

Vermicomposting as a Sustainable Strategy for Organic Waste Management, Nutrient Recovery and Circular Agriculture: A Quantitative Review

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Abstract – Rapid urbanization, agricultural intensification and expansion of food-processing industries have resulted in increasing quantities of biodegradable organic waste. Conventional disposal methods such as open dumping and landfilling can cause nutrient losses, greenhouse-gas emissions, odour generation and contamination of soil and water. Vermicomposting offers an alternative biological technology in which earthworms and associated microorganisms convert organic residues into stabilized, nutrient-rich vermicompost. This review evaluates the quantitative evidence for vermicomposting with particular emphasis on organic-matter degradation, nutrient recovery, physicochemical stabilization, earthworm performance, agricultural benefits and environmental sustainability. Reported studies demonstrate substantial nutrient enrichment during vermicomposting. For example, vermicomposting of food-industry waste increased total nitrogen by 60–214%, available phosphorus by 35.8–69.6% and potassium by 43.7–74.1%, while organic carbon decreased by 28.4–36.1% and the C:N ratio declined by 61.2–77.8% after 15 weeks. A recent agricultural-waste study using *Eisenia fetida* reported a reduction in C:N ratio from 26.43 to 12.23, with the optimized treatment containing 2.63% nitrogen, 1.21% phosphorus and 1.45% potassium. Recent research further demonstrates the potential of vermicomposting to recover nutrients while reducing the environmental burden associated with organic waste disposal. The review therefore considers vermicomposting not merely as a waste-treatment process but as a nutrient-recovery, soil-restoration and circular-bioeconomy technology.

Keywords – Vermicomposting; *Eisenia fetida*; organic waste; nutrient recovery; vermicompost; circular economy; soil fertility; sustainable agriculture

I. INTRODUCTION

Organic waste represents a major component of municipal, agricultural and agro-industrial waste streams. Agricultural residues, animal manure, food waste, vegetable residues, sewage-derived organic matter and food-processing wastes contain substantial quantities of carbon, nitrogen, phosphorus, potassium and micronutrients. When these materials are improperly disposed of, potentially valuable nutrients are lost while environmental problems such as odour, leachate generation and greenhouse-gas emissions may occur.

Vermicomposting provides a biological route for transforming these residues into a stabilized organic amendment. The process combines the activities of earthworms and microorganisms. Earthworms fragment organic materials, increase surface area, modify microbial habitats and facilitate biochemical decomposition. The earthworm gut and casts provide favourable microenvironments for microbial activity, contributing to mineralization and nutrient transformation. Recent research emphasizes that the interaction between earthworms and microorganisms is central to organic-matter degradation and nutrient recovery.

Among earthworm species, *Eisenia fetida* is one of the most frequently studied species because of its suitability for organic-waste conversion. Other species used in vermicomposting include *Eisenia andrei*, *Eudrilus*

eugeniae and *Perionyx excavatus*. The choice of species, substrate and environmental conditions can substantially influence the decomposition rate and characteristics of the final vermicompost.

Importantly, vermicomposting differs from conventional composting because earthworm activity contributes directly to physical fragmentation and biological transformation. Consequently, vermicomposting can produce a relatively fine, stabilized material with improved nutrient availability. The scientific interest in vermicomposting has consequently shifted from simple waste disposal toward **resource recovery and circular agriculture**. A recent review identified nutrient recovery, pollutant transformation and agricultural application as three major dimensions of current vermicomposting research.

II. VERMICOMPOSTING PROCESS AND TRANSFORMATION MECHANISMS

Vermicomposting is a controlled biological process in which earthworms consume partially decomposed organic substrates. The process generally begins with preparation or partial decomposition of the raw material, followed by introduction of earthworms. During feeding, earthworms ingest organic particles and microorganisms. Mechanical grinding within the digestive system and enzymatic activity facilitate further breakdown. The resulting casts contain transformed organic matter and enhanced microbial populations.

