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Original Research

Synergizing Environmental and Economic Profits in Aerobic Composting: An Integrated Life Cycle Assessment and Cost-Benefit Analysis

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Abstract

The growing intensity of animal farming necessitates composting technologies that are both environmentally and economically sustainable. This study evaluates four mainstream aerobic composting methods: static heaps (SH), windrow composting (WC), membrane-covered composting (MC), and reactor composting (RC), using an integrated life cycle assessment (LCA) and cost-benefit analysis. Results show that MC significantly outperformed the others in eco-efficiency (EE). It enhanced environmental performance by 41.8%, 25.4%, and 13.2% compared to SH, WC, and RC, respectively (p<0.01 for SH; p<0.05 for WC and RC). These gains were driven by substantial reductions in greenhouse gas (GHG) emissions (44.9%, 32.7%, and 17.8%) and eutrophication potential (38.6%, 29.1%, and 15.3%) relative to SH, WC, and RC. Economically, MC's operational cost (USD 28.84 t^{-1}) was 33.6% lower than that of RC, underscoring its cost-effectiveness for emission-intensive systems. Consequently, MC's overall EE improved by 168.4%, 92.7%, and 39.6% over SH, WC, and RC, respectively. We conclude that membrane-covered composting presents a balanced and compelling strategy for advancing sustainable waste management in intensive livestock operations.

Keywords: aerobic composting, life cycle assessment, life cycle costing, ecological efficiency, circular economy, membrane-covered composting

Introduction

Modern agriculture is increasingly challenged by the dual imperatives of maintaining food productivity while mitigating the environmental impacts of intensive farming systems. One prominent source of ecological concern stems from the overuse of synthetic fertilizers and the inadequate management of livestock waste, both of which contribute substantially to greenhouse gas emissions and environmental pollution [1]. Simultaneously, the growing volumes of untreated organic waste generated by large-scale livestock operations represent both a significant environmental burden and a latent opportunity for resource recovery [2]. In China alone, annual livestock and poultry manure production exceeds 3.8 billion tonnes, yet only

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65-70% is effectively utilized through composting or biogas generation [2]. The remaining 1.2 billion tonnes of untreated waste releases methane (CH_4) and nitrous oxide (N_2O), accounting for 12-15% of national agricultural GHG emissions [3]. This duality underscores the urgency of bridging the gap between waste generation and circular resource systems.

Aerobic composting has emerged as a promising strategy for addressing these issues [3]. By biologically converting organic residues into stabilized humic substances, composting reduces environmental risks while promoting soil health and supporting circular resource flows. The effectiveness of composting systems, however, varies considerably depending on technological configuration, energy inputs, and emission control capabilities. Conventional composting approaches, including static heaps (SH) and windrow composting (WC), have been observed to exhibit high levels of greenhouse gas emissions and nitrogen losses due to inadequate aeration and exposure to uncontrolled environmental conditions [4].

To improve composting efficiency, various advanced systems have been developed, including RC, which offers precise process control through enclosed structures. However, increasing attention has been directed toward MC, owing to its cost-effective design, enhanced emission control, and suitability for medium-scale operations [5]. These methods utilize forced aeration, semi-permeable membranes, or closed-loop thermal regulation to enhance microbial activity, control moisture, and reduce gaseous emissions [6]. Studies have shown that these advanced technologies can significantly mitigate methane and ammonia volatilization compared to traditional practices, improving both environmental and agronomic outcomes [7]. Despite these environmental benefits, economic feasibility remains a critical barrier to broader adoption of high-performance composting systems. Infrastructure investments, operational complexity, and energy requirements pose challenges, particularly for medium-sized farms [8]. Furthermore, prevailing research on composting systems predominantly examines environmental impacts and economic viability through compartmentalized frameworks, neglecting critical synergies and trade-offs between these dimensions. Moreover, the majority of existing studies have considered the environmental and economic aspects of composting separately, without integrating them, while life cycle assessment (LCA) is well-established for measuring environmental impacts, and life cycle costing (LCC) is often underutilized or applied using overly simplified assumptions [9].

Recent literature emphasizes the need for integrated assessment frameworks that capture both ecological efficiency and financial performance. Such an approach is aligned with the principles of the circular economy, which seeks to decouple economic growth from environmental degradation by optimizing the recovery of value from waste [10]. In sectors such as renewable energy and water treatment, coupling LCA with LCC has led to the development of decision-support tools that enable more sustainable system design. However, similar dual-perspective evaluations are still emerging in the domain of organic waste management [11].

It is important to note that this study is primarily situated within the context of China's waste management systems, agricultural practices, and policy frameworks. The economic data (e.g., labor, energy, and material costs), emission factors (e.g., for grid electricity), and policy incentives (e.g., carbon trading prices) are derived from Chinese sources. While the technological comparisons and their relative performance (e.g., MC's superiority in emission reduction) are expected to hold broadly, the absolute economic figures and the magnitude of environmental benefits may vary in other regions due to differences in economic structures, energy mixes, and regulatory environments. This regional specificity and its implications for the generalizability of our results will be further discussed in the limitations section.

This study aims to bridge this critical knowledge gap by integrating LCA and LCC to evaluate the environmental and economic performance of four mainstream aerobic composting technologies: SH, WC, MC, and RC. Specifically, the objectives are to: (1) quantify the life cycle environmental impacts of each composting method, (2) assess cost-effectiveness through detailed LCC analysis, and (3) explore the synergistic relationship between ecological efficiency and economic sustainability. To achieve this, we introduce two compound indices – Ecological Value Ratio (EVR) and Environmental Efficiency Ratio (EER) – to evaluate system-level trade-offs. Through this integrative framework, we aim to provide actionable insights for promoting low-emission, cost-effective composting strategies aligned with circular economy principles.

Materials and Methods

Methods of Aerobic Composting of Livestock Manure: Performance and Selection

This study evaluated four typical composting methods: SH, WC, MC, and RC, representing a range from traditional to advanced technologies. SH involves static piles without aeration; WC improves decomposition through mechanical turning; MC employs a semi-permeable membrane to control emissions and enhance process efficiency; and RC employs a closed reactor with forced aeration and temperature control, enabling high efficiency and environmental management.

Selection criteria included: (a) Use of real-world full-scale experimental data; (b) Geographical consistency across the North China Plain; (c) Raw materials (pig manure, kitchen waste, and straw) were standardized to ensure consistent physicochemical properties (Table 1).

