Integrating Solid Waste Management into Sustainable Manufacturing Systems: A Life Cycle Assessment Approach

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ABSTRACT

The study aimed to integrate solid waste management (SWM) strategies into sustainable manufacturing systems using the Life Cycle Assessment (LCA) framework to evaluate environmental performance and identify waste reduction opportunities. Conducted among selected manufacturing facilities in Bulacan, Philippines, the research employed a descriptive–analytical design supported by quantitative and qualitative data. The study focused on determining the major sources and types of solid waste, assessing their environmental impacts through LCA, and developing an integrated framework for sustainable waste management. Results revealed that most waste originated from machining, packaging, and post-processing operations, with metal and plastic wastes comprising the largest share. The Life Cycle Impact Assessment (LCIA) indicated a 32% reduction in global warming potential, a 23% decrease in resource depletion, and a 40% reduction in landfill waste after integrating SWM strategies. These improvements were achieved through source segregation, recycling, and lean-green process optimization. The developed framework emphasized four core components: waste identification and classification, LCA-based monitoring, process optimization, and continuous improvement aligned with ISO 14001:2015 and Sustainable Development Goal 12. The findings affirm that the integration of SWM and LCA enhances resource efficiency, reduces environmental impacts, and supports the transition toward circular economy practices in the manufacturing sector.

Keywords: solid waste management, sustainable manufacturing, life cycle assessment, lean-green production, circular economy

INTRODUCTION

The rapid expansion of industrial and manufacturing sectors has significantly contributed to economic growth and technological advancement. However, this progress has also led to a corresponding rise in solid waste generation, resulting in serious environmental and public health challenges. Manufacturing industries are among the largest contributors to solid waste, producing materials such as metal scraps, packaging residues, defective parts, and process by-products. When improperly managed, these wastes contribute to land degradation, air and water pollution, and increased greenhouse gas emissions. According to the World Bank [1], global solid waste generation is expected to reach 3.4 billion tons by 2050, with industrial and manufacturing sources comprising a major share. These realities emphasize the urgent need for an integrated approach that ensures productivity while promoting environmental sustainability.

In response, the concept of sustainable manufacturing has emerged as a central strategy for reducing waste and resource consumption. It integrates environmental considerations into every stage of production—design, processing, assembly, packaging, and disposal—to achieve efficiency without compromising ecological balance. One of the most effective analytical tools for understanding and improving the environmental performance of manufacturing systems is the Life Cycle Assessment (LCA). This methodology evaluates the environmental impact of a product or process from raw material extraction to end-of-life management, providing a scientific basis for identifying waste generation hotspots and improvement opportunities [2].

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This study, titled "Integrating Solid Waste Management into Sustainable Manufacturing Systems: A Life Cycle Assessment Approach," explored the incorporation of solid waste management (SWM) practices within manufacturing operations. The goal was to determine how sustainable waste handling, recycling, and material recovery can be systematically embedded into production systems. Through the use of LCA, the research examined the material flow, energy use, and waste outputs across various stages of manufacturing in selected facilities in Bulacan, Philippines.

Findings revealed that most waste originated during machining and post-processing operations, including packaging residues and unused materials. By adopting structured waste management interventions such as segregation at source, recycling, and the implementation of lean and green manufacturing principles, industries were able to minimize waste volume, enhance operational efficiency, and reduce environmental impacts. The integration of SWM practices also demonstrated measurable improvements in compliance with ISO 14001:2015 environmental management standards and alignment with Sustainable Development Goal 12 – Responsible Consumption and Production.

Overall, the results highlight that integrating solid waste management into manufacturing systems is both an environmental necessity and a strategic advantage. Embedding LCA-guided waste management into the core of manufacturing operations promotes resource optimization, cost reduction, and long-term sustainability. This approach not only transforms traditional linear production systems into circular and resource-efficient processes but also reinforces the vital role of manufacturing engineering in advancing sustainable industrial development.

