Enhanced composting of plant residues from coniferous forests: the role of microorganisms in the chemical decomposition reactions

Előd Melles, Zita Csergő, Arnold Horváth, Attila Korpos, Andrea Benedek

Gheorgheni Forest District, Research and Development Center for Forestry, Gheorgheni, Romania. Corresponding author: E. Melles, ccdsilvicultura@gmail.com

Abstract. Composting is widely recognised as a sustainable method for converting organic residues into valuable soil amendments. However, residues from coniferous forests pose a distinct challenge due to their high lignin and resin content which slows natural biodegradation. This experimental study aimed to develop an enhanced composting technology for producing a nutrient substrate suitable for coniferous-forest seedlings. Laboratory trials compared a classical aerobic composting process with a microbial-inoculated enhanced process under controlled conditions. Temperature, moisture, pH and C:N ratio were systematically monitored. The enhanced process significantly reduced the composting time by several weeks, lowered the C:N ratio from 35.8 to 15.0, and resulted in compost exhibiting higher nitrogen and phosphorus content, improved humification and slow-release nutrient properties. These findings demonstrate that microbial inoculation effectively promotes the decomposition of lignin-rich forest residues and produces a high-quality organic fertilizer for forestry applications.

Keywords: coniferous forest residues, microbial inoculation, C:N ratio, seedling substrate.

Introduction. Composting is a key strategy for converting organic residues into nutrient-rich substrates for plant growth. The composting process involves two distinct stages: preparing the mixture of raw materials necessary for the biodegradation process and the aerobic biodegradation process (Nedeff et al., 2012a). Composting refers to the entirety of the physical, chemical, and biological transformations that biodegradable waste undergoes as it transitions from its initial form to the humification stage. Compost must be properly decomposed to be applied to crops during the seedling growth season. Organic matter with a high C:N ratio competes with plant roots for accessible nitrogen from the soil. Microorganisms that mineralize carbon from organic matter have a higher affinity for nitrogen than plant roots. Compost has a high organic matter content and helps restore many soil properties lost during use. Although compost is not considered a fertilizer, it contains nutrients that enhance seedling growth. Compost reduces the release rate of nutrients by binding them and ensuring their slow release over time. This prevents leaching into groundwater and surface water during rain (Kuo et al., 2004). Compost improves soil porosity, which is essential for fertile soils. Microbiological activity is crucial because microorganisms decompose organic matter and make nutrients available to plants (Thi et al., 2022). This occurs more effectively in porous, aerated soils. An abundant organic matter supply increases soil porosity. Compost also increases the soil's water retention capacity, both by increasing soil porosity and through its ability to absorb water. Additionally, compost enhances soil resistance to erosion by water and wind, improving the soil's physical characteristics and promoting faster plant growth, which helps protect the soil from erosion (Zemánek, 2011). Wood waste comprises a variety of products and materials originating from all stages of the wood industry, from forest exploitation to the manufacturing of finished products (Timofte, 2004). The primary sources of wood waste include forest exploitation: bark, sawdust, small wood pieces, and plant residues. Wood is a compact aggregate of cells and channels or vessels through which the sap of the plant circulates. In conifers, the vessels consist of elongated individual cells. In mature plants, several thick membranes form inside the cells, lining the primary cell wall and filling most of the cell's space. These secondary membranes consist of cellulose, lignin, and other organic and inorganic substances accompanying the cellulose. The chemical composition of various wood species shows some variation among spruce, fir, and pine. The cellulose content is relatively high in all three types, ranging from 52–55% in spruce, 50–54% in fir, and 53–54% in pine. Lignin levels are also significant, with spruce containing 28–33%, fir 29–33%, and pine slightly lower at 27–28%. The hemicellulose content remains fairly consistent across the species, varying between 8–10% for spruce and pine, and 7–9% for fir. The ash content, which includes inorganic elements such as calcium (Ca), potassium (K), sodium (Na), iron (Fe), aluminum (Al), silicon (Si), phosphorus (P), chlorine (Cl), and sulfur (S), is relatively low, measured at 0.2–0.4% in spruce, 0.1–0.4% in fir, and 0.2% in pine (Nenițescu, 1968). Woody plants have an outer layer made up of specific tissues called bark. This layer represents a significant percentage of the total mass of the wood. Bark has certain characteristics that make it suitable for soil fertilization, as it contains a high amount of organic substances and important quantities of minerals. Dried bark has a higher calorific value than wood due to its high lignin content. Chemically, bark differs significantly from wood, characterized by a higher content of extractable substances, lignin, and ash. The bark of coniferous wood is characterized by a high lignin content, which accounts for 35.81% of its composition. Cellulose is also present in significant amounts, comprising 25.07% of the bark. In addition, the ash content, which includes various inorganic elements such as Ca, K, Na, Fe, Al, Si, P, Cl, and S, is measured at 3.27% (Chiriac, 2011). A characteristic of plant residues in coniferous forests is the presence of resin, which has antiseptic effects. This limits and selects the bacteria that decompose plant material, resulting in a lack of specific microbial cultures for decomposing resinous plant material on the market. The role of the mixture of plant residues from coniferous forests is to provide the raw material for anaerobic fermentation and its transformation into humus through the action of microorganisms (Balwant et al., 2023). The balance of carbon-to-nitrogen (C:N) ratio is also critical, as it affects microbial growth and the pace of organic matter decomposition. Optimally, a C:N ratio of approximately 35:1 promotes efficient microbial activity while preventing nitrogen loss or toxicity (Nedeff et al., 2012b). Despite extensive knowledge of microbial processes in composting, the high lignin content and antiseptic properties of coniferous forest residues pose challenges for classical aerobic composting. To address this, microbial inoculation has been proposed as a method to accelerate biodegradation, enhance humification, and improve compost quality. This study aimed to develop and test an enhanced composting technology for coniferous forest residues using selected microbial cultures, by comparing classical aerobic composting with a microbial-inoculated process in terms of composting time, physicochemical parameters, and final compost quality.

