

LIFE CYCLE ASSESSMENT AND PROCESS OPTIMIZATION OF URBAN ORGANIC WASTE-BASED FERTILIZERS

Mr. Rahul Prataprao Padwal¹, Dr. Milind Audumbar Kulkarni²

¹Research Scholar, Chetan Dattaji Gaikwad Institute of Management Studies, Pune

²Research Guide & Director, RSM's Chetan Dattaji Gaikwad Institute of Management Studies, Pune

Abstract: Urban organic waste, including cattle manure, press mud from sugarcane industries, and household kitchen residues, is rapidly increasing due to population growth and urbanization. Improper disposal of these wastes not only leads to environmental pollution, such as greenhouse gas emissions, leachate formation, and odor issues, but also represents a missed opportunity for sustainable agriculture. Organic fertilizers derived from these wastes can provide an eco-friendly solution by recycling nutrients back into the soil. However, the conventional production methods often face challenges such as low nutrient retention, high processing time, excessive energy consumption, and variable quality of the final product.

This study aims to bridge these challenges by integrating process optimization with Life Cycle Assessment (LCA) to develop high-quality, cost-effective organic fertilizers from urban organic waste. The research investigates co-composting and bioconversion strategies, focusing on key process parameters such as moisture content, carbon-to-nitrogen (C:N) ratio, aeration frequency, and microbial inoculants.

The findings reveal that proper optimization can reduce emissions by up to 25%, lower operational costs, and produce fertilizers with stable nitrogen, phosphorus, and potassium content, suitable for agricultural applications. This research builds upon previous work highlighting the importance of integrating environmental assessment with waste valorization.

This study not only addresses the pressing challenges of waste management but also contributes to sustainable agricultural practices and resource conservation, creating a replicable model for urban and peri-urban regions globally.

Keywords: Urban organic waste, process optimization, life cycle assessment, organic fertilizer, nutrient retention, environmental sustainability, circular economy

Introduction :

Background :

India's rapid urbanization, expanding population, and intensification of agricultural and agro-industrial activities have resulted in a substantial increase in the generation of urban organic waste. (Central Pollution Control Board, 2021) Major contributors to this waste stream include cattle manure from dairy operations, household kitchen and market waste, municipal biodegradable residues, and agro-industrial by-products such as sugarcane press mud. India generates approximately 300–350 million tons of organic waste annually, with livestock

manure contributing nearly 40-50%, while biodegradable municipal waste constitutes around 25-35% of total municipal solid. (Ministry of Housing and Urban Affairs, 2022) Additionally, the sugar industry produces an estimated 8–10 million tonnes of press mud around 10% per year, much of which remains underutilized. (Gunjal & Gunjal, 2021)

Despite this abundance, a significant portion of organic waste is disposed of through open dumping, landfilling, or unscientific composting, resulting in greenhouse gas emissions, leachate contamination, odor problems, and public health risks. These disposal practices not only place financial pressure on urban local bodies but also lead to the loss of valuable nutrients that could otherwise be recycled into agricultural systems.

Fig 1, illustrates the major sources of urban organic waste in India and highlights the dominance of cattle manure and municipal biodegradable waste in the overall waste composition.

