Environment and Natural Resources Journal

Volume 24
Issue X
2026

Life Cycle Assessment of Sugarcane Bagasse Takeout Containers: A Case Study in Laibin, Guangxi, China

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ARTICLE INFO

Received: 20 Apr 2025
Received in revised: 21 Oct 2025
Accepted: 31 Oct 2025
Published online: 18 Nov 2025
DOI: 10.32526/ennrj/24/20250100

Keywords:
Biomass-based packaging/ Life cycle assessment (LCA)/ Carbon footprint/ Environmental optimization/ Renewable materials/ Low-carbon innovation/ Circular economy

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ABSTRACT

With growing global concerns over climate change, resource depletion, and environmental degradation, the packaging industry is under increasing pressure to shift toward low-carbon and sustainable alternatives. This study applies a Life Cycle Assessment (LCA) framework to evaluate the environmental impacts of sugarcane bagasse-based takeout containers using a representative enterprise in Laibin, Guangxi, China—a major sugarcane production hub. The system boundary spans from raw material acquisition to end-of-life disposal. Six environmental impact categories—Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Abiotic Depletion Potential (ADP), Ozone Depletion Potential (ODP), and Photochemical Ozone Formation Potential (POFP)—were assessed using the CML 2001 method and compared with plastic, starch, and composite starch containers. The results show that bagasse containers significantly outperform conventional materials, especially in GWP and ADP, reducing total environmental burden by over 70%. Sensitivity analysis identifies bamboo pulp input, additives, and boiler fuel as key contributors. Optimization strategies include adopting cleaner pulping technologies, using green additives, and improving low-carbon logistics. The integrated "sugar mill-pulp mill-container factory" model in Laibin demonstrates high replicability in other agricultural regions of southern China and Southeast Asia. This study provides theoretical insights for promoting biomass packaging as part of the circular economy and sustainable material innovation.

HIGHLIGHTS

1. Cradle-to-grave LCA evaluates sugarcane-bagasse takeout containers in Laibin.
2. CML 2001 covers six impacts; compares bagasse, plastic, starch, and composite.
3. Bagasse cuts total life-cycle impacts by >70%, notably for GWP and ADP.
4. Sensitivity identifies hotspots: bamboo pulp, chemical additives, boiler fuel.
5. Actions proposed: carbon capture and storage, bio-based additives, and electrified logistics.

1. INTRODUCTION

1.1 Research background and objectives

The global packaging industry is under mounting pressure to transition toward low-carbon and sustainable solutions due to intensifying challenges related to climate change, resource depletion, and environmental degradation (Arfelli et al., 2024). As one of the largest packaging consumers globally, China generates enormous quantities of packaging waste, particularly from the fast-growing food delivery sector (Lu et al., 2025). A total of 1.6 million tons of plastic waste was generated by China's takeaway food services in 2020, accounting for 3% of plastic waste within the country's municipal solid waste, exacerbating resource inefficiency and plastic pollution (Zhang and Wen, 2022). In response, the Chinese government has introduced a series of environmental policies—such as the "14th Five-Year Plan for Plastic Pollution Control"—to promote degradable, recyclable, and low-carbon packaging alternatives and phase out conventional plastic products (Fürst and Feng, 2022).

Among the promising substitutes, biomass-based materials have received considerable attention due to their renewable, biodegradable, and carbon-neutral characteristics (Cruz et al., 2022). Sugarcane bagasse, a

Citation: Fan M, Bussracumpakorn C. Life cycle assessment of sugarcane bagasse takeout containers: A case study in Laibin, Guangxi, China. Environ. Nat. Resour. J. 2026;24(X):xx-xx.

by-product of the sugar industry, stands out for its environmental potential (Janika et al., 2024). Its high cellulose content makes it suitable for molded pulp packaging, while its use does not require additional land or compete with food production—hence, it is widely regarded as a “zero-land-use, zero-carbon-source” green material (Hossam and Fahim, 2023).

Although bagasse-based packaging has gained initial traction in the marketplace, current research primarily focuses on mechanical properties and forming processes. There is a lack of comprehensive environmental evaluation based on standardized Life Cycle Assessment (LCA), which is essential for quantifying its true sustainability performance. LCA enables a cradle-to-grave analysis of resource use and emissions throughout all life cycle stages, providing objective and comparable insights.

This study aims to fill these gaps by conducting a cradle-to-grave LCA (ISO 14040/14044) of sugarcane bagasse takeout containers produced in Laibin, Guangxi—one of China’s key sugarcane production hubs. It evaluates the environmental impacts across six key categories using the CML 2001 method: Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Abiotic Depletion Potential (ADP), Ozone Depletion Potential (ODP), and Photochemical Ozone Formation Potential (POFP). The environmental performance of bagasse containers is compared with conventional materials including plastic, starch, and composite starch containers.

The objectives of this study are fourfold: (1) to construct an LCA model for bagasse-based takeout containers and quantify their environmental impacts across life cycle stages; (2) to identify environmental hotspots and key contributing factors through sensitivity analysis; (3) to compare the environmental performance of bagasse containers with other materials and assess their substitution potential; and (4) to propose targeted strategies for material optimization, green processing, and policy support.

By achieving these objectives, this study not only offers robust evidence for the environmental advantages of sugarcane bagasse packaging, but also aligns with broader efforts in promoting sustainable materials and advancing the circular economy.

1.2 Development status and research gaps of bagasse-based packaging

Bagasse, a cellulose-rich agricultural by-product, has a considerable global resource base (Thongsomboon et al., 2023). Taking Laibin City in Guangxi, China as an example—a major national sugarcane production area—the sugarcane planting area reached 1.8302 million mu in 2023, with a total yield exceeding 11.45 million tons (Table 1). The annual output of bagasse, as a by-product, is approximately 3.44 million tons, providing a sufficient and stable raw material foundation for bagasse-based packaging production. Traditionally, bagasse has mostly been used as boiler fuel, livestock feed, or directly discarded, resulting in low resource utilization efficiency (Barasa Kabeyi, 2023). In recent years, with the tightening of environmental regulations and the rising awareness of green consumption, bagasse has attracted increasing attention in the packaging industry due to its natural biodegradability, renewability, and low carbon emissions (Debnath et al., 2022; Liu et al., 2020).

