Jurnal Pijar MIPA
https://jurnalfkip.unram.ac.id/index.php/JPM

ISSN 1907-1744 (Print)
ISSN 2460-1500 (Online)

Environmental Impact Assessment of Paving Block Production from Plastic Waste Using the Life Cycle Assessment (LCA) Approach

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Received: November 21, 2025. Accepted: December 26, 2025. Published: December 31, 2025

Abstract: The growing volume of non-commercial plastic waste poses significant environmental challenges while also presenting opportunities for alternative construction materials. This study aims to assess the environmental impacts of producing paving blocks from plastic waste using the Life Cycle Assessment (LCA) approach. A cradle-to-gate system boundary was applied, encompassing five main production stages: sorting, shredding, melting, hydraulic molding, and cooling. Inventory data were collected from daily production activities, with plastic waste inputs ranging from 1.48 to 2.12 tons per day, and paving block outputs of approximately 0.0018 tons per day, along with electricity consumption between 200 and 250 kWh. The results indicate that the extrusion and molding stages contribute most significantly to environmental impacts due to high energy consumption and thermal emissions. Despite the relatively low product output, converting plastic waste into paving blocks contributes to landfill reduction and supports circular economy principles. The study recommends improving energy efficiency and integrating renewable energy sources to further reduce environmental impacts. Overall, the findings demonstrate the potential of plastic waste-based paving blocks as a sustainable innovation for infrastructure development.

Keywords: Commercial; Plastic; Environmental; Paving Block; Sustainable.

Introduction

The problem of plastic waste has become an increasingly complex global environmental issue, including in Indonesia [1], [2]. According to data from the Ministry of Environment and Forestry (KLHK), Indonesia generates approximately 18 million tons of waste per year, of which around 3 million tons consist of plastic waste [3], [4]. Plastic waste is known to be extremely difficult to decompose in nature, and may persist for hundreds of years [5], [6]. If not properly managed, this waste can contaminate soil, water, and air, posing serious threats to human health and other living organisms [7], [8].

Alongside increasing awareness of the importance of sustainable waste management, various innovative approaches continue to be developed. One emerging approach involves utilizing non-commercial plastic waste, such as plastic bags and multilayer packaging, as alternative raw materials for construction materials [9], [10]. This strategy is expected to reduce pressure on landfills while promoting the development of environmentally friendly products that support the achievement of the Sustainable Development Goals (SDGs).

Paving blocks are one type of construction material widely used in sidewalks, yards, and other public facilities [11], [12]. Generally, paving blocks are made from a mixture of cement, sand, and other aggregates that contribute significantly to carbon emissions [13], [14]. By replacing part of these components with compost-based materials made from plastic waste, there is potential to reduce the product's environmental footprint. However, it is essential to ensure that this process is genuinely more sustainable than conventional methods through systematic and data-driven analysis.

Life Cycle Assessment (LCA) is a scientific approach used to evaluate the environmental impacts of a product or process throughout its entire life cycle [15]. LCA enables a comprehensive analysis of raw material extraction, production processes, and distribution to the final product [16]. This method identifies the contribution of each production stage to various environmental impact categories, such as energy consumption, greenhouse gas emissions, and waste generation. In the context of substituting conventional raw materials with plastic waste, LCA is crucial to ensure that recycling efforts do not introduce additional environmental burdens [17].

The production of plastic-waste-based paving blocks involves several key processes, including sorting, shredding, melting using an extruder, hydraulic molding, and cooling before packaging the final product. Each stage has distinct characteristics in terms of energy use and potential emissions, necessitating careful assessment to identify where the greatest environmental impacts occur. Findings from this analysis can serve as the basis for developing process improvement strategies to enhance efficiency and sustainability.

This study uses primary data from the actual and operational production activities of plastic-waste-based paving blocks. The inventory data include energy consumption, raw materials, and product outputs at each stage of the production process. Using the LCA approach, the analysis examines various impact indicators, including global warming potential, tropospheric ozone formation, and environmental toxicity. The generated information is

How to Cite:
H. I. Johari, "Environmental Impact Assessment of Paving Block Production from Plastic Waste Using the Life Cycle Assessment (LCA) Approach", *J. Pijar.MIPA*, vol. 20, no. 8, pp. 1557–1562, Dec. 2025. https://doi.org/10.29303/jpm.v20i8.10775

expected to serve as a reference for decision-making in waste utilization technology development and the formulation of more environmentally friendly waste management policies.

