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Applying Effective Microorganisms to Optimize Municipal Composting Systems: A Pilot Implementation in Serbia

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ABSTRACT

This study evaluates the application of Effective Microorganisms (EM) in large-scale municipal composting under real operational conditions in Serbia. A controlled field experiment was conducted over a 90-day composting period to compare EM-treated and untreated windrows of urban green waste. Key compost quality parameters were assessed to determine compost maturity and nutrient status. EM application resulted in improved compost properties, with stabilized pH (7.28 ± 0.12), increased humus content (26.52 ± 1.10%), higher total nitrogen (1.33 ± 0.05%), available phosphorus (133.46 ± 5.20 mg/100 g), and potassium (226.00 ± 8.50 mg/100 g), as well as a reduced C/N ratio (20.0 ± 0.9) compared to the control. These results indicate accelerated organic matter decomposition and enhanced compost maturation in EM-treated systems. The findings demonstrate that EM technology can improve compost quality and process efficiency in municipal composting, supporting its practical application within sustainable urban organic waste management frameworks.

Introduction

The growing accumulation of organic waste in urban areas has become a significant environmental, economic, and public health concern. Rapid urbanization has led to a substantial increase in biodegradable waste, intensifying the need for effective and sustainable management practices. Traditional disposal methods, particularly landfilling, are becoming increasingly unsustainable due to limited space, environmental pollution, and greenhouse gas emissions (Gajalakshmi and Abbasi 2008). As a result, cities are shifting toward strategies that align with circular economy principles—reducing, reusing, and recovering resources wherever possible (Rolewicz-Kalińska, Lelicińska-Serafin, and Manczarski 2020).

Composting stands out as a proven, eco-friendly method for managing organic waste. It involves the biological decomposition of organic material under controlled conditions to produce a stable, nutrient-rich soil amendment (Krstić et al. 2019). This process not only diverts biodegradable waste from landfills but also enhances soil structure, fertility, and microbial activity, contributing to sustainable agriculture (Policastro and Cesaro 2022). In urban environments, composting plays a vital role in reducing municipal waste volumes and promoting green infrastructure initiatives, including community gardens and urban farming. Its success depends on efficient waste separation and collection systems, appropriate composting techniques, and strict quality control throughout the process (Friege and Eger 2022). Although earlier reviews (Goldstein 2005) underscored the need for proper input proportioning and process control, more recent studies confirm that well-managed composting yields high-quality compost with balanced moisture, adequate nutrient content, and minimal contamination by heavy metals (Lelicińska-Serafin, Manczarski, and Rolewicz-Kalińska 2023). A significant innovation in composting is the use of Effective Microorganisms (EM)—a mixed culture

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of beneficial microbes, including lactic acid bacteria, actinobacteria, and yeasts. EM accelerates organic matter degradation, improves nutrient retention, and reduces odors, thus enhancing composting efficiency and hygiene (Filogônio et al. 2023). Its application has been shown to suppress pathogenic bacteria and limit the release of unpleasant gases such as ammonia and hydrogen sulfide (Mwegoha 2012). EM technology has proven effective in small-scale and municipal systems across various organic substrates, such as food and plant waste (Jalalipour et al. 2024; Raimi et al. 2024).

The addition of carbon-rich materials like starch, cellulose, and sugars supports microbial growth and sustains thermophilic conditions necessary for rapid decomposition and pathogen elimination (Yumnam et al. 2023). These practices create an optimized composting environment with minimal odor and reduced environmental impact. Moreover, the low-cost nature of EM-based composting makes it particularly suitable for urban public utilities and decentralized systems (Singh et al. 2024). Although EM have been applied in various small-scale composting systems worldwide, their implementation in a large-scale municipal context remains limited. This pilot study addresses that gap by evaluating EM technology under real operational conditions at a public utility company processing substantial volumes of urban green waste, thereby providing a replicable model for other municipalities.

Therefore, the aim of this research was to systematically assess the effectiveness of EM technology in large-scale municipal composting under real operational conditions. The specific objectives were to: (i) compare compost maturity indicators, including pH, humus content, and C/N ratio, between EM-treated and control windrows; (ii) assess differences in macronutrient availability (N, P_2O_5, K_2O) between treatment; (iii) evaluate composting process dynamics relevant to compost stabilization and operational efficiency.