Material and Methods. Temperature, pH, moisture content and C:N ratio were monitored systematically throughout the composting process. Temperature measurements were performed daily using a probe thermometer inserted at three points within the compost mass, and values were averaged. Moisture content and C:N ratio were determined weekly to follow compost dynamics and maturity evolution. The C:N ratio and elemental composition were determined using dry combustion with an Elementar Vario MICRO Cube analyser. pH was measured in $CaCl_2$ suspension using a calibrated pH meter. The microbial inoculum used in the enhanced composting process consisted of indigenous strains isolated from compost and forest soil and selected based on their lignocellulolytic activity.

Biodegradable forest waste. The biodegradable forest waste used in this study originated from coniferous stands after logging operations. The main components included bark, sawdust, small-diameter branches, and other vegetal residues. The raw material was collected using a forwarder and transported to the composting site. Primary processing involved mechanical disintegration with a wood chipper, which reduced the particle size of branches and tree tops left after harvesting. The resulting wood chips were transported in sealed containers to the composting facility, where the material was screened with a rotary screener (mesh size: 20 mm) to remove oversized particles. The screened biomass was arranged in windrows of 40 m length and 1.5 m height. Each windrow represented a composting variant: (1) classic aerobic composting and (2) enhanced composting with microbial inoculation. The enhanced variant was treated with a liquid inoculum containing selected lignocellulolytic microorganisms at a concentration of 10^6 CFU mL^{-1}. Aeration and homogenization were performed weekly using an aeration–mixing machine to maintain oxygen levels above 10%. Temperature, pH, moisture content, and C:N ratio were measured at three points along each windrow regularly throughout the composting process, using standard analytical procedures described in AOAC (2019). Data obtained from these measurements correspond to the parameters presented in the Results and Discussion section (Tables 2–7, Figures 3–7).

Classical composting process. The standard aerobic composting procedure, highlighting the main steps involved in preparing and processing plant residues for decomposition, consists of the following:
1) Reception of raw materials – receiving and inspecting the input materials;
2) Mechanical shredding of plant residues using a shredder – reducing the particle size to facilitate further processing;
3) Sieving – removing oversized or unwanted fractions to ensure uniform particle size;
4) Homogenization – thoroughly mixing the materials to obtain a uniform composition;
5) Aeration using an aerator – introducing air into the material mass to support biological processes and prevent anaerobic conditions;
6) Monitoring and control of process parameters – including pH, moisture content, temperature, and carbon-to-nitrogen (C:N) ratio.

Enhanced composting process. To accelerate composting, a bacterial biopreparation composed of selected microbial cultures was applied. These cultures, isolated from soil and previous composts, enhance cellulose degradation and promote humic substance formation. The inoculum also facilitates rapid fermentation, raising the temperature above 60 °C to inactivate certain vegetative pathogens. Key parameters of the compost were regularly monitored: temperature and pH were measured daily, moisture content weekly, and the C:N ratio was assessed periodically, along with visual observations of material biodegradation.

Chemical analysis of the compost. The total nitrogen, total carbon, and humus content were determined using an Elementar Vario MICRO Cube CHNS analyser via dry combustion, by heating the compost to 1150°C in a helium gas stream containing oxygen and free of carbon dioxide. The extractable phosphorus content was determined using the UV-VIS T92 Plus PG Instruments spectrophotometer at a wavelength of 830 nm. The accessible potassium content was determined using the Perkin Elmer PinAAcle 900T atomic absorption spectrometer at a wavelength of 766.5 nm.

Microbial strains for enhanced composting. Biopreparations are pure cultures of selected microorganisms that stimulate the multiplication, growth, and development of processing microorganisms. The microbial cultures used as inoculants are thermophilic bacteria cultivated in liquid media.

Statistical analysis. The experimental data were analysed using Microsoft Excel with the “Excel Statistics” add-in. Descriptive statistics (mean and standard deviation) were calculated for all monitored parameters. Measurement accuracy ranged between 1–3%. Differences between composting variants were evaluated based on parameter evolution during the composting process, with statistical significance considered at $p<0.05$.