In international markets, several countries have promoted the large-scale application of bagasse-based packaging products. Major sugarcane-producing countries such as the United States, Brazil, and India have widely adopted bagasse for producing disposable biodegradable tableware, food trays, and fast-food packaging containers, and have preliminarily formed industrial chains in the food, airline, and medical packaging sectors (Grand View Research, 2024; Hossam and Fahim, 2023; Stroescu et al., 2024). With the growing stringency of environmental regulations and the continued promotion of green consumption concepts, bagasse has become a key pathway for the resource utilization of agricultural waste in the food packaging sector (Singh et al., 2022; Fan and Bussracumpakorn, 2025). Particularly under the joint influence of “plastic restriction” and “dual-carbon” policies, bagasse-based containers have emerged as an ideal alternative to single-use plastic packaging, owing to their renewability, biodegradability, and low carbon footprint (Varghese et al., 2023). Currently, some domestic enterprises have mastered the core technology of molded bagasse pulp and have preliminarily achieved industrial-scale production. The products are widely applied in scenarios such as food delivery, fast food, and airline catering, with market acceptance continuously improving (Semple et al., 2022).

Despite the promising development momentum of the bagasse-based packaging industry, existing studies and industry practices still reveal several critical issues and research gaps:

(1) Lack of quantitative research on environmental impact from a complete life cycle

perspective. Most existing studies focus on the physical properties, molding processes, or mechanical optimization of bagasse packaging materials. However, there is a lack of systematic Life Cycle Assessment (LCA) analysis. Especially across the entire process—from raw material acquisition and manufacturing to transportation and end-of-life disposal—the environmental impacts of each stage lack comparative data support, making it difficult to provide comprehensive quantitative evidence for its green credentials.

(2) Lack of environmental comparison with other alternative materials (e.g., plastic, starch, composite packaging). Current research mostly takes a single-product perspective and rarely conducts full-process environmental performance comparisons between bagasse packaging and mainstream materials. As a result, it remains unclear how bagasse performs in terms of carbon emissions, resource consumption, and other indicators, limiting its wider promotion and policy endorsement.

(3) Lack of sensitivity analysis and optimization pathway research based on key process parameters. Although bagasse packaging holds strong potential for sustainability, its environmental performance is highly dependent on factors such as raw material composition, energy structure, and transportation methods. There is currently a lack of systematic sensitivity analysis to identify key influencing factors in the life cycle, and no multi-parameter coordinated optimization framework aimed at low-carbon improvement has been established, making it difficult to efficiently manage environmental burdens in real-world applications.

Table 1. Sugarcane planting data table for Laibin City, Guangxi

Year	Sugarcane Price (Yuan/Ton)	Cultivation Cost (Yuan/Mu)	Sugarcane Farmer's Income (Yuan/Mu)	Planting area (10,000 Mu)	Yield (Ton/Mu)	Total output (10,000 tons)	Sugarcane residue output (10,000 tons)	Government subsidy (Yuan/Mu)
2012	470	1,813.42	311	267.96	4.52	1,211.09	363.327	0
2013	475	1,992.61	154.39	260.43	4.52	1,267.47	380.241	0
2014	445	2,016.62	195.03	249.615	4.97	1,241.78	372.534	0
2015	400	2,122.29	13.71	225.315	5.34	1,204.78	361.434	0
2016	440	2,198.8	194.8	219.36	5.44	1,193.22	357.966	0
2017	480	2,317.47	548.13	205.83	5.97	1,229.11	368.733	0
2018	500	2,439.49	615.51	181.545	6.11	1,108.72	332.616	0
2019	490	2,394.37	589.73	177.975	6.09	1,083.20	324.96	0
2020	490	2,433.42	1,003.58	179.1	6.30	1,128.03	338.409	350
2021	490	2,545.46	720.04	178.89	5.95	1,066.25	319.875	350
2022	490	2,582.16	629.44	181.41	5.84	1,059.16	317.748	350
2023	510	2,615.00	907.6	183.015	6.26	1,145.73	343.719	330

2. METHODOLOGY

2.1 Life cycle assessment method and system boundary definition

Life Cycle Assessment (LCA) is a standardized environmental management tool used to quantify the potential environmental impacts of a product, process, or service throughout its entire life cycle (Hauschild et al., 2018). This study adopts the Life Cycle Assessment (LCA) method based on ISO 14040 and ISO 14044 standards to systematically evaluate the environmental impacts of sugarcane bagasse-based takeout containers throughout their entire life cycle, from raw material acquisition to final disposal. A representative manufacturing enterprise located in Laibin, Guangxi, China was selected as the case study. In LCA research, the definition of the system boundary is a fundamental step to ensure the integrity and scientific rigor of the assessment. It determines which processes, activities, and resource flows are included in the analytical scope, thereby directly influencing the accuracy and comparability of the environmental impact results. In accordance with ISO 14040 and ISO 14044, this study adopts a cradle-to-grave system boundary, comprehensively covering the resource inputs and environmental emissions involved in the entire process of bagasse takeout container production—from raw material extraction, manufacturing, and transportation to end-of-life disposal.

