FACTORS INFLUENCING THE COMPOSTING PROCESS OF VEGETAL WASTE: A REVIEW
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FACTORI CARE INFLUENȚEAZĂ COMPOSTAREA DEȘEURILOR VEGETALE: O ANALIZĂ DE SINTEZĂ

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ABSTRACT

Although composting is a well-established method for the biological stabilization of organic matter, in recent years advanced technologies and optimized operational strategies have been introduced, that are aimed at enhancing both compost quality and processing efficiency. These innovations, ranging from improved aeration and moisture control systems to the use of bio-activators and process monitoring tools, have significantly reduced decomposition time, while ensuring a more homogeneous, nutrient-rich final product. The aim of the paper is to systematically centralize relevant information from the literature with the purpose of identifying the key parameters that most significantly influence the composting process and evaluate the advantages and disadvantages of the most widely used composting technologies. Experimental results reported in the literature indicate that emerging processing technologies offer faster composting and improved compost quality, by enabling more efficient optimization of operating parameters. By producing higher-quality compost, these technologies enhance soil fertility, structure, and microbial activity, leading to improved nutrient cycling and water retention. In the long term, it can play a crucial role in promoting sustainable soil management, restoring degraded soils, and enhancing carbon sequestration, thereby contributing to climate change mitigation.

REZUMAT

Deși compostarea este o metodă bine stabilită pentru stabilizarea biologică a materiei organice, în ultimii ani au fost introduse tehnologii avansate și strategii operaționale optimizate, menite să îmbunătățească atât calitatea compostului, cât și eficiența procesului. Aceste inovații – de la sisteme îmbunătățite de aerare și control al umidității, până la utilizarea bioactivatorilor și a instrumentelor de monitorizare a procesului – au redus semnificativ timpul de descompunere, asigurând totodată un produs final mai omogen și mai bogat în nutrienți. Scopul lucrării a fost de a centraliza în mod sistematic informațiile relevante din literatura de specialitate, în vederea identificării parametrilor-cheie care influențează cel mai puternic procesul de compostare și a evaluării avantajelor și dezavantajelor celor mai utilizate tehnologii de compostare. Rezultatele experimentale raportate în literatura de specialitate indică faptul că tehnologiile emergente de procesare oferă o compostare mai rapidă și o calitate superioară a compostului, printr-o optimizare mai eficientă a parametrilor de operare. Prin obținerea unui compost de calitate ridicată, aceste tehnologii sporesc fertilitatea, structura și activitatea microbiană a solului, îmbunătățind ciclul nutrienților și retenția apei. Pe termen lung, compostarea poate juca un rol esențial în promovarea gestionării durabile a solului, restaurarea terenurilor degradate și creșterea sechestrării carbonului, contribuind astfel la atenuarea schimbărilor climatice.

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INTRODUCTION

Since the Green Revolution of the 1960s, the intensive use of chemical fertilizers has played a pivotal role in meeting the growing global food demand by significantly boosting agricultural productivity. While this approach has undeniably increased crop yields, it has also led to serious environmental challenges, including nutrient imbalances, soil degradation, loss of microbial biodiversity, and water pollution. In response to these issues, composting of plant residues has emerged as a promising and sustainable organic waste management strategy. This method recycles valuable nutrients back into the soil, improves soil structure and long-term fertility, and supports microbial diversity, all while maintaining a considerably lower ecological footprint compared to synthetic inputs *(Rehman et al., 2023; Sathiyapriya et al., 2024; Caba et al., 2019)*. Moreover, targeted supplementation with nutrients or microorganisms can enhance both the efficiency of the composting process and the quality of the final product by stabilizing microbial communities and optimizing nutrient dynamics *(Sánchez et al., 2017)*.

Composting is a controlled aerobic process in which organic materials, such as plant residues, food waste, or manure, are biologically decomposed into a stable, nutrient-rich product that can improve soil health and fertility. The process comprises four main stages: the initial mesophilic phase, the thermophilic phase, a second mesophilic phase, and a maturation phase. Successful composting depends on multiple factors, including the carbon-to-nitrogen (C/N) ratio, moisture content, temperature, substrate particle size, pH, oxygen availability, and the composition of the microbial community.

Microorganisms such as bacteria, fungi, and actinomycetes serve as the main decomposers, converting complex organic molecules like lignin, cellulose, and hemicellulose into carbon dioxide, heat, water, humus, and a relatively stable final product compost *(Nemet et al., 2021)*.

Composting is a sustainable alternative or complement to chemical fertilizers, offering significant environmental benefits by mitigating issues such as soil acidification, nitrate leaching, and greenhouse gas emissions. The efficiency of the composting process depends on multiple key factors, including pH, carbon-to-nitrogen (C/N) ratio, moisture content, oxygen availability, raw material type, particle size, and the composting technology employed *(Manea and Popescu, 2022; Poornima et al., 2024; Nenciu et al., 2022)*.

Optimal composting conditions typically include a C/N ratio of around 30:1, moisture content between 50–60%, and adequate aeration to maintain microbial activity and accelerate decomposition *(Manea and Popescu, 2022; Parihar and Sharma, 2021)*. Among these, aeration and temperature are critical: thermophilic conditions between 50 and 60 °C not only speed up compost stabilization but also ensure pathogen destruction.

Several studies also contrast composting with conventional agricultural practices, noting that modern intensive farming relies heavily on synthetic inputs such as chemical fertilizers, pesticides, and herbicides. While these substances can boost short-term yields, their excessive use contributes to soil degradation, reduced microbial biodiversity, groundwater depletion, and increased environmental pollution *(Zainudin et al., 2022; Nemet et al., 2021; Lu Zhang et al., 2018)*.

Globally, composting currently processes around 40% of organic waste streams, reducing dependence on synthetic fertilizers, improving soil health and water retention, and lowering greenhouse gas emissions. Methods such as passive or transitional stacks and closed reactors improve biodegradation by controlling aeration, temperature, and moisture *(Argun et al., 2017)*. In regions such as Morocco, composting is increasingly applied to manage agricultural residues like crop waste and livestock manure. By transforming these materials into nutrient-rich compost, farmers not only enhance soil fertility but also reduce their dependency on costly synthetic inputs. Moreover, composting mitigates greenhouse gas emissions that would otherwise result from traditional practices like open-air burning or anaerobic decay, thus contributing to broader climate change mitigation goals *(Oueld Lhaj et al., 2024)*.

Traditional aerobic composting methods, such as the Indore process, produce high-quality compost through regular turning of large piles, while modern approaches, like municipal solid waste (MSW) composting, are more suited to urban waste streams *(Niladri et al., 2019)*. The integration of microbial inoculants and anaerobic digestion technologies can further improve process efficiency. *(Manea et al., 2024)*. For example, composting vegetable waste from food markets can yield high-quality compost within 60 days, supporting sustainable agricultural practices *(Puntsag et al., 2022)*.

Aerobic composting methods are effective in reducing greenhouse gas emissions, whereas anaerobic processes can produce biogas but may emit methane if not carefully managed *(Esparza et al., 2020)*.

Effective composting requires the implementation of key management practices that sustain microbial activity, maximize process efficiency, and ensure high-quality final compost.

According to *Ansar et al. (2025)*, essential management practices include maintaining optimal thermophilic temperatures, controlling moisture content, ensuring regular aeration, applying microbial inoculants, and continuous monitoring of compost quality. Furthermore, the adoption of advanced composting technologies alongside supportive policy and regulatory frameworks can improve operational efficiency and enhance economic viability.

By diverting organic waste from landfills, reducing greenhouse gas emissions, and recycling nutrients back into the soil, composting directly supports the principles of a circular economy and plays a vital role in regenerative agriculture *(Obuobi et al., 2022; Sánchez et al., 2022; Hidalgo et al., 2021)* (illustrated in Fig.1).