Objectives of the Study. The general objective of the study is to integrate solid waste management practices into sustainable manufacturing systems through the application of a Life Cycle Assessment (LCA) approach. By evaluating the environmental impacts of manufacturing processes and identifying waste generation hotspots, the study aimed to develop a framework that promotes efficient resource utilization, waste minimization, and environmentally responsible production.

Specifically, the study aimed to:

1. Identify and classify the major types and sources of solid waste generated in selected manufacturing processes;

2. Evaluate the environmental impacts associated with waste generation using the Life Cycle Assessment methodology;

3. Assess the effectiveness of existing solid waste management practices implemented within the manufacturing facilities;

4. Develop an integrated framework or model for incorporating sustainable solid waste management into manufacturing systems; and

5. Recommend strategies and policies that will enhance waste reduction, recycling, and resource recovery in alignment with sustainable manufacturing principles and relevant environmental standards such as ISO 14001:2015 and SDG 12 – Responsible Consumption and Production.

Scope and Delimitation. This study focused on the integration of solid waste management (SWM) practices into sustainable manufacturing systems through the use of the Life Cycle Assessment (LCA) approach. It was conducted among selected manufacturing facilities located in Bulacan, Philippines, representing various types of production processes such as metal fabrication, packaging, and assembly operations. The research primarily examined the types, quantities, and sources of solid waste generated within these facilities and evaluated their corresponding environmental impacts throughout the product life cycle, from raw material acquisition to waste disposal. Specifically, the study covered the identification and characterization of solid waste generated at different stages of the manufacturing process, the assessment of environmental impacts based on material flow,

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energy consumption, and waste generation data, the evaluation of existing waste management systems including segregation, recycling, and waste reduction initiatives, and the development of a conceptual framework for integrating sustainable waste management into manufacturing operations.

The study was delimited to manufacturing firms within Bulacan due to their accessibility, operational diversity, and relevance to the region's industrial profile. It did not include hazardous waste analysis, wastewater treatment processes, or air emissions monitoring, as these areas fall under separate environmental domains. The environmental impact assessment was limited to measurable solid waste-related parameters and did not encompass economic or social life cycle assessments in detail. Moreover, the findings and recommendations presented were based on the specific operational conditions and practices observed in the selected facilities, which may differ from other industries with varying production scales or technologies. Despite these limitations, the insights and framework developed in this study provide valuable guidance for improving waste management efficiency and promoting sustainability within the manufacturing sector.

METHODS

This study employed a descriptive – analytical research design using the Life Cycle Assessment (LCA) approach to evaluate the integration of solid waste management (SWM) practices into sustainable manufacturing systems. The descriptive component focused on identifying and classifying the types and sources of solid waste generated in manufacturing operations, while the analytical aspect assessed their environmental impacts throughout the product life cycle. The LCA methodology was selected as it provides a comprehensive and scientific means of evaluating the environmental performance of systems, products, and processes, particularly in identifying hotspots for waste generation and energy inefficiency [3]. The LCA approach, as standardized by the International Organization for Standardization [2], offers a structured framework for assessing inputs, outputs, and potential environmental impacts across each stage of a product's life—from raw material extraction to end-of-life disposal.

The study was conducted in selected manufacturing facilities located in Bulacan, Philippines, an area recognized for its diverse industrial operations including metal fabrication, packaging, and assembly. These facilities were chosen based on accessibility, production diversity, and willingness to participate. Participants consisted of production managers, environmental officers, and quality assurance engineers, who possess technical knowledge and direct involvement in waste handling and environmental compliance. The researcher coordinated with company representatives to ensure accurate, reliable, and confidential data collection.

Data collection followed three major stages: preliminary assessment, on-site data gathering, and validation and analysis. During the preliminary stage, a waste audit checklist and interview guide were developed to identify the types, quantities, and sources of solid waste. On-site data gathering involved direct observation of production areas, measurement of waste volumes, and documentation of material and energy flows. Semi-structured interviews were conducted to gain insights into existing solid waste management practices and sustainability initiatives. The validation stage involved cross-checking data with company reports, production logs, and waste manifests to ensure consistency and accuracy. Similar mixed-method approaches have been found effective in combining quantitative waste analysis with qualitative assessments of process efficiency [4].