Results and Discussion

Composition and microbial degradation of lignin, cellulose, and hemicellulose. Lignin is a major component of plant cell walls, providing structural support, facilitating water and nutrient transport, and protecting against pathogens. It constitutes 15–30% of lignocellulosic biomass and is composed mainly of three monolignols: p-coumaryl, coniferyl, and sinapyl alcohol, with coniferyl alcohol predominating in conifers (Figure 1) (Karunarathna & Smith, 2020; Sapkota, 2022).

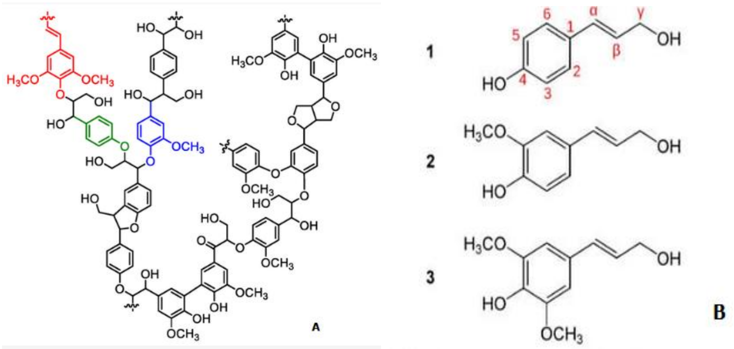

Figure 1. Structure of lignin (A) (Karunarathna & Smith 2020) and the three common monolignols (B): p-coumaryl alcohol (1), coniferyl alcohol (2), and sinapyl alcohol (3) (Sapkota, 2022).

Lignin is highly resistant to decomposition, with degradation rates influenced by species, age, and temperature. Its breakdown involves three main steps: depolymerisation-microbial enzymes, including peroxidases and phenol oxidases, cleave the p-O-4 ether bonds, producing dimeric or oligomeric phenolic units; oxidation of the 3C side chain-formation of aldehydes and aromatic acids occurs, followed by demethylation and decarboxylation to polyphenols, which can oxidize to quinones and polymerize into humic substances (Malschi, 2014); and solubilization and mineralization-smaller lignin molecules are further metabolized by microorganisms, ultimately yielding CO_2 and other bioavailable molecules. Microorganisms with polyphenol oxidase activity play a central role in lignin decomposition, and current research explores engineered bacteria for lignin metabolism (Malschi, 2014).

Cellulose, the primary polysaccharide in plant cell walls, provides mechanical strength and serves as a major carbon and energy source for soil microorganisms. Its degradation is hydrolytic, mediated by cellulase and cellobiase, producing glucose. Mesophilic cellulolytic bacteria include *Cythophaga*, *Myxococcus*, *Cellvibrio*, *Actinomyces*, *Bacillus cellulosae*, *Clostridium*, and *Pseudomonas*, while thermophilic cellulolytic bacteria, such as *Bacillus calefactor* and *Streptomyces thermophilus*, thrive at 50–65°C (Zhao Yi et al., 2017). Cellulase enzymes act either endo- or exo-wise on β-glycosidic bonds, releasing cellodextrins and cellobiose, part of which is assimilated by microbes while the remainder is released as CO_2, H_2O, and minor organic acids (Malschi, 2014).

Hemicellulose is a heterogeneous polysaccharide coexisting with cellulose in plant cell walls. Common types include xylan, glucuronoxylan, arabinoxylan, glucomannan, and xyloglucan, with xylan being the most abundant. Hemicelluloses constitute 6–30% of dry plant matter depending on species and age. Their decomposition is mediated by fungi and bacteria such as *Bacillus*, *Pseudomonas*, *Clostridium*, *Azotobacter*, and *Sporocytophaga myxococcoides*, contributing to overall plant residue degradation (Sapkota, 2022). Soil studies confirm increased CO_2 release during hemicellulose mineralization, reflecting microbial activity.

Biochemistry of hemicellulose decomposition. The hydrolysis of hemicelluloses occurs through the action of extracellular enzymes known as hemicellulases. For example, endo-xylanase hydrolytically cleaves the β-xylosidic bonds within xylan chains, producing oligoxyloses and xylose. In aerobic conditions, the final products of the degradation of reducing sugars are CO_2 and H_2O. Humic substances significantly influence various physical and chemical properties, affecting soil structure, cation exchange capacity, salt formation, and the creation of various organo-mineral compounds, which form the basis of the soil's colloidal complex. The biocompost obtained represents a novel approach due to its characteristic composition from the acidic environment of coniferous forests (Table 3).

Table 3

Composition of forest compost

Forest waste	*Composting biostimulant*	*pH modifier*
Mix of plant residues from coniferous forests	A biopreparation made from thermophilic aerobic microbial cultures (bacteria) that enhances the composting process.	Soil with a high content of $CaCO_3$

Biocompost is an organic mineral fertilizer with no added synthetic inorganic substances containing nitrogen or phosphorus. It is obtained through an aerobic biodegradation process that utilizes a biodegradable mix of plant residues from coniferous forests. Wood waste, even when finely chopped, undergoes natural biodegradation at a very slow rate, but this process can be significantly accelerated with biostimulation using microorganisms. The parameters of compost components were determined (Table 4).

