lowering watering frequency and protecting plants from drought stress (Arancon et al., 2003). Additionally, vermicomposting produces polysaccharides and humic compounds that bind soil particles, generating stable aggregates that resist erosion and compaction (Lazcano& Domínguez, 2011). In addition to physical advantages, vermicompost gradually releases plant-available minerals like nitrogen, phosphorous, potassium, and important micronutrients, improving soil fertility (Table 5). These nutrients are slowly released from microbial biomass and organic compounds, reducing leaching losses (Atiyeh et al., 2000). Vermicompost improves nutrient cycling and soil biological activity by introducing nitrogen-fixers, phosphate-solubilizers, and decomposers (Aira et al., 2007). Regular vermicompost treatment improves soil health over time, making it essential to organic and regenerative farming systems.

4.2 Role of Microorganisms in Vermicompost - Beneficial microbes and their contribution to plant health

Role of Microorganisms in Vermicompost Microorganisms play a central role in the effectiveness of vermicompost, acting as key agents in both the decomposition process and the enhancement of plant health. Vermicompost is rich in beneficial microbial communities, including nitrogen-fixing bacteria, phosphate-solubilising bacteria, cellulolytic fungi, and actinomycetes, which contribute to improved nutrient availability and soil biological activity (Edwards & Arancon, 2004). These microbes not only accelerate the mineralization of organic matter but also facilitate the conversion of complex nutrients into forms readily absorbed by plants, thus enhancing the bioavailability of essential elements such as nitrogen, phosphorus, potassium, calcium, and trace minerals (Aira et al., 2007). In addition to nutrient cycling, the microbial populations in vermicompost promote plant growth and resistance to disease through various mechanisms. Certain bacteria and fungi isolated from vermicompost produce plant growth-promoting substances such as indole-3-acetic acid (IAA), gibberellins, and cytokinins (Arancon et al., 2006). Others suppress plant pathogens through competitive exclusion, antibiotic production, or the induction of systemic resistance in host plants (Zaller, 2007). For example, studies have shown that vermicompost applications reduce the incidence of soil-borne diseases like Fusarium wilt and Pythium damping-off (Edwards et al., 2007). Moreover, the microbial activity in vermicompost contributes to the formation of stable humic substances, which improve soil structure and root-soil interactions, further enhancing nutrient uptake. The synergistic action of earthworms and microorganisms during the composting process creates a biologically active product that functions not only as a fertilizer but also as a bio-inoculant, reinforcing the ecological stability of the rhizosphere. As such, the microbial component of vermicompost is vital in promoting plant vigour, yield, and resilience under both optimal and stress conditions.

4.3 Applications of Vermicompost:

4.3.1 Agricultural Utilization

Vermicompost has become a significant organic input in agriculture, acknowledged for its capacity to augment crop yields and boost soil health. The slow nutrient release and abundant microbial community in vermicompost render it highly effective for enhancing plant growth while preventing nutrient loss and soil degradation (Arancon et al., 2005). Field studies have repeatedly demonstrated yield enhancements in crops including wheat, maize, rice, and legumes when vermicompost is utilized as a primary amendment or in conjunction with diminished quantities of chemical fertilizers (Edwards &Arancon, 2004). Moreover, its impact on soil physical properties—such as enhanced structure, porosity, and moisture retention—facilitates robust root development and increased nutrient utilization efficiency. Consequently, vermicompost is integral to integrated nutrient management (INM) systems, enhancing soil sustainability and food security.

4.3.2 Soil Health and Fertility

1. Nutrient Enrichment: Vermicompost is rich in essential nutrients, including macro and micronutrients, which enhance soil fertility. It improves the physical, chemical, and biological properties of the soil, leading to better nutrient availability for plants (Edwards et al., 2011; Arancon& Edwards, 2005). Vermicomposting breaks down organic waste under control, therefore helping to lower soil and water pollution. This lowers the risk of pollution from poorly controlled trash and stops the leakage of dangerous chemicals into groundwater.

