



## Improvement of organic waste composting technology

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### Abstract

Composting of organic waste is one of the most effective and environmentally sound methods of its processing. The implementation of this approach makes it possible to simultaneously reduce the burden on municipal solid waste landfills and obtain a valuable product — an organic fertilizer with high agronomic value. The recycling of food and plant residues helps decrease the volume of waste sent to landfills, which is especially important under conditions of limited landfill capacity.

Composting gains additional importance in the context of the growing role of agriculture, where traditional organic fertilizers are becoming insufficient, while the use of mineral alternatives is associated with high economic costs. In this regard, the development and optimization of technologies for producing biofertilizers from locally available organic raw materials appears to be a promising direction. The paper examines modern approaches to improving composting technology, taking into account microbiological, temperature, and physicochemical factors of the process.

**Keywords:** Composting, microbial community, aerobic–anaerobic process, organic fraction, municipal solid waste, lignocellulosic waste, natural zeolite

### Introduction

Composting is a biotechnological process of an exothermic nature, based on the aerobic oxidation of organic compounds under the action of complex microbial communities. During biodegradation, the organic substrate is transformed with the participation of bacteria, archaea, and microscopic fungi, which is accompanied by heat release and an increase in the temperature of the composting mass to 50–60 °C and higher. Optimal process conditions are characterized by a relative moisture content of about 60% at the initial stage and 40–50% during the compost maturation phase.

At present, composting is recognized as an environmentally sound and economically viable method for the treatment of organic waste, primarily of agricultural and municipal origin. This disposal method aligns with the principles of sustainable development and the rational use of natural resources. In a number of countries, composting is considered a priority alternative to thermal treatment methods for biodegradable waste, as it is not accompanied by toxic gaseous emissions hazardous to human health and the environment<sup>[1, 2]</sup>.

The result of the composting process is an organic fertilizer enriched with humic substances and biologically available plant nutrients. Livestock, poultry, and crop production wastes, including materials of lignocellulosic origin, are traditionally used as feedstock. Despite the substantial body of research devoted to composting, the microbiological mechanisms that determine the efficiency of organic matter decomposition and the formation of high-quality compost remain insufficiently studied.

It has been established that numerous groups of microorganisms participate in the composting process, including more than two thousand species of bacteria, over one hundred species of microscopic fungi, as well as representatives of archaea<sup>[3, 4]</sup>. A significant portion of the microbial community consists of non-culturable forms, which are identified primarily through molecular biological

methods. The intensity of the composting process is determined by the combined influence of factors such as temperature regime, moisture content, substrate porosity ensuring aeration, and the availability of nitrogen in forms accessible to microorganisms.

Municipal organic waste is of particular interest as a feedstock for composting, including food residues, paper and cardboard materials, wood waste, plant litter, and sewage sludge. Sewage sludge is characterized by a high content of biodegradable organic compounds and, after appropriate stabilization, can be considered a promising component of compost mixtures. At large wastewater treatment plants, such sludge undergoes anaerobic stabilization at elevated temperatures, which helps reduce the content of pathogenic microorganisms and promotes the decomposition of readily oxidizable organic matter<sup>[5]</sup> compost, temperature regimes during the composting of conventional organic waste, and to assess the feasibility of using the composting process for the treatment of fresh and anaerobically stabilized sewage sludge, as well as the organic fraction of municipal solid waste, with the addition of lignocellulosic materials and natural zeolites

### Temperature dynamics and microbial composition at different stages of composting

The temperature regime during composting is formed as a result of self-heating of the composting mass, driven by the metabolic activity of microorganisms, and serves as an important indicator of process efficiency (fig.1). Temperature changes reflect shifts in microbial communities and the intensity of organic matter biodegradation. Depending on temperature conditions, the composting process is conventionally divided into several successive stages: mesophilic, thermophilic, cooling, and maturation stages<sup>[6, 7]</sup>.