Materials and Methods

Study Area

The composting process was conducted at the Public Utility Company (PUC) City Greenery in Čačak, Serbia, where a significant volume of biodegradable waste, approximately 1000 m^3 annually, is collected from public urban and suburban areas (Ćurčić 2019). This waste consists primarily of leaves, grass, weeds, branches, and sawdust, which are accumulated and processed for composting. The facility features mixing equipment and a water supply system to ensure optimal composting conditions, aligning with recommended infrastructure for decentralized organic waste management (Daskal et al. 2022).

Sampling Strategy

Biodegradable waste was systematically collected throughout the year using 10 m^3 vacuum collection machines (Ćurčić et al. 2020). The collected materials, primarily consisting of leaves, grass clippings, weeds, and shrub branches, were transported to designated composting facilities. Upon arrival, all incoming waste was weighed and recorded for mass balance tracking. Sampling was conducted to assess the biochemical composition and moisture content of the composting materials at different stages. Random sampling techniques were applied to ensure representativeness, following established protocols for municipal waste recycling (Rolewicz-Kalińska, Lelicińska-Serafin, and Manczarski 2020; Friege and Eger 2022). Samples were taken at four key composting stages: initial (Day 0), thermophilic peak (Day 15), cooling phase (Day 45), and maturation phase (Day 90). At each stage, composite samples were collected from multiple points and depths within compost windrows, homogenized, and stored at 4°C prior to analysis.

Experimental Design

The experimental setup was designed as a randomized complete block design (RCBD) to ensure the reliability of results and to control spatial variability within the composting site. Two treatments were established:

- EM treatment: Compost windrows inoculated with EM, aimed at accelerating composting processes and improving compost quality.

- Control treatment: Compost windrows prepared without the addition of EM, serving as the baseline for comparison.

Each treatment was applied in triplicate, resulting in a total of six windrows arranged randomly across the composting area to minimize environmental gradients such as shading, airflow, and moisture variability.

Windrows measured approximately 45 meters in length, 15 meters in width, and 4 meters in height, reflecting standard industrial-scale composting operations. The large scale ensures realistic conditions and applicability of findings to practical composting systems.

Prior to the start of composting, all windrows were prepared using shredded green organic waste adjusted to optimal moisture (50–60%) and particle size (1–5 cm) to facilitate microbial activity. The EM inoculum was applied at a standard rate of 10 liters per tonne of waste during windrow formation. Throughout the composting period, the treatments were maintained under identical environmental and operational conditions—same watering regimes, turning frequency, and monitoring schedules—to isolate the effect of EM inoculation. The experimental design allows for statistical evaluation of treatment effects on key composting parameters such as temperature dynamics, nutrient profiles, humification rate, and final compost quality, ensuring that observed differences can be attributed to EM application with confidence.

Composting Process

The composting process was carried out in open windrows, prepared from shredded biodegradable green waste with particle sizes ranging from 1 to 5 cm and adjusted to 50–60% moisture content. Initial windrows were layered with moist organic material at the base, fresh shredded waste in the middle, and covered with mature compost or untreated organic matter to stabilize microbial activity and reduce odors (Mwegoha 2012; Raimi et al. 2024). Prior to windrow formation, all biodegradable materials were mechanically shredded and thoroughly mixed to ensure homogeneity in particle size and composition. This procedure minimized variability in microbial access to substrates and ensured comparable starting conditions across treatments.

The EM-1® inoculum (EM Research Organization, Japan) is one of several commercial microbial consortia available for composting. It contains lactic acid bacteria, photosynthetic bacteria, yeasts, actinobacteria, and fermenting fungi, each contributing to organic matter degradation, nutrient cycling, and odor suppression. The chosen application rate (10 L per tonne at a 1:500 dilution) follows manufacturer recommendations and prior field trials (Filogônio et al. 2023; Jalalipour et al. 2024), ensuring effective microbial colonization while maintaining cost efficiency.