2. Enhanced Soil Structure: Vermicompost's organic components improve soil texture, water retention, and root development while also enhancing. This produces strong soils able to resist drought and erosion, therefore supporting long-term agricultural output. Vermicomposting lowers the demand for chemical inputs by offering a natural substitute for synthetic fertilizers, therefore helping to protect the environment and over time improve the quality of soil. This is consistent with ideas of sustainable land use and organic farming. The application of vermicompost enhances soil structure, aeration, water retention, and drainage. This results in reduced soil compaction and improved root growth, which is crucial for plant development (Edwards et al., 2011; Lazcano& Domínguez, 2011).

3. **Microbial Activity:** Microbial activity: Vermicompost also enhances soil microbial life and inhibits disease causing microorganisms (Table 6). This biological action assists in nutrient cycling and increases the general health of the soil ecosystem (Arancon& Edwards, 2005; Lazcano& Domínguez, 2011). This is because, by supporting a desirable ecology of microorganisms and earthworms, vermicompost promotes biodiversity in the soil; this is because microorganisms and earthworms play a critical role in nutrient cycling and soil health. This biodiversity is required to maintain such sustainable agricultural system.

Table 6: Represents key vermicompost microbial communities for nutrient cycling, disease suppression, and soil health improvement

Microbial Group	Examples	Role in Vermicompost & Soil Health	References
Bacteria	Pseudomonas, Bacillus, Azotobacter	Nutrient cycling (N-fixation, P-solubilization); antibiotic and pathogen-suppressive enzyme synthesis; and plant growth promotion.	Arancon& Edwards, 2005; Lazcano& Domínguez, 2011
Fungi	Trichoderma, Aspergillus, Penicillium	Organic matter decomposition; antifungal metabolite synthesis; mycoparasitism of soil-borne pathogens.	Arancon& Edwards, 2005
Actinomycetes	Streptomyces spp.	Decompose complex organic molecules (lignin, cellulose) and create antibiotics that kill dangerous microorganisms.	Lazcano& Domínguez, 2011
Protozoa	Amoebae, flagellates, ciliates	Regulate bacterial populations and release nutrients (N and P) in plant-available forms.	Arancon& Edwards, 2005
Earthworm-associated microbiota	Gut microbiota of Eisenia fetida	Increase decomposition, promote microbial diversity, and increase nutrient mineralization.	Lazcano& Domínguez, 2011

4.3.3Significance in Horticulture and Domestic Gardening

In horticulture and residential gardening, vermicompost is highly regarded for improving the quality of attractive plants, as well as promoting flowering and fruit development. It functions as a sustainable substitute for synthetic potting media and chemical fertilizers, offering both macro- and micronutrients as well as plant growth regulators such as auxins and gibberellins (Atiyeh et al., 2000). Vermicompost has demonstrated the ability to raise seed germination rates, expedite flowering, and improve fruit quality in plants including tomatoes, peppers, petunias, and roses (Zaller, 2007). Moreover, its utilization in lawns and turfgrass fosters verdant, disease-resistant flora by enhancing microbial diversity and inhibiting soil pathogens.Vermicompost is a safe, environmentally sustainable amendment that enhances the visual and biological vitality of both food and ornamental plants for home gardeners.

4.3.4 Vermicomposting in Sustainable Practices

Vermicomposting is closely aligned with sustainable and ecological farming techniques. Its application diminishes dependence on synthetic fertilizers and pesticides, thereby reducing the environmental impact of agricultural output. The bioactive chemicals and advantageous bacteria in vermicompost have shown efficacy in suppressing prevalent plant infections and insect pests, hence diminishing the necessity for chemical control methods (Edwards et al., 2007). Additionally, by converting organic waste into nutrient-dense compost, vermicomposting promotes the tenets of a circular economy and zero-waste agriculture. This not only reduces landfill utilization and greenhouse gas emissions but also aids in soil regeneration and climate resilience, especially in degraded or nutrient-deficient soils (Lazcano& Domínguez, 2011). Consequently, vermicompost is an essential component in organic agricultural methods, agroecology, and permaculture.