Through this approach, the research contributes to reducing the accumulation of plastic waste while strengthening the scientific foundation for sustainable innovation in construction materials. LCA-based evaluation serves as a critical tool in assessing the effectiveness of recycling and material reuse, ensuring that the proposed solutions genuinely align with long-term sustainability principles.

Research Methods

Research Approach

This study employs the Life Cycle Assessment (LCA) approach to evaluate the environmental impacts associated with the production process of paving blocks made from composted plastic waste. LCA is selected because it provides a comprehensive assessment of material flows, energy consumption, and emissions generated throughout the production chain from waste sorting to the final product [18]. The data used in this research were obtained through direct observation of daily production activities, technical documentation of equipment and materials, and interviews with production operators. This combination of data sources enables the development of a reliable life-cycle inventory that reflects actual operational conditions.

Study Site and Data Collection

The research was conducted at the Sandubaya Integrated Waste Processing Facility (TPST Sandubaya), located in Cakranegara District, Mataram City, West Nusa Tenggara. This site serves as the case study because it is an active waste management facility that has implemented plastic-to-construction-material innovation, particularly in the production of plastic-based paving blocks.
Data collection took place from February to April 2025. During this period, primary data were recorded, including energy use, material inputs, process duration, machine operations, and production outputs.

Figure 1. TPST Sandubaya

Production Process Flowchart

The production process flowchart for paving blocks made from plastic waste illustrates the sequence of technical activities from the initial stages to the final product. The stages start with waste collection and sorting, followed by shredding, melting, molding, and then cooling and packaging the product. This workflow serves as an important foundation for analyzing inputs and outputs, as well as calculating process efficiency.

Table 1 above summarizes the daily inventory data of the plastic-waste-based paving block production process. The input components include sorted plastic raw materials, production equipment, electrical energy, and labor, while the recorded outputs consist of paving blocks as the main product and heat emissions as by-products. Each element in the table demonstrates its strategic role within the production system, from influencing energy efficiency to its potential impact on environmental sustainability.

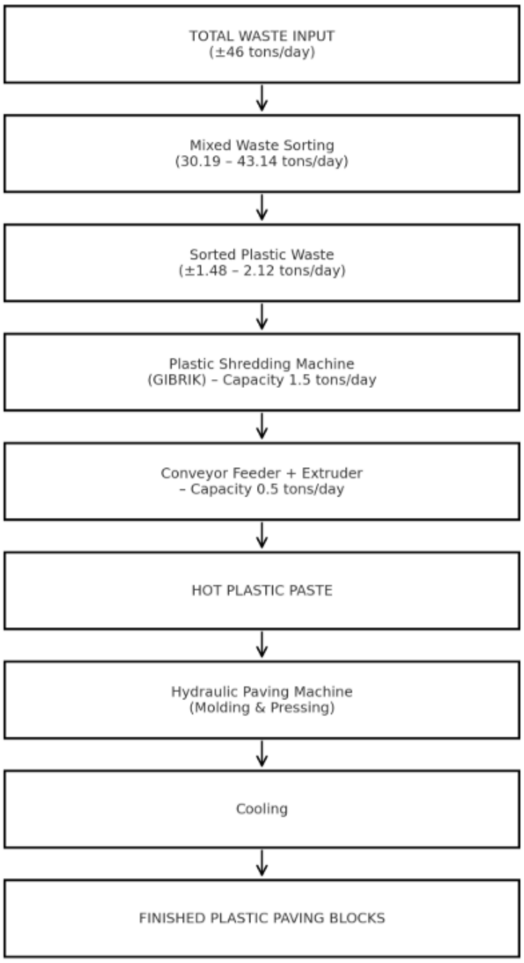

Figure 2. Flowchart of the Plastic Waste Compost-Based Paving Block Production Process

System Boundary and Functional Unit

The system boundary in this study was defined using a cradle-to-gate approach, encompassing all processes from raw material acquisition to the final paving block product leaving the production facility. The assessed stages include plastic waste sorting, shredding, melting, hydraulic molding, and cooling. The functional unit applied in this life cycle assessment was one ton of plastic waste-based paving blocks, which served as the reference flow for all input and output calculations.