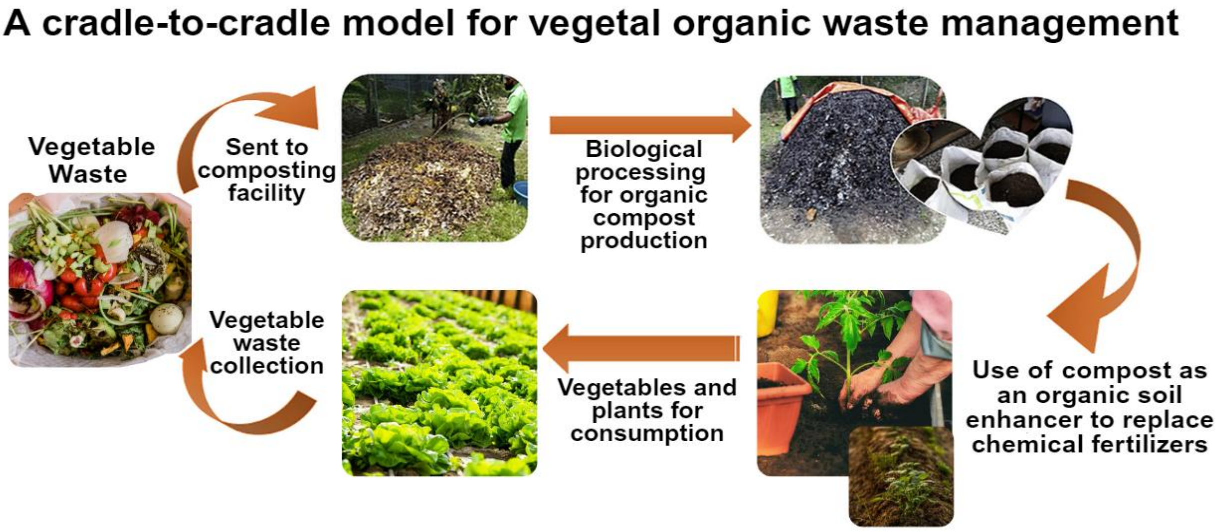

Fig. 1 - A cradle-to-cradle model for vegetal organic waste management
(adapted from Zi Xiang Keng et al., 2020)

The aim of the paper was to systematically centralize relevant information from the literature in order to identify the key parameters that most significantly influence the composting process and to evaluate the advantages and disadvantages of the most widely used composting technologies. To this end, relevant literature from major academic databases (Web of Science and Scopus) has been evaluated. Research papers with solid experimental models have been selected.

RESULTS

The efficiency of microbial activity during composting is governed by several key factors, including temperature, moisture content, the carbon-to-nitrogen (C/N) ratio, oxygen availability, and the characteristics of the plant material being composted *(Azim et al., 2018; Luo et al., 2024)*. The interdependence of these factors in the composting process is illustrated in Figure 2(a), adapted from *Kluczek-Turpeinen et al. (2007)*. Maintaining adequate oxygen levels (above 10%) through natural or forced aeration is essential to prevent anaerobic conditions, reduce harmful gas emissions such as methane and ammonia, and consequently improve compost quality while contributing to climate change mitigation *(Zelong Liu et al., 2025; Li M. et al., 2023)*. Various composting technologies, including aerated static piles, windrows, and in-vessel systems, play a significant role in determining the degradation rate and the final quality of the compost, as shown in Figure 2(b) *(Tiquia-Arashiro and Tam, 2002; Rajin et al., 2025)*. Recent technological advancements, such as automated aeration and real-time monitoring, have enhanced energy efficiency and microbial performance. Furthermore, pre-treatment methods, including particle size reduction and homogenization, facilitate microbial access to the substrate and accelerate the decomposition process *(Ponsá et al., 2009)*.

Composting proves particularly effective for managing plant-based organic waste, such as peels, crop residues, and pruning materials, which are rich in cellulose and hemicellulose. These materials, however, also present challenges due to high moisture content and variable C/N ratios *(Gezu et al., 2024; Plazzotta et al., 2017; Liu et al., 2025)*. Nevertheless, mature compost provides numerous agronomic and environmental benefits: it restores degraded soils, enhances fertility, promotes carbon sequestration, suppresses plant diseases, and improves soil water retention *(Pergola et al., 2018; Miyamoto et al., 2022; Pane et al., 2016)*.

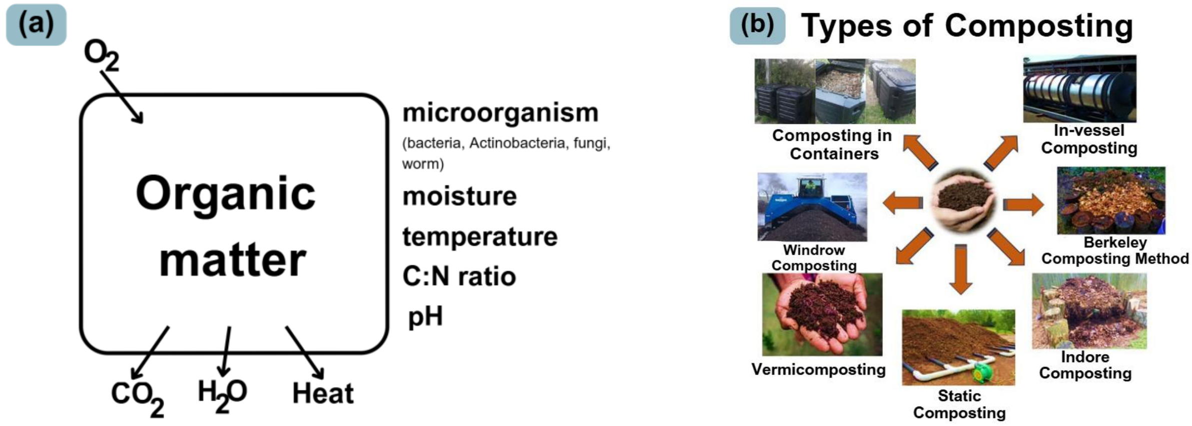

Fig. 2 - Overview of the composting process and associated technologies:
(a) The composting process and key factors affecting it *(adapted from Kluczek-Turpeinen et al., 2007)*
(b) Types of composting technologies *(adapted from Chakravorty et al., 2024)*

Moreover, it reduces dependence on chemical fertilizers and pesticides, thereby lowering production costs and minimizing environmental impact *(Ștefan et al., 2021)*. Nevertheless, current composting technologies remain insufficiently standardized for vegetal waste streams, making process optimization essential for improving compost quality and maximizing ecological benefits.

Sustainable organic waste management through composting, combined with complementary treatments, facilitates circular nutrient flows and contributes to the development of sustainable agriculture *(Mancuso et al., 2024)*. This review highlights the key factors influencing the composting of plant-based waste, offering a synthesis of recent technological innovations, microbial dynamics, and operational challenges. Special attention is given to optimizing conditions such as moisture, aeration, and the C/N ratio, specifically tailored to plant-based substrates.

By integrating these elements, the review supports the advancement of efficient and sustainable composting practices for both agricultural and urban applications *(Manea and Popescu, 2022; Aguilar-Paredes et al., 2023)*. This biologically driven thermogenic process is powered by the intense respiration of thermophilic bacteria and fungi, which naturally heat the organic mass. Consequently, it facilitates rapid decomposition of organic matter, destruction of pathogens and parasites (including helminth eggs and larvae), and the formation of stable humic substances, an indicator of compost maturity *(Avramović and Janković, 2018; Finore et al., 2023; Voicea et al., 2024)*.