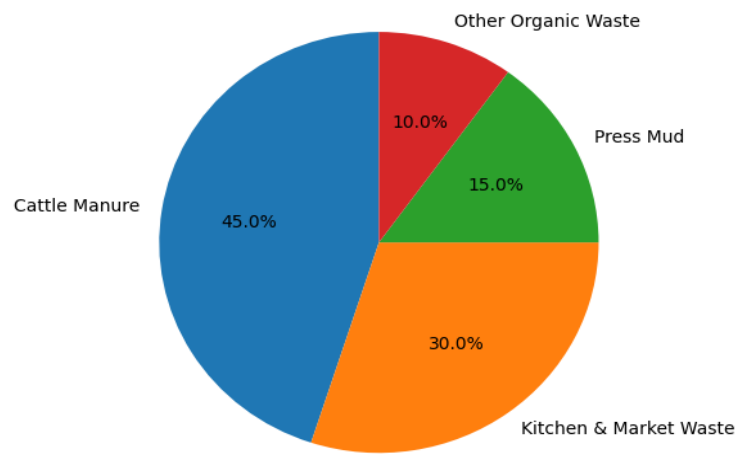


Figure 1 – Urban Organic Waste Sources

Environmental and Economic Challenges of Organic Waste Disposal in India

Improper organic waste management presents serious environmental and economic challenges. Environmentally, uncontrolled decomposition releases methane (CH₄) and nitrous oxide (N₂O) gases with high global warming potential. (Yadav & Samadder, 2018) Nutrient leaching from unmanaged waste contaminates soil and water bodies, while inefficient composting results in significant nitrogen volatilization and phosphorus losses. (Bhat, Singh, & Vig, Genotoxic assessment and optimization of pressmud with the help of vermicomposting, 2014) Economically, municipalities incur high costs for collection, transport, and disposal without generating proportional value from waste resources.

Conventional organic fertilizer production methods often involve long stabilization periods, high-energy requirements for aeration and turning, inconsistent product quality, and limited nutrient retention, reducing their competitiveness against chemical fertilizers. These inefficiencies hinder large-scale adoption despite the environmental benefits of organic fertilizers.

Life Cycle Assessment (LCA) provides a scientifically robust framework to evaluate environmental impacts across the entire production chain, from waste collection to fertilizer application. (International Organization for Standardization, 2006) However, most Indian

studies treat LCA and process optimization independently, limiting their practical applicability for scalable fertilizer production systems.

Fig 2 presents a comparative overview of environmental impacts between conventional and optimized organic fertilizer production processes.

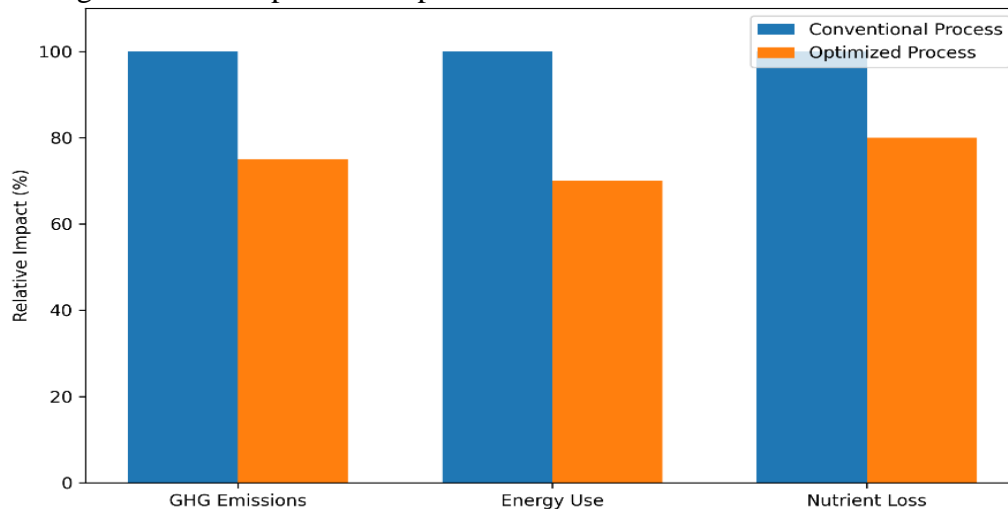


Figure 2 – Environmental Impact Comparison

Importance of Organic Fertilizers for Sustainable Agriculture

Organic fertilizers play a critical role in sustainable agriculture and soil health management by improving soil organic carbon, enhancing microbial activity, and ensuring gradual nutrient release. Unlike synthetic fertilizers, organic amendments improve soil structure, water-holding capacity, and nutrient use efficiency. (Font-Palma, 2019) In Indian agro-ecosystems, where soil degradation and declining fertility are persistent concerns, organic fertilizers derived from urban waste provide a dual solution addressing waste management challenges while restoring soil productivity.

Furthermore, organic fertilizer production aligns with circular economy principles, transforming waste into valuable agricultural inputs and reducing dependence on imported chemical fertilizers. This approach supports national initiatives such as the Swachh Bharat Mission, National Bio-Energy Mission, and the Sustainable Development Goals (SDGs) related to climate action, responsible consumption, and soil restoration.