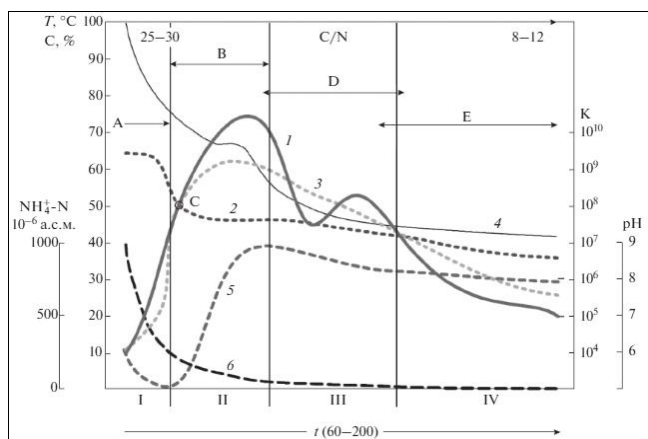
At the initial mesophilic stage, at temperatures up to 40 °C, mesophilic bacteria and microscopic fungi actively participate in the decomposition of readily available organic

compounds. As heat accumulates and the temperature rises, mesophilic forms are gradually displaced by thermophilic microorganisms. It has been established that within the temperature range of 10 to 50 °C, an increase of 10 °C accelerates microbiological processes 2–3 times, due to the enhanced activity of enzymatic systems.

The thermophilic stage of composting is characterized by a temperature rise to 50–60 °C and above and represents the key phase of intensive organic matter decomposition. During this period, complex organic compounds undergo active mineralization, and most pathogenic microorganisms are inactivated. In certain cases, when composting livestock waste with added structuring materials, the temperature can reach 70 °C or higher [8]. High-temperature composting processes have also been described, where the temperature of the composting mass exceeds 90 °C, ensuring accelerated decomposition of sewage sludge and recalcitrant organic components [1].

Under extremely high temperatures, new thermophilic microorganisms capable of growth above 80 °C have been isolated from compost substrates [9]. These strains belong to the family Bacillaceae and are characterized by strict aerobiosis and high thermotolerance. However, it should be noted that excessive temperature increase (above 65–85 °C) may lead to a decrease in the overall rate of biodegradation, as such conditions become unfavorable for most moderately thermophilic microorganisms and soil mesofauna. The composting process under changing temperature regimes involves a wide range of microorganisms, predominantly from four bacterial phyla: Firmicutes, Proteobacteria, Bacteroidetes, and Actinobacteria, which together account for up to 80–85% of all identified microorganisms in compost [10].

At the early stages of composting, members of the order Enterobacteriales (phylum Proteobacteria) play a significant role; these are facultative anaerobes widely found in soil and the intestines of animals. Moderately thermophilic bacteria of the order Lactobacillales (phylum Firmicutes) show high activity at the initial heating of the composting mass, as well as after mechanical loosening of the material during the cooling stage.



**Fig. 1.** Different stages of composting as a function of time, biota type, temperature, and chemical characteristics of the substrate (based on [6, 7]):

1 – Temperature; 2 – mesophiles; 3 – thermophiles; 4 – carbon balance; 5 – pH; 6 – -N;  
 A – utilization of labile substrates; B – mineralization of cell walls, mineralization; C – replacement of mesophiles by

thermophiles; D – formation of humic substances; E – appearance of soil fauna; K-axis – number of cells per 1 g of substrate; C, % – carbon content relative to the initial value; t – composting time, days; I – mesophilic stage; II – thermophilic stage; III – cooling stage; IV – maturation stage.

During the thermophilic phase of composting, *Bacillus* species dominate, accounting for up to 80% of the bacterial community. The most frequently identified species in compost are *Bacillus subtilis*, *Bacillus licheniformis*, and *Bacillus circulans*, which are highly capable of synthesizing exoenzymes and decomposing complex organic compounds. At temperatures of 65–80 °C, members of the genus *Thermus* are active, participating in the degradation of macromolecules of various types [11].