The process can be considered as a sequence of substrate fragmentation → microbial decomposition → mineralization → stabilization. Earthworm movement also improves aeration and mixing, thereby increasing contact between microorganisms and biodegradable organic matter. Research has shown that earthworms act as ecosystem engineers by modifying the physical environment and microbial communities associated with organic matter.

Quantitative transformation of organic matter

One of the most consistent indicators of vermicomposting efficiency is the reduction in organic carbon and C:N ratio. During decomposition, carbon is lost largely through microbial respiration as CO₂, whereas nitrogen and mineral nutrients become relatively concentrated in the remaining material.

Garg *et al.* demonstrated the effectiveness of *Eisenia foetida* in processing kitchen waste, agro-residues, institutional waste and industrial wastes over a 100-day period. Total Kjeldahl nitrogen increased by 4.4–5.8-fold, while available phosphorus increased by 1.4–6.5-fold depending on the feedstock. Organic carbon reduction was also substantial, with the greatest reduction observed in agro-residues.

This finding is important because it demonstrates that feedstock composition determines vermicomposting performance. A single conversion rate cannot therefore be applied to all organic wastes.

III. NUTRIENT RECOVERY AND VERMICOMPOST QUALITY

The major scientific advantage of vermicomposting is the conversion of organically bound nutrients into forms that are more readily available for plant uptake. Nitrogen, phosphorus and potassium are particularly important because they determine the fertilizer value of the final product.

A quantitative study of food-industry sludge mixed with organic wastes provides strong evidence. After 15 weeks of vermicomposting with *Eisenia fetida*, total nitrogen increased by 60–214%, available phosphorus by 35.8–69.6%, sodium by 39–95% and potassium by 43.7–74.1%. At the same time, organic carbon decreased by 28.4–36.1%, while the C:N ratio decreased by 61.2–77.8%.

Table 1. Quantitative changes during vermicomposting of food-industry waste

Parameter	Reported change
Total nitrogen	↑ 60–214%
Available phosphorus	↑ 35.8–69.6%
Total sodium	↑ 39–95%
Total potassium	↑ 43.7–74.1%
Organic carbon	↓ 28.4–36.1%
C:N ratio	↓ 61.2–77.8%
Processing period	15 weeks
Earthworm	<i>Eisenia fetida</i>

These changes indicate that vermicomposting simultaneously promotes organic-matter stabilization and nutrient concentration.

A more recent 2026 study further supports this pattern. Four agricultural-waste treatments were evaluated over 60 days using *Eisenia fetida*. The C:N ratio declined from 26.43 in the control to 12.23, indicating substantial stabilization. The best treatment recorded 2.63% total nitrogen, 1.21% phosphorus and 1.45% potassium.

This recent evidence is particularly valuable for a review because it demonstrates that vermicomposting remains relevant under contemporary agricultural conditions rather than being restricted to older laboratory studies.

IV. COMPARATIVE PERFORMANCE OF DIFFERENT ORGANIC WASTES

One important limitation in vermicomposting research is the variability of feedstock composition. Kitchen waste generally contains readily degradable carbohydrates and proteins, whereas straw and agricultural residues contain greater proportions of cellulose and lignocellulose. Animal manure supplies nitrogen and microorganisms, while industrial wastes may contain both nutrients and potentially toxic compounds.

Garg *et al.* compared several organic substrates and demonstrated differences in nitrogen enrichment and carbon degradation. Textile sludge produced the highest TKN enrichment, whereas agro-residues showed the greatest organic-carbon reduction.

More recent Indian research comparing buffalo dung, pressmud, moong straw, paddy straw and wheat straw found that 32–36% of raw material was reduced during vermicomposting, with final recovery ranging from approximately 64.23 to 67.37%. The reported increases in total nitrogen, phosphorus and potassium were substantial, although they varied with feedstock. For example, phosphorus increased by up to 271.4%, potassium by up to 243.18%, and manganese by up to 776.66% in selected treatments.