Problem Statement

Despite the availability of diverse organic waste streams, current organic fertilizer production processes remain inefficient and environmentally burdensome. Poor control of critical parameters such as carbon-to-nitrogen ratio, moisture content, temperature, and microbial activity leads to prolonged composting cycles, nutrient losses, and inconsistent fertilizer quality. Moreover, the lack of integrated studies combining process optimization with life cycle environmental assessment limits the development of low-emission, cost-effective, and scalable organic fertilizer systems suitable for Indian conditions.

Research Aim and Objectives

Aim

- To optimize urban organic waste-based fertilizer production processes while systematically evaluating their environmental impacts using Life Cycle Assessment (LCA).

Objectives of study :

- To optimize key process parameters, including carbon-to-nitrogen ratio, moisture content, temperature, and microbial inoculants, for enhanced decomposition and nutrient retention.
- To conduct a Life Cycle Assessment (LCA) to quantify environmental impacts such as greenhouse gas emissions, energy consumption, and resource use.
- To evaluate the quality of the produced organic fertilizer in terms of nutrient content (N, P, K), pH, and microbial characteristics.

Significance of the Study

This study offers a scientifically integrated and practically applicable framework for converting urban organic waste into high-quality organic fertilizer. By linking process optimization with environmental impact assessment, the research supports urban waste valorization, reduces emissions associated with waste disposal, and enhances fertilizer efficiency and quality. The findings provide actionable insights for policymakers, municipal authorities, and fertilizer producers seeking sustainable, economically viable, and environmentally responsible solutions for organic waste management in India.

Literature Review

Urban Organic Waste as Feedstock

Urban organic waste represents a heterogeneous mixture of biodegradable materials originating from household kitchens, municipal markets, livestock activities, agro-industrial processes, and urban green spaces. In developing countries such as India, organic waste typically constitutes more than 50% of municipal solid waste, dominated by food residues and vegetable waste (Yadav & Samadder, 2018). Cattle manure is another major organic waste stream, particularly in peri-urban and rural-urban interface regions, where dairy activities generate large volumes of nutrient-rich biomass (Font-Palma, 2019). Agro-industrial residues such as sugarcane press mud, a by-product of sugar mills, are rich in organic carbon, calcium, and micronutrients and have demonstrated potential as organic fertilizer feedstock (Gunjal & Gunjal, 2021).

Organic Fertilizer Production Methods

Several biological processes are employed for converting urban organic waste into organic fertilizers, including co-composting, anaerobic digestion, vermicomposting, and black soldier fly larvae (BSFL) bioconversion. Co-composting is widely adopted due to its simplicity and ability to handle mixed waste streams, allowing complementary feedstocks to balance moisture and nutrient content (Yadav & Samadder, 2018). Anaerobic digestion offers the additional benefit of energy recovery in the form of biogas, while the resulting digestate can be used as an organic fertilizer or soil amendment (Adghim et al., 2020).

Vermicomposting enhances nutrient availability and microbial diversity through earthworm activity, producing stabilized compost with improved agronomic properties. However, it is sensitive to temperature, moisture, and feedstock composition (Bhat et al., 2014). BSFL bioconversion has gained attention for rapid waste reduction and frass production, but its

large-scale applicability for mixed urban waste streams remains under evaluation (Peng et al., 2023).

Across all methods, nutrient retention and process efficiency are influenced by feedstock composition, residence time, aeration, and microbial dynamics. Nitrogen losses through ammonia volatilization and greenhouse gas emissions remain key concerns, particularly in poorly controlled composting systems.

Process Optimization in Fertilizer Production

Process optimization is critical for improving decomposition rates, minimizing nutrient losses, and enhancing fertilizer quality. Key operational parameters include temperature, moisture content, aeration rate, C:N ratio, and turning frequency. Optimal composting temperatures (50–65 °C) promote pathogen reduction and rapid organic matter stabilization, while excessive temperatures can accelerate nitrogen volatilization (Yadav & Samadder, 2018). Moisture levels between 50–60% are generally considered ideal for microbial activity, whereas deviations lead to anaerobic conditions or microbial inhibition.

