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Microbial valorisation of bio-waste for sustainable bio-based fertilizer production: Advancing nutrient recovery and the circular economy

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Abstract
The increasing generation of agricultural residues, livestock manure, municipal organic waste, food-processing residues, and sewage-derived organic materials has created simultaneous environmental and resource-management challenges. These waste streams contain substantial quantities of nitrogen (N), phosphorus (P), potassium (K), carbon, and other elements required for agricultural production. Recovering these nutrients through biological and microbial processes provides an opportunity to convert waste streams into value-added bio-based fertilizers while reducing dependence on conventional synthetic fertilizers. This paper reviews microbial-assisted approaches for bio-waste valorisation, with particular emphasis on composting, vermicomposting, microbial consortia, nutrient solubilisation, nitrogen transformation, and integrated biological processing. Microorganisms such as Azotobacter, *Nitrosomonas*, and *Nitrobacter* can contribute to nitrogen transformation and nutrient enrichment during organic-waste processing. Vermicomposting combined with microbial inoculation represents a promising approach because it integrates microbial decomposition with earthworm-mediated fragmentation and stabilization of organic matter. Reported studies have demonstrated nutrient concentrations of approximately 2.1–2.6% nitrogen, 1.5–1.7% phosphorus, and 1.4–1.6% potassium in certain microbially assisted vermicomposting systems. Beyond nutrient supply, bio-based fertilizers may improve soil organic matter, microbial activity, nutrient retention, and overall soil quality. However, variability in feedstock composition, pathogen and contaminant risks, nutrient-release rates, process standardization, economic viability, and long-term field performance remain significant barriers to large-scale adoption. This paper proposes an integrated microbial bio-waste valorisation framework linking waste characterization, microbial processing, nutrient recovery, product quality assessment, agricultural application, and circular-economy evaluation.

Keywords: Bio-waste valorisation, Bio-based fertilizer, Microbial consortium, Nutrient recovery, Vermicomposting, Circular economy, Sustainable agriculture, Soil health, Organic waste management

I. Introduction

The rapid growth of population, urbanization, industrialization, and agricultural production has resulted in a substantial increase in the generation of organic and biological wastes. Agricultural residues, livestock manure, food-processing residues, municipal organic fractions, and wastewater-derived organic materials contain considerable quantities of nutrients that can potentially be returned to agricultural systems. When these resources are inadequately managed, however, they may contribute to environmental pollution, greenhouse-gas emissions, nutrient losses, odor generation, and soil and water contamination.

Conventional agriculture is strongly dependent on mineral fertilizers for supplying nitrogen, phosphorus, and potassium. Although synthetic fertilizers have played a major role in increasing agricultural productivity, their intensive and inefficient use can contribute to nutrient leaching, eutrophication, soil degradation, greenhouse-gas emissions, and depletion of non-renewable resources. Consequently, increasing attention is being directed toward nutrient recycling and alternative fertilizer sources.

Bio-based fertilizers provide an opportunity to connect waste management with agricultural production. Nutrient-rich biowastes can be transformed into fertilizer products through biological, physical, chemical, or integrated processes. Microorganisms are particularly important because they participate in decomposition, mineralization, nitrification, nitrogen fixation, phosphorus solubilization, potassium mobilization, and formation of stable organic matter.

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Vermicomposting represents a promising biological technology in which earthworms and microorganisms jointly convert organic residues into stabilized organic material. The integration of selected microbial consortia with vermicomposting can further enhance nutrient transformation and product quality. This paper examines microbial technologies for bio-waste valorisation, identifies mechanisms responsible for nutrient recovery, discusses vermicomposting-based fertilizer production, and proposes an integrated framework for sustainable bio-based fertilizer production.

II. Bio-waste as a resource for nutrient recovery

Bio-waste should not be regarded only as a disposal problem; it can also be treated as a secondary resource for recovering nutrients and organic carbon. Major sources include agricultural residues, livestock manure, municipal organic waste, food-processing waste, and selected sewage-derived organic materials.

Agricultural residues such as straw, husks, stalks, leaves, and vegetable residues contain organic carbon and varying concentrations of N, P, K, and micronutrients. Livestock manures contain organic nitrogen, phosphorus, potassium, and micronutrients but require stabilization and hygienic treatment before agricultural application. The biodegradable fraction of municipal solid waste contains food residues and garden waste and requires effective source segregation. Food-processing wastes are often rich in biodegradable organic matter and can serve as substrates for microbial conversion. Sewage-derived materials may contain nutrients but require stringent monitoring because pathogens, heavy metals, pharmaceutical residues, and other contaminants can pose risks.