Composting comprised four phases: anaerobic, thermophilic, cooling, and maturation. In the initial anaerobic phase, lactic acid bacteria from the EM inoculum promoted lactic fermentation, which suppressed undesirable butyric fermentation and reduced odor formation. This activity supported a smoother transition into the thermophilic phase, where elevated temperatures accelerated pathogen elimination and organic matter degradation. The subsequent cooling and maturation phases stabilized the compost, with EM contributing to humus formation and nutrient availability (Chen et al. 2011; Meena et al. 2021). The composting procedure followed a standardized sequence—collection and shredding of green waste, windrow formation with EM inoculation, controlled turning and watering, and final maturation, outlined here to provide a replicable model for other municipalities.

Monitoring and Maintenance

Temperature within the compost windrows was monitored daily at a depth of 30–50 cm using calibrated digital thermometers. Maintaining thermophilic conditions, typically between 40°C and 70°C, was critical for accelerating organic matter decomposition and ensuring effective pathogen inactivation, as supported by established composting standards (Meena et al. 2021; Daskal et al. 2022). Temperature data were recorded systematically to track the progression through mesophilic, thermophilic, and maturation phases (Figure 1).

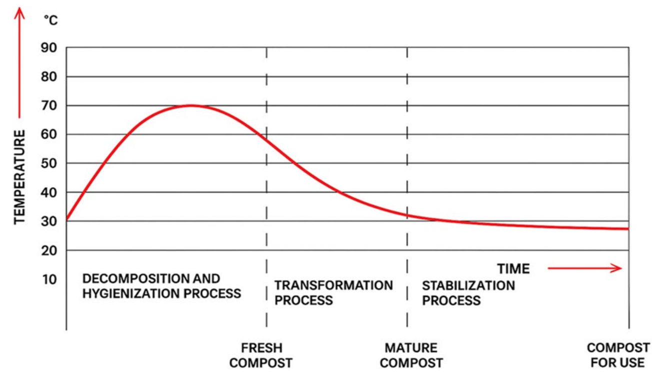

Figure 1. Temperature dynamics and process phases during composting.

Figure 1 illustrates the temperature trajectory during composting, which reflects the sequential phases of decomposition, transformation, and stabilization. After a short heating phase, temperatures rose rapidly, reaching thermophilic levels above 60°C. This period was marked by intensive microbial activity, rapid degradation of organic matter, and effective hygienization. As substrates were gradually consumed, the temperature declined, signaling the cooling and stabilization phases. The final stabilization at mesophilic levels indicated the onset of compost maturation, when microbial activity slowed and the organic matrix stabilized. Maintaining temperatures within the optimal range was decisive for achieving hygienization, weed seed destruction, and the production of agronomically valuable compost.

To sustain aerobic conditions essential for microbial metabolism, the compost piles were turned weekly using mechanical windrow turners. This turning operation promoted uniform aeration, prevented anaerobic zone formation, enhanced substrate homogenization, and facilitated heat dissipation. Regular turning also prevented compaction and helped maintain optimal porosity within the windrows (Chen et al. 2011; Lelicińska-Serafin, Manczarski, and Rolewicz-Kalińska 2023).

Moisture content was closely regulated to remain within the ideal range of 50–60%, which supports microbial activity without causing anaerobic conditions. Moisture levels were assessed periodically using gravimetric methods (drying samples at 105°C to constant weight) complemented by hand-squeeze tests for rapid field estimation. When moisture content dropped below the optimal threshold, controlled watering was applied to restore adequate moisture, ensuring continuous microbial efficiency and preventing process stagnation (Daskal et al. 2022; Jalalipour et al. 2024). Additionally, pH and oxygen levels were monitored at regular intervals to ensure environmental conditions favorable to EM activity and overall compost stability, following protocols outlined in recent composting studies (Filogônio et al. 2023).

Sample Analysis

Compost samples collected at designated composting stages were subjected to comprehensive physico-chemical analyses to evaluate their quality and maturity. The parameters analyzed included:

- Moisture content, determined gravimetrically by drying samples at 105°C until constant weight, following ISO 11465 standard. Moisture influences microbial activity and aeration within the compost matrix.
- pH, measured potentiometrically in a 1:10 (w/v) compost-to-water suspension using a calibrated pH meter, according to ISO 10390, to assess the acidity or alkalinity which affects microbial populations and nutrient availability.
- Electrical conductivity (EC), evaluated using a conductivity meter in the same compost suspension to estimate soluble salt concentration, a key indicator of compost salinity and potential phytotoxicity (ISO 11265).