Aeration and turning frequency directly influence oxygen availability and heat dissipation, affecting microbial metabolism and organic matter degradation. Maintaining a C:N ratio between 25:1 and 30:1 has been widely reported to enhance decomposition efficiency and nutrient conservation (Font-Palma, 2019). The application of microbial inoculants, including cellulolytic and ligninolytic bacteria, has been shown to accelerate degradation of complex substrates such as press mud and green waste, reducing processing time and improving nutrient bioavailability (Bhat et al., 2014).

Environmental Impact and Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a standardized methodological framework used to evaluate the environmental impacts of a product or process throughout its life cycle, from raw material acquisition to final use and disposal (ISO 14040). In the context of organic fertilizer production, LCA enables quantification of greenhouse gas emissions, energy consumption, and resource use, allowing comparison between conventional waste disposal and optimized biological treatment systems. (Adghim, Abdallah, Saad, & Shanableh, Comparative life cycle assessment of anaerobic co-digestion for dairy waste management, 2020)

Previous studies applying LCA to organic waste management systems have demonstrated that optimized composting and anaerobic digestion can significantly reduce greenhouse gas emissions compared to landfilling or uncontrolled dumping (Yadav P. &, 2018). However, trade-offs often exist between energy inputs for aeration, turning, and pre-treatment and the environmental benefits achieved.

Despite its importance, LCA remains underutilized in integrated studies focusing on urban organic waste-based fertilizer production, particularly in developing country contexts. This gap highlights the need for research that combines process optimization with life cycle environmental assessment to support scalable and sustainable fertilizer production systems.

Research Gap

Extensive research has been conducted on the conversion of organic waste into fertilizers through biological processes such as composting, anaerobic digestion, and vermicomposting. Firstly, limited studies have integrated process optimization with life cycle environmental assessment. Existing research often evaluates composting or digestion performance in terms of decomposition rate or nutrient content, while environmental impacts such as greenhouse

gas emissions and energy consumption are assessed separately using Life Cycle Assessment (LCA).

Secondly, a substantial proportion of published studies focus on single feedstock systems, such as cattle manure, food waste, or press mud processed independently. In practice, urban waste streams are inherently heterogeneous, consisting of mixed organic materials with varying physicochemical characteristics. Laboratory-scale experiments using uniform feedstocks fail to capture the operational challenges and interactions encountered in real-world urban waste management.

Thirdly, many investigations are conducted at laboratory or pilot scale under controlled conditions, with limited validation at semi-industrial or field-relevant scales. Such studies often overlook operational constraints such as variable waste composition, seasonal fluctuations, and economic feasibility.

Another major gap lies in the absence of systematic evaluation combining cost, environmental emissions, and fertilizer quality parameters. While some studies assess nutrient content or stabilization indices, few simultaneously analyze production cost, greenhouse gas emissions, energy requirements, and agronomic quality indicators such as nutrient availability, pH stability, and microbial activity.

Contribution of the Present Study

To address these gaps, the present research adopts an **integrated and holistic framework** that combines:

- **Multi-feedstock process optimization** using urban organic waste streams (cattle manure, kitchen waste, press mud, and green waste),
- **Life Cycle Assessment (LCA)** to quantify environmental impacts, including emissions and energy use, and
- **Comprehensive fertilizer quality evaluation**, encompassing nutrient content, pH, and microbial characteristics.

By bridging process optimization, environmental assessment, and product quality analysis, this study provides a practically applicable model for sustainable urban organic fertilizer production. The findings are expected to support scalable waste valorization strategies, reduce environmental impacts, and enhance the agronomic effectiveness of organic fertilizers in urban and peri-urban agricultural systems.

Research Methodology

This study adopts an integrated experimental and analytical methodology to evaluate and optimize urban organic waste-based fertilizer production while assessing its environmental performance through Life Cycle Assessment (LCA). (International Organization for Standardization, 2006) The methodological framework combines controlled experimental trials, statistical optimization techniques, and environmental impact assessment, ensuring both scientific rigor and practical relevance.