KEY PARAMETERS INFLUENCING COMPOSTING EFFICIENCY

The reviewed literature highlights that temperature, along with other key factors such as the carbon-to-nitrogen ratio, moisture content, aeration frequency, and microbial activity, plays a significant role in determining both the quality and duration of the composting process *(El-mrini et al., 2022; Adugna, 2018)*. Effective composting practices typically involve regular turning of the pile, temperature monitoring, and careful management of thermal phases, ensuring that the final product is mature, stable, and biologically safe *(El-mrini et al., 2022; Adugna, 2018; El Boudihi et al., 2024)*. Depending on these variables and the nature of the raw materials, composting durations range from 1 to 12 months. Recent advancements have further improved composting efficiency. These include the use of microbial inoculants, vermicomposting, and various pre-treatment methods, all contributing to enhanced nutrient transformation, faster decomposition rates, and improved oxygen diffusion within the compost matrix *(Parihar and Sharma, 2021; Vladut et al., 2024)*. Additionally, biochar amendments have been shown to enhance compost quality by improving aeration and stabilizing nutrients, offering a promising strategy for organic waste management *(Poornima et al., 2024)*.

However, challenges persist, particularly concerning the management of contaminants such as heavy metals and microplastics, which can compromise the safety and agronomic value of the final compost product *(Mengistu et al., 2018)*.

Carbon-to-nitrogen ratio

During composting, carbon (C) and nitrogen (N) are key nutrients for microorganisms. Carbon provides energy, while nitrogen is essential for building cellular structures. If nitrogen is deficient, microbial growth and carbon decomposition slow down. If nitrogen is excessive, it can cause ammonia emissions and harmful salt accumulation. Microorganisms consume carbon 30 to 35 times faster than nitrogen, so maintaining an optimal C/N ratio is critical. A low C/N ratio leads to nitrogen loss as ammonia gas, while a high C/N ratio limits microbial activity and slows composting. To adjust the initial C/N ratio, materials like rice husks, wood chips, peanut shells, and urea are often added. Overall, the initial C/N ratio strongly influences organic matter mineralization and nitrification during composting *(Tianming Chen et al., 2020)*.

The carbon-to-nitrogen ratio (C/N) is widely acknowledged as a key parameter in composting, influencing both process efficiency and the quality of the final product. Most studies agree that the optimal C/N ratio lies between 25:1 and 30:1, though some standards accept a broader range of 20:1 to 30:1 *(Zhang et al., 2024; El-mrini et al., 2022)*. Maintaining a ratio within this range promotes microbial activity, accelerates organic matter degradation, and supports nutrient cycling, all contributing to the production of stable, mature compost *(Zhang et al., 2024; Sole-Mauri et al., 2007)*. A lower C/N ratio, particularly values around 15–16:1, has been shown to raise composting temperatures and prolong the thermophilic phase, thus enhancing pathogen elimination and organic breakdown *(Cai et al., 2024; Vladut et al., 2023a)*. However, excessively low ratios may increase ammonia (NH_3) emissions and reduce nitrogen retention *(El-mrini et al., 2022)*.

Conversely, higher C/N ratios can delay the onset of composting and extend the overall process. Still, they support the breakdown of lignocellulosic materials like hemicellulose and contribute to sulphur retention, improving plant nutrient availability *(Cai et al., 2024)*. Additionally, a C/N ratio of approximately 25 has been linked to reduced mobility of heavy metals such as copper and zinc, despite a potential increase in their total concentration during composting. Biochemically, the C/N ratio influences enzymatic activity, such as urease function, by affecting metal ion availability. It also plays a role in organic matter and nitrogen losses, although it does not significantly impact pH or temperature trends throughout the composting process *(El-mrini et al., 2022)*. In practice, managing the C/N ratio alone is not sufficient. Other operational factors, such as moisture content, aeration, and pH, must also be carefully controlled to maintain process stability *(Cerda et al., 2018)*.

While the ideal C/N ratio is typically cited as 25–30, studies have also reported successful composting outcomes outside this range. For example, ratios as high as 45 or as low as 15 can still produce mature compost if supplementary strategies such as enhanced aeration, microbial additives, or extended processing time are applied *(Bo Shen et al., 2024)*. However, these adjustments may lead to increased nutrient loss, higher costs, and inconsistency in compost quality. The diversity of input materials and methodologies further complicates the comparative evaluation of the C/N ratio's effects Ultimately, integrated C/N ratio management, combined with optimized operational parameters, not only supports compost maturity and pathogen reduction, but also minimizes harmful emissions like hydrogen sulphide (H_2S) *(Mengistu et al., 2018)*, contributing to sustainable agriculture and the principles of the circular economy *(Sole-Mauri et al., 2007; El-mrini et al., 2022)*.

Table 1

Impact of C/N ratio on composting efficiency

Impact	Description	Reference
Microbial Efficiency	Microorganisms require carbon for energy and nitrogen for growth. A balanced ratio ensures rapid and complete decomposition.	*Sun et al., 2025*
Compost Maturity	Compost with a proper C/N ratio matures faster and has lower phytotoxicity. Ratios of 25:1 showed better germination index and root development.	*Alkoaik et al., 2015*
Pathogen Reduction	C/N ratios influence temperature and microbial dynamics, which affect pathogen elimination. Ratios around 22:1 were most effective in reducing *Salmonella* and helminth eggs.	*Macias-Corral et al., 2019*
Material Selection	Different organic materials have varying C/N ratios. For example, sawdust has a high C/N (~400:1), while manure is low (~15:1). Mixing them balances the overall ratio.	*Qasim et al., 2018*

Temperature and moisture content

The composting process generates a significant amount of heat, particularly during the early stages, due to the rapid breakdown of organic matter. This heat production raises the compost temperature, promoting the activity of thermophilic microorganisms that accelerate decomposition and effectively eliminate pathogens.

Maintaining an optimal temperature range, typically between 40 and 65 °C, is essential for efficient composting and high-quality end products *(Shiyang Fan et al., 2021; Amuah et al., 2022; Assandri et al., 2021)*.

Temperatures above 55 °C are particularly important for pathogen destruction, with recommended thresholds of 65 °C sustained for several hours or 70 °C for 30 minutes to ensure proper sanitization.

Moisture content is another critical factor influencing microbial activity and overall process efficiency. Adequate moisture levels, generally between 40 and 60%, facilitate microbial metabolism by supporting nutrient solubilization, gas exchange, and preventing conditions detrimental to aerobic decomposition. Insufficient moisture causes drying and microbial inactivity, while excess moisture results in waterlogging, creating anaerobic zones that slow down the process and generate unpleasant odours *(Shiyang Fan et al., 2021; Ebrahimi et al., 2024; Ghinea and Leahu, 2020; Vladut et al., 2023)*. Therefore, maintaining optimal moisture is crucial for balancing these conditions and optimizing both the decomposition rate and the quality of the final compost. Temperature significantly impacts composting progress, affecting the four main phases and microbial populations. Most methods begin with Phase I – Mesophilic Phase (Initiation phase), where temperatures rise from ambient levels to around 40 °C, driven by mesophilic microorganisms metabolizing simple compounds such as sugars and amino acids *(Amuah et al., 2022)*. This is followed by Phase II – Thermophilic Phase, characterized by temperatures ranging from 40 to 70 °C, during which thermophilic bacteria and fungi degrade more complex organic compounds, ensuring pathogen inactivation *(Assandri et al., 2021)*. Subsequently, temperatures decline during Phase III – Mesophilic Cooling Phase, as microbial activity slows and mesophilic organisms recolonize the compost. This phase continues until the temperature stabilizes at ambient levels for at least three consecutive days *(opanatura.com)*. Finally, Phase IV – Maturation Phase involves the stabilization of humic substances and overall compost quality over a period of 30 to 60 days or longer, depending on the composting materials and conditions *(Amuah et al., 2022)*.