Table 4

Parameters of compost components

Characteristic	*Mix of wood chips and plant residues*	*pH modifier*
Moisture (%)	70-80	40-50
pH	5.722-5.773	9.190
Organic matter (%)	>5	<1

The C:N ratio is very important in composting processes (Figure 2) because, on the one hand, microorganisms need carbon as an energy source for metabolic processes and as a constituent element of specific compounds, while on the other hand, they need nitrogen for the synthesis of microbial biomass, predominantly proteinaceous (Nedeff et al., 2012b). Extreme amounts of nitrogen in the composting mass can create a toxic environment for microbial populations, inhibiting the composting process. Excess nitrogen can also be lost through leaching, in the form of nitrate, ammonia, or organic nitrogen. Table 5 outlines the carbon-to-nitrogen ratios for various types of wood waste, highlighting the balance necessary for effective composting. The optimal value for the carbon-to-nitrogen (C:N) ratio is considered to be 35:1, as it has been observed that microorganisms thrive and function well at this ratio. Higher C:N ratios can inhibit microbial growth, while lower initial values can accelerate microbial growth and decomposition. However, this rapid growth consumes the available oxygen, leading to anaerobic conditions. The C:N ratio decreased from 35.8±1.4 to 15.0±0.8 in the enhanced composting system, indicating compost maturity (C:N≤15). This reduction was significantly faster compared to the classical composting process ($p<0.05$).

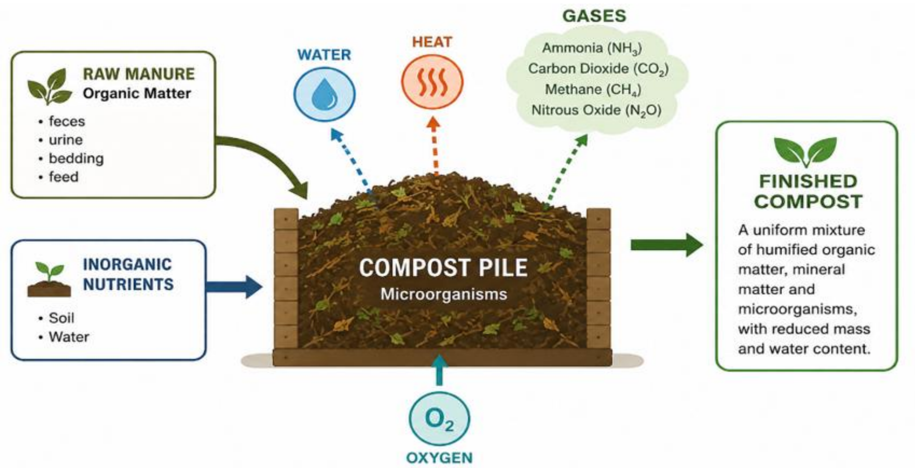

Figure 2. Diagram of the composting process with input and output materials (developed by the authors based on Kuo et al., 2004).

Table 5

Wood waste rich in carbon and nitrogen

Types of waste	*C:N ratio*
Vegetable waste	13:1
Pine needles	80:1
Tree bark	100-130:1
Shrub residues	100-150:1
Wood shavings and chips	100-500:1

pH adjustment and organic matter decomposition. Due to the naturally acidic nature of forest soils and wood waste (pH 5–6), a pH modifier, such as calcium carbonate ($CaCO_3$)-rich soil, is necessary to stabilize pH and enhance microbial activity at the start of composting. Low pH levels inhibit microbial processes, while homogenization and aeration of the fibrous mass improve porosity, accelerate decomposition, and produce a substrate similar to natural forest litter but obtained faster. Enhancements like intermittent forced aeration and adding wood chips (10–20% of total mass) improve self-aeration and overall composting efficiency. The decomposition of organic matter occurs in three stages: (1) Hydrolysis – complex substances are broken down into simpler compounds: proteins → peptides, amino acids, carbohydrates → hexoses, pentoses, cellulose, lignin → polyphenols, lipids and resins → glycerol, fatty acids; (2) Oxidation-reduction – hydrolysis products are further degraded into simpler organic or mineral compounds: proteins → organic acids, alcohols, NH_3, CO_2, H_2O, CH_4, H_2S, carbohydrates → oxoacids, volatile organic acids, aldehydes, CO_2, H_2O, CH_4, Lignins and tannins → phenols, quinones, CO_2, H_2O, lipids/resins → unsaturated acids, hydrocarbons, CO_2, H_2O; and (3) Complete mineralization – formation of stable mineral compounds occurs, producing CO_2, H_2O, NH_3, and salts (e.g., Ca^{2+}, Mg^{2+}, K^+, Na^+) under aerobic or anaerobic conditions. The intensity of decomposition depends on the organic residue composition and environmental conditions (aeration, pH, temperature, texture, structure). Organic residues rich in proteins and basic elements decompose most rapidly, whereas lignin- and tannin-rich wood residues decompose slowly, yielding lower-quality humic compounds. Optimal decomposition occurs in aerobic conditions, high temperature, neutral pH, and sandy soils; slower decomposition is observed under anaerobic, cold, acidic, or strongly alkaline conditions. Humus formation, a dominant biochemical process, occurs in two phases: microbial decomposition of residues into low-molecular-weight compounds (phenols, amino acids) under slow oxidation; and condensation and polymerization of these products into humic acids, where polyphenols from lignin, cellulose, tannins, and amino acids from proteins are key contributors. Humus and partially humified organic matter provide a permanent nutrient reserve, improving soil fertility and supporting microbial activity. Microbial metabolism releases CO_2 and H^+ ions, promoting mineral weathering and modulating soil pH, which sustains plant nutrient cycles (Puiu et al., 1983).