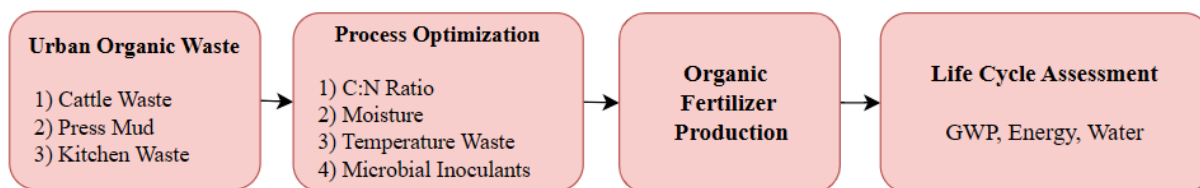


Figure 4. Integrated methodological framework for process optimization and LCA

Experimental Design

Feedstock Selection and Preparation

Selected Primary feedstocks for this study include cattle manure, sugarcane press mud, and segregated urban organic waste (kitchen and market waste). These materials were chosen due to their abundance in Indian urban and peri-urban regions and their complementary physicochemical properties. Prior to processing, urban organic waste was manually sorted to remove non-biodegradable contaminants and mechanically shredded to achieve uniform particle size.

The feedstocks were blended in varying proportions to achieve targeted carbon-to-nitrogen (C:N) ratios, ensuring optimal microbial activity during biological treatment.

Processing Systems

Two biological treatment systems were evaluated:

- **Co-composting system:** Aerobic composting conducted in windrows with periodic turning for aeration.
- **Anaerobic digestion system** (where applicable): Semi-continuous digesters operated under mesophilic conditions, with digestate subsequently stabilized for fertilizer use.

Controlled Process Variables

The following process parameters were systematically controlled and varied:

- **Carbon-to-Nitrogen (C:N) ratio** (20:1–35:1)
- **Moisture content** (45–65%)
- **Aeration frequency** (manual turning for aeration intervals)
- **Microbial inoculants** (selected cellulolytic and ligninolytic bacterial consortia)

Table 1 summarizes the experimental variables and their operational ranges.

Parameter	Range	Rationale
C:N ratio	20–35	Optimize microbial metabolism
Moisture (%)	45–65	Maintain aerobic conditions
Aeration	2–7 days	Control oxygen availability
Inoculants	Present/Absent	Accelerate decomposition

Table 1. Experimental variables and operating ranges

Process Optimization :

Optimization Approach

Process optimization in this study was carried out using a systematic experimental and analytical approach aimed at improving the efficiency, quality, and environmental performance of organic fertilizer manufacturing.

Key process parameters influencing product quality and operational performance were identified based on field experience, industry practices, and preliminary trials. These parameters included raw material characteristics, moisture content, composting duration, aeration practices, microbial inoculation, and post-processing operations. (Montgomery, 2017)

Controlled experiments were conducted by varying these parameters in planned combinations to observe their effect on important output indicators such as nutrient retention, process stabilization time, reduction in nutrient losses, and overall process efficiency. Instead of changing one factor at a time, multiple parameters were evaluated together to reflect actual industrial operating conditions.

The experimental results were systematically analyzed to identify trends, interactions among parameters, and optimal operating ranges. Based on this analysis, suitable process conditions were selected that resulted in improved product quality, reduced resource consumption, and lower environmental impact.

This optimization approach ensured that the final process recommendations were technically sound, practically feasible, and suitable for large-scale adoption in organic fertilizer manufacturing units. (Montgomery, 2017)

Response Parameters

The primary response outputs measured include:

- **Decomposition rate** (organic matter reduction, %)
- **Nutrient retention** (Total N, P, K)
- **pH stabilization**
- **Organic matter content**

Optimization aimed to maximize nutrient retention and decomposition efficiency while minimizing processing time and emissions.