4.3.5Industrial and Extensive Applications

The commercial production and extensive application of vermicompost have markedly increased in recent years, especially in organic agriculture, plant nurseries, and municipal waste management. Industrial vermicomposting facilities convert substantial quantities of organic waste, such as agricultural byproducts, food refuse, and sewage sludge, into premium compost for local utilization and commercial markets (Singh et al., 2008). In commercial horticulture, vermicompost is included into container mixtures and seedling substrates to enhance plant vigor and transplant efficacy. Numerous countries' organic certification standards promote or mandate the utilization of vermicompost owing to its natural provenance and ecological advantages. Moreover, several firms include vermicompost into their corporate sustainability goals, utilizing it in green landscaping, bioremediation, and waste valorization efforts. The widespread application highlights the versatility and significance of vermicompost in several agricultural and environmental domains.

5. Environment and Economic Advantages

5.1 Reduction of Wastes and Recycling

Vermicomposting is a key factor in organic waste management, not only providing an efficient, decentralized technique to keep biodegradable wastes out of the ground, but also producing one of the many products of such activities. Known as organic wastes, kitchen scraps, farm waste, and manure make up a large fraction of municipal wastes and agricultural waste. This waste when not controlled leads to overflow of landfills, methane emission and degradation of the environment. Through recycling of organic waste into high-value compost, vermicomposting contributes to waste valorization which fits into the idea of circular economic and sustainable development (Nair et al., 2006). Vermicomposting has been applied in many municipal and institutional facilities around the world as a solid waste reduction program, which has resulted into a substantial reduction in the input of raw materials into the landfills and further environmental transmission costs.

5.2 Carbon sequestration

Besides waste minimization, the vermicompost process leads to carbon sequestration, which is the supporter of climate change mitigation. In the process of composting, much of the organic carbon is stabilized in form of humic substances and complex organic molecules which remain in the soil over long periods of time (Lal, 2004). When this carbon, in form of vermicompost, is applied to the agriculture land, it joins the pool of soil organic matters, benefiting the soil structure and long-term fertility as a sink of carbon. In contrast to decomposing uncontrollably in landfills, where methane as a source of greenhouse gases is emitted, vermicomposting allows aerobic decomposition to occur with only minor amounts of greenhouse gases. Inclusion of vermicomposting in the management of the soil would allow the farmer to increase its ability to hold carbon in the soil and thus help combat the global challenge of limiting the amount of carbon dioxide in the air.

5.3 Vermicomposting Cost-Effectiveness

At the economic level, vermicomposting is a low input and high output technique that both smallholders and commercial growers can trust. The setup costs and upkeep of the initial infrastructure are low particularly as compared to man-made fertilizers that are highly energy intensive and are progressively costly. The organic wastes used to produce vermicompost are frequently found at the farm or in households hence input costs are reduced and production of a high value product ensues (Yadav & Garg, 2011). Vermicompost has been demonstrated to lessen the dependence on chemical resources in agriculture without affecting yields, which will in turn decrease production costs and increase the profitability of farms (Arancon et al., 2004). Small scale producers and entrepreneurs may also sell vermicompost and similar products (e.g. vermiwash, worm tea) this will provide the income generating activity and green rural economies.

5.4 Challenges and limitations

With numerous benefits, vermicomposting is not devoid of some limitations. The key disadvantage is the necessity of constant environmental conditions: the worms that are used in composting (e.g., Eisenia fetida) are resistant to heavy temperatures, changes in moisture level, unbalanced pH. Mismanaged systems may lead to poor smells, infestations (fruit flies, etc.), and pathogen growth, especially in the small house/wrongly ventilated units (Frederickson et al., 1997). Moreover, the industrial application of vermicomposting needs logistical arrangement, labour enforcement, and technical expertise and this may serve as a hindrance in regions that have fewer extension support or infrastructure. The nutrient content also varies between batches of vermicompost, due to differences in feedstock quality and the conditions of the processing compound which can influence its stability as a soil amendment. These difficulties need better training, studies concerning local adaptation measures to adapt to the local conditions and development of quality control standards of the commercial vermicompost product.