In Life Cycle Assessment (LCA), clearly defining the system boundary is essential for ensuring the completeness and accuracy of the environmental evaluation, as it determines the scope of all included processes and flows (El Haouat et al., 2025). The system boundary includes four main stages (Figure 1). The first stage, raw material acquisition, covers the procurement and transportation of sugarcane bagasse, bamboo pulp, water-repellent agents, and oil-repellent agents. Sugarcane bagasse, as a by-product of sugar processing, is sourced from local sugar mills with a transportation distance set at 30 kilometers. The acquisition of bamboo pulp and chemical additives is also included in the evaluation of resource consumption and emissions. The second stage, production, involves pulp preparation, molding, hot pressing, trimming, drying, disinfection, and packaging, as well as the consumption of water and biomass fuel. The third stage, distribution, is represented by the delivery of takeout containers from the factory to the city center, with a transportation distance set at 10 kilometers. The fourth stage, disposal, adopts incineration as the main method of end-of-life treatment, in line with China's ongoing policy of restricting landfill usage, and includes the evaluation of greenhouse gases and other pollutants generated during the incineration process (Liu and Zheng, 2023).

Throughout all stages, the study considers inputs such as material flows (including raw materials, water resources, and biomass fuels) and energy flows (e.g., thermal energy), with outputs primarily consisting of the final product and environmental emissions (e.g., CO_2, SO_2, NO_x, particulate matter). Additionally, Figure 1 presents the system boundary as a flowchart, clearly outlining key activities and data collection points at each stage. The figure also indicates the six characterization indicators—Global Warming Potential (GWP), Acidification Potential (AP), Abiotic Depletion Potential (ADP), Eutrophication Potential (EP), Ozone Depletion Potential (ODP), and Photochemical Ozone Formation Potential (POFP)—and adopts the CML 2001 method for normalization and weighting to ensure that environmental impacts across each life cycle stage can be quantitatively and systematically assessed.

The functional unit of this study is defined as the production and disposal of "10,000 standard sugarcane bagasse takeout containers," a unit that reflects a practical production scale and serves as the basis for normalizing all input and output data. This functional unit was selected for its strong representativeness and operability, making it well-suited for actual production contexts and facilitating horizontal comparison with other types of containers such as those made from plastic, starch, or composite materials.

In Life Cycle Assessment (LCA), characterization translates inventory flows into environmental impacts, normalization contextualizes these impacts against a reference system, and weighting aggregates them based on relative importance, while sensitivity analysis identifies the parameters most influencing the results—together forming a robust basis for environmental decision-making (Heijungs and Huijbregts, 2004; Pizzol et al., 2017). To achieve a comprehensive environmental assessment, the study incorporates characterization, normalization, and weighting analysis methods, and further conducts sensitivity analysis to identify key influencing factors, thereby enhancing the robustness of the model. This LCA study provides quantitative evidence for evaluating the environmental performance of bagasse-based packaging and offers theoretical support for its optimization in green design and life cycle management.

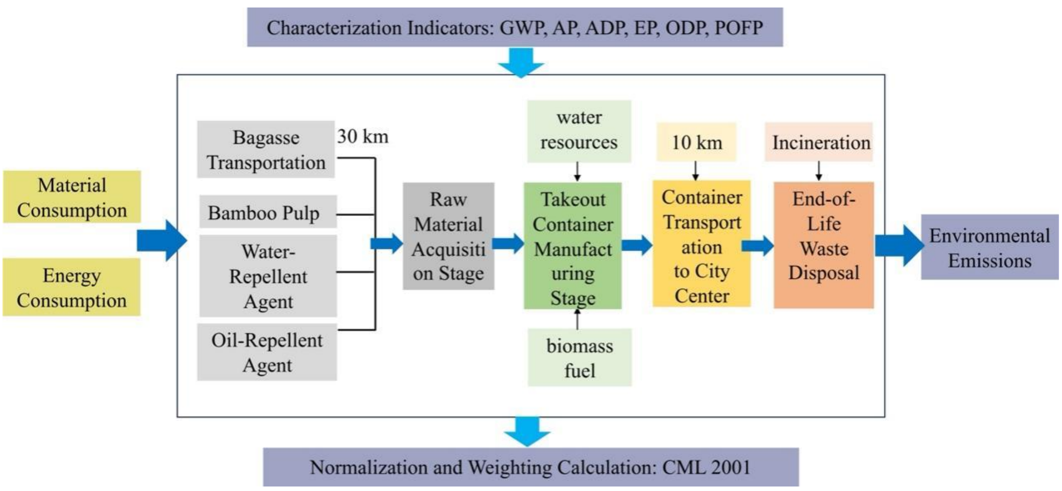

Figure 1. System boundary and life cycle flow of bagasse-based takeout container production

2.2 Life cycle inventory data

To comprehensively assess the environmental burden of bagasse containers, an LCI was developed within the cradle-to-grave boundary, covering all stages from material acquisition to final disposal. The functional unit is defined as the production and use of 10,000 sugarcane bagasse takeout containers. LCI data were primarily sourced from enterprise environmental reports, production records, and databases such as Ecoinvent and CLCD. Inputs include bagasse pulp, bamboo pulp, water-repellent and oil-repellent agents, biomass fuel, and water, as well as transport distances and emission factors. Emissions from boiler operations, including particulate matter, SO_2, and NO_x, are also considered. All data were standardized and unified in measurement units to serve as the basis for the Life Cycle Impact Assessment (LCIA) modeling. Detailed input-output data are shown in Table 2. The Life Cycle Inventory (LCI) data used in this study are primarily derived from 2024 enterprise environmental impact assessment reports, process records, and authoritative databases such as Ecoinvent and CLCD. Although no field investigation was conducted, cross-verification from multiple sources ensured the consistency and applicability of the data. As a major sugarcane-producing region, Laibin City exhibits industrial characteristics that are representative of Guangxi and other agricultural areas in southern China, making the developed model regionally applicable to a certain extent.