The life cycle inventory data consisted of material and energy flows associated with the production process. Inputs included sorted plastic waste as the primary raw material, electricity consumption required for processing operations, and the use of machinery and labor throughout the production stages. The outputs comprised finished paving blocks, heat and air emissions generated during melting and molding processes, as well as residual materials and process-related waste. These data were collected from daily production activities and used to quantify the environmental impacts associated with each stage of the system.

Impact Assessment Method

The environmental impact assessment was performed using a midpoint-oriented approach based on the ReCiPe 2016 methodology. This method was selected due to its comprehensive coverage of environmental impact categories and its widespread application in life cycle assessment studies. The analysis evaluated multiple impact categories, including global warming potential, particulate matter formation, human and ecological toxicity, and resource consumption.

The contribution of each production stage to the identified impact categories was quantified to determine the stages with the highest environmental burdens. The results of this assessment were subsequently analyzed to identify key processes responsible for significant environmental impacts. These findings were used as the basis for formulating recommendations aimed at improving process efficiency, reducing energy consumption, and minimizing overall environmental impacts associated with plastic waste-based paving block production.

Results and Discussion

Life Cycle Inventory (LCI)

The Life Cycle Inventory results describe the complete set of inputs and outputs involved in producing plastic-based paving blocks at TPST Sandubaya. Daily observations indicate that approximately 1.5–2.0 tons of mixed plastic waste enter the facility, although only a portion is suitable for processing due to contamination, multilayer packaging, and degraded polymer conditions. After sorting, the acceptable materials are shredded using the gibrik screw machine, generating about 1.5 tons of plastic flakes each day. These flakes are then transported via a conveyor feeder to the extruder, where thermal processing yields roughly 0.5 tons of molten plastic paste.

Energy use is one of the most significant components recorded in the LCI [19]. The facility consumes 200–250 kWh of electricity per day, mainly during the melting stage in the extruder and the molding stage in the hydraulic press. The production line is supported by 8–10 workers daily, who handle sorting activities, operate the machinery, supervise product quality, and manage post-processing tasks. Additional inputs include a 50 m² drying area and 1–2 forklifts for internal movement of materials.

In terms of outputs, the process generates only 0.0018 tons of final paving blocks per day. This extremely low conversion rate compared to the large volume of incoming waste reveals substantial inefficiencies in the production system. The process also results in heat emissions and gaseous by-products from the extruder and cooling units, along with residual waste such as unmelted plastic fragments and impurities. Overall, the LCI highlights significant losses throughout the production chain and emphasizes that energy-intensive stages play a major role in shaping the environmental footprint of the system.

Table 1. Inventory of the Production Process of Plastic-Waste-Based Paving Blocks

No	Component	Input			Output		
		Category	Unit	Estimate/Day	Category	Unit	Estimate/Day
1	Sorted plastic waste	Raw Material	Ton	1.48–2.12	Plastic Paste	ton	±0.5
2	Gibrik Screw Machine	Production Equipment	Unit	1	Plastic Flakes	ton	±1.5
3	Conveyor Feeder	Production Equipment	Unit	1	–	–	–
4	Extruder Machine	Production Equipment	Unit	1	Plastic Paste	ton	±0.5
5	Hydraulic Paving Machine	Production Equipment	Unit	1	Paving Block	ton	±0.0018
6	Labor	Human Resources	Persons	±8–10	–	–	–
7	Electricity	Energy	kWh	±200–250	–	–	–
8	Drying Area	Facility	m²	±50	–	–	–
9	Forklift / Transporter	Supporting Equipment	Unit	1–2	–	–	–
10	Heat/Air Emissions	Gas Waste	–	–	Gas Waste	–	–

Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment (LCIA) results reveal that the production of plastic-waste-based paving blocks generates several notable environmental burdens, particularly in impact categories associated with energy-intensive processes. The Global Warming Potential (GWP) emerges as the most dominant impact, largely driven by electricity consumption during extrusion and hydraulic pressing stages, which rely on high thermal energy for melting and compaction. Energy Use represents the second-highest impact category, reflecting the system's dependence on conventional grid electricity throughout production. Meanwhile, Water Use contributes minimally to the overall impact profile, as the process does not require significant water inputs. Human Toxicity presents a moderate impact level, primarily originating from heat emissions and airborne particulates released during thermal processing.