Table 1. Selected physicochemical characteristics of substrates used in composting construction (dry-weight based).

Composting material	pH	Total C (g kg^{-1})	Total N (g kg^{-1})	(C/N)	Moisture Content (%)	Moisture Adjustment Method
Pig manure	7.31	321.65	18.69	17.20	70.12	Natural sun-drying dehydration to 65%±3%
Kitchen Waste	6.91	241.78	16.83	14.36	32.37	Centrifugal dehydration (2000 rpm)
Straw	7.18	412.94	1.87	220.82	9.02	Rotary drying (60ºC±5ºC)

Life Cycle Assessment (LCA)

The study systematically collected inventory data for LCA and LCC following ISO 14040:2006 standards [12]. Primary data sources included enterprise production logs (75%), the ecoinvent database (20%) [13], and on-site monitoring (5%). The detailed life cycle inputs and outputs are summarized in Table 2. LCA methodology adhered to stages such as goal and scope definitions, inventory analysis, and interpretation, enabling a comprehensive evaluation of environmental and economic impacts according to the research publication of LCA [14], the functional unit (FU) defines the treatment of 1 t of solid pig manure (dry weight), which was applied to evaluate the potential environmental and ecological effects of solid manure resource utilization effectiveness. All environmental and economic indicators, including costs and revenues, were normalized to this FU to ensure consistency and comparability across composting technologies [15]. To ensure consistency, all data were normalized to the functional unit (1 t dry pig manure). Enterprise production logs provided activity data, including energy consumption, labor inputs, and equipment usage, which were cross-checked against farm-scale operational records. Ecoinvent was used to supplement background processes (e.g., electricity generation, diesel production, transport of materials), with regionalized Chinese datasets selected where available. When local data were unavailable, global averages were adjusted to Chinese conditions using energy mix and emission factors reported by the International Energy Agency and China's Ministry of Ecology and Environment. On-site monitoring data (e.g., GHG emissions, leachate composition) were used to validate enterprise-reported figures, and discrepancies greater than 10% were reconciled through weighted averaging. This integration approach ensured that system inputs and outputs were both regionally representative and methodologically comparable across the four composting technologies.

The system boundary extends from cradle-to-gate, encompassing five stages:

(1) Composting material preparation stage:

This phase includes the collection of pig manure, procurement and delivery of auxiliary materials (such as sawdust), and the mechanical mixing of the primary and auxiliary ingredients.

(2) Composting infrastructure construction stage:

This stage involves material transportation from the manufacturer to the construction site, assembly of components, and potential replacements over the building's lifespan. It also includes energy consumption for excavation and operation of hydraulic excavators, as well as both continuous and discontinuous building usage.

(3) Composting equipment preparation stage:

This phase covers the transportation of equipment from the manufacturer to the construction site, the assembly of components, and the expected replacements throughout the equipment's lifetime. It also includes energy consumption from excavators and hydraulic excavators, along with equipment usage and maintenance.

(4) Composting process stage:

This stage includes all composting-related operations, covering the entire material and energy flows for activities such as feeding, manufacturing, ventilation, mixing, and turning.

(5) End emission stage:

During the composting process, methane, nitrous oxide, and ammonia are released as key gaseous emissions. Additionally, leachate generated from the composting mass is treated using an activated sludge process, which removes over 85% of its chemical oxygen demand (COD). The excess biological sludge produced from this treatment is subsequently dewatered and landfilled [16].

Background processes, such as the production and transport of electricity, diesel, fertilizers, and construction materials, are also included. This comprehensive boundary ensures that all direct and indirect costs and emissions associated with composting are captured in both the LCA and LCC models [17]. The system boundary is shown in Fig. 1.

Additionally, the study explored extended recycling scenarios aiming to maximize resource recovery, including chattel conversion into liquid fertilizer, compost residue cannibalization into biochar, and waste heat recovery for regional heating. SimaPro 9.4 software was used for modeling material and energy flows across different composting technologies, and the inventory construction supported topological analysis of carbon and nitrogen cycles as well as emission distribution.

Life Cycle Cost (LCC)

LCC encompasses all economic investments borne by stakeholders throughout the entire technological

Table 2. Input-output inventory of composting technologies.

Parameter Type	Unit	SH	WC	MC	RC
Input Data					
Raw Material Consumption					
Pig Manure	kg t^{-1} dry base	520	500	490	480
Straw	kg t^{-1} dry base	260	280	270	290
Kitchen Waste	kg t^{-1} dry base	220	220	240	230
Energy Consumption					
Electricity	kWh t^{-1}	18.5	42.3	35.7	68.9
Diesel	L t^{-1}	3.2	5.8	2.1	1.5
Water Resources	M^3 t^{-1}	0.8	1.2	0.6	0.9
Conditioning Agents (sawdust)	kg t^{-1}	45	38	50	30
Equipment Investment					
Membrane Material (only MC)	M^2/cycle	-	-	12.5	-
Reactor Depreciation (only RC)	USD t^{-1}	-	-	-	11.90
Output Data					
Products					
Matured Compost	kg t^{-1} dry base	680	710	750	720
Emissions					
CH_4 Emissions	kg CO_2-eq t^{-1}	1.32	0.94	0.41	0.25
N_2O Emissions	kg CO_2-eq t^{-1}	0.68	0.53	0.29	0.17
NH_3 Volatilization	kg t^{-1}	9.2[a]	7.5[b]	3.8[c]	2.1[c]
Total CO_2-eq Emissions	kg CO_2-eq t^{-1}	285[a]	224[b]	158[c]	98[d]
By-products					
Chattel	L t^{-1}	120	95	65	40
Residue (Landfill)	kg t^{-1}	55	45	30	25
Economic Indicators					
Treatment Cost	USD t^{-1}	16.80	81.20	42.00	19.88
Carbon Trading Revenue	USD t^{-1}	3.70	6.26	18.50	16.46
Net Profit	USD t^{-1}	79.52	17.50	62.30	87.92

Note: All inventory flows are calculated per functional unit (1 t dry pig manure, dry weight basis).

life cycle, covering processes from raw material acquisition to end-of-life emission treatment [18]. The cost components include raw material pretreatment, facility construction, equipment operation, labor management, and environmental remediation expenses. This study employed the LCC method to evaluate the comprehensive costs of different composting technology pathways, which is calculated as follows (Equation (1)) [19]:

$$LCC = C_{material} + C_{construction} + C_{operation} + C_{treatment} \tag{1}$$

$C_{material}$ is costs of raw material collection and pretreatment, including transportation, crushing, and magnetic separation. $C_{construction}$ is composting facility construction costs, covering equipment procurement and on-site installation. $C_{operation}$ is energy consumption and maintenance costs during operation, including electricity, diesel consumption, and equipment depreciation. $C_{treatment}$ is end-of-life emission treatment costs, including leachate treatment and residue landfilling.