- Organic carbon content was quantified by dry combustion or wet oxidation methods (e.g., Walkley-Black), reflecting the amount of decomposable organic matter and soil amendment potential.
- Total nitrogen (N) content was measured via Kjeldahl digestion or combustion elemental analysis, providing insight into nutrient availability and mineralization status.
- Available phosphorus (P_2O_5) and potassium (K_2O) concentrations were determined by standard extraction methods (e.g., Olsen or Mehlich) followed by spectrophotometric or flame photometric quantification, indicating macronutrient content essential for plant growth.
- Humus content, evaluated through oxidation techniques, represents the stable fraction of organic matter important for soil structure and fertility.
- Carbon to nitrogen (C/N) ration was calculated from organic carbon and total nitrogen data, serving as a maturity and stability indicator for compost (optimal values generally range between 15 and 25).

All analyses were conducted at the accredited laboratory of the Faculty of Agronomy, Čačak, ensuring adherence to quality control protocols and reliable data (Filogônio et al. 2023; Singh et al. 2024). The use of internationally recognized ISO standards and validated methods guarantees comparability of results with other studies and compliance with regulatory requirements.

Fermentation of organic green waste with the use of effective microorganisms takes place in several stages, which are characterized by appropriate biochemical processes. There are four stages of composting: I - anaerobic, II - aerobic, thermophilic, III - cooling, IV - ripening. Stages I to III last a few weeks and days, and stage IV - a few months (Krstić et al. 2019). In the first (I) anaerobic phase, the hydrolysis of easily soluble carbohydrates and the breakdown of proteins occurs, the acidity (pH) of the fermentation material increases, and the formation of: lactic, acetic and butyric acids, as well as the ethanol and ammonia. The most important thing is that in this phase, under the influence of effective probiotic microorganisms, the dominance of lactic acid over other products of this phase is achieved. It is necessary to ensure the most favorable anaerobic conditions and avoid the presence of air. In the presence of larger amounts of air, more intensive oxidation processes are carried out, higher temperatures are created (over 45°C) and conditions are created for the work of acetic fermentation bacteria, that is, the production of acetic acid. Under the conditions of such an increased temperature, the undesirable process of proteolysis is more intense. In green waste with an insufficient amount of lactic acid, conditions are created for the work of butyric fermentation bacteria, that is, the production of butyric acid, butyl alcohol and acetone, which can make the composted material almost unusable. In addition, there are conditions for the development of fungi and mold in such material.

Statistical Analysis

Descriptive statistics (means and standard deviations) were used to summarize measured parameters. Independent sample *t*-tests were applied to compare EM-treated and control windrows at each composting stage, while one-way ANOVA was used to evaluate temporal changes across the four sampling points (Day 0, 15, 45, and 90). When ANOVA indicated significant effects, post-hoc Tukey's HSD tests were performed. Statistical significance was set at $p < 0.05$. All analyses and graphical visualizations were carried out using OriginPro 2022 (OriginLab Corporation, Northampton, MA, USA). This approach aligns with methodologies applied in recent composting research, where combined statistical treatments are used to evaluate treatment performance under operational field conditions (Lelicińska-Serafin, Manczarski, and Rolewicz-Kalińska 2023; Jalalipour et al. 2024).

Results and Discussion

Compost Maturity and Agrochemical Improvements

The results of the analysis of the produced compost are presented in Table 1, demonstrating statistically significant improvements ($p < 0.05$) in all analyzed agrochemical parameters when EMs were applied compared to the control group.

Table 1. Agrochemical composition of compost produced using EMs at the municipal facility.