Table 2. Life cycle inventory of sugarcane bagasse takeout container production

Input/output	Item	Quantity
Input	Sugarcane bagasse pulp	207.83 kg
	Bamboo pulp	36.68 kg
	Biomass fuel	290.1 kg
	Water repellent agent	6.11 kg
	Oil repellent agent	2.69 kg
	Water	1,252.43 kg
	Transport distance of bagasse pulp	30 km
	Transport distance of containers	10 km
Output	Particulate matter (dust)	0.087 kg
	Sulfur dioxide (SO_2)	0.25 kg
	Nitrogen oxides (NO_x)	0.30 kg

2.3 Environmental impact assessment method and key factor identification

To enhance the systematization and comparability of the life cycle assessment, this study adopts the CML 2001 method to evaluate the environmental impacts of bagasse-based containers across six categories: Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Abiotic Depletion Potential (ADP), Ozone Depletion Potential (ODP), and Photochemical Ozone Formation Potential (POFP). These categories cover key environmental burdens such as climate change, pollutant emissions, and resource depletion. Emissions data are converted into equivalent units (e.g., kg CO_2 eq) using characterization factors. Normalization and weighting are applied to improve cross-indicator comparability and interpretation. Normalization. After characterization, we normalized each impact category by dividing the LCIA result per functional unit by the CML 2001 "World" normalization factor for that category, yielding a dimensionless score that is comparable across categories (e.g., GWP=229 kg CO_2-eq per 10,000 units ÷ 4.22×10^{13} kg $CO_2\text{-eq}\cdot yr^{-1}=5.42\times10^{-12}$). The same procedure was applied to AP, EP, ADP, ODP, and POFP. Where an overall index is presented, we adopt equal weights (1/6 per category) for visualization only; all substantive comparisons rely on characterized and normalized results. Sensitivity analysis is also introduced to test the effects of variations in key input parameters, helping to identify major impact drivers and support low-carbon design and optimization strategies.

In the sensitivity analysis, a ±10% variation range is standard practice in LCA studies and is used to assess the model's robustness to parameter uncertainty. This range is consistent with ISO 14044's requirement to perform sensitivity analysis and with common LCA practice (Heijungs and Huijbregts, 2004), and it reflects the level of short-term variability typically observed in industrial practice—specifically, variability in raw-material sourcing and production unit operations—which is generally on the order of 5-15%. Choosing 10% as a mid-point effectively identifies key parameters without introducing extreme bias, ensuring the practicality and comparability of the analysis. If the variation is too small (e.g., 5%), sensitivity may be underestimated; if too large (e.g., 20%), uncertainty may be overstated. The data in this study come from enterprise reports and databases, and the ±10% range is consistent with the variability observed in these sources.

3. RESULTS

3.1 Characterization results of environmental impact

To comprehensively assess the environmental impact of sugarcane bagasse-based takeout containers, this study adopts the CML 2001 method to conduct a characterization analysis across six key indicators: Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Abiotic Depletion Potential (ADP), Ozone Depletion Potential (ODP), and Photochemical Ozone Formation Potential (POFP) (Figure 2).

The results show that GWP is the most significant impact, primarily due to incineration (55.56%), followed by bamboo pulp production (22.58%), both of which are closely associated with carbon emissions. The introduction of carbon capture and storage (CCS) systems and the replacement of fossil fuels with renewable energy are recommended. CCS is recommended primarily to capture and store CO_2 emissions released from the incineration stage, which is the dominant contributor to Global Warming Potential (GWP). By separating CO_2 from the flue gas and storing it underground, CCS directly mitigates greenhouse gas impacts without affecting other pollutants such as SO_2 or NO_x. In parallel, fuel substitution beyond fossil fuels is encouraged to further reduce life-cycle GWP, including the use of biomass residues from sugarcane and bamboo as boiler fuel, biogas from wastewater treatment, and electrification of low-temperature processes powered by renewable energy. These combined strategies can significantly decrease dependence on fossil fuels and enhance the overall carbon reduction potential of the production system. AP is mainly caused by boiler emissions (50%), suggesting the need for SNCR denitrification technology and real-time monitoring systems to reduce SO_2 and NO_x emissions. The SNCR (Selective Non-Catalytic Reduction) process reduces NO_x emissions by injecting ammonia or urea into the flue gas at 850-1,050°C, where it reacts with NO_x to form N_2 and H_2O. The typical removal efficiency ranges from 30-60%, depending on temperature, residence time, and mixing uniformity. Proper control of reagent dosage is essential to minimize ammonia slip and secondary pollution. The real-time monitoring system is not only for detecting emissions but also serves as a closed-loop control platform. Continuous emission monitoring systems (CEMS) with sensors for NO_x, SO_2, and O_2 provide feedback to automatically adjust reagent injection and combustion conditions, ensuring stable emission levels and reducing reagent waste. EP is concentrated in the bamboo pulping stage (28.49%), which can be mitigated through improved agricultural management and enhanced wastewater treatment. ADP is dominated by transportation (35.44%), indicating the need to adopt electric vehicles and localized production models to reduce fossil resource consumption. ODP mainly results from additives (32.52%) that may contain ozone-depleting substances like CFCs; thus, bio-based materials should be used as alternatives. POFP is driven by VOC emissions during bamboo pulp drying (33.06%), which can be addressed through VOC recovery systems and process optimization.

Incineration, bamboo pulp processing, boiler emissions, additives, and transportation are the main contributors to the environmental burden. The proposed optimization strategies—including low-carbon energy adoption, bio-based additives, cleaner production, and electric logistics—can support the sustainable and low-carbon development of bagasse-based packaging.

The optimization strategies derived from the LCA results focus on three key areas: adopting cleaner pulping and combustion technologies to reduce energy consumption and pollutant emissions identified in bamboo pulp and boiler processes; substituting bio-based and biodegradable additives to eliminate ozone-depleting substances and enhance product sustainability; and developing low-carbon logistics, including electric transport and localized supply chains, to mitigate abiotic depletion and reduce the overall carbon footprint. These targeted measures effectively address the environmental hotspots revealed by the life cycle analysis and form the foundation for the subsequent discussion.