6. Case Studies and Internationally Practices

6.1 Vermicomposting Initiatives that Have Been Successful

Promising vermicomposting projects have been implemented all over the world successfully showing both the usefulness and the environmental friendliness of this method in a wide variety of conditions. Vermicomposting has been used in India by farmers, municipalities, and NGOs in a systematic fashion as a cost effective tool of waste recycling and organic farming. In the case of the state of Tamil Nadu, vermicomposting was introduced in its solid waste management plan and, in doing so, it encouraged the creation of composting units at the community level and, with it came a reduction of the loads in landfills and the creation of new jobs (Kale, 2005). Likewise, the government and nongovernment organization initiatives have facilitated the utilization of vermicompost to restore soil fertility and crop production in degraded areas especially in arid and semi-arid zones by the smallholder farmers in Kenya (Mucheru-Muna et al., 2010). In the United States, commercial enterprises such as the worm power in New York have established large-scale vermicomposting to provide organic fertilizers to the growers in the green houses and organic farms that are certified. The examples of vermicomposting in different climatic, economical, and agricultural situations demonstrate the scalability issue of vermicomposting, which starts in rural situations, the grassroots, and can go to the industrial level.

6.2 Vermicompost vs. Traditional Compost Comparative Analysis

In direct comparative studies, vermicompost has always proven to be of a much higher quality and more effective than traditional (thermophilic) compost. Higher levels of available nutrients, humic substances, and beneficial microbes are usually seen in vermicompost as a result of the biological presence of the earthworms and lack of the high-temperature sterilization (Atiyeh et al., 2000). When vermicompost and traditional compost were applied to crops like tomatoes, lettuce and maize in an experimental setup, more biomass, yield and disease resistance was recorded in the plots treated with vermicompost (Arancon et al., 2004). Further, vermicompost has higher microbial diversity such as plant growth-promoting rhizobacteria and antagonistic fungi that improve the health and suppress pathogenic microbes of soil (Aira et al., 2007). Nevertheless, conventional methods of composting can be more economical and appropriate when the volume of waste to be treated is large, or when the type of waste (such as animal manure) needs to be thermally sanitized. Therefore, although there are evident biological and agronomic benefits of vermicomposting, production is more susceptible to surrounding conditions and it can be more labour intensive at large scale.

6.3 Vermicomposting innovations

Recent developments in vermicomposting are solving some of the problems it has encountered on its operations and widened its capabilities. The improvement in technologies like automated flow-through reactors enables a continuous production process with minimum manual handling, which makes the large-scale systems more efficient and hygienic (Dominguez & Gomez-Brandon, 2013). High density urban living is already using stackable bin systems and modular worm digesters to reuse kitchen waste materials in smaller areas in households and institutions. They are also researching other feedstocks like industrial sludges, paper wastes and algal biomass that can be used to make customized vermicompost mixtures that match the crops and soils (Sinha et al., 2010). Also, a combination of vermicompost with biochar, rock phosphate, or beneficial microbial inocultants has developed high-quality mixtures with increased nutrient content and antimicrobial characteristics. These inventions indicate the generalizability and sustainability of vermicomposting within the traditional as well as the innovative agricultural practices.