Economic benefits were evaluated using a net revenue model (Equation (2)):

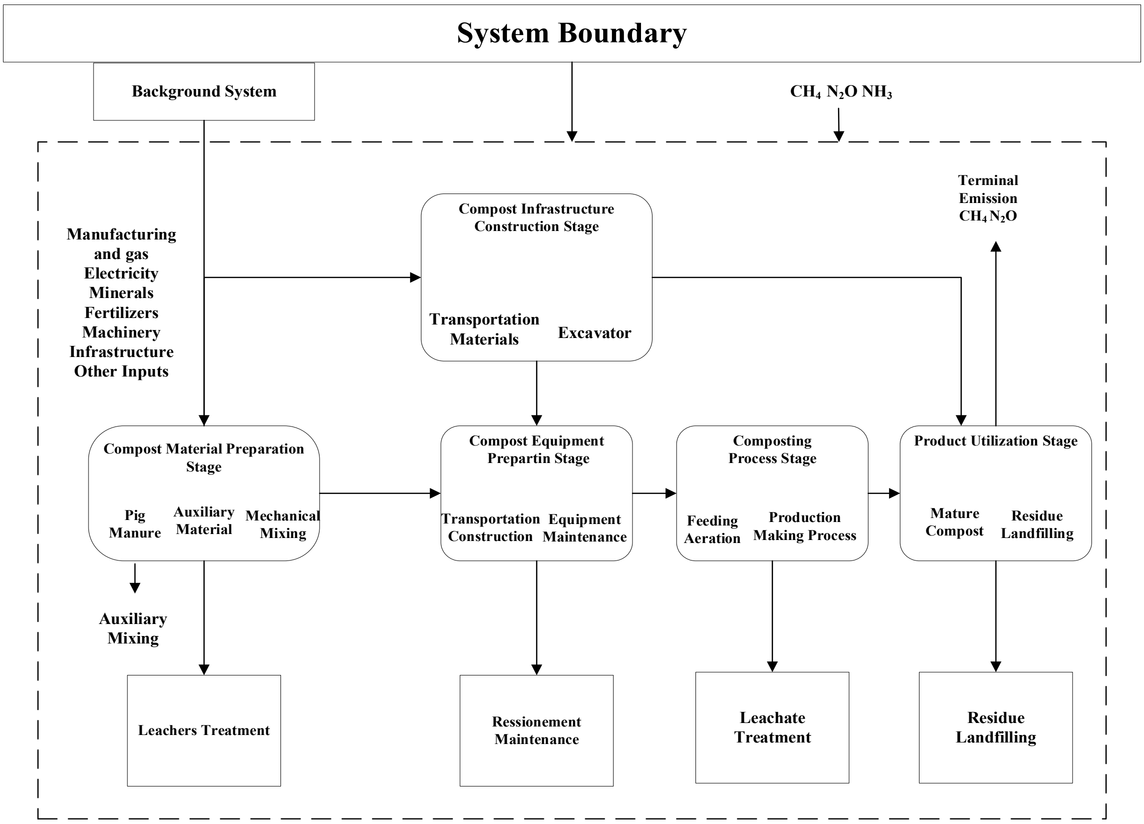

Fig. 1. System boundary of composting technologies.
The system boundary of the life cycle assessment covers five stages: material preparation, infrastructure construction, equipment preparation, composting process, and end-emission treatment. Background processes such as energy production and transportation are also included. The functional unit is the treatment of 1 t of pig manure mixed with crop residues.

$$\text{NetRevenue} = \text{Compostproductsalesrevenue} + \text{Carbontradiingrevenue} - \text{LifeCycleCost(LCC)} \quad (2)$$

Data collection was based on the following assumptions:

Composting cycles ranged from 20 to 65 days, depending on composting method type, with a single-batch processing capacity of 1 t (dry weight) of swine manure and corn stover mixtures. Raw material and end-product of compost application transportation were applied at 50 km and 100 km (diesel truck, 10 t payload), respectively. Equipment depreciation was calculated using the straight-line method over a 10-year lifespan. Electricity costs were evaluated based on China's grid emission factor (0.583 kg CO_2-eq kWh^{-1}) and a diesel emission factor of 1.52 kg CO_2-eq L^{-1}.

All financial data, including costs for raw materials, energy (electricity, diesel), labor, equipment, and environmental remediation, were sourced from enterprise production records, manufacturer quotations, and national standards (e.g., HJ776-2015) within China [20]. Consequently, the economic results presented herein are most directly applicable to the Chinese context. Translating these findings to other regions requires careful consideration of local cost structures, energy profiles, and policy frameworks. The detailed life cycle cost components for each composting technology are summarized in Table 3.

The Key Cost Parameters of Typical Composting Methods

Raw material unit prices were obtained from enterprise production records, equipment costs were referenced from manufacturer quotations, and environmental remediation costs were calculated based on the HJ776-2015 standard [20]. To improve transparency, all economic values were harmonized to 2022 USD using the annual average exchange rate (1 USD = 6.73 RMB) and inflation-adjusted using China's Consumer Price Index. Raw material and labor costs derived from enterprise records were normalized to the functional unit (USD t^{-1} dry pig manure). Equipment costs were converted from manufacturer quotations into annualized depreciation values using a 10-year lifespan assumption, while environmental remediation expenses were estimated according to HJ776-2015 and scaled to the FU. This normalization ensured comparability across technologies and avoided distortions arising from differences in scale or reporting format.

Table 3. Life cycle cost components of composting technologies.