Overall, the LCIA analysis indicates that although plastic-waste-based paving blocks offer environmental benefits in terms of waste reduction and material circularity, the production system remains constrained by high energy intensity. These findings suggest that integrating renewable energy sources or improving machine efficiency could substantially reduce the environmental footprint of the process. The graphical summary of LCIA outcomes is presented in Figure 3.

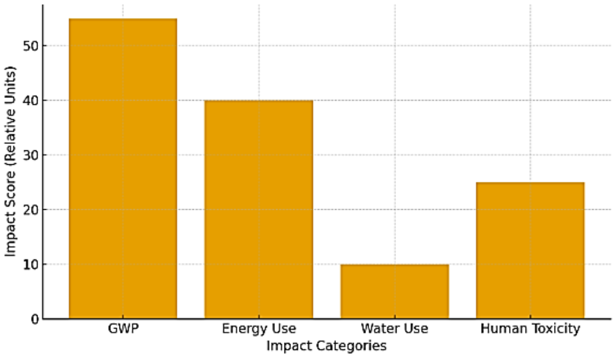

Figure 3. LCA Result for Plactic-Waste-BasedPaving Block

This diagram illustrates that from a large amount of incoming waste, only a small fraction of plastic waste can be processed into the final product. The production process takes place in several stages and involves various high-energy machinery, particularly during the melting and molding phases.

Hotspot Identification and Key Contributors

The hotspot analysis conducted in this study reveals several specific stages in the production workflow that exert the greatest influence on the overall environmental impacts. The extrusion phase, where pre-sorted plastic waste is heated and processed into molten plastic paste, stands out as the dominant contributor across multiple impact categories, including Global Warming Potential (GWP), Energy Demand, and Human Toxicity. This substantial contribution is largely due to the significant amount of electricity required to sustain high processing temperatures, as well as the emissions produced during the thermal breakdown of plastic materials.

The hydraulic pressing step represents the second most impactful hotspot. Although its energy consumption is lower than that of extrusion, the hydraulic press demands considerable mechanical force and additional heat, making it a noteworthy source of indirect emissions and energy use. Together, the extrusion and hydraulic pressing processes form the core contributors to the system's environmental burden, highlighting them as priority areas for targeted improvements.

In contrast, preliminary stages such as manual sorting and mechanical shredding show minimal environmental impact. These processes depend heavily on human labor and low-power equipment, resulting in relatively low emissions and negligible influence on toxicity- or water-related categories. Internal material movement involving forklifts contributes only slightly to overall impacts due to its limited operational duration and short travel distances.

Overall, the hotspot assessment emphasizes that efforts to reduce environmental impacts should be directed primarily toward high-energy thermal operations. Potential improvements may include the adoption of renewable energy sources like solar power, upgrading extrusion equipment for enhanced thermal efficiency, or adjusting operating temperatures to minimize unnecessary energy consumption. Implementing such measures could substantially reduce the system's environmental footprint and further validate the potential of plastic-waste-based paving blocks as an environmentally responsible construction material.

Interpretation of Results

The findings of this assessment provide a comprehensive understanding of how each stage in the production chain contributes to the overall environmental performance of plastic-waste-based paving blocks. The Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) results, when combined, reveal that the system's impacts are largely shaped by the energy-intensive processes, particularly extrusion and hydraulic pressing. These stages dominate the environmental profile due to substantial electricity consumption and emissions associated with thermal processing.

In contrast, early-stage activities, such as sorting and shredding, exert a relatively minor influence on the overall impacts. Their low energy requirements and minimal emissions underscore their secondary role in shaping the system's environmental footprint. This divergence between stages emphasizes the unequal distribution of burdens within the production cycle.

The interpretation also highlights the overall efficiency challenges present in the system. While the use of non-marketable plastic waste aligns with circular economy principles, the low conversion rate from raw waste to final product significantly reduces the ecological benefits that could otherwise be realized. This inefficiency amplifies the environmental load per functional unit, suggesting that improvements in material recovery and processing performance are essential.

