Nanotechnology in Compost Microbiology: A New Frontier for Sustainable Agriculture

Sonika[1], Monika Kayasth[1]*, Yamini Bhanot[1] and Riya Dua[1]

[1]*Department of Microbiology, COBS&H, CCSHAU, Hisar*

Corresponding Author
Monika Kayasth
Email: monakayasth@gmail.com

OPEN ACCESS

Keywords

Nanotechnology; Compost microbiology; Nanoparticles; Soil fertility; Nano-fertilizers; Microbial activity; Sustainable agriculture; Waste management

How to cite this article:

Sonika., Kayasth, M., Bhanot, Y. and Dua, R. 2026. Nanotechnology in Compost Microbiology: A New Frontier for Sustainable Agriculture. *Vigyan Varta* 7 (06): 80-84.

ABSTRACT

Composting is a biologically regulated process in which diverse microbial communities transform organic waste into stable, humus-rich, nutrient-enriched manure. It plays a crucial role in sustainable waste management, soil fertility improvement, and circular agricultural systems. Recent developments in nanotechnology have introduced innovative tools to improve compost microbiology and process efficiency. Nanomaterials such as metal oxide nanoparticles, nano-biochar, nanoclays, nanofertilizers, carbon nanomaterials, and nanosensors are increasingly explored for enhancing microbial activity, accelerating organic matter degradation, retaining nutrients, immobilizing pollutants, and enabling smart monitoring systems. Nanomaterials can interact with microorganisms at cellular, molecular, and biochemical levels, thereby influencing enzymatic activity, microbial growth, metabolic efficiency, and pollutant degradation. Furthermore, nanosensors and nano-enabled fertilizers are facilitating precision composting through real-time monitoring and controlled nutrient delivery. The integration of nanotechnology with compost microbiology offers significant potential to improve compost quality, reduce environmental losses, and support climate-smart agriculture. This article reviews the major applications, benefits, challenges, and future prospects of nano-enabled composting systems. Despite its promising potential, comprehensive assessment of environmental safety, nanoparticle toxicity, and long-term ecological impacts remains essential for responsible and sustainable implementation.

INTRODUCTION

The rapid growth of global population, urbanization, industrialization, and intensified agricultural practices has resulted in the generation of enormous quantities of biodegradable organic waste, including crop residues, animal manure, food waste, municipal green waste, and agro-industrial by-products. Improper disposal or unmanaged accumulation of these organic residues contributes significantly to environmental pollution, greenhouse gas emissions, nutrient loss, pathogen proliferation, and deterioration of soil and water. Therefore, the development of sustainable and efficient waste management strategies has become a major priority worldwide. Among the available biological approaches, composting is recognized as one of the most environmentally sound, economically feasible, and widely adopted technologies for converting organic waste into value-added products.

Composting is a controlled aerobic biodegradation process in which diverse microbial communities transform raw organic matter into stable, humus-like material rich in essential plant nutrients (Wang *et al.*, 2019). This process is mediated by a dynamic succession of microorganisms, including bacteria, fungi, actinomycetes, and other beneficial microbes, which decompose complex organic compounds such as cellulose, hemicellulose, lignin, proteins, and lipids into simpler forms. In addition to waste stabilization, composting provides several important agronomic and ecological benefits. It improves soil structure, enhances water-holding capacity, promotes beneficial microbial diversity, suppresses soil-borne pathogens, and ensures the slow and sustained release of essential macro- and micronutrients needed for plant growth. Despite its broad advantages, conventional composting processes often face several operational and technical limitations. These include relatively long composting duration, inefficient degradation of lignocellulosic materials, nitrogen loss through ammonia volatilization, emission of methane and nitrous oxide, unpleasant odor generation, uneven temperature distribution, and variability in final compost quality (Zhao *et al.*, 2025). Furthermore, compost derived from contaminated feedstocks may contain heavy metals, pesticide residues, antibiotics, or pathogenic microorganisms, reducing its environmental safety and agricultural value. These constraints have stimulated increasing scientific interest in innovative technologies aimed at enhancing composting efficiency, improving product consistency, and minimizing environmental impacts (Liang *et al.*, 2025).