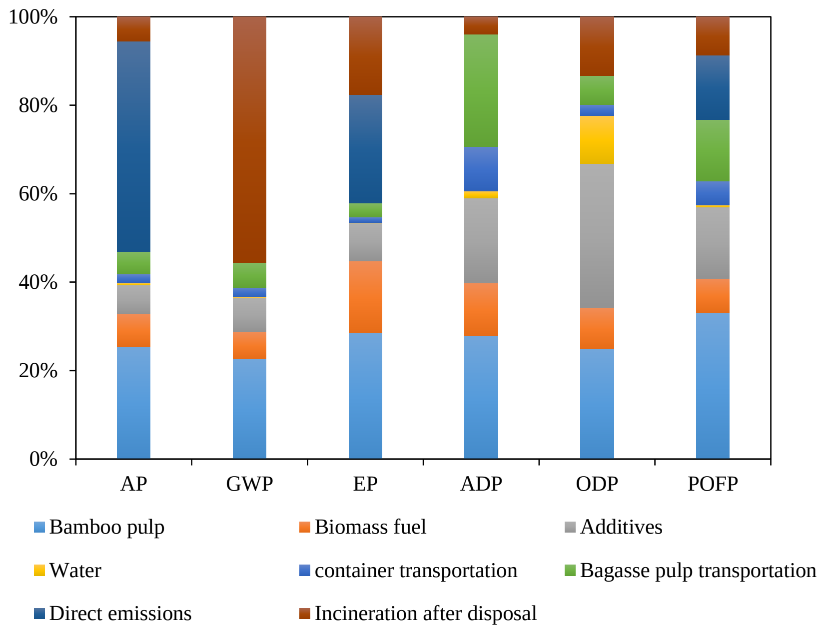

Figure 2. Contribution analysis of characterization results

3.2 Normalization and weighting analysis results

To further clarify the relative importance of different environmental impact categories in the life cycle of sugarcane bagasse takeout containers, this study conducted normalization and weighting analysis based on the CML 2001 method, aiming to identify key environmental burdens and provide optimization strategies.

The normalization results show that Global Warming Potential (GWP) is the most significant impact, with a normalized value of 5.42E-12, mainly due to CO_2 emissions from the incineration stage and fossil fuel use in bamboo pulp production. Ozone Depletion Potential (ODP) is the lowest, indicating a substantial reduction in CFC-containing additives, though residual risks in the supply chain require continued monitoring. Acidification Potential (AP) and Eutrophication Potential (EP) are mainly influenced by boiler emissions and wastewater from bamboo pulping, respectively. Abiotic Depletion Potential (ADP) and Photochemical Ozone Formation Potential (POFP) have relatively lower impacts but should still be considered in environmental optimization (Figure 3(a)).

The weighting analysis further highlights incineration (31.12%), bamboo pulp production (25.29%), and boiler emissions (15.87%) as the most critical stages in the life cycle. Although additives, fuel, and transportation showed significant differences during characterization, their impacts were balanced after weighting, revealing non-linear interactions among life cycle stages (Figure 3(b)). GWP accounted for 46.94% of the total weighted impact, making it the primary concern in environmental decision-making.

Normalization and weighting analysis revealed the environmental hotspots under current production and disposal conditions. These findings provide a scientific basis for promoting cleaner production, material substitution, and policy intervention, while further validating the environmental potential and optimization paths of sugarcane bagasse packaging in advancing low-carbon and sustainable development (Figure 3(c)).

3.3 Sensitivity analysis and key parameter identification

To identify the sensitivity of different raw materials and process parameters to the environmental impacts of sugarcane bagasse takeout containers throughout their life cycle, this study conducted a one-way sensitivity analysis by applying a ±10% variation to key input parameters. The results are shown in Figure 4.

The analysis reveals that bamboo pulp has the highest sensitivity coefficient (0.253), significantly higher than other factors, indicating that its pulping process has the most substantial impact on environmental burdens. It is therefore recommended to prioritize low-energy pulping technologies and optimize raw material sourcing to reduce its environmental footprint. Additives (0.089) and biomass fuel (0.086) follow in sensitivity. Additives are influenced by potential ozone-depleting substances in chemical coatings, suggesting an urgent need to develop bio-based water- and oil-resistant alternatives. Biomass fuel sensitivity is linked to boiler emissions; thus, improving combustion efficiency and flue gas treatment could effectively lower environmental impacts.