The analysis followed the Life Cycle Assessment framework as described in ISO 14040:2019, consisting of four key phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. The goal and scope phase defined the boundaries of the manufacturing system and identified waste generation hotspots. The LCI phase quantified the inputs (materials and energy) and outputs (products, by-products, and waste) of each process, while the LCIA evaluated potential environmental impacts such as resource depletion, waste accumulation, and greenhouse gas emissions. The interpretation phase synthesized the results to identify improvement opportunities and propose sustainable manufacturing interventions. Data were processed using OpenLCA and SimaPro software, supported by Microsoft Excel for tabulation and visualization. Following the analytical phase, a conceptual framework was developed to integrate solid waste management strategies into manufacturing operations, emphasizing recycling, waste reduction, and process optimization.

Ethical standards were observed throughout the study. Informed consent was obtained from all participants and partner facilities, and data confidentiality was strictly maintained. Company names and specific operational details were withheld to protect proprietary information. All research procedures complied with institutional ethics guidelines and environmental research standards to ensure data integrity and respect for participant rights [5].

RESULTS AND DISCUSSION

The analysis of data gathered from selected manufacturing facilities in Bulacan revealed significant insights into the types, sources, and environmental impacts of solid waste generated during various stages of production. The findings were presented and discussed based on the four phases of the Life Cycle Assessment (LCA) framework, goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation.

Types and Sources of Solid Waste. The analysis of the selected manufacturing facilities revealed that the majority of solid waste originated from machining, packaging, and post-processing operations. The most common types included metal scraps, plastic packaging, defective components, and paper-based residues, with metal and plastic waste comprising the largest proportion. As presented in Table 1, metal scraps accounted for approximately 35% of total waste, primarily generated from cutting and machining operations. Plastic packaging materials contributed 28%, largely from assembly and shipment activities, while paper and cardboard accounted for 12% from administrative and packing functions.

Table 1. Types and Sources of Solid Waste Generated by Manufacturing Facilities

Type of Waste	Main Source/Process	Average Quantity (kg/month)	Percentage of Total Waste (%)	Disposal or Recovery Method
Metal scraps	Machining, cutting	1,200	35	Recycled or sold to scrap buyers
Plastic packaging	Assembly, packaging	950	28	Collected for recycling
Paper and cardboard	Office, packing	420	12	Reused or sold
Defective components	Production rejects	380	11	Reprocessed where possible
Mixed solid waste	Cleaning, canteen, etc.	450	14	Sent to landfill

These findings are consistent with previous studies [6], which reported that small- and medium-scale manufacturers typically produce large quantities of recyclable but underutilized materials due to weak waste segregation and handling systems. The data emphasize the potential for material recovery, particularly in metal and plastic waste streams, which can be recycled to reduce production costs and environmental burden.

Material and Energy Inputs (Life Cycle Inventory). The Life Cycle Inventory (LCI) analysis quantified the material and energy consumption at each stage of production. As shown in Table 2, the machining and forming stage demonstrated the highest energy demand, averaging 4.6 kWh per unit, and produced the largest quantity of waste at 2.1 kg per unit. Meanwhile, the raw material processing stage showed the greatest material input per unit at 8.5 kg, highlighting the intensity of resource use during early manufacturing.

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Table 2. Life Cycle Inventory (LCI) Data Summary for Material and Energy Inputs

Manufacturing Stage	Material Input (kg/unit)	Energy Use (kWh/unit)	Waste Generated (kg/unit)	Recyclable Portion (%)
Raw material processing	8.5	3.2	1.2	60
Machining and forming	7.8	4.6	2.1	50
Assembly and finishing	6.2	2.5	0.9	30
Packaging	2.4	1.1	0.8	40
Distribution	1.8	0.6	0.2	10

This result supports previous findings [3], which showed that the processing stage contributes the most to waste generation and energy consumption due to inefficient conversion rates and lack of waste recovery systems. The LCI findings suggest that implementing cleaner production technologies and recycling systems at these stages could significantly enhance resource efficiency and reduce waste disposal.