Figure 3 illustrates the dynamics of temperature and microbial communities throughout the composting process, highlighting the transitions between the active, cooling, and maturation phases. The figure *(Kluczek-Turpeinen et al., 2007)* demonstrates how temperature fluctuations drive microbial succession and the transformation of organic compounds, from initial decomposition to the final stabilization of humified material.

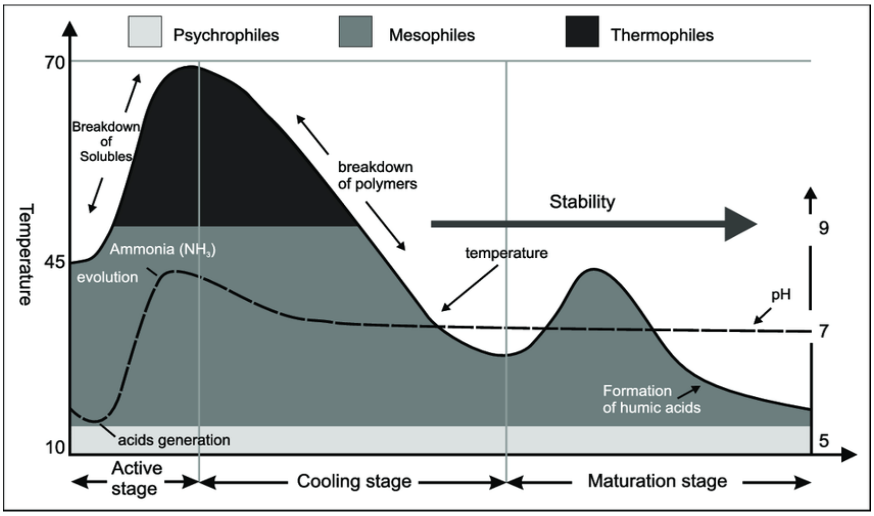

Fig. 3 - Dynamics of Temperature and Microbial Community during Composting
(Kluczek-Turpeinen et al., 2007)

In large-scale operations, piling is considered one of the most effective techniques for maintaining optimal temperature and moisture levels, ensuring faster degradation and the production of high-quality compost *(Rawoteea et al., 2017)*.

Aeration and particle size

Aeration and particle size are two interdependent parameters that critically influence the efficiency of composting processes for vegetal waste. An adequate oxygen supply is essential for microbial respiration and the degradation of organic matter. This is typically achieved through physical mixing, natural convection, or forced aeration, each with specific implications for process efficiency, depending on the system type.

In enclosed composting systems, forced aeration becomes necessary due to the absence of natural airflow. In contrast, units with perforated sidewalls allow passive air diffusion, reducing energy costs while maintaining aerobic conditions, which is highly relevant for optimizing system performance *(Vilela et al., 2022)*.

The aeration rate must be carefully controlled: insufficient oxygen leads to anaerobic zones, reducing efficiency, while excessive airflow can cool the compost mass and inhibit microbial activity.

Effective aeration rates reported for agricultural waste range between 0.3 and 1.16 $L \cdot min^{-1} \cdot kg$ organic $matter^{-1}$, and for municipal solid waste between 0.06 and 0.5 $L \cdot min^{-1} \cdot kg$ $waste^{-1}$ *(Rasapoor et al., 2009)*. Specifically, a flow of 2.6 $L \cdot kg^{-1}$ dry $solid \cdot min^{-1}$ combined with intermittent agitation has been shown to markedly improve microbial efficiency and accelerate decomposition *(Sarkar et al., 2016)*. In addition to controlling aeration, the use of strategic additives can optimize the composting environment. Materials such as sawdust and microbial inoculants help maintain porosity and create favourable conditions for microbial growth, thereby promoting faster organic matter breakdown *(Borkute and Hedaoo, 2022; Azim et al., 2018)*. Furthermore, amendments like biochar and zeolite improve aeration, reduce greenhouse gas emissions, and enhance nutrient cycling. These benefits contribute to more sustainable and agriculturally valuable compost, which is especially important for reducing the environmental footprint of composting *(Ayilara et al., 2020; Nenciu et al., 2021)*.

Particle size also plays a crucial role in composting efficiency. Smaller particles offer a greater surface-area-to-volume ratio, enhancing microbial colonization and enzymatic activity, which accelerates degradation rates *(Somera et al., 2023)*. Shredding fibrous materials such as leaves, grass, and small branches improves the structural uniformity of the compost mass, supports moisture retention, and promotes even aeration. Finer particles release more nitrogen and phosphorus and degrade at nearly twice the rate of coarser materials. Recommended particle sizes range from 1.3 to 7.6 cm, although many studies classify them broadly as "small" (under 1 cm) or "large" (over 5 cm), which is relevant for practical composting strategies. Despite general agreement on the benefits of smaller particles, research gaps remain, particularly concerning the impact of particle size on rapid composting of garden waste using microbial inoculants and vessel composting systems. Further investigation is needed to determine how different particle sizes influence the physicochemical and biological parameters of compost, which remains a significant topic for advancing composting technologies *(Mishra and Yadav, 2022)*. Moreover, particle size affects not only composting efficiency but also the properties of the final compost and its interaction with soil. Smaller particles tend to increase microbial biomass and phosphorus availability due to higher degradability, while larger fractions have shown stronger potential for disease suppression.

Soil characteristics such as pH, electrical conductivity, organic matter content, nutrient levels, and heavy metal concentrations are also influenced by compost granulation. However, limited research exists on how particle size affects the physical properties of soil and whether these effects vary depending on raw materials and application rates, making this an important area for future study *(Głąb et al., 2025)*.

When aeration is properly managed, particle size is optimized, and additives are strategically used, the composting process results in faster decomposition, improved microbial efficiency, and higher-quality compost with considerable environmental and agronomic benefits. These factors are highly relevant for sustainable waste management and soil health *(Barthod et al., 2018)*. Given this complexity, advanced treatment technologies such as nitrification-denitrification, biofiltration, activated carbon adsorption, and advanced oxidation processes are essential to reduce toxicity and enable safe disposal or reuse of leachate *(Brown et al., 2013)*.

Nutritional composition and compost maturity

Compost quality is essential for sustainable agriculture, influencing soil fertility, plant nutrition, microbial dynamics, and disease suppression. Key nutrient-related parameters of high-quality compost include increased nitrogen and potassium levels, a balanced pH (6.5 to 9.4), and reduced electrical conductivity (EC), all of which contribute to improved plant and soil *health (Borkute and Hedaoo, 2022; Ghinea and Leahu, 2020; Popa et al., 2023)*. Compost-amended soils (CAS) not only provide essential nutrients but also enhance microbial communities that outcompete pathogens such as Rhizoctonia and Fusarium, through nutrient competition and antimicrobial production, contributing to overall soil health *(Mehta et al., 2014)*. For instance, the application of CAS in spinach cultivation led to increased phenolics and flavonoids and reduced nitrate content, improving both plant quality and safety *(Hernández-Lara et al., 2023)*.

Similarly, food waste compost (FOWC) and vermicompost improved radish growth by enhancing the uptake of nitrogen, phosphorus, and potassium while maintaining a favourable soil pH *(Almaramah et al., 2024)*.

Composting techniques and raw material sources significantly influence nutrient outcomes. Successive composting of vegetable waste, for example, sustained thermophilic temperatures (55-68°C) and increased nitrogen content from 9.4% to 32.4%, highlighting its potential as a potent organic amendment *(Kim E.Y. et al., 2018)*. Plant-based composts, especially from agricultural residues, enhance soil structure and nutrient content. Methods such as windrow composting have proven effective, increasing nitrogen by 37–71% in soybean-based composts and potassium by 7-37% in maize-based composts *(Adediran et al., 2003)*.