Parameter	EM treatment (Mean ± SD)	Control group (Mean ± SD)	Significance ($p < 0.05$)
pH	7.28 ± 0.12	7.05 ± 0.10	0.006
$CaCO_3$ (%)	4.22 ± 0.15	3.90 ± 0.13	0.003
Humus (%)	26.52 ± 1.10	21.80 ± 1.00	0.0001
Total N (%)	1.33 ± 0.05	1.10 ± 0.04	0.0001
P_2O_5 (mg/100g)	133.46 ± 5.20	110.30 ± 4.80	0.0001
K_2O (mg/100g)	226.00 ± 8.50	190.00 ± 7.40	0.0001
C/N ration	~20 ± 0.9	~22 ± 1.1	0.007

The pH value of the EM-treated compost was 7.28 ± 0.12, significantly higher than the control (7.05 ± 0.10, $p = 0.005$). This mild alkalinity is optimal for microbial activity and nutrient availability, creating a favorable environment for compost maturation and supporting findings by Kuo et al. (2004) and Becher et al. (2018). A pH within the neutral to slightly alkaline range (6.5–8.0) enhances microbial decomposition efficiency and nutrient solubilization, confirming that EM application contributes to producing high-quality compost suitable for a broad range of crops.

The $CaCO_3$ content was 4.22 ± 0.15% in the EM treatment, significantly higher than 3.90 ± 0.13% in the control ($p = 0.003$). This increase improves the compost's buffering capacity, supporting soil pH stabilization upon application and enhancing nutrient accessibility for plants (Von Willert and Stehouwer, 2003). Such buffering is critical in urban green spaces where soil acidification can limit plant growth.

EM-treated compost had a humus content of 26.52 ± 1.10%, significantly exceeding the control value of 21.80 ± 1.00% ($p < 0.0001$). This substantial increase reflects enhanced humification processes facilitated by EMs, resulting in higher organic matter stability (da Silva Gaspar et al. 2023). Elevated humus content improves soil structure, aeration, and water-holding capacity, contributing to long-term soil fertility (Pandao et al. 2024).

The total nitrogen content was 1.33 ± 0.05% in the EM-treated compost, significantly higher than 1.10 ± 0.04% in the control ($p < 0.0001$). This elevated nitrogen concentration indicates improved mineralization efficiency due to EM activity, enhancing the compost's fertilizing potential. Nitrogen is a critical macronutrient for plant growth, and its higher availability promotes sustainable nutrient recycling in urban landscaping and agriculture (Griffin and Hutchinson 2007). However, High nitrogen concentrations can: Damage vegetation by adversely affecting plant roots and foliage through nutrient imbalance or ammonia toxicity. Decrease flowering and fruiting, as excessive nitrogen may promote vegetative growth at the expense of reproductive development. Cause environmental contamination, as surplus nitrogen can leach into groundwater or surface water, leading to eutrophication and associated ecological risks.

Available Phosphorus (P_2O_5): The EM treatment resulted in 133.46 ± 5.20 mg/100g of available phosphorus, significantly greater than 110.30 ± 4.80 mg/100g in the control ($p < 0.0001$). Phosphorus is essential for root development, flowering, and fruiting (Awad et al. 2010). The statistically significant increase demonstrates EMs' ability to enhance phosphorus solubilization and availability, improving the agronomic quality of compost.

Potassium levels were significantly higher in the EM-treated compost (226.00 ± 8.50 mg/100g) compared to the control (190.00 ± 7.40 mg/100g, $p < 0.0001$). Potassium is vital for plant physiological processes, including enzyme activation, photosynthesis, osmoregulation, and stress tolerance (Awad et al. 2010). The statistically significant increase in K_2O content indicates that EM treatment enhances potassium availability, which contributes to improved plant growth, disease resistance, and yield potential. This finding underscores the agronomic value of EM-enriched compost in urban greening and agricultural applications where potassium supply is critical for crop productivity and resilience.

The C/N ration in the EM-treated compost was 20.0 ± 0.9, which was significantly lower compared to the control (22.0 ± 1.1, $p = 0.006$). A lower C/N ration indicates more advanced compost maturity and stabilization, suggesting that EM application accelerates organic matter decomposition and humification processes. This is crucial for producing stable, mature compost suitable for direct soil application, minimizing risks of nitrogen immobilization upon incorporation.

The maturity of compost is determined by achieving a stable chemical composition and providing essential nutrients for soil improvement. In this study, the maintenance of favorable process conditions—balanced carbon-to-nitrogen ration, adequate moisture, oxygen availability, and stable pH—proved essential for producing a high-quality end product. Within this optimized environment, the application of EM significantly enhanced the agrochemical profile of the compost. Higher humus content, increased nitrogen, phosphorus, and potassium availability, together with stable pH and an optimized C/N ration, confirmed that the final product reached an advanced level of maturity. These results validate EM technology as an effective and sustainable strategy for urban organic waste management, yielding high-quality compost that enhances soil fertility, crop productivity, and environmental resilience.