Biological degradation of lignin. The isolated strains exhibited lignin, cellulose, and hemicellulose-degrading capabilities, confirming previous reports on the role of *Bacillus*, *Pseudomonas*, and Actinomycetes in lignin biodegradation (Sapkota, 2022).

Enzymes involved in lignin degradation. Lignin lacks hydrolysable bonds, meaning that the enzymes required for its degradation must be of an oxidative nature. Lignin is a stereo-irregular compound, indicating that enzymes attack the substrate in a less specific manner compared to other natural polymers. Primarily, three different enzymes are involved in lignin degradation: manganese peroxidase (MnP), lignin peroxidase (LiP), and lactases. However, many other enzymes also contribute to lignin degradation. The lignin degradation process can be influenced by a number of factors such as: moisture content – an increase in water amount has a limited effect on the degradation process; added nitrogen – it is observed that the lignin degradation rate increases with higher nitrogen concentration, but only to a certain extent; aeration – the rate of lignin and carbohydrate metabolism increases as the oxygen content in the environment rises. This is because most of the microorganisms involved in lignin degradation are aerobic organisms that thrive in an oxygen-rich atmosphere (Sapkota, 2022).

Compost production technology comprises several distinctive steps resulting in a complex biotechnology. The method is ecological, it considers the utilization of biodegradable forest waste in a non-polluting product, with high nutritional value for softwood saplings. The presented activity consists of the analysis of observational data on improved composting, with the help of these data a methodology for obtaining forest bio compost for softwood saplings was developed. During the enhanced composting process, parameters were monitored as in a classic composting process. The control of the enhanced compost's parameters was carried out periodically, including daily temperature measurements, daily pH determination, weekly moisture content measurements, and C:N ratio assessments, along with observations on the progress of material biodegradation. A comparison was carried out between the enhanced composting process and the classic one (Figure 3), as well as between the properties of the products obtained from both processes in the 20th week of composting. The enhanced composting process (Figure 4), using a bacterial biopreparation, reached the maturation phase faster, and the parameters of the enhanced compost were significantly improved, as expected. The main parameters provide information on the state of the composting process, especially when transitioning from the active phase to the maturation phase.

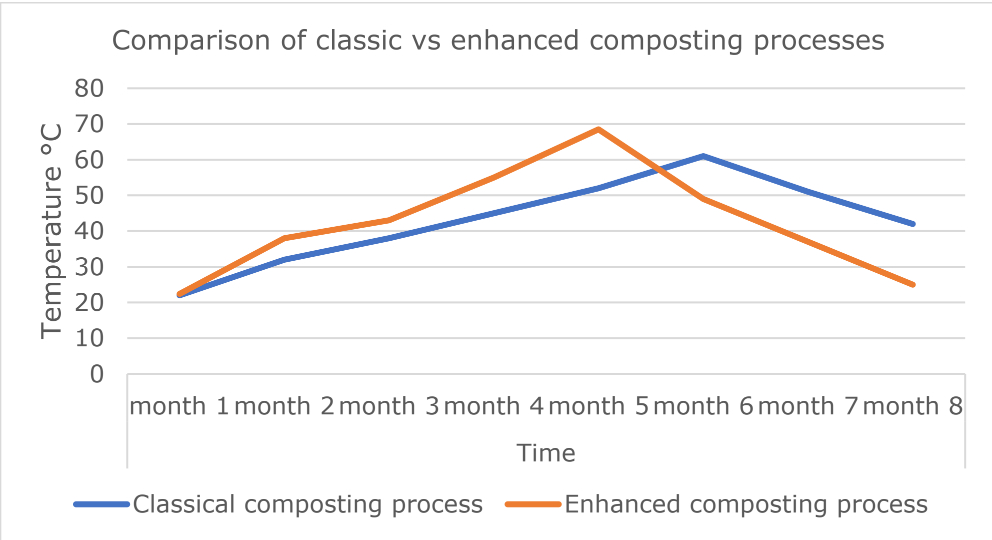

Figure 3. Comparison of classic vs enhanced composting processes.