Cost Category	Cost Element	SH	WC	MC	RC	Weighted Average
Raw Material Costs	Pig Manure Collection and Dehydration	11.48	11.90	12.32	11.20	11.90
	Straw Crushing and Magnetic Separation	-	5.60	6.02	6.30	5.32
Construction Costs	Main Structure Construction	3.92	24.50	-	7.00	9.10
	Ventilation System Integration	-	-	6.30	81.2	21.70
	Membrane Material Purchase (only MC)	-	-	62.53	-	15.63
Operating Costs	Electricity Consumption	0.70	9.52	12.50	6.02	9.52
	Diesel Consumption	-	1.68	8.20	2.52	3.45
	Labor and Maintenance	-	-	8.14	34.86	8.14
Treatment Costs	Leachate Treatment	14.70	18.90	13.72	17.50	18.90
	Residue Landfilling	-	3.50	3.92	2.10	3.92
Special Costs	Reactor Depreciation (only RC)	-	-	-	11.90	11.90
Total Cost		30.80	75.60	121.59	180.60	119.28

Note: All costs are expressed as USD per functional unit (1 t dry pig manure, dry weight basis).

Notes: a) Weighted averages were calculated based on the adoption ratio of large-scale farms in China in 2022 (SH: 35%; WC: 28%; MC: 12%; RC: 25%). b) MC technology includes imported polymer membrane components (unit price: 39.90 USD/m^2; lifespan: 3 cycles). c) RC reactor was equipped with a waste heat recovery module, reducing electricity consumption costs by 18%. d: SH manual turning cost incorporates a seasonal temporary worker premium (+15%).

Eco-Efficiency Indices

This study introduced the Ecological Value Ratio (EVR) to quantify the dynamic relationship between the ecological cost and net economic benefits of composting technologies. The EVR indicator reflects the environmental cost associated with each unit of economic benefit. Its calculation logic was shown in Equations (3)-(5) [21]:

$$\mathrm{EEI} = \frac{\mathrm{N_v}}{\mathrm{E_c}} \tag{3}$$

$$\mathrm{EVR} = \frac{\mathrm{E_c}}{\mathrm{N_v}} \tag{4}$$

$$\mathrm{EER} = (1 - \mathrm{EVR}) \times 100\% \tag{5}$$

Definitions: E_c (kg CO_2-eq t^{-1}): Life cycle ecological cost, encompassing greenhouse gas emissions, nitrogen/phosphorus losses, and other environmental externalities. N_v (USD t^{-1}): Net value, calculated as compost product sales revenue plus carbon trading income, minus equipment depreciation and operational costs.

Statistical Analysis

Differences in environmental impacts (GHG emissions, eutrophication potential) and economic indicators (operational costs) among composting technologies (SH, WC, MC, RC) were evaluated using one-way ANOVA followed by Tukey's HSD post-hoc test (α = 0.05). Data normality was confirmed by the Shapiro-Wilk test, and homogeneity of variances by Levene's test. Analyses were performed in SPSS 26.0 (IBM, USA). Significance is indicated by lowercase superscript letters (a, b, c) in tables, where different letters denote statistically significant differences ($p<0.05$).

Results and Discussion

Interpretation of LCA

The LCA results revealed substantial disparities in the environmental performance of the four composting methods. Of which, MC consistently demonstrated the most balanced and favorable outcomes across multiple impact categories (Table 4). This aligns with the findings of Zhang et al. (2021), who also reported reduced CH_4 and N_2O emissions under semi-aerobic membrane systems. Specifically, MC's total CO_2-eq emissions (132 kg CO_2-eq t^{-1}) were 53.7% lower than those of SH (285 kg CO_2-eq t^{-1}), and its total greenhouse gas reductions, including CH_4 and N_2O expressed in CO_2-eq, reached 41.8%, 25.4%, and 13.2% relative to SH, WC, and RC, respectively (Fig. 2). This advantage was primarily attributed to the controlled micro-environment created by the semi-permeable membrane, which

Table 4. Midpoint eco-efficiency indicators of different composting methods.

Impact Category	SH	WC	MC	RC
Greenhouse Gas Emissions				
CO_2-eq total emissions (kg CO_2-eq)	285[a]	224[b]	132[c]	98[d]
CH_4 emissions (kg CO_2-eq)	1.32	0.94	0.68	0.25
N_2O emissions (kg CO_2-eq)	0.68	0.53	0.29	0.17
Eutrophication Potential				
NH_3 volatilization (kg PO_4^{3-}-eq)	9.2[a]	7.5[b]	2.9[c]	2.1[c]
Leachate nitrogen loss (kg N-eq)	4.7	3.9	1.6	1.2
Particulate Matter Emissions				
PM_{10}-eq emissions (kg PM_{10}-eq)	5.20×10^3	6.70×10^3	2.80×10^2	4.85×10^3
Resource Consumption				
Non-renewable energy demand (MJ)	1,850	1,650	1,620	890
Toxicity Impact				
Heavy metal leaching (kg 1,4-DCB-eq)	1.2	1.7	1.1	2.1

Note: All values are calculated per functional unit (1 t dry pig manure, dry weight basis). Different superscript letters (a, b, c) within a row indicate significant differences ($p<0.05$).

suppresses anaerobic zones, thereby limiting methane generation from anaerobic digestion and nitrous oxide emissions [22]. Similar mechanisms have been described by Fang et al. (2020), although their reported CH_4 reductions were less significant, possibly due to higher initial moisture content and insufficient temperature control. This suggests that membrane efficiency may depend on specific operational parameters, such as aeration intensity and compost mix properties [23]. Moreover, MC also reduced ammonia volatilization and nutrient leaching by minimizing convective gas exchange and retaining nitrogen in stable forms, thereby