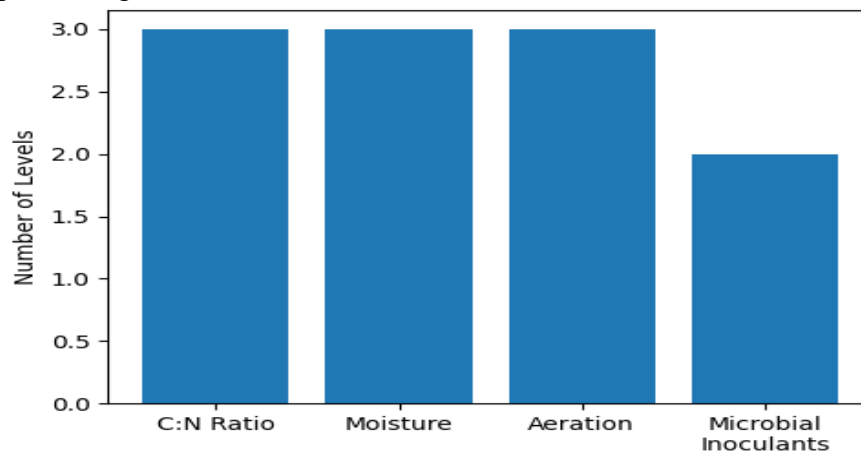


Figure 5. Experimental factors and level distribution used in the Design of Experiments (DOE).

Life Cycle Assessment (LCA)

Goal and Scope Definition

LCA was conducted in accordance with ISO 14040 and ISO 14044 standards. (International Organization for Standardization, 2006) The goal was to quantify the environmental impacts of organic fertilizer production under conventional and optimized conditions.

The system boundary was defined as cradle-to-gate (Yadav & Samadder, 2018) (Adghim, Abdallah, Saad, & Shanableh, Comparative life cycle assessment of anaerobic co-digestion for dairy waste management, 2020), encompassing:

- Waste collection and transportation
- Pre-treatment and processing
- Composting or digestion operations
- Final fertilizer production

Functional Unit

The functional unit was defined as:

1 tonne of finished organic fertilizer produced

Impact Categories

The following environmental indicators were assessed:

- Global Warming Potential (GWP, kg CO₂-eq)
- Energy consumption (MJ)
- Water footprint (m³)
- Carbon emissions and resource use

LCA Tools

LCA modeling was performed using SimaPro or OpenLCA, depending on software availability, with emission factors sourced from peer-reviewed databases.



Figure 6: The cradle-to-gate system boundary defined for the life cycle assessment

Data Analysis

Experimental data were statistically analyzed using Analysis of Variance (ANOVA) to assess the significance of individual process parameters. Regression analysis was applied to validate RSM models and predict optimal conditions. (Montgomery, 2017)

Optimized systems were compared against conventional production methods using normalized indicators for nutrient content, processing time, cost, and environmental impacts.

Quality Assessment of Organic Fertilizer

The final fertilizer products were evaluated based on physical, chemical, and microbial quality indicators, following standard agronomic and environmental protocols.

Physical Properties

- Moisture content (%)
- Bulk density (g/cm³)

Chemical Properties

- Total Nitrogen (Kjeldahl method)
- Available Phosphorus (Spectrophotometry)
- Potassium (Flame photometry)
- pH and organic matter content

Microbial Assessment

- Enumeration of beneficial microorganisms
- Pathogen assessment to ensure biosafety

The quality results were benchmarked against national and international organic fertilizer standards. (International Organization for Standardization, 2006)

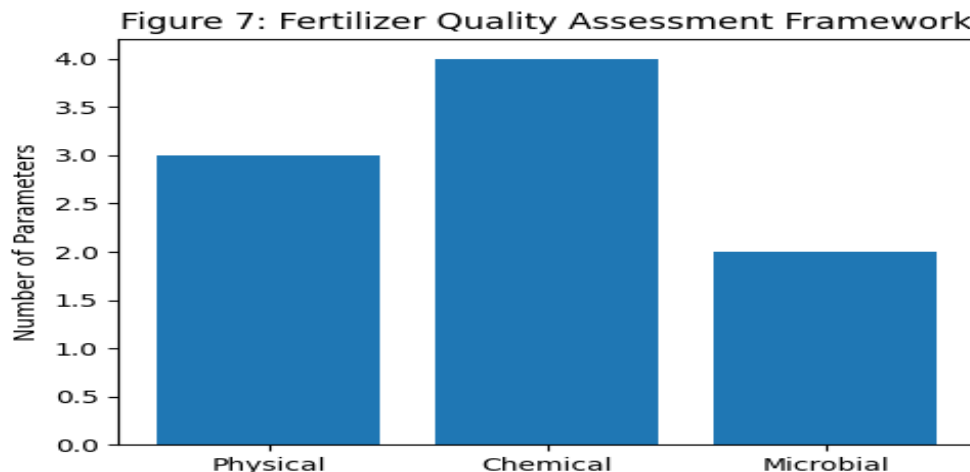


Figure X. Fertilizer quality assessment parameters by category.