In the cooling stage and within stabilized layers of compost, the abundance of actinobacteria, particularly from the genera *Thermobifida* and *Bacillus*, as well as microscopic fungi from the genera *Thermomyces* and *Aspergillus*, increases [12]. These microorganisms ensure deeper processing of residual organic matter and contribute to the formation of a stable structure in mature compost.

Thus, the temperature dynamics of composting are closely linked to the sequential succession of microbial communities, each performing specific functions in the biodegradation of organic substrates and the formation of the final product.

**Role of microscopic fungi and degradation of recalcitrant substrates**

Microscopic fungi play a significant role in the composting process due to their high enzymatic activity and ability to decompose complex organic polymers. The activity of these fungi is largely determined by the temperature conditions of the composting mass. When the temperature rises above 55 °C, many fungal species are temporarily inactivated; however, as the temperature subsequently decreases, they re-colonize the compost from cooler zones throughout the mass.

**The Most Important Participants in Composting: Filamentous Fungi and Degradation of Recalcitrant Substrates**

Filamentous fungi, characterized by a well-developed hyphal mycelium, are considered the most important participants in the composting process. This mode of growth gives them a competitive advantage in colonizing solid substrates and utilizing poorly soluble nutrients. Several thermophilic fungi belonging to the phylum Ascomycota, together with thermophilic actinobacteria, actively participate in the decomposition of lignin and lignocellulosic complexes, particularly within the 40–50 °C range typical of the thermophilic composting stage [11].

It has been established that the abundance of microscopic fungi in the composting mass decreases as the temperature rises, and at 60–65 °C they are almost undetectable. However, certain thermophilic species, such as *Thermomyces lanuginosus*, maintain high metabolic activity at elevated temperatures and are capable of synthesizing significant amounts of extracellular enzymes, including hemicellulases, cellulases, and ligninases. These enzymes play a key role in the degradation of hemicellulose and lignocellulose components of plant residues [13].

In addition to temperature, fungal development in compost is limited by the availability of nutrients, particularly

nitrogen sources. Many filamentous fungi specialize in decomposing high-molecular-weight carbohydrates. For example, members of the genera *Mucor*, *Rhizopus*, and *Aspergillus* actively produce amylases, while cellulase synthesis is characteristic of *Trichoderma reesei*, *Trichoderma lignorum*, *Chaetomium cellulolyticum*, and white-rot fungi. Lignin is the most resistant component of plant material and can be fully mineralized only by a limited group of higher fungi. In addition to fungi, protozoa and viruses are also found in the composting mass, including obligate parasites of plants, animals, and humans. The thermophilic stage of composting contributes to a sharp reduction in the number of pathogenic viruses, thereby enhancing the sanitary safety of the final product.

### Degradation of lignocellulosic components

During the decomposition of plant residues, intermediate compounds are formed that serve as precursors to humic substances [15]. Bacteria with low guanine–cytosine content in their DNA play a major role in the degradation of lignocellulosic biomass during composting, particularly members of the orders Bacillales, Clostridiales, Actinomycetales, and Thermoanaerobacterales [10, 16].

Metaproteomic studies indicate that bacterial communities are the primary agents of cellulose hydrolysis. A significant portion of cellulolytic enzymes is synthesized by bacteria of the genus *Thermobifida*, which can account for up to 40% of all detected cellulases [12]. Moderately thermophilic actinobacteria, such as *Thermoactinomyces vulgaris*, *Actinobifida chromogena*, *Micromonospora carbonacea*, and members of the genus *Streptomyces*, also participate in lignocellulose decomposition [4].

It should be noted that most ligninolytic actinobacteria are capable only of modifying and solubilizing lignin molecules, while their potential for complete mineralization of this polymer is limited compared to white-rot fungi [11, 17]. Under composting conditions, actinobacteria develop more slowly than most bacteria and microscopic fungi, and at early stages of the process, they are unable to compete effectively with them. However, during the thermophilic stage, their contribution to organic matter biodegradation becomes significant [18].