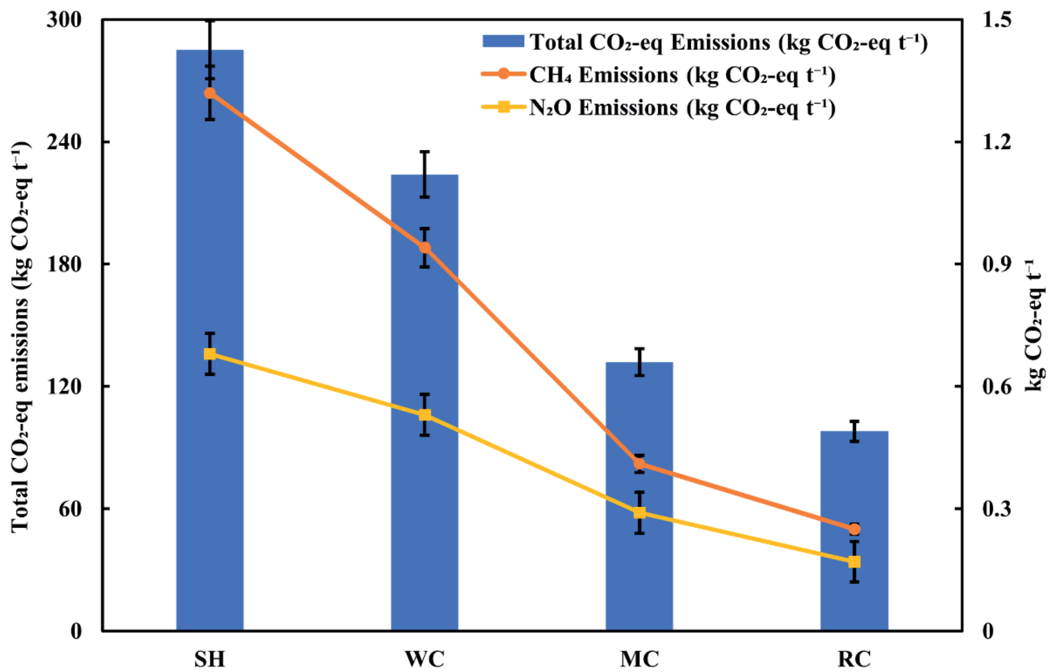

Fig. 2. Comparison of greenhouse gas emissions (CO_2-eq) among four composting technologies.
Total greenhouse gas emissions (kg CO_2-eq t^{-1} of dry waste) for SH, WC, MC, and RC systems. MC exhibits the lowest emissions due to effective anaerobic inhibition and gas retention.

enhancing compost quality while reducing the risk of eutrophication [24]. Although RC exhibited slightly lower non-renewable energy consumption (890 MJ t^{-1}) than MC (1,620 MJ t^{-1}), its higher infrastructure complexity and operational energy demand diminished its overall environmental advantages (Table 4). Thus, considering emission mitigation and resource efficiency holistically, MC emerged as the most sustainable option.

Beyond greenhouse gas mitigation, MC excelled in reducing other pollutant emissions across multiple categories. Its NH_3 volatilization (2.9 kg PO_4^{3-}-eq t^{-1}) and leachate nitrogen losses (1.6 kg N-eq t^{-1}) were substantially lower than those of SH and WC and only marginally higher than RC (2.1 and 1.2 kg, respectively) (Table 4). Furthermore, MC substantially curtailed airborne particulate matter (PM_{10}-equivalent: 280 kg t^{-1}), far outperforming SH (5,200 kg), WC (6,700 kg), and RC (4,850 kg). This outcome highlighted the membrane's dual role in physical barrier function and gas filtration, which restricts particulate dispersion and mitigates secondary pollution risks during field operations [25]. In terms of toxicity impact, MC recorded the lowest heavy metal leaching (1.1 kg 1,4-DCB-eq), slightly outperforming SH (1.2 kg), WC (1.7 kg), and RC (2.1 kg). These results consolidate MC's environmental superiority across air, water, and soil compartments.

Taken together, the multi-indicator comparisons position MC as the most environmentally sustainable technology among the methods evaluated. Its ability to simultaneously reduce greenhouse gas emissions, air pollutants, nutrient losses, and toxic leachates, while maintaining moderate energy consumption, highlights its potential as a viable strategy for sustainable organic waste management. The accumulated evidence suggested that the environmental advantages of MC arise from its effective management of aerobic conditions, moisture regulation, and gaseous containment. This balance confirms its applicability in both temperate and subtropical composting environments, as demonstrated by Fei et al. (2024) in their pilot-scale study, which highlighted the importance of operational parameters such as moisture content and aeration in optimizing composting performance [26]. Overall, both LCA evidence and impact pathway analyses demonstrated that MC offers the most well-rounded and scalable environmental benefits compared to other methods.

LCC Assessment Results

The Life Cycle Cost (LCC) analysis was conducted to evaluate the economic feasibility of four composting technologies: SH, WC, MC, and RC. The results indicated that MC achieved the most favorable LCC outcomes, balancing both economic and environmental considerations.

Economic Performance

MC incurred a higher initial investment (USD 187.60 t^{-1} for membrane material) compared to SH (USD 3.92 t^{-1}). However, MC demonstrated significantly lower operational costs (USD 28.84 t^{-1}), achieving a 33.6% reduction relative to RC (USD 43.40 t^{-1}) (Fig. 3). This operational cost advantage primarily stems from

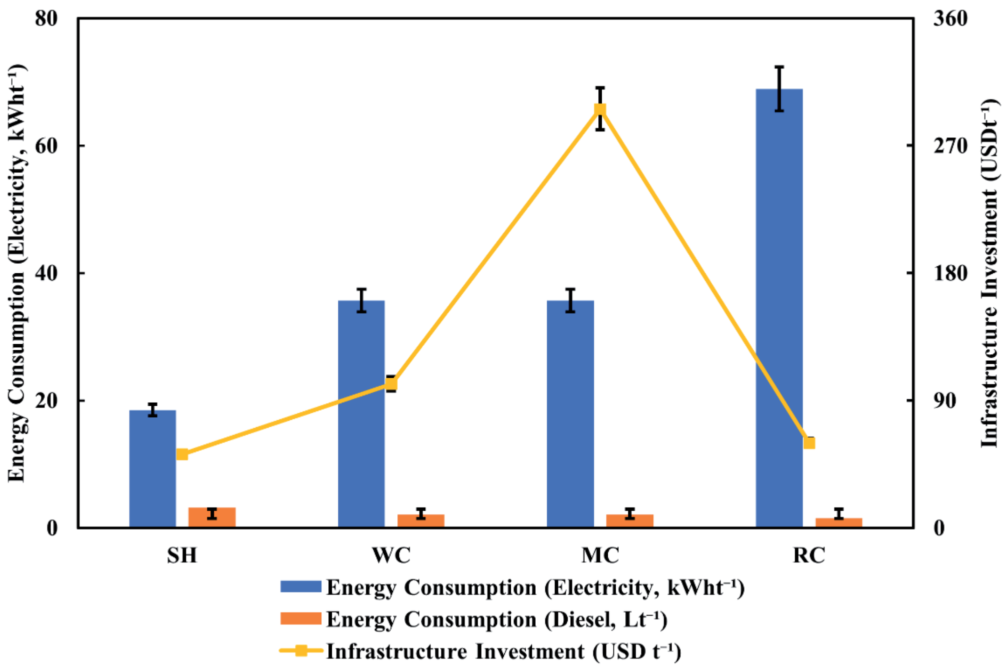

Fig. 3. Energy consumption and infrastructure investment of composting technologies. Bars show energy consumption (left Y-axis; kWh t^{-1} or L t^{-1}); the line graph represents infrastructure investment (right Y-axis; USD t^{-1}). MC optimizes energy use and infrastructure input compared to RC.

an 18% reduction in diesel consumption enabled by passive aeration, alongside lower overall energy requirements and a simpler system design. The trade-off between initial capital investment and ongoing operational costs for all four technologies is visually summarized in Fig. 4. While MC requires a higher initial investment than traditional methods (SH, WC), its operational cost is substantially lower than that of RC. This favorable cost structure underscores MC's potential for long-term economic viability, particularly for medium-scale operations where high capital costs of RC are prohibitive. Furthermore, MC’s overall cost-effectiveness is enhanced by its efficient process control and shorter composting cycles, which increase throughput and reduce labor demands.