The suitability of a bio-waste for fertilizer production therefore depends on nutrient concentration, nutrient availability, contamination risk, processing requirements, transport requirements, and agricultural demand.

III. Microbial mechanisms involved in bio-waste valorisation

Microorganisms are primary biological drivers of organic-matter transformation. Heterotrophic microorganisms produce extracellular enzymes that degrade cellulose, hemicellulose, proteins, lipids, and other complex organic compounds. During nitrogen transformation, organic nitrogen may be mineralized to ammonium and subsequently oxidized through nitrification:

$$\text{Organic-N} \rightarrow NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^-$$

Nitrogen-fixing microorganisms such as Azotobacter can contribute biologically available nitrogen under suitable conditions. Phosphate-solubilizing microorganisms can increase phosphorus availability through organic-acid production, chelation, and phosphatase activity. Potassium-mobilizing microorganisms can enhance the release of potassium from mineral forms. Some beneficial microorganisms may additionally produce metabolites such as indole-3-acetic acid, siderophores, and hydrolytic enzymes that influence plant growth and nutrient acquisition.

Because organic-waste conversion involves several interconnected biochemical pathways, microbial consortia with complementary functions may be more effective than isolated strains.

IV. *Microbial consortia* for bio-waste conversion

A microbial consortium can combine decomposers, nitrogen-transforming microorganisms, nitrogen-fixing microorganisms, phosphate-solubilizing microorganisms, and potassium-mobilizing microorganisms. Such combinations can support rapid organic-matter degradation, nutrient transformation, stabilization, and improved nutrient availability.

The interaction between microorganisms and earthworms is particularly relevant in vermicomposting. Microbial activity facilitates biochemical degradation, whereas earthworms physically fragment organic material and modify the microbial environment. A properly designed consortium should therefore be selected according to feedstock composition, process conditions, desired nutrient profile, and fertilizer quality requirements.

V. Microbial-assisted vermicomposting

Vermicomposting is an aerobic biological process in which earthworms and microorganisms jointly convert organic residues into stabilized organic material. A typical process consists of bio-waste collection, segregation, preprocessing, microbial inoculation, vermicomposting, maturation, screening, quality assessment, and fertilizer application.

Earthworms consume partially decomposed organic matter, fragment the material, and create conditions favorable for microbial growth. Microbial inoculation may be introduced before or during vermicomposting depending on the selected organisms and process conditions.

Reported studies involving microbial consortia such as *Nitrosomonas*, Azotobacter, and *Nitrobacter* in municipal solid-waste vermicomposting have indicated enhanced nutrient enrichment. Nutrient concentrations reported for such systems have reached approximately 2.1–2.6% N, 1.5–1.7% P, and 1.4–1.6% K. These values should be interpreted as reported values for particular processing conditions rather than universal performance benchmarks because feedstock composition, microbial inoculum, earthworm species, moisture, temperature, aeration, and processing duration can significantly affect fertilizer composition.

VI. Proposed integrated bio-waste valorisation framework

The proposed framework contains seven stages: (1) waste characterization, (2) segregation and preprocessing, (3) microbial consortium selection, (4) microbial-assisted biological conversion, (5) nutrient recovery and stabilization, (6) product quality assessment, and (7) agricultural validation.

During characterization, moisture, organic carbon, total nitrogen, available phosphorus, potassium, C/*N* ratio, pH, electrical conductivity, heavy metals, and pathogens should be assessed. Non-biodegradable materials should then be removed and the substrate adjusted for moisture and particle size. Selected microbial cultures can be introduced according to the feedstock. The biological conversion stage may employ composting, vermicomposting, anaerobic digestion, microbial fermentation, phosphate solubilization, or integrated processes.

The final product should be evaluated for NPK concentration, nutrient availability, C/*N* ratio, pH, moisture, organic carbon, pathogens, heavy metals, phytotoxicity, germination index, and storage stability. Pot, greenhouse, and field experiments should subsequently establish agronomic effectiveness.

VII. Comparative analysis of bio-based fertilizer production technologies

Composting provides relatively simple organic-matter stabilization but can experience nutrient losses. Vermicomposting combines earthworm and microbial activity and can produce biologically active amendments, although process conditions must be controlled. Anaerobic digestion provides simultaneous organic-matter conversion and biogas recovery, but digestate may require further treatment. Biochar production can improve carbon stabilization and nutrient retention but requires thermochemical processing. Microbial fermentation enables targeted biological conversion but requires control of microbial and process conditions. Microbial-assisted vermicomposting combines several biological functions and is therefore particularly attractive for integrated nutrient recovery.