Process Dynamics and Operational Efficiency

The efficiency of composting depends on the regulation of several dynamic parameters that govern microbial activity and organic matter transformation (Figure 2). A balanced C/N ration of 25–30:1 provides sufficient energy and nutrients for microbial growth while preventing nitrogen immobilization or volatilization. Maintaining moisture content between 50% and 60% ensures hydration necessary for microbial metabolism while avoiding anaerobic conditions. Adequate aeration, achieved by sustaining oxygen concentrations above 12% and controlling particle size between 1 and 2.5 cm, promotes porosity and uniform decomposition. Temperature control within the thermophilic range of 50–60°C is critical for sustaining microbial populations, accelerating organic matter breakdown, and ensuring pathogen reduction.

Figure 2 complements this profile by illustrating the trajectories of temperature (°C) pH, C/N ration, and moisture content over the 90-day period. The temperature increased rapidly in the initial phase, reaching a thermophilic peak of 58°C at Day 45, and gradually decreased to 46°C by Day 90. This pattern reflects the active microbial metabolism and effective hygienization during the thermophilic stage, followed by cooling and stabilization as substrates were depleted. The pH shifted from acidic conditions in the early phase (5.6 at Day 15) to alkaline values (7.8 at Day 45), and stabilized around neutrality by the end of the process (7.1 at Day 90). This progression reflects the breakdown of organic acids, nitrogen mineralization, and the establishment of buffering capacity in mature compost. The C/N ration decreased from 22:1 at the start to 24:1 by mid-process, before stabilizing at approximately 30:1 in the final stage. This trend indicates effective carbon mineralization and the attainment of compost maturity suitable for agronomic application. Moisture content remained within the optimal 50–60% range, fluctuating between 49% and 58%, thereby sustaining microbial activity, preventing anaerobic conditions, and ensuring steady organic matter degradation.

Taken together, these temporal dynamics confirm that the composting process advanced smoothly through its distinct phases under operational conditions. Beyond changes in the C/N ratio, EM application influenced the rate of degradation of high-carbon materials compared to the control, as reflected by sustained thermophilic temperatures and accelerated stabilization. This

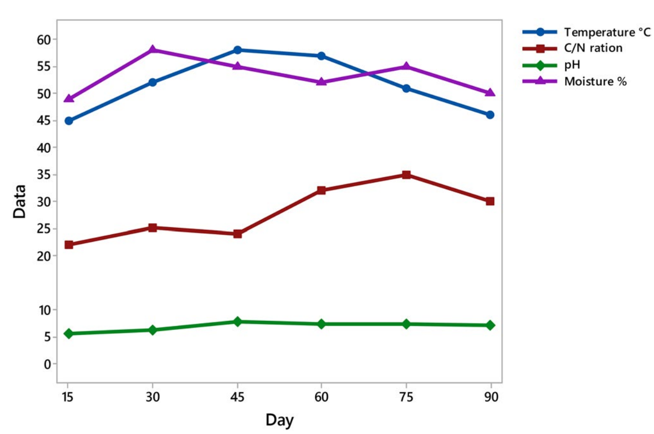

Figure 2. Dynamics of pH, C/N ration, and moisture content during the 90-day composting process.

indicates enhanced microbial efficiency in breaking down lignocellulosic fractions typical of urban green waste. As the process progressed, the organic material also underwent a notable sensory transformation, losing unpleasant odors and developing an earthy, soil-like fragrance by the end of maturation (Mironov, Vanteeva, and Merkel 2021; Jiang et al. 2024), further supporting effective microbial degradation and compost stabilization.

Practical Implications and Limitations for Municipal Systems

The implementation of composting practices at the municipal facility represents a significant advancement in urban organic waste management. Such practices are particularly advantageous in urban environments where space and time constraints demand efficient composting techniques (Obsa et al. 2022; Lelicińska-Serafin, Manczarski, and Rolewicz-Kalińska 2023). The resulting compost serves as an effective amendment for rehabilitating degraded urban soils, enhancing their fertility and structure, and facilitating restoration for agricultural or landscaping purposes (Gajalakshmi and Abbasi 2008; Policastro and Cesaro 2022). This aligns with global objectives of promoting sustainable land management and circular economy principles (Rolewicz-Kalińska, Lelicińska-Serafin, and Manczarski 2020).