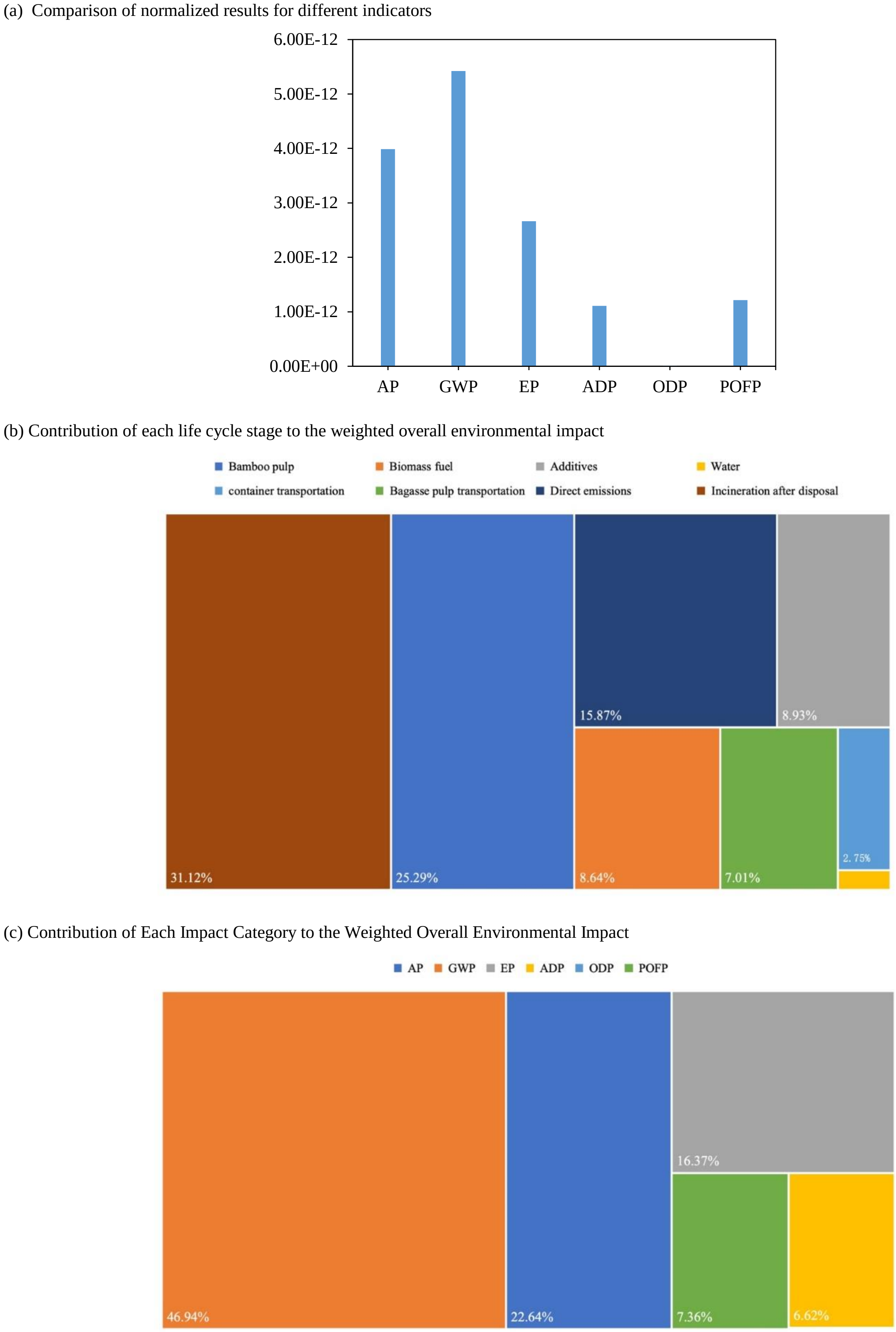

Figure 3. Normalization and weighting results

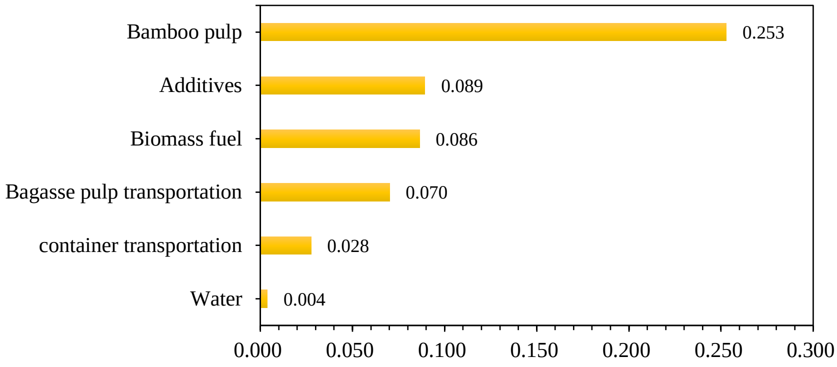

Figure 4. Sensitivity analysis results

In contrast, transport-related parameters and water use exhibit lower sensitivity (bagasse pulp transportation: 0.070; container transportation: 0.028; water use: 0.004), indicating limited optimization potential. However, improvements in these areas should still be pursued in conjunction with regional industrial planning and green logistics strategies.

The priority order for environmental optimization is: bamboo pulp processing > additive substitution > boiler emissions control > transportation and water management. This sensitivity analysis identifies the key impact factors and provides strategic guidance for process improvements and eco-design of bagasse-based packaging. In this study, the ±10% variation range for input parameters was determined based on the actual fluctuations observed in current industrial processes and raw material procurement, aligning with common variability in real-world operations. Although on-site data and authoritative databases were used as much as possible for model construction, some upstream and downstream processes—such as bamboo pulp sourcing and additive composition—still involve a degree of uncertainty. Sensitivity analysis helps assess the model's responsiveness to these variations, thereby enhancing the robustness and interpretability of the LCA results.

3.4 Comparative environmental impacts of different container materials

To clarify the environmental advantages of sugarcane bagasse takeout containers, this study conducted a comprehensive life cycle comparison with plastic, starch-based, and composite starch containers across six key environmental impact categories (Figure 5).

The results show that bagasse containers performed best in all indicators. For Global Warming Potential (GWP), the bagasse container recorded only 229 kg CO_2 eq—81.67%, 70.69%, and 82.52% lower than plastic, starch, and composite starch containers, respectively. Acidification Potential (AP) was 0.953 kg SO_2 eq, just about one-seventh of that of composite starch. Eutrophication Potential (EP) reached 0.421 kg PO_4^{3-} eq, 87.22% lower than composite starch. Regarding resource consumption, the Abiotic Depletion Potential (ADP) was only 0.401×10^{-3} kg Sb eq, significantly lower than that of other materials. In terms of Ozone Depletion Potential (ODP), bagasse containers achieved the lowest value at 0.261×10^{-5} kg CFC-11 eq. Photochemical Ozone Formation Potential (POFP) was also the lowest at 0.448×10^{-1} kg ethylene eq.