Nanotechnology, which involves the design and application of materials within the size range of approximately 1–100 nm, has emerged as a rapidly advancing field with significant applications in agriculture, environmental remediation, and sustainable waste management. Owing to their nanoscale dimensions, nanomaterials possess distinctive physicochemical characteristics, including large surface area, enhanced reactivity, improved catalytic performance, adjustable porosity, and high adsorption capacity, making them substantially different from their bulk-form materials. These characteristics make them highly suitable for influencing biological and chemical processes within composting systems. Recent studies indicate that nanomaterials can interact with microbial cells, extracellular enzymes, organic substrates, and nutrient ions, thereby enhancing microbial metabolism, accelerating decomposition, improving nutrient retention, and facilitating pollutant immobilization or degradation. The integration of nanotechnology into compost microbiology has opened new possibilities for developing advanced composting systems. Carbon-based nanomaterials and nano-biochar can improve aeration, moisture retention, and microbial habitat formation within compost matrices. Metal oxide nanoparticles may enhance enzymatic activity and suppress harmful pathogens when applied at optimized concentrations. In addition, nanosensors are increasingly being explored for real-time monitoring of compost temperature, pH, moisture, oxygen concentration, and gaseous emissions, enabling precision compost management and automation. Similarly, the integration of nanosensors with artificial intelligence, machine learning, and Internet of Things technologies is driving the development of intelligent composting reactors capable of predicting compost maturity, optimizing aeration cycles, and minimizing greenhouse gas emissions. These advancements suggest that composting is transitioning from a traditional waste treatment practice toward a data-driven and technologically enhanced bioconversion process. Despite the considerable potential of nano-enabled composting systems, several important challenges and concerns still need to be addressed. These include the potential toxicity of nanoparticles to beneficial microorganisms, their persistence in soil ecosystems, possible bioaccumulation within food chains, economic constraints, and the lack of comprehensive regulatory frameworks governing their agricultural application (Nederstigt *et al.*, 2025). The integration of nanotechnology with compost microbiology represents a promising interdisciplinary field with significant potential for sustainable waste valorization, improved nutrient recycling, and enhanced agricultural productivity. By improving decomposition kinetics, nutrient dynamics, contaminant control, and process monitoring, nano-enabled composting systems have the potential to revolutionize organic waste management and support resilient agricultural systems in the future.

1. Role of Microorganisms in Composting

Microorganisms are the fundamental driving force behind the composting process, actively transforming organic waste into stable, humified, and nutrient-rich compost through aerobic biodegradation. Composting is increasingly recognized as a microbiome-driven process in which microbial succession, metabolic interactions, and ecological dynamics determine composting efficiency and final compost quality. Recent microbiome and metagenomic studies have provided deeper insights into the structure, succession, and functional roles of microbial communities during different composting stages. Bacteria, fungi, and actinomycetes function synergistically to degrade cellulose, hemicellulose, lignin, proteins, lipids, and other complex organic polymers into simpler compounds that can be reutilized within soil ecosystems. Bacteria dominate the early and thermophilic phases because of their rapid growth and ability to utilize soluble substrates, whereas fungi are particularly important in lignocellulosic degradation through extracellular enzymes such as cellulases, laccases, and peroxidases.

Recent studies using high-throughput sequencing and metagenomic approaches have demonstrated that microbial succession during composting is strongly influenced by environmental factors including temperature, pH, moisture content, oxygen availability, and carbon-to-nitrogen ratio. Optimized microbial consortia and microbiome engineering strategies can significantly improve compost maturity, nutrient recovery, and pathogen suppression, highlighting microorganisms as the central biological component of sustainable composting systems (Meilander & Caporaso, 2024).

2. Applications of Nanotechnology in Compost Microbiology

2.1 Enhancement of Microbial Activity

Nanoparticles such as carbon nanodots, iron oxides, zinc oxide, and silica nanoparticles can stimulate microbial growth, enzyme secretion, and metabolic activity when applied at optimized concentrations. These interactions enhance microbial respiration and accelerate decomposition of organic matter.