VIII. Effect of bio-based fertilizers on soil health

The value of microbial bio-based fertilizers extends beyond NPK delivery. Addition of stabilized organic material can increase soil organic carbon and contribute to improved soil structure. Organic substrates can provide energy sources for soil microorganisms and potentially increase microbial biomass and functional activity. Organic

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matter can also improve nutrient retention, aggregation, porosity, and water-holding capacity. Microbial components may further enhance nutrient acquisition and plant-growth-related processes.

Consequently, bio-based fertilizers should be evaluated using a broader set of indicators that includes soil physical, chemical, biological, and agronomic properties rather than nutrient concentration alone.

IX. Circular economy perspective

A linear nutrient system follows resource extraction, fertilizer production, agricultural use, food consumption, and waste disposal. A circular nutrient system instead seeks to connect bio-waste generation with microbial conversion, nutrient recovery, bio-based fertilizer production, crop production, and subsequent return of organic residues to the cycle.

The circular-economy value of microbial bio-waste valorisation therefore arises from three simultaneous outcomes: waste reduction, nutrient recovery, and agricultural resource generation. The objective should not simply be to replace mineral fertilizers with organic products; it should be to maximize nutrient recycling while considering environmental, economic, agronomic, and social conditions.

X. Environmental and economic benefits

Microbial bio-waste conversion can reduce uncontrolled organic-waste disposal, reduce open burning of agricultural residues, recycle nitrogen and phosphorus, reduce dependence on virgin nutrient resources, support soil carbon management, and reduce nutrient losses when properly processed.

Economically, the principal opportunity is the simultaneous generation of a waste-management service and a fertilizer product. However, economic feasibility depends on collection costs, preprocessing, microbial inoculum costs, processing infrastructure, transportation distance, product quality, market demand, regulatory requirements, and farmer acceptance.

XI. Challenges and research gaps

Major challenges include feedstock variability, nutrient-release uncertainty, pathogens and contaminants, lack of standardization, uncertain long-term field performance, economic feasibility, microbial stability, and incomplete environmental assessment.

Bio-waste composition changes according to source, season, moisture, and handling conditions. Total NPK concentration does not necessarily indicate plant availability. Municipal and sewage-derived materials may contain pathogens, heavy metals, pharmaceutical residues, and plastics. Standardized production and quality-control procedures are needed to improve product consistency. Long-term multi-season field trials are also required to establish agronomic effectiveness. Finally, life-cycle assessment should account for collection, transportation, processing energy, emissions, and field application.

XII. Future research directions

Future research should focus on microbial consortium optimization, process optimization, artificial intelligence and machine-learning prediction of nutrient recovery, precision bio-based fertilization, life-cycle assessment, long-term field trials, smart bio-based fertilizers, and digital monitoring.

Machine-learning models may predict nutrient recovery from feedstock characteristics and process parameters. IoT-based monitoring of temperature, moisture, pH, oxygen, and other variables may improve process control. Future fertilizer products may combine microbial inoculants, stabilized organic matter, recovered nutrients, and controlled-release technologies.

XIII. Proposed research model

The proposed research model follows the sequence: Bio-Waste Characterization → Segregation and Preprocessing → Microbial Consortium Selection → Microbial-Assisted Vermicomposting → N–P–K Transformation and Recovery → Fertilizer Stabilization → Physicochemical and Microbiological Quality Assessment → Pot/Greenhouse Evaluation → Field Validation → Life-Cycle and Economic Assessment → Circular Bio-Based Fertilizer System.

This model integrates biological processing with agronomic, environmental, and economic evaluation rather than assessing nutrient concentration alone.

XIV. Conclusion

Microbial valorisation of bio-waste represents a promising pathway for addressing organic-waste management and sustainable nutrient supply simultaneously. Agricultural residues, animal manure, municipal organic waste, food-processing residues, and selected wastewater-derived materials contain valuable nutrients that can be recovered and transformed into bio-based fertilizers.

Microbial processes contribute to organic-matter decomposition, nitrogen transformation, phosphorus solubilisation, potassium mobilization, and development of biologically active fertilizer products. Microbial-assisted vermicomposting offers an integrated approach in which microbial degradation and earthworm activity work together to stabilize organic wastes and enhance nutrient enrichment.

Nevertheless, laboratory-scale nutrient enrichment should not be interpreted as proof of universal field effectiveness. Feedstock variability, contaminant risks, nutrient-release behavior, process standardization, production economics, microbial stability, and long-term agronomic performance require systematic investigation. Combining microbial biotechnology, vermicomposting, sensor-based monitoring, artificial intelligence, life-cycle assessment, and precision agriculture could provide a pathway toward reliable and environmentally resilient bio-based fertilizer production.

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