The importance of actinobacteria is further enhanced by their ability to synthesize antibiotic compounds, which helps suppress phytopathogenic microorganisms and increases the phytosanitary value of compost. In addition, some members of this group produce substances that stimulate plant growth and development [4]. In pile composting, enzymatic activity is heterogeneous along the height of the pile: amylase activity, associated with carbohydrate decomposition, predominates in the lower layers, whereas proteolytic enzyme activity is more commonly observed in the upper layers of the compost mass [1].

### Microorganisms of the nitrogen cycle in the composting process

Nitrogen is one of the key elements of plant mineral nutrition, and its transformations during composting largely determine the agronomic value of the final product. The formation of available nitrogen forms is carried out through the activity of specialized groups of microorganisms involved in the biogeochemical nitrogen cycle, including nitrogen-fixing, nitrifying, and ammonifying microorganisms.

### Nitrogen Fixation

Nitrogen-fixing microorganisms, or diazotrophs, are capable of assimilating atmospheric molecular nitrogen due to the presence of the nitrogenase enzyme complex. The development of these microorganisms in compost plays an important role in enhancing soil fertility, as atmospheric nitrogen is the primary but largely inaccessible source of this element for plants.

Various nitrogen-fixing bacterial genera have been isolated from composted substrates, including *Azotobacter*, *Klebsiella*, *Pseudomonas*, *Xanthomonas*, *Alcaligenes*, *Stenotrophomonas*, *Caulobacter*, *Achromobacter*, and *Clostridium* [19, 20, 21]. These microorganisms also participate in the decomposition of organic matter, linking carbon mineralization processes with the supply of biologically available nitrogen. The ability to fix atmospheric nitrogen has also been observed in certain archaea present in compost [4].

### Nitrification and the Role of Ammonium-Oxidizing Microorganisms

Nitrification is a crucial process in nitrogen transformation, providing the formation of oxidized nitrogen forms that are available to plants. This process occurs in two consecutive stages. In the first stage, ammonium is oxidized to nitrites by ammonium-oxidizing bacteria belonging to genera such as *Nitrosomonas*, *Nitrosococcus*, *Nitrosolobus*, and others.



In the second stage, nitrites are oxidized to nitrates by nitrite-oxidizing bacteria, represented by genera such as *Nitrobacter*, *Nitrococcus*, and others.



Активность нитрифицирующих микроорганизмов в компосте наиболее выражена на стадии созревания, когда температура и содержание доступного кислорода создают благоприятные условия для их развития [22]. Установлено, что на ранних этапах компостирования в составе нитрифицирующего сообщества преобладает род *Nitrosospira*, тогда как в термофильной фазе доминируют бактерии *Nitrosomonas europaе*. По мере охлаждения компостируемой массы вновь наблюдается восстановление популяции *Nitrosospira* [23, 24].

Особый интерес представляет *Nitrosospira inopinata* — представитель группы соматтох-бактерий, способный осуществлять полное аэробное окисление аммония до нитратов в рамках одного организма. Данный микроорганизм содержит гены, кодирующие ключевые ферменты нитрификации, и проявляет максимальную активность при температуре около 37 °C [25].

### Ammonium-Oxidizing Bacteria and Archaea

Ammonium-oxidizing bacteria (AOB) and ammonium-oxidizing archaea (AOA) function in compost at oxygen concentrations ranging from 1 to 10 vol. %, but occupy different ecological niches. Molecular biological studies have shown that the archaeal *amoA* gene is present throughout the entire composting process, whereas the bacterial analog of this gene is absent during the thermophilic and cooling stages [26, 27]. This indicates a higher resistance of archaea to elevated temperatures and stressful conditions.

Archaea involved in ammonium oxidation exhibit significant ecophysiological diversity and can have competitive advantages under high temperatures and low oxygen concentrations. Genomic studies suggest that AOA are capable of functioning in a mixotrophic mode, utilizing both inorganic carbon in the form of CO<sub>2</sub> and organic compounds. Additionally, AOA have a higher temperature optimum, which increases their contribution to nitrification processes as the composting mass heats up<sup>[28]</sup>.