Environmental and Operational Advantages

MC’s superior LCC performance was further reinforced by its environmental benefits. Studies have demonstrated that MC significantly reduces greenhouse gas emissions and nitrogen losses during composting. For instance, Li et al. (2024) [27] reported that MC reduced ammonia (NH_3) and nitrous oxide (N_2O) emissions by 48.5% and 44.1%, respectively, compared to traditional composting methods. This reduction in emissions not only mitigated environmental impact but also preserved nitrogen content in the compost, enhancing its agronomic value.

Additionally, the semi-permeable membrane in MC systems maintained optimal moisture and temperature conditions, promoting microbial activity and accelerating the composting process. This led to a higher-quality compost product in a shorter time frame, further contributing to the economic viability of the MC approach [28].

Comparative Analysis

Compared to RC, MC offers similar environmental benefits but at a significantly lower operational cost, making it a more economically sustainable option. This advantage primarily stems from the MC system’s design, which utilizes a semi-permeable membrane that enables passive ventilation and reduces the need for intensive mechanical inputs. As a result, diesel consumption in MC systems was significantly lower compared to RC systems. In contrast, RC systems incurred operational expenses due to the requirement of higher energy inputs and involved more complex maintenance procedures, although providing precise control over composting parameters.

Fig. 3 compares energy consumption and infrastructure requirements across composting technologies. MC reduced diesel consumption by 18% relative to RC, attributable to its passive membrane aeration versus RC’s energy-intensive forced aeration. This reduction in energy input directly contributes to MC’s lower operational costs (USD 28.84 t^{-1} vs. RC’s USD 43.40 t^{-1}), despite both systems achieving comparable levels of emission control.

EEI Results: Unveiling the Superiority of Membrane-Covered Composting

The Eco-Efficiency Index (EEI) serves as a crucial metric for evaluating the delicate balance between environmental impact and economic output across different composting technologies. Table 5 summarizes the ecological costs and economic benefits driving EEI calculations, with MC demonstrating the lowest GHG cost (USD 22.12 t^{-1} CO_2-eq) and competitive carbon trading revenue (USD 11.90 t^{-1}). Among the methods analyzed, MC stands out not only for its remarkable environmental efficiency but also for its ability to

Table 5. Ecological costs, economic benefits, and efficiency indices.

Category	Unit	SH	WC	MC	RC
Ecological Costs					
Greenhouse gas cost	USD t^{-1} CO_2-**eq**	39.90	31.36	22.12	13.72
Eutrophication cost	USD t^{-1} PO_4^{3-}-**eq**	6.51	5.21	4.02	2.98
Non-renewable resource cost	USD MJ^{-1}	0.12	0.15	0.35	0.08
Economic Benefits					
Compost sales revenue	USD t^{-1}	95.20	99.40	105.00	100.80
Carbon trading revenue	USD t^{-1}	3.70	6.26	11.90	16.46
Efficiency Indices					
EEI	Dimensionless	2.1	1.3	3.7	4.2
EVR	Dimensionless	0.9	0.7	1.4	1.5

Note: All values are expressed per functional unit (1 t dry pig manure, dry weight basis).

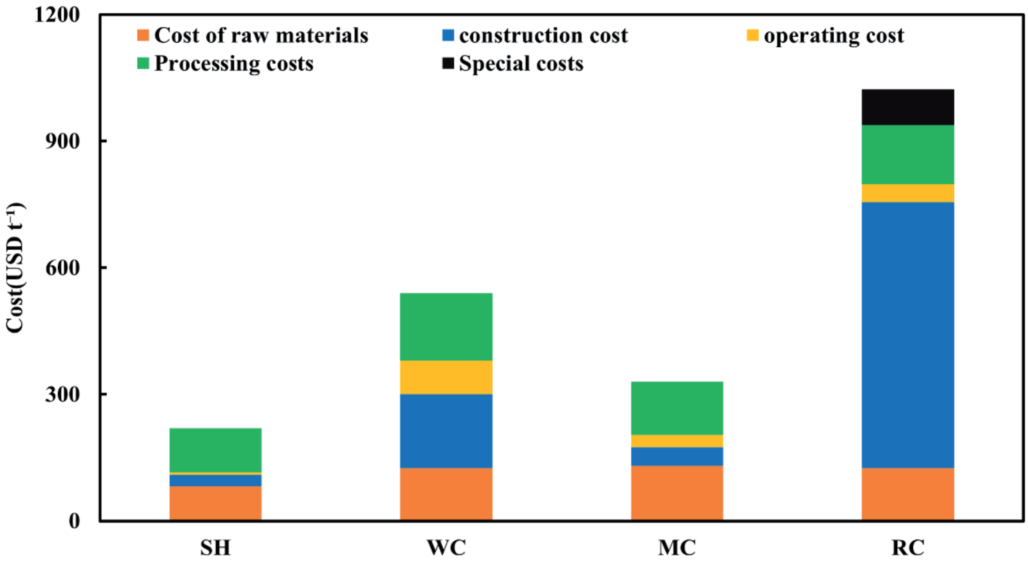

Fig. 4. Capital investment versus operational cost analysis of composting technologies. Comparison of initial capital investment and operational cost among four composting technologies (SH, WC, MC, and RC). Each bar represents the cost per ton of treated waste in United States Dollar (USD). The blue bars indicate initial investment costs, while the orange bars represent operational costs. Exact values are labeled on the top of each bar.

significantly minimize both carbon emissions ($p<0.01$ vs SH and WC; $p<0.05$ vs RC) and ammonia volatilization ($p<0.01$ vs SH and WC; $p<0.05$ vs RC).