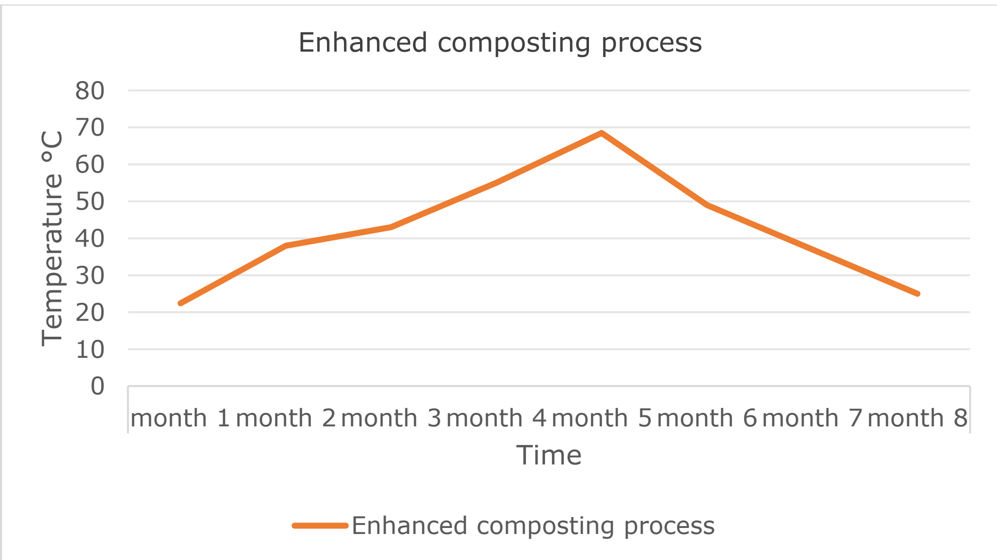

Figure 4. Enhanced composting process.

The composting process of wood chips and plant residues lasted 8 months (April–November), with pH values ranging from 5.75 to 6.97, moisture content between 34.09 and 67.94%, and temperatures from 22.4 to 68.5°C. The C:N ratio decreased from 35.8 to 15.0, indicating compost maturity, as compost is considered stable at C:N≤15. After pile rearrangement, temperatures did not rise again, signalling the end of active composting and entry into the maturation phase. During maturation, microbial activity declined, allowing prolonged storage without further handling. Humus content decreased from 80.39 to 41.55%, reflecting substantial decomposition. Enhanced composting showed faster temperature rises, indicating earlier fermentation and reduced composting time compared to the classical process.

Maturation and stabilization. The additional time provided by the maturation process allows for better stabilization of the material and decomposition of malodorous organic acids and phytotoxins that may have been generated during the initial composting phase. Active compost piles can be ready to enter the maturation phase after a few weeks; however, most recommendations suggest several months. Special attention should be given to the decrease in temperature in the active pile, ensuring that it is not the result of limitations, such as insufficient or excessive moisture. Maturation is maintained as long as necessary to achieve the desired level of compost stability, which can take from a few weeks to several months. The conclusion of the useful composting process is marked by the appearance of nitrates, a consequence of the reactivation of the aerobic microflora responsible for mineralizing humified matter. During the composting process, the humus content decreased significantly from 80.39 to 41.55%. It can be established that, in the case of enhanced composting, the compost temperature increased much more rapidly, indicating that fermentation occurred earlier. The time required for composting was reduced, leading to the production of forest compost in a shorter period. Compost respiration, expressed as CO_2 production, reflects microbial decomposition and nutrient cycling potential (Ichim & Ichim, 2010). Monitoring confirmed that enhanced composting with microbial inoculants accelerated microbial activity and substrate mineralization. To improve composting efficiency, a bacterial consortium including *Bacillus* sp. (*Nitrososphaeria*)*,* *Pseudomonas* sp. (Gammaproteobacteria), *Actinomycetes cellulosae* (Streptomycetaceae), *and Micrococcus* sp. (Micrococcaceae) was applied. These cultures were isolated from soil and compost during laboratory-scale composting to accelerate cellulose degradation and promote the formation of humic substances. Since aerobic processes take a long time, and to quickly initiate fermentation and raise the temperature above 60°C (to eliminate certain pathogens in vegetative form), treatment with biopreparations was necessary. Biopreparations are pure cultures of selected microorganisms that stimulate the multiplication, growth, and development of processing microorganisms. The microbial cultures used as inoculants are thermophilic bacteria cultivated in liquid media. The quality of the biocompost is closely related to the synthesis processes driven by microbial activity (Ichim & Ichim 2010).

Biopreparations are selected microbial cultures specifically intended for this purpose. The microbial community from the litter zone of the forest waste exploitation area was studied, and composting experiments were conducted at the laboratory scale under controlled conditions. During these activities, bacterial strains that contribute to the decomposition of plant residues from coniferous forests were isolated and identified. The obtained strains were tested for their ability to degrade cellulose and hemicellulose at the laboratory scale. The most promising strains were sequenced and identified.

Selected microbial strains for enhanced composting. Based on the laboratory results, it was determined that the isolated and identified microorganisms play a key role in the decomposition of plant residues from forest exploitation. Among the isolated bacterial strains, the most promising were selected based on their properties in degrading lignin, cellulose, and hemicellulose. After analysing the sequencing results, the selected microbial strains responsible for decomposition belonged to the Nitrososphaeria class, Actinobacteria class, and Gammaproteobacteria class. From the Nitrososphaeria class, *Bacillus* sp. was selected. *Bacillus* strains can degrade alkaline lignin and, when combined with lactic bacteria, improve cellulase performance. From the Actinobacteria class, species such as Micrococcus and *A. cellulosae* were isolated from the thermophilic stage of composting. Actinobacteria play a key role in the microbial community during composting. These bacterial cultures were multiplied in a biofermentor, and wood chips were inoculated to accelerate the composting process, with the goal of achieving enhanced composting compared to the classical method. Thermophilic cellulolytic actinomycetes can significantly enhance cellulase activity, accelerate cellulose degradation, and change the structure of the actinomycete community, especially when inoculated during the thermophilic stage of composting.