The maturity of compost is a defining quality criterion, as immature compost may compete with plants for oxygen and nitrogen and release phytotoxic compounds (e.g., ammonia, organic acids) that inhibit seed germination and plant growth. Thus, only mature and stable compost should be used in agriculture and landscaping *(Chang Y-T et al., 2023)*. Various indicators have been developed to assess compost maturity, grouped into physical, chemical, biological, and spectroscopic methods. Physical indicators like temperature, colour, odour, and moisture offer qualitative but sometimes subjective insights *(Zaghloul et al., 2019)*. Chemical indicators such as pH, EC, carbon-to-nitrogen (C/N) ratio, and the humic acid to fulvic acid ratio (HA/FA) provide quantifiable information, though they must be interpreted in relation to raw material types and composting conditions. For example, high EC values might not necessarily reflect immaturity depending on feedstock composition *(Chang Y-T et al., 2023; Abaker et al., 2025; Kong Y. et al., 2024)*.

Biological indicators such as germination index (GI), nitrification potential, microbial respiration, and enzyme activities like dehydrogenase offer insights into microbial activity and compost stability *(Mahapatra et al., 2022)*. More recently, spectroscopic techniques like 3D fluorescence excitation-emission matrix (EEM) analysis have enabled detailed, non-destructive characterization of organic matter evolution during composting. Additionally, dissolved organic matter (DOM) profiling reveals valuable information on the humification process, a key aspect of compost maturity *(Kong Y. et al., 2024; Chang Y-T et al., 2023)*. However, no single indicator is universally applicable due to the variability of feedstocks and composting conditions, underscoring the need for integrated evaluation methods *(Antil et al., 2014)*.

Recent studies have applied these indicators with promising results. In a 60-day composting trial using pig and chicken manure alongside agricultural by-products, *Chang et al. (2023)* monitored parameters such as temperature, pH, EC, C/N ratio, E4/E6 absorbance, humic substances, HIX, and GI. They found that by day 30, the C/N ratio, humic substances, and GI stabilized, with most indicators plateauing by day 45, indicating full compost maturity. The study further validated fluorescence spectroscopy as a valuable complement to traditional assessments.

Similarly, *Lončarić et al. (2024)* evaluated compost derived from vegetal waste, combining chemical indicators like C/N ratio and ammonium/nitrate ratio with germination tests. While diluted extracts (1:10 v/v) stimulated growth in dicotyledonous species (*Lepidium sativum*, *Cucumis sativus*), higher concentrations (1:2.5 v/v) caused phytotoxicity in monocots (*Hordeum vulgare*, ×*Triticosecale*), highlighting the species-specific nature of phytotoxic responses and the need for multi-species bioassays when evaluating compost maturity.

Table 2

Degree of compost maturity and their properties

Characteristic	Immature	Mature	Fully Mature
Toxicity	High	Moderate	Absent
Composting Progress	Incomplete	Substantial	Complete
Nitrogen Impact	Strong	Minimal	None
Odour	Strong and Unpleasant	Slight and Earthy	Neutral or None

Maturity and stability are distinct yet interrelated aspects of compost quality. Maturity reflects the completeness of organic matter transformation, while stability refers to the resistance to further microbial degradation and the potential release of phytotoxins *(Martín-Ramos and Martín-Gil, 2020)*. Mature compost is characterized by minimal odour, low phytotoxicity, and negligible nitrogen immobilization, whereas immature compost can exhibit strong odours, unstable temperatures, and high microbial respiration. Table 3 summarizes the stages of compost maturity, highlighting toxicity, composting progress, nitrogen impact, and odour. Table 4 presents the commonly used indicators for assessing compost maturity and stability, including organic matter content, temperature profile, germination test results, nitrifying activity, microbial respiration, dehydrogenase enzyme activity, the Bc/Bn ratio (cellulolytic to nitrifying bacteria), and the C/N ratio, which typically stabilizes around 10–15 in mature compost.

Table 3

Key indicators for assessing compost maturity and stability

Indicator	Description
Organic Matter	Reflects the degree of organic matter decomposition; mature compost has low and stable OM content.
Temperature Profile	Tracks temperature changes over time; maturation is marked by a decline in temperature.
Germination Test	Measures indirect seed toxicity; mature compost does not inhibit germination.
Nitrifying Activity	Assesses the conversion of ammonium to nitrates, indicating beneficial biological activity.
Microbial Respiration	Microbial respiration rates (e.g., CO_2) reflect biological stability.
Dehydrogenase Activity	Enzyme activity indicating the intensity of microbial decomposition processes.
Bc/Bn Ratio	Ratio of cellulolytic bacteria (Bc) to nitrifying bacteria (Bn); balanced values indicate maturity.
C/N Ratio	Carbon-to-nitrogen ratio; mature compost typically has values around 10–15, showing nutrient balance.

Microbial processes in composting

Composting is mediated by diverse microbial communities that decompose organic matter into stable compounds and precursors of humic substances *(Sánchez et al., 2017)*. These microbial agents, including bacteria, fungi, and actinomycetes, operate in succession throughout the composting stages *(Nemet et al., 2021)*, each performing distinct enzymatic and metabolic roles in transforming waste into nutrient-rich compost. Macro-organisms, such as worms, also support microbial activity.

During the initial mesophilic and thermophilic phases, bacteria dominate the microbial community, actively degrading easily biodegradable compounds such as sugars and proteins. Their rapid metabolism generates substantial heat, which sanitizes the compost and creates favourable conditions for thermotolerant microorganisms *(Aguilar Paredes et al., 2023)*. Thermophilic bacteria, particularly from the genera *Bacillus* and *Thermus*, play a key role by secreting thermostable enzymes including proteases, ureases, cellulases, and lignin modifying enzymes that are essential for breaking down complex biomolecules such as fats, lignin, and cellulose *(Finore et al., 2023)*.

As the compost cools, fungi become increasingly active, contributing to the decomposition of recalcitrant compounds that bacteria cannot efficiently degrade. Their enzymatic activity, especially during the maturation phase, is crucial for nutrient mineralization and humus formation *(Aguilar-Paredes et al., 2023)*. *Actinomycetes*, filamentous bacteria with fungal-like characteristics, also emerge at this stage. They further degrade resistant organics, release antimicrobial compounds that suppress pathogens, and are responsible for the earthy smell associated with mature compost *(Aguilar-Paredes et al., 2023; Nemet et al., 2021)*. Collectively, these microbial dynamics are fundamental to transforming organic waste into nutrient-rich and stable compost.

Optimal moisture and pH levels support enzymatic functions, and a balanced C/N ratio supplies essential nutrients for microbial proliferation. Maintaining these parameters within ideal ranges is crucial for producing stable, mature compost *(Nemet et al., 2021; Luo et al., 2023)*. Maintaining optimal environmental conditions significantly enhances microbial metabolism, thereby improving the efficiency and effectiveness of the composting process. Microorganisms not only drive the rapid decomposition of organic matter but also improve the biological stability and nutrient content of the final product, making compost a high-quality amendment for agricultural and horticultural *applications (Zainudin et al., 2022; Tianming Chen et al., 2020)*.

Recent advances demonstrate how microbial management strategies can accelerate the composting process. *Somera et al. (2023)* showed that the addition of vegetable waste as a bio-activator enriched beneficial microbes such as *Streptococcus* and *Lactobacillus*, which produce lactic acid. This acidification process suppresses pathogenic organisms and enhances nutrient availability.