In particular, MC exhibits the lowest GHG emissions, recording only 85 kg CO_2-eq t^{-1}, representing a substantial improvement over both SH and WC systems. Additionally, NH_3 losses were reduced to 1.8 kg t^{-1}, marking a decrease of more than 60%. These results, largely attributable to the controlled aeration and semi-enclosed nature of the system, reflect a significant reduction in the inefficiencies commonly associated with open-air decomposition. The membrane's ability to effectively capture and retain gases underlines its role in reducing fugitive emissions, which has been corroborated in other studies that highlight similar gains from sealed or semi-enclosed composting designs [29].

Although Liu et al. (2022) [30] identified RC as the most eco-efficient approach, their framework excluded carbon trading revenues and nutrient loss valuations, focusing primarily on resource recovery. In contrast, our analysis integrates emissions control efficiency, carbon market benefits, and nitrogen retention, under which MC, despite having simpler infrastructure, outperforms RC in terms of emissions-to-cost ratio. MC's ability to suppress fugitive emissions through its semi-enclosed membrane system, while maintaining moderate operational demands, fundamentally explains its superior eco-efficiency in our context. The introduction of carbon costs significantly enhances MC's economic-environmental alignment, especially in regions where stringent emissions regulations are in place. Under scenarios with carbon prices above USD 11.90 t^{-1} CO_2-eq, the EEI of MC surpasses 4.0, which not only surpasses RC, but positions MC as a highly adaptable technology for regions navigating the transition to a low-carbon economy [31].

The system's performance suggests that, although RC maintains an edge in integrated resource recovery, MC offers optimal emissions-to-cost ratios, making it a strategic option for medium-scale composting operations focused on minimizing environmental

Table 6. Summary of environmental and economic performance of four composting technologies.

Technology	EEI	GHG (kg CO_2-eq t^{-1})	NH_3 (kg t^{-1})	Operation Cost (USD t^{-1})	Environmental Cost Weight	Remark
SH	2.1^a	286^a	9.2^a	15.68^c	High	Baseline, low-cost
WC	2.8^b	215^b	6.5^b	21.56^b	Moderate	Practical, low-tech
MC	3.7^c	132^c	1.8^c	28.84^b	Low	Emission optimal
RC	4.2^d	98^d	2.1^c	42.14^a	Low	Recovery-integrated

Note: All indicators are expressed per functional unit (1 t dry pig manure, dry weight basis). Different superscript letters indicate significant differences ($p<0.05$).

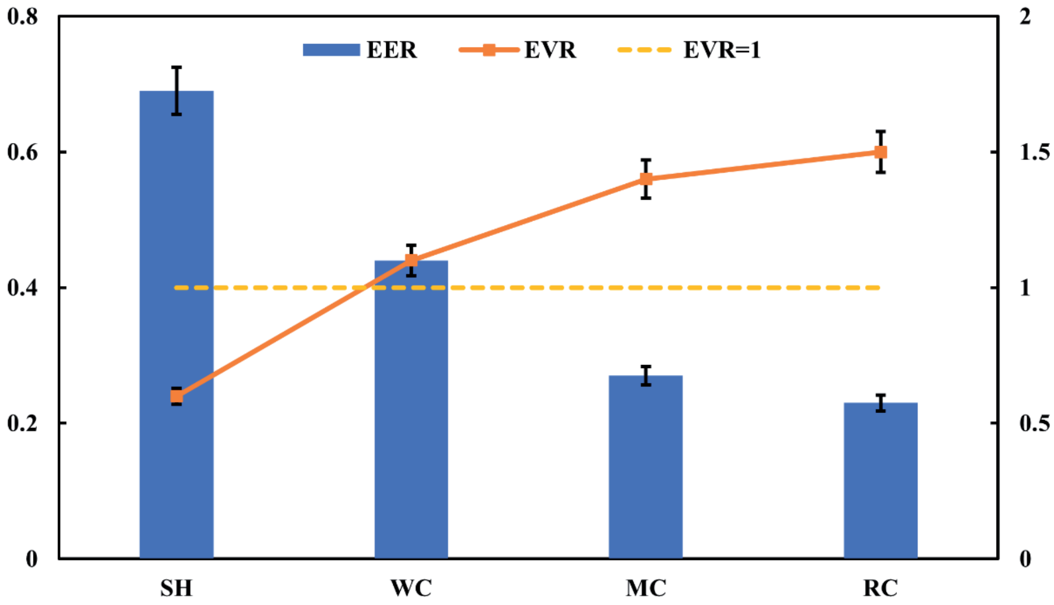

Fig. 5. Comparison of Environmental Efficiency Ratio (EER) and Ecological Value Ratio (EVR) among composting technologies. MC and RC demonstrate favorable eco-economic profiles, with EVR exceeding the ecological break-even threshold (dotted line at EVR = 1). Lower EER indicates reduced environmental cost per economic unit.

footprint while ensuring economic sustainability [5]. The integration of low-cost emissions control, coupled with reduced ammonia losses, presents MC as an exceptional candidate for implementing sustainable waste management practices, especially when economic and regulatory constraints are paramount. A detailed comparison of eco-efficiency indicators, including EEI, GHG emissions, ammonia losses, and operational costs, is presented in Table 6.

EER and EVR Results: Marginal Gains and System Boundaries in MC Optimization

To further scrutinize the sustainability thresholds of composting technologies, this study focused on two critical indicators: the Environmental Efficiency Ratio (EER) and the Ecological Value Ratio (EVR). These metrics serve as diagnostic tools for assessing the balance between environmental costs and economic

Table 7. Comparative summary of key advantages and limitations of the four composting technologies.

Technology	Key Advantages	Key Limitations	Ideal Application Scenario
SH	Lowest capital cost Simple operation	Highest GHG & ammonia emissions	Small-scale farms with low environmental regulatory pressure and ample space.
		Poor process control	
	Simple operation	Long composting cycle	
		High land use	
WC	Moderate capital cost	Significant GHG & ammonia emissions during turning	Medium-scale operations where some emission control is needed but capital is limited.
	Better aeration than SH	Weather-dependent	
		High labor/energy for turning	
MC	Excellent emission control (GHG, NH_3, PM)	Membrane requires periodic replacement	Medium-scale farms under emission constraints, seeking a balance between cost and environmental performance
	Moderate capital & operational cost		
	Shortened composting cycle	Requires some technical knowledge for setup	
	Weather-independent		
RC	Best emission control	Highest capital and operational cost	Large-scale, capital-intensive facilities with strict environmental mandates and access to technical expertise.
	Fastest process	High mechanical complexity	
	Precise control over parameters	High energy consumption	

returns. Specifically, EER quantifies the environmental cost per unit of net profit, while EVR evaluates the economic return per unit of ecological burden, both of which are key to identifying whether a system remains within an optimal eco-economic operating range [32].