Environmental Impact Assessment (LCIA) Results. The Life Cycle Impact Assessment (LCIA) results revealed that integrating solid waste management practices had a measurable positive effect on environmental performance. As shown in Table 3, the Global Warming Potential (GWP) decreased from 18.5 kg CO_2 equivalent per unit to 12.6 kg, reflecting a 32% reduction after SWM interventions. Likewise, resource depletion decreased by 23%, while waste sent to landfill dropped by 40%. These results affirm previous studies [7], which found that life cycle-based material recovery significantly reduces both energy consumption and greenhouse gas emissions in manufacturing systems.

Table 3. Life cycle Impact Assessment (LCIA) Results

Impact Category	Unit of Measurement	Baseline Value	After SWM Integration	% Reduction
Global Warming Potential (CO_2 eq.)	kg CO_2 eq./unit	18.5	12.6	32%
Resource Depletion	MJ energy/unit	520	400	23%
Waste to Landfill	kg/unit	5.2	3.1	40%
Water Use	L/unit	210	190	10%

The findings also indicated a 10% reduction in water consumption, primarily due to process optimization and reuse strategies introduced during production. Overall, the environmental improvements validate the effectiveness of integrating waste management and life cycle analysis in achieving sustainable manufacturing outcomes.

Evaluation of Existing Waste Management Practices. An evaluation of existing waste management systems revealed partial implementation of environmental programs, with strong emphasis on recycling and collection but limited activities focused on source reduction. As summarized in Table 4, recycling and reuse programs

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scored the highest effectiveness rating of 4.2 out of 5, particularly for metal and plastic waste. However, employee training and monitoring systems were found to be underdeveloped, with scores below 3.0, reflecting minimal engagement and inconsistent reporting practices.

Table 4. Evaluation of Existing Solid Waste Management Practices

Practice	Implementation Frequency	Effectiveness Rating (1–5)	Remarks
Segregation at source	Moderate	3.8	Inconsistent across departments
Recycling/reuse programs	High	4.2	Effective for metal and plastic waste
Employee training on waste handling	Low	2.7	Limited participation
Monitoring and reporting	Moderate	3.5	Needs digital tracking tools
Process optimization initiatives	High	4.1	Lean practices show positive impact

These findings are supported by previous studies [8], which emphasized that lean and green integration, when paired with proper workforce participation, leads to significant improvements in environmental performance. Strengthening employee awareness, monitoring tools, and management policies could therefore enhance compliance with ISO 14001:2015 and the goals of Sustainable Development Goal (SDG) 12 – Responsible Consumption and Production.

Framework for Sustainable Waste Integration. Based on the synthesis of findings, an integrated framework for sustainable solid waste management in manufacturing systems was developed, as shown in Table 5. The framework includes four key components: (1) Waste Identification and Classification, (2) LCA-Based Impact Monitoring, (3) Process Optimization through Lean-Green Integration, and (4) Continuous Improvement and Policy Alignment. Each component provides a structured approach for embedding waste management into manufacturing processes while supporting continuous improvement and compliance with environmental standards.

Table 5. Framework for Integrating Solid Waste Management into Manufacturing Systems

Framework Component	Objective	Key Activities	Expected Outcomes
Waste Identification and Classification	Determine waste sources	Conduct audits and waste profiling	Accurate waste quantification
LCA-Based Impact Monitoring	Quantify environmental impacts	Apply LCA tools (OpenLCA, SimaPro)	Measurable sustainability metrics
Process Optimization	Reduce waste and emissions	Implement lean-green manufacturing	Reduced resource use
Continuous Improvement and Policy Alignment	Ensure sustainability	Conduct regular reviews, ISO compliance	Institutionalized SWM integration

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The framework reflects a holistic approach to sustainability, aligning with previous studies [9], which emphasized that LCA-driven waste management systems promote operational resilience, efficiency, and corporate accountability. It serves as a strategic tool for manufacturers to systematically reduce waste, conserve resources, and institutionalize environmentally responsible production practices.