The normalization and weighting analysis (Figure 6) further confirmed the environmental superiority of bagasse containers, with an overall impact value of just 1.075×10^{-10}—81.03%, 74.20%, and 85.65% lower than that of plastic, starch, and composite starch containers, respectively. In contrast, composite starch containers, despite being labeled as “green materials,” showed significantly higher impacts due to the use of high-burden inputs, highlighting the risks of “false green” alternatives.

Sugarcane bagasse containers—made from agricultural and forestry waste—demonstrate clear advantages in carbon reduction, energy efficiency, and pollution control, making them a promising solution for green transformation in the packaging industry. Future efforts should focus on technological innovation and policy incentives to expand their market adoption while remaining cautious of environmentally harmful materials disguised as sustainable options.

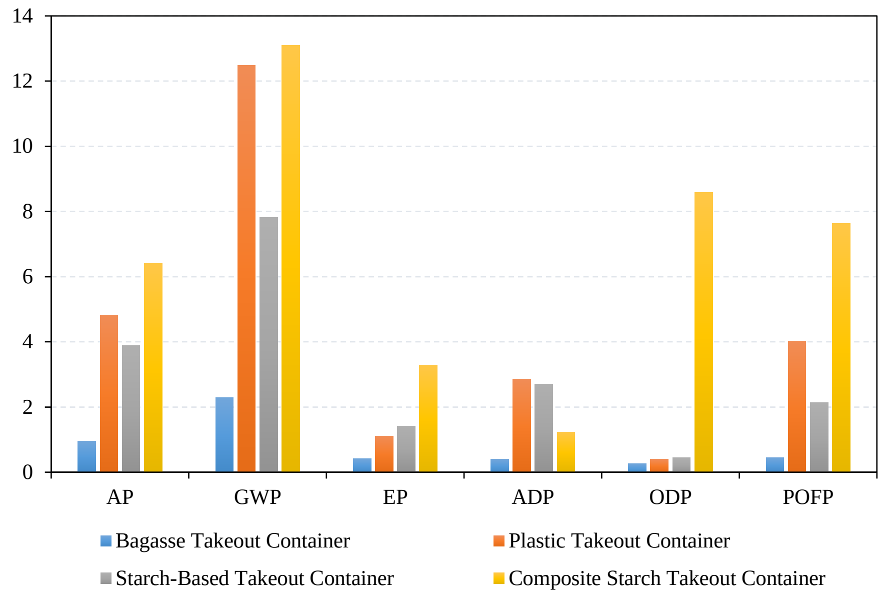

Figure 5. Characterization of environmental impacts for different container materials (Units: GWP (kg CO_2-eq), AP (kg SO_2-eq), EP (kg PO_4^{3-}-eq), ADP (kg Sb-eq $\times 10^{-3}$), ODP (kg CFC-11-eq $\times 10^{-5}$), POFP (kg ethene-eq $\times 10^{-1}$)).

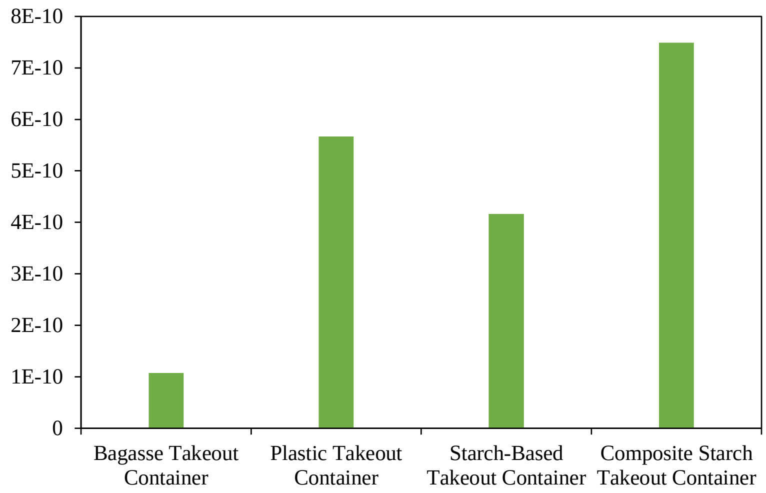

Figure 6. Comparative normalized and weighted environmental impacts of different container

4. DISCUSSION

The results of this life cycle assessment (LCA) highlight the superior environmental performance of sugarcane-bagasse takeout containers relative to conventional alternatives, particularly in reducing Global Warming Potential (GWP) and Abiotic Depletion Potential (ADP) by more than 70%. However, to validate these conclusions and enhance their practical relevance, it is necessary to examine real-world applications and policy implementations that demonstrate the feasibility and scalability of bagasse packaging. This section expands the policy implications by integrating empirical case studies, comparative LCA validations from analogous biomass-based systems, and strategic recommendations grounded in ongoing initiatives in China and Southeast Asia. By applying the LCA findings to these contexts, we confirm the robustness of the model and identify pathways for broader adoption within a circular-economy framework.

4.1. Application-based empirical validation and case studies

The LCA model in this study, based on a representative enterprise in Laibin, Guangxi, is consistent with broader empirical evidence regarding sugarcane bagasse in packaging and waste management. For example, in Southeast Asia, the SWITCH-Asia "Only One Planet" initiative reportedly replaced more than 4 million foam food boxes with household-compostable sugarcane-based products in food service, significantly reducing non-biodegradable waste. This initiative corroborates the end-of-life benefits emphasized in our LCA: compared with plastic landfilling, incineration of bagasse containers contributes lower GWP; the project's waste-diversion efforts have led to measurable reductions in greenhouse-gas emissions and improved resource recovery within circular systems.