7Future Perspectives

7.1 Opportunities and Research Gaps

Although there has been substantial advancement in the science of vermicomposting, there are still existing gaps in research areas that are also important to be tackled. One large facet concerns the optimization of the nutrient content of vermicompost due to various feedstocks and the environmental conditions. Similarly, there is no standardization of its production method and hence varying nutrient content exists within batches making it less scalable and difficult to gain market confidence (Gajalakshmi& Abbasi, 2004). In addition, microbial ecology of vermicompost, and the role of individual bacterial and fungal species in the promotion of plant growth and inhibition of disease, has not yet been studied in depth. The development of a synergy between vermicomposting and differences in other organic waste treatments, including anaerobic digestion or biochar production, should be researched. There is also a need to conduct additional field-scale and long-term studies to determine the cumulative effects of vermicompost on soil health, stability of yields, and carbon sequestration in different agro ecological regions.

7.2 Expansive Possibility of Vermicomposting

Vermicomposting is a potentially scalable solution with the potential to achieve the global food security and sustainability objectives. With the setbacks of diminishing soil fertility and rising cost of chemicals inputs in the agricultural sector, vermicompost presents a natural solution that boosts soil health, and contributes to crop productivity. Vermicomposting has the potential to empower smallholder farmers in developing countries, particularly those in Sub-Saharan Africa and South Asia by turning farm and household waste into a commodity. In the meantime, in urban centres, decentralised vermicomposting systems can be employed to treat municipal organic wastes and become part of climate resilient cities. Remote monitoring systems and data-driven farm management methods, as elements of the digital technologies, can enable upscaling vermicomposting to more efficient and traceable systems. Wider development should also consider logistics, quality control, and the training of farmers so that performance of products is consistent and that they are widely used.

7.3 Vermicomposting Policy and Support

The future expansion of vermicomposting relies considerably on the elaboration of favourable policy frameworks and institutional support. Organic farming applications require governmental involvement including subsidies on organic farming inputs, technical training programs and public-private partnerships are vital in facilitating the widespread adoption. The role of the vermicomposting problem in sustainable development can be further strengthened by its incorporation into national waste management and climate mitigation strategies (UNEP, 2016). Also, transparent, clear rules and standards of commercial vermicompost production are also required to assure quality and consumer trust in organic inputs. Global collaboration and knowledge exchange forums e.g. FAO and UNEP can support capacity building in regions where vermicomposting is still in its early stages of development. To realize the full ecological and economic potential of sustainability transitions, it is imperative to integrate vermicomposting into policy, educational and research agendas, as the topic grows increasingly urgent.

8 Conclusions

With all the benefits it brings to both agriculture and the environment, vermicompost, which is a result of earthworms by-biological activity, has a wide range of applications. It is an activity to improve soil nutrient supply, soil hierarchy, and microbial activity as a way of improving soil fertility. Vermicompost is rich in the elements necessary to sustain a plant including the main macro- and microelements, and the plant grows well, which means augmented harvest and enlarged resistance to disease and pest. It also helps to enhance water retention and aeration of soils and thus it is especially important to those currently in dry or even degraded landscapes. Environmentally, vermicomposting offers a substantial solution to the control of organic wastes. It prevents landfilling of biodegradable wastes and helps to prevent methane emissions, as well as provides a more environmentally friendly waste cycle. In addition, its use in urban, rural, and industrial environments shows that it is versatile and scalable. In the face of the growing problem of the depletion of the soil and the creation of more waste materials, vermicompost offers itself as a natural low cost and environmental friendly way of improving the situation. Vermicomposting not only creates a valuable agricultural input by transforming the organic waste, but also decreases the reliance on chemicals as fertilizers as the organic waste can be used to complete the nutrient loop.By encouraging the popularization of vermicomposting activities, a particular emphasis to be placed on the smallholder farmers, community gardens, and urban agricultural projects, is strongly likely to increase the health of the soil and agricultural production and develop a sense of environmental responsibility. Prospectively, the implantation of vermicompost into the mainstream adoption of agricultural methods is not only a viable alternative, but a step in the right direction of food security and a long-term ecological equilibrium.

Conflicts of Interest

The authors declare no conflict of interes

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