Among the four composting systems analyzed, the MC system demonstrated competitive performance, achieving an EER of 0.27 and an EVR of 1.4, as illustrated in Fig. 5. While not surpassing RC, which registered an EER of 0.23 and an EVR of 1.5, MC outperformed both SH and WC, which showed lower efficiency (EER: 0.69 and 0.44; EVR: 0.6 and 1.1, respectively). These findings affirm that MC technology offers a significantly favorable return per unit of environmental input ($p<0.05$ vs. SH and WC), and more importantly, it approaches the ecological break-even threshold (EVR = 1), indicating integrated environmental and economic sustainability.

The EER of MC suggests that the system achieves substantial environmental impact mitigation without an unsustainable financial burden. This is largely attributed to its capacity to control emissions via membrane regulation and reduced leachate generation [28]. Moreover, the economic viability of MC is further enhanced in carbon-conscious policy frameworks, where mechanisms such as carbon trading and environmental taxation can internalize ecological externalities.

Although RC maintains a slight advantage due to its integration of biochar production and waste heat recovery, which contributes to additional carbon credits and thermal energy reuse [33], MC is notably more scalable and easier to deploy in decentralized waste management contexts. It presents a lower capital investment profile, making it suitable for small to medium-sized facilities lacking access to advanced control infrastructure.

Importantly, emerging literature highlights that such marginal eco-efficiency improvements, especially under policy-driven incentives like carbon pricing, can significantly influence technology adoption patterns in the waste management sector [34]. Under dynamic environmental pricing schemes, even moderate improvements in EVR and EER can tip the balance in favor of MC due to its relatively lower lifecycle cost per ton of waste processed.

In this context, MC represents a highly cost-effective and environmentally conscious pathway, especially in jurisdictions with environmental compliance pressure. Its moderate investment requirements and strong emission control capabilities make it particularly attractive under anticipated shifts in regulatory frameworks that target nitrogen volatilization and carbon emission reduction [35]. Thus, MC technology not only aligns with current circular economy principles but also offers resilience against policy and market fluctuations, cementing its position as a transitional composting strategy toward full system circularity.

Conclusions

This study provides compelling evidence that MC represents a superior composting strategy by synergizing environmental and economic gains. MC emerges as the optimal strategy for medium-scale farms where high RC investments are prohibitive. Under carbon pricing (>USD 11.90 t^{-1} CO_2-eq), its EEI exceeds 4.0, enabling faster payback periods through carbon trading revenues (USD 11.90 t^{-1}). Through comprehensive LCA and cost-benefit analysis, MC consistently outperformed traditional methods by substantially and significantly reducing greenhouse gas emissions ($p<0.01$), curbing ammonia volatilization ($p<0.01$), and minimizing secondary pollution risks ($p<0.05$), all while maintaining moderate energy demands and operational costs. Its controlled process environment, facilitated by the semi-permeable membrane, enables enhanced nitrogen retention and superior compost quality, making MC highly suitable for intensive livestock production systems under increasing environmental and regulatory pressures. Importantly, this research bridges the critical gap between ecological efficiency and economic sustainability by introducing an integrated assessment framework that captures dual benefits. The findings highlight MC not only as a practical solution for current waste management challenges but also as a forward-compatible and scalable technology aligned with circular economy principles. As regions worldwide advance towards stricter emission controls and sustainable resource utilization, MC emerges as a pivotal transitional strategy capable of supporting both near-term regulatory compliance and the longer-term vision of full system circularity in organic waste management. Its suitability for medium-scale operations – where prohibitive RC investments are impractical – and responsiveness to carbon pricing mechanisms (e.g., EEI>4.0 at USD 11.90 t^{-1} CO_2-eq) position MC as a scalable solution. To aid stakeholders in selecting the most appropriate technology based on their specific operational contexts and constraints, a comparative summary of the key advantages, limitations, and ideal application scenarios for each composting technology is provided in Table 7.

To accelerate the adoption of MC, policymakers and industry stakeholders should prioritize incentive mechanisms such as carbon credits, technology subsidies, and regulatory fast-tracking to promote the deployment of MC-based facilities [36]. Additionally, the establishment of standardized technical guidelines and pilot demonstration projects will be critical for facilitating knowledge transfer, enhancing stakeholder confidence, and supporting the large-scale implementation of MC systems in regions with intensive livestock production and stringent emission targets.

Regional Applicability and Future Research Directions

This study is primarily based on Chinese conditions, including cost parameters, emission factors, and policy frameworks. Such regional specificity provides valuable insights into intensive livestock systems in China, where rapid industrialization and large-scale operations create unique environmental and economic pressures. However, this reliance also limits the direct transferability of results to other regions. For example, in Europe and North America, differences in energy structures, manure management practices, carbon pricing mechanisms, and regulatory frameworks may substantially influence both the life cycle environmental impacts and the cost-effectiveness of composting technologies.

In addition to regional bias, several other limitations should be noted. First, the dataset mainly relies on enterprise production logs and on-site monitoring, which, although cross-validated, may still be affected by measurement discrepancies and reporting practices. Second, the life cycle costing (LCC) analysis incorporates assumptions such as a 10-year equipment depreciation period, a fixed exchange rate (1 USD = 6.73 RMB), and carbon prices above USD 11.90 t^{-1} CO_2-eq. These parameters are subject to uncertainty, and their variation could influence the relative cost-effectiveness of the composting technologies.

Nevertheless, the methodological framework integrating LCA and LCC with eco-efficiency indicators remains broadly applicable across contexts. By adjusting local parameters such as energy mixes, wage levels, and carbon market values, the comparative advantages of composting technologies, particularly the strong performance of membrane-covered composting, can still be meaningfully evaluated. Future research should therefore extend this analysis to region-specific datasets in Europe, North America, and other parts of Asia to enhance the robustness and generalizability of policy and investment recommendations.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

All data generated or analysed during this study are included in this published article.

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