2.2 Acceleration of Composting Process

Nanomaterials increase specific surface area, improve substrate contact, and enhance aeration within compost piles. This facilitates faster microbial colonization, stronger thermophilic activity, and reduced composting duration.

2.3 Nano-enabled Nutrient Management

Nano-fertilizers incorporated into compost can provide slow and controlled release of nutrients such as nitrogen, phosphorus, zinc, and iron. This improves nutrient use efficiency, minimizes nutrient losses, and increases fertilizer value of compost.

2.4 Pollutant Removal and Detoxification

Certain nanomaterials function as strong adsorbents for heavy metals, pesticide residues, antibiotics, and toxic organic compounds. This improves compost safety and environmental quality, especially when waste feedstocks contain contaminants.

2.5 Smart Monitoring Using Nanosensors

Nanosensors enable real-time monitoring of compost parameters such as:

- Temperature
- Moisture
- pH
- Oxygen level
- Ammonia emission
- Methane release

This allows precise control of microbial activity and composting conditions through smart management systems

3. Advantages of Nanotechnology in Composting

- Faster decomposition rates
- Improved nutrient availability
- Enhanced compost quality and maturity
- Better pathogen suppression
- Reduced environmental pollution
- Lower greenhouse gas emissions
- Smart real-time monitoring
- Support for circular bioeconomy and sustainable agriculture

4. Challenges and Environmental Concerns

Despite its benefits, the use of nanotechnology in compost microbiology presents several challenges:

- Potential toxicity of nanoparticles to beneficial microbes
- Accumulation of nanomaterials in soil ecosystems
- Possible uptake by plants and food chain transfer
- Limited knowledge of long-term environmental effects

- High production cost of advanced nanomaterials
- Need for regulatory frameworks and safety guidelines

5. Future Perspectives

Future research should focus on:

- Development of eco-friendly and biodegradable nanomaterials
- Understanding nano–microbe interactions at molecular and genomic levels
- Integration of nanotechnology with artificial intelligence for precision composting
- Use of biosynthesized nanoparticles from plant or microbial sources
- Large-scale field applications and safety assessments
- Climate-smart compost systems with carbon sequestration potential

The combination of nanotechnology and microbiology holds significant potential for transforming waste management and agricultural practices in the coming decades.

CONCLUSION

Nanotechnology is revolutionizing compost microbiology by enhancing microbial processes, improving nutrient management, reducing contaminants, and enabling smart monitoring systems. Its integration into composting systems offers a promising pathway toward sustainable agriculture, improved soil fertility, and efficient waste utilization. Recent advances in nano-biochar, nano-fertilizers, nanosensors, and green nanomaterials indicate strong future potential. However, ensuring environmental safety, economic feasibility, and sustainable implementation will be crucial for long-term success,

REFERENCES

Liang, X., Yu, S., Ju, Y., Wang, Y., & Yin, D. (2025). Integrated management practices foster soil health, productivity, and agroecosystem resilience. *Agronomy*, *15*(8), 1816.

Meilander, Jeff, and J. Gregory Caporaso. "Microbiome science of human excrement composting." *The ISME Journal* 18, no. 1 (2024): wrae228.

Nederstigt, T. A., Frische, R. K., Ouwehand, J., & Vijver, M. G. (2025). Impacts of a nano-enabled pesticide formulation (nTiO2-coated carbendazim) and its constituents on the freshwater snail Lymnaea stagnalis & damselfly Ischnura elegans assessed via in-situ bioassays. *Ecotoxicology and Environmental Safety*, *303*, 118809.

Wang, M., Ma, L., Kong, Z., Wang, Q., Fang, L., Liu, D., & Shen, Q. (2019). Insights on the aerobic biodegradation of agricultural wastes under simulated rapid composting conditions. *Journal of Cleaner Production*, *220*, 688-697.

Zhao, L., Huang, Y., Ran, X., Xu, Y., Chen, Y., Wu, C., & Tang, J. (2025). Nitrogen transformation mechanisms and compost quality assessment in sustainable mesophilic aerobic composting of agricultural waste. *Sustainability*, *17*(2), 575.