In China, analogous applications in food packaging support our findings on the integrated "sugar mill-pulp mill-container factory" model. Case studies by Bioleader Packaging show how bagasse tableware (including trays and containers) has been implemented in commercial settings, yielding benefits such as reduced waste and enhanced compostability. Practical performance tests for lidded bagasse trays—including strength evaluations and food-safety assessments—confirm the material's durability during production and use and its low environmental burden, aligning with our sensitivity analysis that identified bamboo pulp and additives as hotspots. These applications validate the model's prediction of >70% reduction in environmental burden, as independent comparative LCAs in related studies indicate that, when recovery is included, bagasse outperforms expanded polystyrene in categories such as eutrophication and acidification.

Moreover, global validations from LCAs of biomass-based packaging reinforce our conclusions. A systematic review of sugarcane-bagasse utilization—including packaging—highlights similar environmental effects, such as carbon-footprint reductions through valorization of agricultural residues, reflecting our cradle-to-grave boundary. Within food and beverage applications, LCAs show that biomass-derived materials like bagasse can reduce greenhouse-gas emissions by up to 25% relative to conventional plastics, providing quantitative support for our comparative results among plastic, starch, and composite-starch containers. These real-world validations address uncertainties identified in our sensitivity analysis for upstream processes (e.g., bamboo-pulp sourcing), as field implementations—such as low-energy pulping—have been shown to effectively mitigate these hotspots.

4.2 Policy implications and strategic recommendations

Building on these validations, policy efforts should prioritize coordinated actions along the value chain to enable large-scale adoption. In China, the 14th Five-Year Plan for Plastic Pollution Control provides a framework for promoting bagasse packaging. As demonstrated in Guangxi, implementation integrates agricultural residues into the circular economy. To strengthen source control, policies can mandate designated collection systems for resources such as bagasse, similar to centralized processing in ASEAN member states, which enhances feedstock stability and reduces waste. This approach validates our LCA's replicability across South China and Southeast Asia, where sugarcane hubs like Laibin can export the integrated model to regions with comparable agricultural profiles.

For process optimization, investment in clean pulping technologies and eco-friendly functional additives is essential. Case studies from sustainable-packaging alliances indicate that adopting bio-based substitutes reduces ODP and POFP impacts, consistent with our weighted analysis. Governments should incentivize R&D through subsidies and encourage firms to form synergies under the "sugar mill-pulp mill-container factory" model, which has demonstrated enhanced resource efficiency in real-world biofuel and packaging applications.

At end-of-life, establishing low-carbon logistics and recycling mechanisms is necessary. India's national circular-economy roadmap for reducing plastic waste offers parallel experience for Southeast Asia, emphasizing carbon labeling and green procurement to realize environmental value. In China, including bagasse containers in government procurement catalogues can accelerate market uptake, as studies show biodegradable alternatives can mitigate pollution from takeaway services. Promoting new-energy vehicles and centralized distribution—recommendations consistent with our optimization strategy—aligns with ASEAN's eco-friendly packaging ecosystems, in which such measures decrease transport-related ADP.

By applying the LCA conclusions to these validated applications, this study confirms the potential of bagasse packaging to drive green transitions. Future research should focus on longitudinal case studies to monitor long-term impacts and ensure that policies evolve with emerging data on biomass valorization. This integrated approach not only substantiates our findings but also positions sugarcane bagasse as a core sustainable material within the circular economy.

5. CONCLUSION

Using a representative manufacturing enterprise in Laibin, Guangxi, China, as a case study, this study employs life cycle assessment (LCA) to systematically evaluate the full life-cycle environmental impacts of sugarcane bagasse takeout containers. Using the CML 2001 framework, six key environmental indicators were assessed: Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Abiotic Depletion Potential (ADP), Ozone Depletion Potential (ODP), and Photochemical Ozone Formation Potential (POFP). The results demonstrate that bagasse-based containers outperform conventional plastic, starch, and composite starch containers in all assessed categories. Notably, the advantages in GWP and ADP are particularly significant, with overall environmental burdens reduced by more than 70% compared to traditional materials. This confirms the feasibility of sugarcane bagasse packaging as a low-carbon, biodegradable, and resource-efficient alternative. However, environmental hotspots remain within the product life cycle, particularly in bamboo pulp production, biomass combustion, and incineration at the end-of-life stage. Sensitivity analysis further identifies bamboo pulp input, additive use, and boiler fuel as the key contributors to environmental impact. Therefore, future optimization efforts should focus on adopting cleaner pulping technologies, substituting green additives, improving biomass combustion efficiency, and developing low-carbon logistics systems.

Additionally, this study examines the regional scalability of bagasse packaging. As one of China's major sugarcane-producing areas, Laibin has implemented an integrated "sugar mill-pulp mill-container factory" model that improves resource efficiency and reduces environmental load. This model holds potential for replication across other agricultural regions in South China and Southeast Asia.

To promote the large-scale adoption of bagasse-based packaging, policy measures should focus on three coordinated areas: (1) Source control—ensuring stable supply of agricultural residues and promoting regional resource utilization; (2) Process optimization—enhancing investment in clean technologies, modular equipment, and industrial collaboration; (3) End-of-life management—developing green logistics and recycling systems, and establishing carbon labeling and green procurement standards. Overall, sugarcane bagasse packaging demonstrates strong potential for low-carbon innovation and is poised to play a key role in the green transformation of the packaging industry and the advancement of the circular economy. Looking ahead, continuous efforts in technological innovation, policy incentives, and regional cooperation will be essential to amplify its environmental and economic benefits, supporting the dual goals of sustainable materials development and green industry transition.

AUTHOR CONTRIBUTIONS

Conceptualization, Methodology, Investigation, Data Curation, Formal Analysis, and Writing-Original Draft: Meng Fan. Supervision and Writing-Review and Editing: Chokeanand Bussracumpakorn.

DECLARATION OF CONFLICT OF INTEREST

The authors disclosed no conflict of interest.

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