The results underscore the need for targeted interventions focused primarily on the system's high-impact thermal operations. Reducing electricity intensity, enhancing equipment performance, or integrating renewable energy sources would substantially improve the sustainability of the process. Moreover, these improvements would strengthen the environmental justification for employing plastic waste as an alternative construction material and support broader objectives related to sustainable production and waste reduction.

This study reveals that converting non-recyclable and economically worthless plastic waste into paving blocks holds potential as both a waste management solution and an innovative construction material supporting sustainable development. Based on the inventory results, approximately 1.5–2 tons of processed plastic waste are generated per day, with only around 0.0018 tons successfully converted into the final product in the form of paving blocks. This very low conversion efficiency indicates a significant gap in optimizing the production process. Nevertheless, the successful diversion of low-value plastic waste from landfills to useful products demonstrates the practical implementation of circular economy principles at the local level. These findings are in line with [20], [21], who highlight the importance of utilizing non-commercial plastic waste for functional construction products.

The evaluation of the production process shows that the melting stage in the extruder and the molding stage with the hydraulic press machine are the critical points in the system, both in terms of energy consumption and emission contributions. Electricity consumption of approximately 200–250 kWh/day is predominantly used for heating and compaction processes. From a Life Cycle Assessment (LCA) perspective, these stages significantly contribute to impact categories such as Global Warming Potential (GWP) and Photochemical Oxidant Formation. These findings are supported by the study of [22], [23], which shows that thermal processes used in plastic waste utilization for building materials contribute substantially to carbon footprint, especially when relying on fossil-based energy sources.

Compared to conventional cement–sand paving blocks, plastic waste-based alternatives offer advantages in waste reduction and reduced reliance on carbon-intensive materials. [24] reported that alternative building materials made from waste have the potential to reduce GWP by 30–40% relative to traditional materials, depending on process efficiency. However, the present study also indicates that process efficiency remains a major challenge, considering the very low ratio between input materials and final product output. This should be addressed to ensure that the proposed solution generates meaningful environmental and economic benefits.

From a process-stage perspective, waste sorting and shredding exhibit relatively low environmental impacts, as these activities require moderate labor and minimal energy, and they do not generate significant emissions. In contrast, extrusion and hydraulic molding are the primary contributors to environmental burdens, as also noted by [25] in an LCA study of plastic waste–based building panels in Surabaya. Their study recommends energy optimization and improved machinery design as crucial efforts to reduce environmental impacts in the plastic recycling industry.

Overall, plastic waste–based paving blocks demonstrate promising potential as environmentally friendly materials supporting national plastic waste reduction strategies. However, to enable wider adoption, improvements are needed in material conversion efficiency, reducing energy intensity, and integrating renewable energy sources into the production system. Therefore, this innovation holds relevance not only in technical and environmental aspects but also in contributing to the Sustainable Development Goals (SDGs), particularly Goals 11 (Sustainable Cities and Communities) and 12 (Responsible Consumption and Production).

Conclusion

This study concludes that converting low-value plastic waste into paving blocks presents a promising approach for sustainable waste management and implementing a circular economy. Although daily processing of approximately 1.5–2 tons of plastic waste results in a very limited output of about 0.0018 tons of paving blocks, the initiative successfully diverts plastic waste from landfills and transforms it into a useful construction material. The Life Cycle Assessment (LCA) findings indicate that the extrusion and hydraulic molding stages are the most energy-intensive and environmentally impactful processes, contributing significantly to global warming and air emission-related categories. Therefore, improving process efficiency, minimizing energy consumption, and integrating cleaner energy sources are crucial to enhancing the environmental benefits of this innovation. Despite current limitations, plastic waste–based paving blocks still demonstrate environmental advantages compared to conventional cement–sand paving products, particularly in reducing waste generation and lowering dependence on carbon-intensive raw materials. To support wider adoption and achieve scalable impact, continuous technological optimization, better material conversion rates, and strengthened policy support are needed.

Author's Contribution

H.I. Johari: Conceptualization of research; Methodology; Data analysis; Preparing initial draft of manuscript, drafting the discussion & conclusion.

Acknowledgements

I would like to express my deepest gratitude to my colleagues who have provided guidance, support, and motivation throughout the writing of this article

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