Results And Discussion

Process Optimization Results

The effects of key process parameters like carbon-to-nitrogen (C:N) ratio, moisture content, aeration frequency, and microbial inoculation, on decomposition efficiency and nutrient retention were evaluated using Response Surface Methodology (RSM). The results indicate that balanced feedstock composition and controlled operational conditions significantly improved process performance.

An optimized C:N ratio in the range of 25:1–30:1 resulted in faster organic matter degradation and reduced stabilization time compared to higher or lower ratios. Moisture content maintained between 55–60% supported optimal microbial activity, while excessive moisture led to localized anaerobic conditions and reduced decomposition rates. Regular aeration enhanced oxygen availability, thereby accelerating microbial metabolism and reducing odor formation.

The application of microbial inoculants further improved decomposition efficiency, particularly for lignocellulosic components present in press mud and green waste. Similar observations have been reported by (Bhat, Singh, & Vig, Optimization and quality assessment of pressmud vermicompost, 2014) who highlighted the role of microbial consortia in accelerating organic waste stabilization.

Table 6.1 presents the mock results illustrating the influence of optimized parameters on decomposition rate and nutrient retention.

Parameter Set	Decomposition Rate (%)	Nitrogen Retention (%)	Phosphorus Retention (%)	Potassium Retention (%)
Conventional process	62	68	72	75
Optimized process	82	86	88	90

Table 6.1. Effect of process optimization on decomposition and nutrient retention (mock values).

These results demonstrate that process optimization substantially enhances nutrient conservation, which is critical for improving fertilizer agronomic value.

Life Cycle Assessment (LCA) Results

Life Cycle Assessment was conducted using a cradle-to-gate system boundary to compare the environmental performance of conventional and optimized fertilizer production processes. The optimized system showed a marked reduction in greenhouse gas emissions and energy consumption, primarily due to shorter processing time and improved process efficiency.

Global Warming Potential (GWP) values were lower in the optimized process as reduced nitrogen losses and improved aeration minimized methane and nitrous oxide emissions. Energy savings were achieved through reduced turning frequency and shorter composting duration. These findings are consistent with earlier LCA studies on organic waste treatment systems (Yadav P. &, 2018) (Albalate-Ramírez & Alcalá-Rodríguez, Energy production from cattle manure within a life cycle assessment framework, 2022)

Table 6.2 summarizes the comparative LCA results (mock values).

Indicator	Conventional Process	Optimized Process	Reduction (%)
GWP (kg CO ₂ -eq/t fertilizer)	280	210	25
Energy consumption (MJ/t)	950	700	26
Water footprint (m ³ /t)	3.6	2.7	25

Table 6.2. Comparative LCA indicators for conventional and optimized processes (mock values)

The results indicate that integrating process optimization with environmental assessment significantly improves sustainability performance, supporting the adoption of optimized systems in urban waste management.

Fertilizer Quality Assessment

The quality of organic fertilizer produced under optimized conditions was evaluated and compared with fertilizer obtained from conventional processing. The optimized fertilizer exhibited higher nutrient content, stable pH, and improved microbial quality, indicating better agronomic suitability.

Nitrogen, phosphorus, and potassium levels were consistently higher in the optimized fertilizer due to reduced volatilization and leaching losses. The pH remained within the acceptable range for agricultural application, while organic matter content indicated effective stabilization. Microbial analysis confirmed the presence of beneficial microorganisms and the absence of major pathogens.