Discussion Summary. Overall, the results underscore the critical role of Life Cycle Assessment as a decision-support tool in achieving sustainable manufacturing. The findings revealed that integrating solid waste management into production systems can significantly reduce waste volume, improve resource efficiency, and enhance environmental compliance. Facilities that adopted LCA-guided waste strategies experienced measurable improvements in energy use and waste reduction, confirming the practical applicability of life cycle-based methodologies in industrial sustainability. This aligns with global trends emphasizing circular economy principles, where waste materials are continuously recovered and reintegrated into production systems [10].

The study highlights that the transition from conventional to sustainable manufacturing requires not only technological upgrades but also cultural and organizational shifts toward environmental accountability. The integration of LCA-based waste management offers a pathway for manufacturers to strengthen competitiveness while contributing to ecological preservation and sustainable development.

CONCLUSION AND RECOMMENDATIONS

The results of the study revealed that the integration of solid waste management (SWM) strategies into sustainable manufacturing systems through the Life Cycle Assessment (LCA) framework significantly improves environmental performance, operational efficiency, and compliance with sustainability standards. The assessment of selected manufacturing facilities in Bulacan showed that the majority of solid waste originated from machining, packaging, and post-processing operations, with metal and plastic waste comprising the largest proportion. These materials presented high potential for recycling and material recovery, which could considerably reduce landfill dependency and production costs. The Life Cycle Impact Assessment (LCIA) further indicated that the most critical environmental impacts occurred during material processing and machining stages, primarily due to high energy consumption and inefficient material utilization. The application of LCA-guided waste management strategies, including segregation at source, recycling, and process optimization, resulted in measurable reductions in greenhouse gas emissions, resource depletion, and total waste generation.

Moreover, the study developed an integrated framework for sustainable solid waste management that includes four essential components: waste identification and classification, LCA-based monitoring, process optimization through lean-green integration, and continuous improvement with policy alignment. This approach aligns with previous studies highlighting the synergy between life cycle thinking and lean manufacturing for sustainability enhancement [11]. The model also reinforces the alignment of industrial practices with ISO 14001:2015 Environmental Management Standards and the United Nations Sustainable Development Goal 12 (Responsible Consumption and Production) [12]. The findings underscored the vital role of manufacturing engineers and environmental managers in advancing sustainability by embedding environmental accountability and data-driven decision-making into each stage of production. Overall, the study concluded that sustainable manufacturing can be achieved through the synergy of solid waste management principles and life cycle thinking, leading to minimized environmental impacts, improved cost efficiency, and enhanced industry competitiveness.

In light of these findings, several recommendations are proposed to strengthen the integration of solid waste management into manufacturing systems. First, manufacturing firms are encouraged to institutionalize Life Cycle Assessment practices as part of their routine environmental management to identify waste-intensive stages and guide improvements toward sustainability. Second, industries should establish comprehensive solid waste management policies aligned with ISO 14001:2015 standards, incorporating waste segregation protocols, recycling targets, and compliance monitoring mechanisms. Third, employee training and awareness programs should be strengthened to foster environmental responsibility and encourage active participation in waste reduction initiatives. Fourth, manufacturers are advised to adopt lean-green manufacturing techniques such as

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5S, Kaizen, and Value Stream Mapping to minimize waste, optimize energy use, and improve overall efficiency. Fifth, companies should invest in waste recovery and recycling technologies to promote material circularity and reduce external disposal costs. Sixth, collaboration with academic institutions, local government units, and environmental agencies should be enhanced to support research, technical assistance, and innovation in sustainable manufacturing. Lastly, manufacturers should establish continuous improvement programs that include regular performance evaluations and feedback mechanisms to ensure that sustainability efforts remain adaptive to technological and market developments.

By implementing these recommendations, manufacturing industries can achieve a balance between productivity and environmental stewardship. The integration of solid waste management and life cycle assessment fosters a shift toward circular economy principles, where waste is treated as a valuable resource and sustainability becomes an integral component of industrial growth, competitiveness, and resilience.

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