When combined with precise process control measures such as a seeding rate of 14.5%, air suction of 2.6 L/kg dry solids per minute, and alternating agitation cycles, these conditions allow compost to mature in just four days, achieving a carbon conversion rate of 14.54%.

Another strategy to improve composting performance involves the use of microbial inoculants *(Huang et al., 2022)*, either as pure strains or mixed cultures. These inoculants, typically composed of bacteria, fungi, or actinobacteria, can significantly accelerate the degradation of lignocellulosic materials, improve compost quality, and reduce the required maturation time *(Babett Greff et al., 2022; Zainudin et al., 2022)*.

However, their effectiveness depends on selecting strains compatible with specific substrates and environmental conditions, and practical application must also consider production and implementation costs.

The incorporation of vegetable waste as a bio-activator further promotes microbial proliferation, especially of lactic acid producing bacteria that both suppress pathogens and enhance compost stabilization.

Microbial activity is also essential in composting-based bioremediation, facilitating the breakdown of organic pollutants into non-toxic compounds such as carbon dioxide and water. Under thermophilic conditions, achieved through proper temperature management, microbial metabolism is enhanced, while the compost matrix immobilizes pollutants, reducing their bioavailability and environmental impact *(Girish et al., 2020)*. Compost particle size influences microbial dynamics and phosphorus availability. *Verma and Marschner (2013)* demonstrated that finer fractions (<3 mm or <2 mm) increased microbial biomass carbon (MBC) and phosphorus (MBP) more effectively than coarser particles (>5 mm), likely due to improved microbial colonization. Soil properties, such as organic matter content, pH, and texture, also affect phosphorus pools. Organic-rich soils had higher Fe/Al-bound and organic phosphorus, while alkaline soils favoured Ca-bound phosphorus. These findings highlight the complex interactions between compost characteristics, soil properties, and microbial activity. The microbial community's enzymatic potential is central to compost transformation. *Finore et al. (2023)* highlighted thermophilic bacteria, particularly *Bacillus* and *Thermus*, as major producers of thermostable enzymes such as proteases, ureases, cellulases, hemicelluloses, and esterases. These enzymes catalyse the breakdown of complex polymers into simpler compounds. Advances in metagenomics have provided deeper insight into these microbial communities and their functional capabilities, enabling the optimization of composting conditions for higher efficiency. For instance, the Life Tirsav Plus project demonstrated effective composting of olive oil waste using both dynamic and static methods, resulting in high-quality compost within controlled environments.

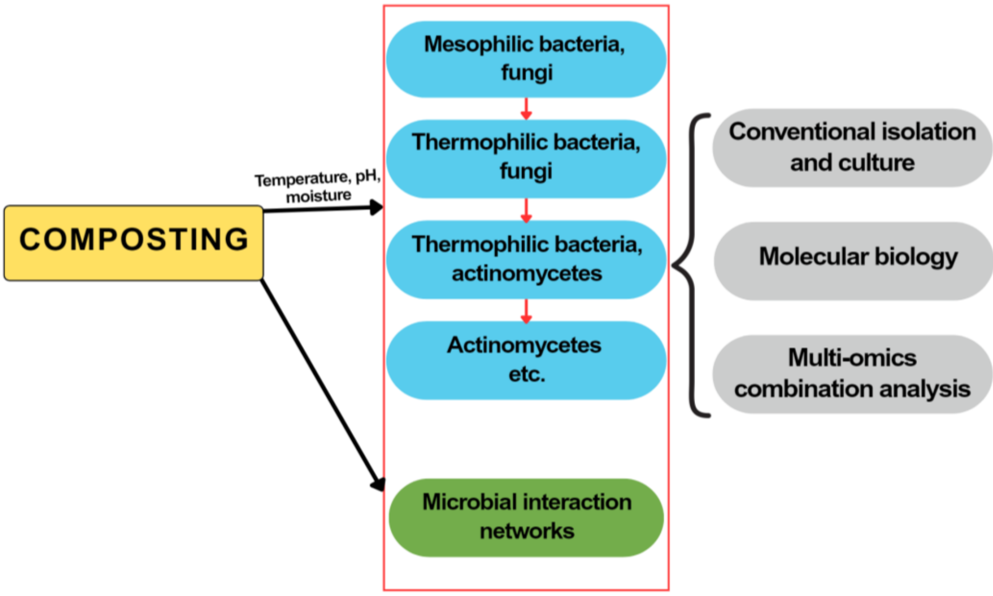

Fig. 4 - Outlines of microbial communities in composting process and related biological technologies
(adapted from Luo et al., 2023)

Composting is thus a multi-stage, microbially mediated process that involves successive actions by bacteria, actinomycetes, and fungi. Initially, mesophilic bacteria metabolize sugars, elevating the temperature. *Thermophilic bacteria* and actinomycetes subsequently degrade cellulose, followed by fungal decomposition of lignin. Composting methods vary in terms of oxygen availability and biological agents used, ranging from anaerobic systems (several months), aerobic methods (including heap, pit, and Berkeley techniques), to vermicomposting with earthworms. For effective composting, conditions such as oxygen availability, moisture, and temperatures up to 75 °C are crucial, ensuring both microbial efficiency and pathogen suppression *(Zafar, 2022)*.

COMPOSTING TECHNOLOGIES AND OPTIMIZATION APPROACHES

Traditional composting still has some disadvantages, such as nitrogen loss, leachate generation, odour problems, greenhouse gas emissions (CH_4 and N_2O), heavy metal (HM) mobility, antibiotic residues, and the diffusion of antibiotic resistance genes.

During the composting process, between 9.6% and 46% of the initial total nitrogen (N) is lost due to NH_3 volatilization, which not only decreases the quality of the compost but also worsens air pollution *(Wang, Q. et al., 2018)*.

To overcome these drawbacks, recent advances in composting technologies have greatly enhanced the production of high-quality organic fertilizers, supporting sustainable agriculture and improving soil health.

For example, vegetable waste composting, particularly when combined with amendments such as sawdust, meets agricultural safety standards while improving soil properties *(Somera et al., 2023; Leahu, 2020)*.

Food waste composting has been shown to reduce harmful emissions and increase the nutrient content of vegetables *(Guo et al., 2018)*. Furthermore, the application of bioinoculants, as demonstrated by the National Institute of Plant Health Management, has shortened composting times and promoted better plant growth *(Girish et al., 2020)*.

Additional organic amendments, including insect frass and shiitake mushroom compost, have been reported to improve tree growth and water retention, although their effectiveness in pathogen suppression may vary *(Somera et al., 2023)*. For instance, technologies such as windrow composting (WC) and windrow-vermicomposting (WVC) can achieve thermophilic temperatures (> 45 °C) within just 2-3 days. The WVC method has been found more effective in meeting WHO safety standards and in reducing volatile solids, organic carbon, and the C/N ratio *(Mengistu et al., 2018)*. During composting, carbon and ammonium (NH_4^+) concentrations typically decline, while pH decreases in the early stages and later rises as the compost reaches maturity. Microbial metabolism converts organic substrates into humic substances, releasing by-products such as CO_2, H_2O, NH_3, SO_4^{2-}, and heat, the latter serving as a key indicator of microbial activity *(Manea and Popescu, 2022)*. Composting methods strongly influence temperature and moisture control. Windrow-vermicomposting (WVC) quickly reaches and sustains thermophilic conditions, improving pathogen destruction rates and accelerating the process. By contrast, slower techniques like pit composting (PC) require longer maturation periods due to limited aeration and reduced turning *(Mengistu et al., 2018)*. Both laboratory-scale and co-composting studies emphasize that controlled aeration, appropriate moisture, and balanced substrate composition are critical for maximizing microbial activity and carbon conversion efficiency *(Somera et al., 2023; Amiruddin et al., 2023)*. The main differences among composting technologies are summarized in Table 4.