Research confirms that composting significantly reduces organic waste volumes while enriching soil physical, chemical, and biological properties (Lelicińska-Serafin, Manczarski, and Rolewicz-Kalińska 2023). The compost produced in this study met quality standards for moisture, humus, nutrient content, and pH, supporting its use in urban horticulture and agriculture (Rahman et al. 2020; Daskal et al. 2022). The integration of EM technology further enhanced process efficiency. EM inoculation accelerates decomposition by introducing beneficial microbial consortia that promote fermentation, suppress pathogens, and facilitate nutrient mineralization (Mwegoha 2012; Ezeagu, Omotosho, and Suleiman 2023; Raimi et al. 2024). This is especially beneficial where rapid processing is required due to limited urban space.

Although the present findings highlight the agronomic and operational value of EM-based composting, one limitation of this study is the absence of systematic monitoring of heavy metals. Regulatory thresholds for heavy metals in compost are well established (e.g., European Parliament and Council of the European Union 2019; EU Regulation 2019/1009), and ensuring compliance with these limits is essential for confirming safe agricultural use. Compost exceeding these thresholds may still be suitable for nonagricultural applications, such as parks, forests, or roadside areas, where risks of direct food chain exposure are minimal. Addressing this gap should therefore be a priority in future research to provide a more comprehensive assessment of compost safety and to support broader application options.

Overall, the composting practices implemented by the municipal facility, represent a successful, scalable, and cost-effective model of sustainable organic waste management within the public sector (Clark 2019). By integrating EM into conventional composting systems, the company significantly enhanced compost quality, accelerated organic matter degradation, and contributed to broader circular economy and environmental sustainability objectives (Ćurčić 2019; Ćurčić et al. 2020). In addition to confirming the effectiveness of EM technology, this study highlights the complementary value of vermicomposting and blatt composting as part of an integrated bioresource recovery strategy (Boldrin et al. 2009; Daskal et al. 2022). The Čačak case study provides a replicable framework for municipalities seeking to improve soil health, reduce landfill dependency, and strengthen urban resilience through innovative composting solutions. The economic impact of EM application is modest relative to overall composting expenses, while operational benefits such as faster maturity and reduced turning frequency contribute to improved efficiency. Previous studies have also indicated favorable benefit–cost rations for EM adoption (Getu et al. 2013), supporting its characterization as a cost-effective and scalable solution for municipal waste management.

Although EM application markedly improved compost agrochemical parameters, the absence of contaminant monitoring limits our ability to confirm full compliance with agronomic safety standards. Therefore, the present findings should primarily be interpreted as evidence of enhanced process efficiency and nutrient enrichment under operational field conditions. To establish comprehensive safety and expand potential agricultural applications, future research should incorporate systematic assessment of heavy metals (e.g., Pb, Cd, Zn, Cu) alongside agrochemical indicators.

Conclusions

This study provides empirical evidence that the integration of EM into the composting process significantly improves key agrochemical parameters of compost produced from green urban waste. Compared to the untreated control, EM application led to higher humus content, increased nitrogen, phosphorus, and potassium availability, improved pH balance, and a more favorable C/N ration—demonstrating both enhanced compost maturity and nutrient richness. These results confirm that microbial enhancement not only accelerates organic matter degradation but also yields compost suitable for diverse agronomic applications, including soil fertility improvement, organic farming, and ecological land restoration. The findings validate EM technology as an effective tool in upgrading composting performance within municipal waste systems. From a socio-economic perspective, the adoption of EM-based composting by municipal utilities may reduce waste management costs, improve urban soil quality, and support local circular economy strategies. Building on these outcomes, future research should prioritize field crop trials to evaluate agronomic effectiveness, long-term soil health monitoring to assess sustainability, and the integration of EM with complementary processes such as vermicomposting and blatt composting to maximize resource recovery. Such combined strategies can further strengthen urban resource efficiency, support biowaste vaporization, and enhance environmental sustainability in alignment with circular economy goals.

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