Table 2. Comparative quantitative performance of vermicomposting

Feedstock/study	Major observation	Quantitative response
Kitchen/agricultural/industrial wastes	TKN enrichment	4.4–5.8-fold
Different organic mixtures	P enrichment	1.4–6.5-fold
Food-industry waste	N increase	60–214%
Food-industry waste	P increase	35.8–69.6%

Food-industry waste	K increase	43.7–74.1%
Agricultural residues	Raw material reduction	32–36%
Agricultural residues	Final recovery	64.23–67.37%
Agricultural residues	Maximum P increase	271.4%
Agricultural residues	Maximum K increase	243.18%
Agricultural residues	Maximum Mn increase	776.66%

This comparison demonstrates that substrate selection is one of the most important determinants of vermicompost quality.

V. AGRICULTURAL BENEFITS AND ENVIRONMENTAL SIGNIFICANCE

The value of vermicompost extends beyond nutrient composition. Application to soil can influence organic matter, microbial activity, nutrient availability, soil structure and crop growth. Vermicompost can therefore function as both an organic fertilizer and a soil-conditioning material.

Recent reviews have reported that vermicomposting can improve soil health and crop production while simultaneously contributing to organic-solid-waste recycling. The nutrient-recovery process is particularly important because nitrogen, phosphorus and potassium present in waste materials can otherwise be lost during uncontrolled decomposition.

A review focusing on agricultural waste and vermicomposting reported that nitrogen recovery can reach approximately 76% under suitable conditions and identified an appropriate C:N range of approximately 10–23 for vermicompost-related nutrient management.

Vermicomposting may also contribute to pollutant management. The 2024 review by Wang et al. examined heavy metals, antibiotic-resistance genes, plastics and pathogens and concluded that earthworm–microorganism interactions can contribute to pollutant transformation and stabilization. However, this should not be interpreted as complete detoxification in every feedstock; contaminated substrates require specific safety assessment before agricultural application.

Challenges, Research Gaps and Future Perspectives

Despite its potential, vermicomposting is not universally applicable without process control. Earthworms are sensitive to excessive heat, salinity, unsuitable moisture, extreme pH and toxic contaminants. Feedstocks containing high concentrations of heavy metals, pesticides or industrial chemicals require particular attention.

Another important challenge is standardization. Studies use different earthworm densities, substrate combinations, moisture levels, processing durations and analytical methods. This makes direct comparison between studies difficult.

Recent research suggests that optimization should focus on carbon availability, microbial interactions, vermireactor design and mathematical modelling. A 2024 study found that managing the balance between bioavailable and recalcitrant carbon can regulate earthworm productivity and vermicompost quality, with an optimal ratio reported around 1:(0.5–1.3) under the investigated conditions.

The integration of vermicomposting with anaerobic digestion, composting, biochar and other waste-bioconversion technologies is another promising research direction. Such integrated systems could maximize recovery of carbon and nutrients while reducing the quantity of residual waste requiring disposal.

VI. CONCLUSION

Vermicomposting represents a multifunctional biological technology capable of converting organic wastes into nutrient-rich agricultural amendments. Quantitative evidence demonstrates that the process can increase nitrogen, phosphorus and potassium concentrations while reducing organic carbon and C:N ratio. Reported studies show nitrogen increases of up to 214%, phosphorus increases approaching 271% in selected agricultural-residue systems, potassium increases exceeding 243%, and substantial reductions in C:N ratio.

The evidence indicates that vermicomposting should be considered within the broader framework of circular bioeconomy and nutrient recovery, rather than simply as an alternative waste-disposal technique. Nevertheless, feedstock variability, contaminant risks, process standardization and economic scalability remain important research gaps. Future research combining quantitative mass balances, life-cycle assessment, crop-response experiments and techno-economic analysis would strengthen the evidence required for large-scale adoption.

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