The small cell size of archaea, compact genome, and oligotrophic metabolism contribute to their successful survival under conditions of limited substrate availability, characteristic of mature compost and soil environments<sup>[29]</sup>. Thus, the balance of AOB and AOA activity in compost is determined by the combined effects of temperature, pH, and oxygen concentration, which significantly influences the nitrogen composition of the final product.

### **Factors accelerating the composting process and improving compost quality**

The efficiency of composting and the agronomic value of the resulting product are determined by the combined influence of physicochemical and biological factors. Alongside temperature regime, moisture, and aeration, the chemical composition of the initial mixture, the carbon-to-nitrogen ratio, and the use of functional mineral additives play a key role.

#### **Carbon-to-Nitrogen Ratio**

One of the most important parameters determining the rate of organic matter biodegradation is the carbon-to-nitrogen (C/N) ratio. For active microbial growth and metabolism, the optimal value of this ratio is in the range of 26–35, while for the organic fraction of municipal solid waste, the recommended ratio is 30–35<sup>[2]</sup>. Excess nitrogen increases the activity of microorganisms, leading to nitrogen losses as molecular N<sub>2</sub>, which reduces the nutritional value of the compost<sup>[30]</sup>.

In composted substrates, sources of organically bound nitrogen, such as proteins and amino acids, are often limiting. Therefore, to stimulate the composting process, the addition of nitrogen-containing supplements, including urea and ammonium salts, is commonly practiced. Treating sewage sludge with ammonium compounds can simultaneously serve a disinfecting function and enhance the availability of nitrogen for microorganisms.

#### **Use of Mineral Additives**

A promising approach to improving compost quality is the incorporation of natural minerals with pronounced sorptive properties into the initial mixture. Of particular interest are zeolites—a group of microporous hydrated aluminosilicates capable of binding gaseous compounds and mineral ions. The use of zeolites in the composting process helps reduce ammonia emissions, minimize nitrogen losses, and increase the bioavailability of nutrients<sup>[31]</sup>.

Several studies have shown that the addition of mineral fillers, such as modified attapulgite and clinoptilolite, promotes the retention of ammonium cations and ammonia, leading to an increase in ammonium nitrogen content in composts derived from livestock and poultry waste<sup>[32, 34]</sup>. Additionally, natural zeolites can adsorb heavy metals, reducing their mobility and toxicity, which positively affects the environmental characteristics of the final product<sup>[35]</sup>.

The introduction of zeolites also provides bioavailable silicon, which can favorably influence plant growth. However, excessive use of zeolites may lead to the sorption of not only ammonium ions but also part of the beneficial microbiota, as well as reduce the intensity of nitrification due to decreased substrate availability for nitrifying microorganisms. Therefore, detailed studies are needed to determine optimal dosages and application methods for zeolites at various stages of composting.

#### **Control of Gaseous Nitrogen Losses**

An important task in composting is the minimization of nitrogen losses in the form of ammonia and nitrous oxide (N<sub>2</sub>O). The formation of these compounds is closely linked to the rate of ammonium oxidation and the structure of the ammonium-oxidizing bacterial and archaeal communities. By regulating aeration, moisture, and the chemical composition of the composting mass, it is possible to reduce the intensity of gaseous emissions and increase the nitrogen content in the finished compost.

Thus, optimizing the C/N ratio, using mineral additives, and controlling gaseous nitrogen transformations are key tools for intensifying the composting process and improving the quality of the resulting biofertilizer.

#### **Eration and aerobic–anaerobic conditions in composting**

Composting is predominantly an aerobic biotechnological process, as the decomposition of organic matter primarily occurs in the presence of oxygen. Therefore, the regime and intensity of aeration of the composting mass are among the key factors determining the rate of biodegradation and process stability. At the same time, even with active aeration, microaerophilic and anaerobic zones form within the compost due to the heterogeneous structure of the substrate and limited oxygen diffusion into the inner regions of particles.