Microbial strains from the Gammaproteobacteria class. The species that appeared in significant proportions from the Gammaproteobacteria class include families such as Pseudomonadaceae, Moraxellaceae, and Enterobacteriaceae. These species can depolymerize high molecular weight lignin's and can also catabolize a wide variety of lower molecular weight lignin. From the Gammaproteobacteria class, *Pseudomonas* sp. was selected. The bacterial biopreparation was composed of microbial cultures that included species from the Nitrososphaeria family (*Bacillus* sp.), Pseudomonadaceae family (*Pseudomonas* sp.), Streptomycetaceae family (*A. cellulosae*), and Micrococcaceae family (*Micrococcus*). *Pseudomonas* metabolizes various low molecular weight lipids found in lignocellulose biomass. The enzyme is highly specific, cleaving only anisoin (4,4'-dimethoxybenzoin) and benzoin (Sapkota, 2022). Significant results were obtained using microbial cultures, such as *Bacillus* sp., *Pseudomonas* sp., and *Micrococcus* sp., grown on synthetic culture media. The role of these cultures is to rapidly hydrolyze part of the substrates, thereby creating favorable conditions for the development of active microorganisms involved in physiological processes such as nitrogen fixation and the degradation of cellulose, hemicellulose, and xylan.

Cellulolytic activity and humification. During the thermophilic phase, microbial cultures from the Streptomycetaceae family (*Streptomycetes cellulosae*) were inoculated to accelerate cellulose degradation and to promote the maturation stage of composting, due to their humification properties. During the research, the cultivation conditions of bacterial strains were optimized, and the optimal technological conditions for producing the biopreparation were established. The optimal conditions to produce the selected bacterial strains for the biopreparation formation can be seen in the Table 6.

Table 6

Optimal production conditions for selected bacterial strains

Parameters	*Bacillus sp.+ Pseudomonas sp.+Micrococcus sp.*	*Streptomycetes cellulosae*
Culture medium composition	24.77 g L^{-1} soy flour 1.25 g L^{-1} K_2HPO_4 1.25 g L^{-1} D-glucose	4 g L^{-1} yeast extract 10 g L^{-1} malt extract 1.25 g L^{-1} K_2HPO_4 4 g L^{-1} D-glucose
Inoculum dilution	100x	100x
Temperature, °C	24	28
pH	7.3	7.2
Aeration (culture medium/air)	1/4	1/4
Incubation time, hours	14	12

The bacterial biopreparation, consisting of the consortium of *Bacillus* sp., *Pseudomonas* sp., and *Micrococcus* sp., was used to improve the composting process and to facilitate temperature rise during the thermophilic stage. This facilitation reduced the composting time, thus obtaining forest compost in a shorter period. The *S. cellulosae* strains (Actinomycetes) were used to accelerate cellulose degradation and to speed up the maturation stage of composting, having humification properties. The role of these cultures is to rapidly hydrolyse part of the substrates, thereby preparing favourable conditions for the development of active microorganisms in physiological processes, such as nitrogen fixation and cellulose degradation.

Forest compost. Forest compost is an organic product derived from shredded forest plant residues, with particle sizes ranging from 1-20 mm and a brown to black colour, with the following properties (Table 7).

Table 7

Composition of enhanced compost

Parameter	*Content*
pH	5.970
Moisture	34.09%
C:N ratio	15:1
Total nitrogen (N)	1.55%
Extractable phosphorus (P_{AL})	37.44 ppm
Potassium (Ka)	40.00 ppm
Microelements	2-2.5%
Organic carbon (C)	24.09%
Organic matter	41.55%
Degree of humification	25%

Figure 5 shows the extractable phosphorus (PAL) content of the enhanced forest compost. The measured concentration was 37.44 ppm. The presence of extractable phosphorus indicates that part of the phosphorus contained in the original plant residues was converted or maintained in forms accessible for extraction during composting. Microbial decomposition may contribute to phosphorus mobilization through the mineralization of organic phosphorus compounds and the activity of phosphatases and other extracellular enzymes. The detected phosphorus content, together with the other measured nutrient parameters, indicates the potential of the enhanced compost as a nutrient-containing organic substrate for coniferous seedlings.

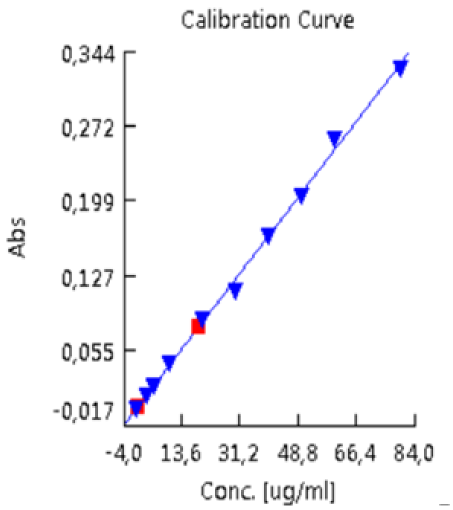

Figure 5. Phosphorus content results (spectrometric).