Table 4

Composting methods overview: temperature, moisture, and process timing

Method	Thermophilic Onset	Duration	Maturity Time	Notes	References
Windrow composting	2-3 days	15-19 days	~60 days	High microbial activity, efficient pathogen removal	*Mengistu et al., 2018*
Static Composting	Delayed	Short	~80 days	Poor aeration, slower degradation	*Mengistu et al., 2018*
In-Vessel Bioreactor	Controlled	Variable	~50 days	Allows precise control of temperature and moisture	*Chang et al., 2023; Rawoteea et al., 2017*
Vermicomposting	No thermophilic phase	Continuous	~45–60 days	Uses earthworms; ideal for organic kitchen waste; low odour	*Vuković et al., 2021; Nemli et al., 2008*
Berkeley Composting Method	1-2 days	18 days	~30 days	Rapid composting with frequent turning; high temperature maintained	*De Almeida Leal et al., 2022*
Indore Composting	3-5 days	20–25 days	~90 days	Traditional method; layered approach; moderate temperature rise	*Pathak et al., 2025; Kanaujiya et al., 2020*
Composting in Containers	2-4 days	10–20 days	~60 days	Suitable for small-scale urban composting; temperature varies	*Schrader et al., 2015; Mengistu et al., 2018*

Windrow composting

Windrow composting is an aerobic technique for treating organic waste, in which the material is arranged in long, narrow piles (windrows). These rows are periodically turned in order to maintain oxygen levels, stimulate microbial activity, and promote efficient decomposition. The method is widely adopted for large-scale composting of agricultural residues, municipal solid waste, and industrial organic by-products.

Typically, a windrow represents a stack of raw materials organized in elongated rows. For effective composting, the piles should be kept relatively small, generally not exceeding 6 feet in height, and sufficiently porous to allow proper air exchange *(Mengistu et al., 2018; Degefe et al., 2025)*.

Turning is usually performed mechanically, with the help of windrow turners, manure spreaders, or bucket loaders. This operation improves aeration, ensures uniform decomposition, and exposes all material to microbial colonization. During the process, heat, water vapour, and gases are released from the pile. Despite its advantages, windrow composting also has drawbacks: it requires high labour input, and both temperature and moisture content are difficult to control effectively *(Lynch and Cherry, 1996; Hashim et al., 2024)*.

To overcome these limitations, in-vessel composting systems have been developed. These systems improve process efficiency by providing controlled aeration, better regulation of temperature, and faster stabilization of the final product. Two common types of in-vessel systems include *(Manyapu et al., 2017)*:

- Passively Aerated Windrow System (PAWS);
- Forced Aerated Static Piles (FASP).

Passively Aerated Windrow System (PAWS) represents a modified method of windrow composting designed to enhance aeration without the need for frequent mechanical turning. In this system, perforated pipes are strategically placed at the base of the windrow, enabling natural convective airflow to pass through the compost pile and maintain aerobic conditions essential for microbial activity. Prior to layering the organic substrates over the pipes, the materials are thoroughly mixed to ensure homogeneity and promote uniform decomposition. To sustain thermophilic conditions and minimize heat loss, the outer surface of the windrow is covered with a layer of finished compost, which also serves to reduce odour emissions and prevent excessive moisture evaporation. Research has shown that the effectiveness of PAWS depends heavily on factors such as feedstock composition, compaction, porosity, and permeability, which influence airflow and temperature regulation within the pile *(Veeken et al., 2003)*. Studies also confirm that passive aeration can achieve composting temperatures above 57°C, comparable to forced aeration systems, while saving energy and reducing operational complexity. Additionally, PAWS has been successfully applied in emergency composting scenarios, such as animal mortality management, due to its ability to inactivate pathogens and limit environmental contamination *(Manyapu et al., 2017)*.

Table 5

Advantages of the PAWS system

Benefit	Explanation
Efficient aeration	No energy consumption for mechanical turning
Reduced costs	Less labour and fewer equipment required
Odour control	Mature compost acts as a bioactive cover
Moisture conservation	Reduced evaporation, maintaining ideal conditions for composting
Biological safety	High temperatures destroy pathogens and weed seeds

Forced Aerated Static Piles (FASP) is a composting method derived from the Passively Aerated Windrow System, but improved through the use of forced aeration. In this system, perforated pipes are connected to blowers that actively regulate airflow, ensuring adequate oxygen supply and maintaining thermophilic conditions. Airflow is typically controlled based on temperature feedback, with blowers activated around 65°C to optimize microbial activity, accelerate decomposition, and ensure pathogen inactivation. By eliminating the need for manual turning, FASP increases process efficiency, reduces labour requirements, and produces a uniform and stable compost product *(Manyapu et al., 2017; Oñiguez et al., 2018)*.

This setup enables forced aeration, which aerates the compost pile by a fan or blower to maintain adequate oxygen levels. The forced air passes through the pile via the network of pipes, enhancing microbial activity and accelerating decomposition without the need for manual turning *(Riaz et al., 2021)*.

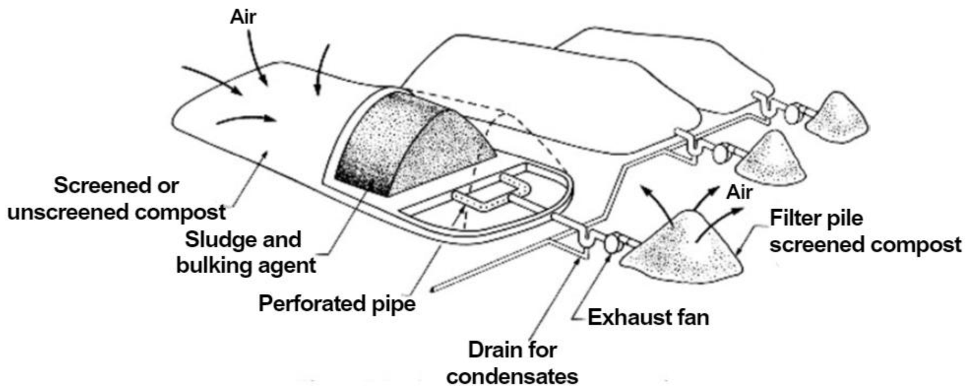

Fig. 5 - Schematic diagram of composting in aerated static piles (FASP)
(Riaz et al., 2021)

Table 6

Comparative evaluation of in-vessel composting system
(*adapted from, Manyapu et al., 2017*)

Sl. No.	Parameters	PAWS	FASP
1	Moisture control	Partial	Full
2	Temperature control	Partial	Full
3	Aeration control	Yes	Yes
4	Exhaust air control	No	Yes
5	Climate suitability	Best in warm and dry climates	Suitable for both warm and cold climates
6	Risk of recontamination	Possible if poorly managed	Minimal
7	Occupational risks	Low	Low
8	Odour emissions	Low	Low
9	Space requirement	Medium	Medium
10	Skill level required	Moderate	Moderate
11	System design complexity	Simple	Moderate
12	Processing time	Long (8-12 weeks)	Fast (2-4 weeks)
13	Operational cost	Low	Moderate

Vermicomposting

Vermicomposting is an eco-friendly biotechnological method that transforms organic waste into nutrient-rich fertilizer, significantly improving soil fertility through the production of vermicompost with a low carbon-to-nitrogen (C/N) ratio. This process addresses common challenges in organic waste management, such as phytotoxicity and nitrogen leaching, thereby producing a safer and more effective fertilizer for agricultural applications. By reducing environmental impacts and supporting sustainable farming practices, vermicomposting aligns with the European Union's circular economy objectives *(Gabur et al., 2024)*.