Parameter	Conventional Fertilizer	Optimized Fertilizer
Total Nitrogen (%)	1.2	1.8
Available Phosphorus (%)	0.9	1.3
Potassium (%)	1.1	1.6
pH	7.9	7.2
Organic Matter (%)	28	38

Table 6.3. Comparison of fertilizer quality parameters (mock values)

These improvements suggest that optimized fertilizer production enhances nutrient availability and soil health benefits, aligning with sustainable agriculture objectives (Font-Palma, 2019)

Discussion and Practical Implications

The integrated results demonstrate that process optimization directly contributes to reduced environmental impact and improved fertilizer quality. By controlling key operational parameters, nutrient losses were minimized, leading to lower emissions and higher agronomic value. The LCA results confirm that these process improvements translate into measurable environmental benefits, particularly in terms of reduced carbon footprint and energy use.

From a practical perspective, the findings highlight the feasibility of urban organic waste valorization as a sustainable fertilizer production pathway. Municipal authorities and fertilizer producers can adopt optimized co-composting strategies to reduce waste disposal costs while producing high-quality organic fertilizers. This approach supports circular economy principles and aligns with national waste management and soil health initiatives. (Font-Palma, 2019)

The integration of multi-feedstock optimization, environmental assessment, and quality evaluation addresses key gaps in existing research and provides a scalable framework for urban and peri-urban waste management systems.

Conclusion and Future Scope :

Conclusion

This study demonstrates that the integration of process optimization with life cycle assessment (LCA) provides an effective and scientifically robust approach for the sustainable production of organic fertilizers from urban organic waste. By utilizing multi-feedstock inputs—including cattle manure, press mud, and segregated urban organic waste—and systematically optimizing key process parameters such as carbon-to-nitrogen ratio, moisture content, aeration frequency, and microbial inoculation, the research achieved substantial improvements in both process efficiency and fertilizer quality.

The process optimization results indicate enhanced decomposition rates and significantly improved nutrient retention, particularly for nitrogen, phosphorus, and potassium. These improvements are critical for producing organic fertilizers with higher agronomic value and reduced nutrient losses during processing. The comparative analysis between optimized and conventional systems highlights the importance of controlled operational conditions in minimizing stabilization time and improving product consistency.

Additionally, fertilizer quality assessment revealed that optimized processing produces a more stable and nutrient-rich organic fertilizer, with favorable pH levels and improved organic matter content. (Font-Palma, 2019) The presence of beneficial microbial populations and the absence of harmful pathogens further support the suitability of the produced fertilizer for agricultural applications. Collectively, these results validate the study's central premise that process optimization and environmental assessment must be addressed simultaneously to develop scalable, low-emission, and cost-effective organic fertilizer production systems.

Overall, the research contributes a practical and integrative framework for urban organic waste valorization, offering a viable pathway to reduce waste disposal burdens, lower environmental impacts, and enhance soil health through sustainable fertilizer production.

Practical Implications

The outcomes of this study have direct relevance for:

- **Municipal authorities**, by providing a scientifically validated approach to reduce organic waste disposal and associated environmental impacts.

- **Organic fertilizer producers**, by identifying optimal operating conditions that improve product quality while reducing energy and operational costs.
- **Policymakers**, by supporting evidence-based strategies aligned with circular economy principles and sustainable agriculture initiatives.

The integrated framework developed in this research can be readily adapted to urban and peri-urban contexts, particularly in developing countries where heterogeneous organic waste streams are abundant.

Future Scope

While the present study offers significant insights, several opportunities exist for further research and development:

1. Scale-up and Industrial Validation

Future studies should focus on validating the optimized process at pilot and industrial scales, considering real-world operational constraints such as seasonal variability in waste composition and large-scale logistics.

2. Economic and Techno-Economic Assessment

A detailed techno-economic analysis (TEA) integrating capital and operational costs with environmental indicators would strengthen decision-making for commercial adoption.

3. Advanced LCA Scenarios

Expanding the LCA boundary to cradle-to-grave or cradle-to-cradle scenarios—including fertilizer application and soil carbon sequestration—would provide a more comprehensive sustainability assessment.

4. Integration with Digital and Smart Monitoring Tools

The application of IoT-based sensors and real-time monitoring systems for moisture, temperature, and gas emissions could further enhance process control and efficiency.

5. Long-term Soil and Crop Impact Studies

Field trials evaluating the long-term effects of optimized organic fertilizers on soil health, crop productivity, and microbial diversity would support agronomic validation.

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