Figure 6 presents the extractable potassium content of the enhanced forest compost. The measured concentration was 40.00 ppm. Potassium is an essential macronutrient involved in plant water regulation, enzyme activation, and stress tolerance. The detected potassium content indicates that the compost retains a measurable amount of plant-available K and may contribute to the nutrient supply of coniferous seedlings.

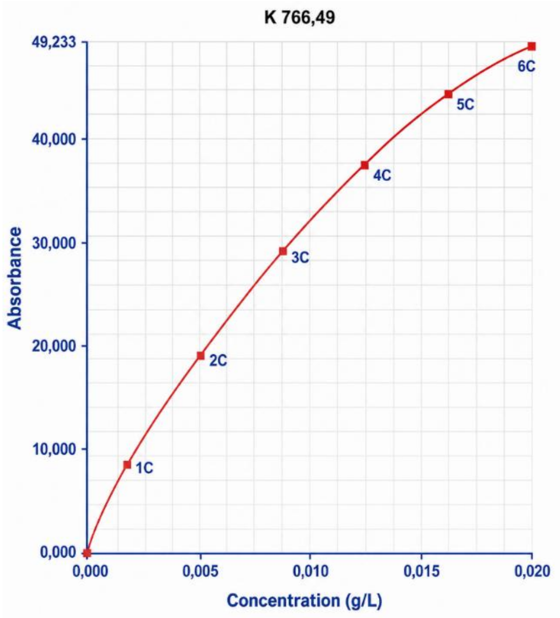

Figure 6. Potassium content results (spectrophotometric).

Through mineral nutrition and growth processes, plants can synthesize and accumulate biomass from energy and mineral substances present in the environment. Mineral nutrition takes place through the absorption of nutrients from the soil, which serves as the primary source and reservoir for these elements. Depending on the amount needed for plant nutrition and growth, macroelements such as carbon, hydrogen, nitrogen, phosphorus, and potassium are essential (Chiriță, 1974). Nitrogen in the soil is an indispensable macroelement for plants, playing a role in their vegetative growth and fruiting processes. The accumulation of nitrogen in the soil is mainly due to biological processes. The total nitrogen content in the soil is closely linked to the amount of organic matter present (Stoica et al., 1986). Nitrogen is absorbed by plant roots from the soil, contributing to the formation of essential organic compounds that play a crucial role in the plant's composition and vital processes (Chiriță, 1974) The nitrogen in the soil affects the growth and development of green leaves and the plant's resistance to winter conditions. Phosphorus plays an important role in plant growth and development and in resistance to winter conditions, while potassium is responsible for protection against diseases and pests.

Compost process improvement. The composting protocol was improved at the composting station to incorporate lessons learned throughout the activities. The composting process was enhanced by applying intermittent forced aeration and using wood chips as a structural amendment in approximately 15% of the total mass. This helped achieve more efficient self-aeration of the compost piles. Based on the results obtained from observational data comparing classic and enhanced composting, a new composting technology was developed to produce an ideal forest compost for coniferous seedlings in a shorter time compared to traditional composting. The enhanced composting process was accomplished by adding a pH modifier and treating the main compost pile with a bacterial consortium derived from research, which actively decomposes plant residues. The plants grown on compost appeared vigorous and exhibited only minimal signs of stress due to salts and nutrients.

Conclusions. The results of this study demonstrate that enhanced composting using microbial inoculation significantly improves the biodegradation of lignin-rich coniferous forest residues. The accelerated composting process was evidenced by a faster temperature increase and a more rapid reduction of the C:N ratio from 35.8 to 15.0, indicating earlier compost maturity. The application of selected indigenous microbial strains contributed to improved organic matter decomposition and enhanced compost quality, including increased nutrient availability and improved humification. The developed composting approach represents an efficient and sustainable method for valorizing forest residues and producing high-quality organic substrates suitable for coniferous seedling cultivation. These findings highlight the potential of microbial inoculation to optimize composting processes and support sustainable forest management practices.

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Authors:
Előd Melles (EM), Gheorgheni Forest District, Research and Development Center for Forestry, Gheorgheni 535500, Romania, e-mail: elodmelles@gmail.com
Zita Csergő (ZC), Gheorgheni Forest District, Research and Development Center for Forestry, Gheorgheni 535500, Romania, e-mail: csergozita1979@gmail.com
Arnold Horváth (AH), Gheorgheni Forest District, Research and Development Center for Forestry, Gheorgheni 535500, Romania, e-mail: horvathzarnold@gmail.com
Attila Korpos (AK), Gheorgheni Forest District, Research and Development Center for Forestry, Gheorgheni 535500, Romania, e-mail: atikorpos@gmail.com
Andrea Benedek (AB), Gheorgheni Forest District, Research and Development Center for Forestry, Gheorgheni 535500, Romania, e-mail: benedek_andrea@yahoo.com

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