The proportion of anaerobic microorganisms in the compost microbial community is largely determined by the characteristics of the starting material, its level of pre-treatment, moisture content, and aeration regime. Experimental data indicate that the abundance of anaerobes in the composting mass can range from 1 to 10% of the total microbial population. It has been observed that, in some cases, the rate of exoenzyme synthesis by anaerobic microorganisms can exceed that of aerobic forms<sup>[36]</sup>.

Strictly anaerobic bacteria of the genus *Clostridium* have been experimentally confirmed to participate in the enzymatic decomposition of organic compounds in composted substrates<sup>[37]</sup>. However, unlike aerobic microorganisms, anaerobes release significantly less heat when decomposing the same amount of organic matter, which affects the temperature dynamics of the process.

Anaerobic degradation of organic matter occurs through several sequential stages: hydrolysis of complex biopolymers into monomers, enzymatic conversion of monomers into volatile fatty acids, alcohols, carbon dioxide, and hydrogen, followed by an acetogenic stage with acetate formation, and under strictly anaerobic conditions, methanogenesis with methane production. The latter stage is possible only at very low redox potentials (–200 to –300 mV or lower)

Methane formation during composting is undesirable because the gas is highly flammable and poses a potential fire hazard. Regular turning of the compost mass or forced

aeration generally prevents the establishment of conditions required for methanogenesis, limiting anaerobic decomposition to the production of volatile fatty acids, carbon dioxide, and hydrogen.

At the same time, creating limited anaerobic zones can positively influence the retention of ammonium nitrogen and reduce the pH of the composting mass. Increasing the contribution of anaerobic processes, which do not require oxygen input, potentially reduces energy costs for aeration and improves the energy efficiency of composting. However, implementing this approach requires strict process control and optimization of the aeration regime.

The formation of a balanced community of aerobic and anaerobic microorganisms through microbiological and engineering approaches is considered a promising method for minimizing nitrogen losses and enhancing the agronomic value of the final product.

Despite its practical significance, the mechanisms of interaction between aerobic and anaerobic microbial communities in compost remain insufficiently understood. Further studies on organic matter decomposition under alternating anaerobic fermentation and active aerobic oxidation regimes could contribute to the intensification of composting and the improvement of the final product quality.

### Conclusions

This work summarizes and analyzes current data on composting as an effective and environmentally safe method for processing municipal and agricultural organic waste into biofertilizers. It has been shown that composting simultaneously addresses the reduction of waste volumes sent to landfills and helps compensate for the shortage of organic fertilizers in agriculture.

It has been established that the biodegradation of organic components, detoxification of pollutants, and formation of humic compounds during composting are driven by the activity of complex microbial consortia, including bacteria, archaea, and microscopic fungi. Changes in the temperature stages of composting are accompanied by sequential restructuring of the microbial community, which determines the direction and intensity of biochemical transformations of organic matter.

It has been demonstrated that the formation of plant-available nitrogen compounds in compost is carried out by microorganisms of the nitrogen cycle, including nitrogen-fixing, ammonium-oxidizing bacteria, and archaea. Ammonium-oxidizing archaea play a particularly important role under conditions of elevated temperatures and limited oxygen due to their high thermotolerance and ecological flexibility. The use of mineral additives, particularly natural zeolites, has been noted to reduce nitrogen losses, adsorb heavy metals, and enhance the agronomic value of compost. At the same time, a more detailed study of the effects of these additives on microbiological processes and nitrification at different stages of composting is required.

The use of compacted, anaerobically stabilized sewage sludge as a component of compost mixtures provides an initially developed community of anaerobic microorganisms and creates opportunities for regulating the aerobic-anaerobic regime of composting. Optimization of aeration parameters and the balance between aerobic and anaerobic processes allows for increased energy... efficiency of the technology, minimize nitrogen losses, and improve the quality of the final product.

Thus, further research into the microbiological mechanisms of aerobic-anaerobic composting and the development of rational technological regimes for processing organic waste are promising directions for creating efficient and environmentally sustainable biofertilizer production technologies.

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