Economically, vermicomposting offers multiple benefits: it produces valuable organic fertilizers that enhance nutrient availability, accelerates organic matter decomposition, and serves as a sustainable alternative to conventional chemical fertilizers *(Borkute and Hedaoo, 2022; Savage, 1996; Gabur et al., 2024)*.

Unlike traditional composting, vermicomposting utilizes earthworms, commonly species such as *Eisenia fetida*, that biologically digest organic waste within an optimal temperature range of 10 °C to 32 °C. This biological activity significantly improves decomposition efficiency. However, important knowledge gaps remain regarding ammonia volatilization and greenhouse gas emissions during vermicomposting, particularly in the context of plant residues and manure in mountainous regions. While organic waste management and manure reuse have been extensively studied, research on gas emissions specific to vermicomposting is still limited, thus requiring further investigation. Gaining a deeper understanding of these emissions is essential for developing alternative waste management strategies and ensuring the long-term sustainability of organic waste recycling *(Raza et al., 2022)*.

Economically, vermicomposting offers multiple benefits: it produces valuable organic fertilizers that enhance nutrient availability, accelerates organic matter decomposition, and serves as a viable sustainable alternative to conventional chemical fertilizers *(Borkute and Hedaoo, 2022; Savage, 1996; Gabur et al., 2024)*.

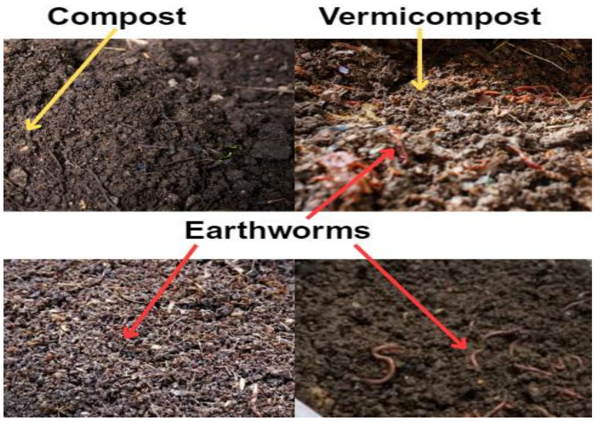

Fig. 6 - Appearance of compost and vermicompost
(adapted from Raza et al., 2022)

Vermicompost results from synergistic interactions between earthworms and microorganisms, leading to a non-thermophilic stabilization of organic materials. It is recognized as an environmentally friendly method for recycling organic waste and acts as a potent soil amendment that promotes plant growth. Additionally, vermiculture involves the mass production of earthworms in waste environments, which supports large-scale vermicomposting operations *(Raza et al., 2022)*. The vermicomposting process typically takes place in containers with perforated bottoms to allow drainage of nutrient rich leachate, commonly referred to as "compost tea." The procedure involves layering cow manure, introducing earthworms, covering with shredded food waste, and maintaining moisture through regular watering. Earthworms efficiently convert a variety of organic substrates including sludge, manure, and household waste into nutrient rich compost that is beneficial for agricultural and horticultural applications *(Waqas et al., 2023)*.

Table 7

Benefits of vermicomposting

Benefit	Description	Scientific Source
Soil Fertility Enhancement	Improves nutrient availability (N, P, K, Ca, Mg), humic substances, and enzymes	*Cruz et al., 2024*
Improved Soil Structure	Enhances porosity, water retention, and aggregate stability	*Patra and Parihar, 2023*
Plant Growth Promotion	Boosts germination, root development, and crop yield	*Blouin et al., 2019*
Microbial Activity Increase	Enriches soil with beneficial microbes (e.g. nitrogen fixers, phosphate solubilizers)	*Vuković et al., 2021*
Eco-Friendly Waste Management	Converts organic waste into valuable fertilizer, reducing landfill burden	*Thakur et al., 2021*
Disease Suppression	Vermicompost suppresses soil-borne pathogens and pests	*Mohite et al., 2024*
Rapid Processing Time	Faster than traditional composting; produces stable compost in < 2 months	*Cruz et al., 2024*
Heavy Metal Immobilization	Reduces bioavailability of toxic metals in soil	*Vuković et al., 2021*

Comparative evaluation of the main composting technologies

Composting methods differ considerably in terms of efficiency, processing time, and environmental impact. Traditional windrow composting can require 120–150 days to complete, whereas modern technologies, such as in-vessel composting, can complete the composting process in as little as 10 days *(Stentiford and Sánchez-Monedero, 2016)*. The incorporation of organic amendments, including vermicompost and vegetable peels, can further reduce composting time to 45–75 days *(Borkute and Hedaoo, 2022)*.

An important aspect of composting management is the treatment of leachate, the nutrient-rich but pollutant-laden liquid formed by water percolating through waste.

Leachate contains high organic loads (measured by biochemical oxygen demand, BOD_5, and chemical oxygen demand, COD), toxic ammoniacal nitrogen, heavy metals (e.g., Zn, Pb, Hg), phenols, and other recalcitrant compounds that threaten soil and groundwater quality *(Siciliano et al., 2019; Sanadi et al., 2019)*.

Static pile systems, although often challenged by difficulties in maintaining thermophilic conditions, can yield compost of comparable quality to industrial systems when properly managed. Additionally, they offer advantages such as lower greenhouse gas emissions and the absence of plastic contamination *(Sánchez, 2022)*.

Efficient separation of organic waste also plays a critical role in improving compost quality by increasing nutrient content and minimizing contaminants *(Savage, 1996)*. Microbial inoculants and organic additives accelerate the decomposition process and improve overall compost quality. For instance, the 'heaping' composting method, which can achieve temperatures up to 65.9°C, ensures effective pathogen sanitization *(Manea et al., 2024; Sarkar et al., 2016)*. Supplementing compost with microbial agents and organic amendments has also been shown to enhance degradation rates and product quality *(Sun et al., 2021)*.

Table 8

Compost management practices and their main objectives

Management Practice	Main Objective
Thermophilic temperature	Eliminates pathogens and weed seeds
Moisture control	Prevents microbial inhibition and undesirable emissions
Regular aeration	Maintains aerobic conditions and prevents foul odours
Microbial inoculants	Enhances organic matter degradation
Compost quality monitoring	Ensures product safety and improves soil quality
Advanced composting technologies	Increases efficiency, control, and energy optimization
Policy and regulatory support	Facilitates scalability and economic viability

CONCLUSIONS

Composting of plant waste is a complex process that relies on microbial activity and several essential parameters. The most critical factors include the carbon-to-nitrogen ratio, temperature, humidity, aeration, pH, and the characteristics of the materials used. When these factors are properly controlled, the composting process develops efficiently, producing a stable compost that is free of harmful bacteria and rich in nutrients, making it ideal for soil fertilization.

The composting process can be further optimized through modern technologies that enable rapid and efficient transformation of waste into high-quality compost. These include automatic aeration systems that supply oxygen necessary for microbial activity without manual turning, as well as grinding and sorting equipment that prepare the waste for uniform decomposition. Pretreatment techniques, such as controlled fermentation or soaking of dry materials, facilitate faster microbial degradation. Vermicomposting, which employs decomposer worms to convert organic residues into natural fertilizer, represents another highly efficient and environmentally friendly approach. Collectively, these technologies make composting faster, cleaner, and less labour-intensive. While these technological advancements offer significant advantages, they also affect compost quality and processing time, and may increase overall operational costs. Future perspectives should focus on balancing efficiency and quality while minimizing expenses.

In conclusion, producing efficient compost from plant waste requires an integrated approach that combines scientific knowledge with practical process management. Composting thus serves not only as an effective method for valorising plant waste but also as a key strategy for promoting sustainable agriculture and advancing circular economy objectives by closing resource loops and reducing environmental impact.

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