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Assessing the Environmental Impact of Bubble Wrap: A Life Cycle Assessment using LCA FE Software

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Abstract

Packaging plays a key role in protecting goods, especially in e-commerce and logistics, where bubble wraps are valued for their lightweight and durable nature. However, its widespread use raises environmental concerns, including resource depletion and waste. This study explores the sustainability of remanufacturing secondary packaging, specifically bubble wrap, using a Life Cycle Assessment (LCA) approach via LCA for Experts (LCA FE) software. The assessment covers the full life cycle of single-layer LLDPE bubble wrap—from raw material extraction and manufacturing (extrusion, bubble formation, cooling, cutting) to end-of-life disposal. The LCA tracks energy use, materials, and environmental impacts to identify hotspots. Results show fossil resource depletion (ADP Fossil) is the dominant impact, accounting for 95.47%, mainly due to LLDPE production. Other notable impacts include global warming potential and freshwater aquatic ecotoxicity, largely driven by manufacturing energy use, while transport and disposal have minor effects. The study highlights the need for more sustainable packaging through biodegradable materials, better recycling, and circular economy principles to reduce environmental impact.

1. Introduction

This paper investigates the environmental challenges associated with the widespread use of bubble wrap in online shopping, focusing on the need for sustainable packaging practices. Bubble wrap is widely used for transporting goods due to its cushioning, durability, and lightweight properties [1]. Bubble wrap, commonly used to protect fragile items during transportation, contributes significantly to environmental concerns such as plastic waste, fossil resource depletion, and greenhouse gas emissions [2]. It contains air-filled bubbles that cushion that can protect items [3]. As e-commerce continues to grow, the demand for packaging materials, including bubble wrap, has increased, exacerbating these environmental issues [4].

This research employs a Life Cycle Assessment (LCA) using LCA FE software to evaluate the environmental impact of single-layer bubble wrap. The functional unit (FU) is defined as a 50 cm × 100 m roll of single-layer bubble wrap. The study examines each stage of its life cycle; from raw material extraction and production to usage and end-of-life disposal. By analyzing resource consumption, energy use, and emissions at every phase, the LCA offers critical insights into the environmental implications of bubble wrap. The findings aim to identify key environmental hotspots and support actionable strategies to reduce its environmental footprint. Ultimately, this research contributes to more sustainable practices in the packaging industry.

In this paper, the widespread use of bubble wrap in online shopping presents significant environmental challenges, including pollution, excessive plastic waste, and the lack of effective life cycle management. To address these issues, this research aims to develop a comprehensive Life Cycle Assessment (LCA) model for secondary packaging materials, focusing on a 50cm x 100m single-layer bubble wrap and analyzing its environmental impacts using LCA FE software. The findings will provide critical insights into resource consumption, emissions, and waste management, guiding the development of sustainable packaging solutions that align with global sustainability goals and support more eco-friendly practices in the e-commerce sector.

1.1 Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a tool used to measure the environmental impacts of a product or service across its entire life cycle, from raw material extraction to disposal [5]. It helps identify the stages that cause the most harm, such as resource use, energy consumption, and greenhouse gas emissions, and provides valuable insights for reducing these impacts. LCA software like SimaPro and LCA FE simplifies the process by automating data collection and analysis, making it easier for businesses to evaluate environmental footprints and work toward sustainability goals [6]. These tools offer a clear framework for analyzing data, helping organizations optimize resource use and reduce waste [7].

Other than that, Life Cycle Assessment (LCA) evaluates key environmental impacts to understand and reduce harm. Global Warming Potential (GWP) measures the effects of greenhouse gases like CO_2 and methane on climate change [8]. Acidification Potential (AP) tracks pollutants like SO_2 and NOx that cause soil and water acidification, harming ecosystems and structures [9]. Eutrophication Potential (EP) assesses nutrient pollution from fertilizers and wastewater, leading to harmful algae growth and oxygen depletion in aquatic systems [10]. Abiotic Depletion Potential (ADP) evaluates the depletion of non-renewable fossil resources, emphasizing the need for recycling and sustainable resource use [11]. Photochemical Ozone Creation Potential (POCP) measures VOC emissions that contribute to smog and ground-level ozone, impacting air quality [12]. Freshwater Aquatic Ecotoxicity Potential (FAETP) examines toxic substances' effects on aquatic life, highlighting the need for pollution control [13]. These metrics guide sustainability efforts and resource management.

1.2 LCA FE Software

LCA FE software (formerly GaBi) is a powerful tool by Sphera. It is used for Life Cycle Assessment (LCA) and sustainability analysis. It provides extensive databases and supports detailed assessments of environmental impacts like resource depletion and global warming potential. LCA FE helps businesses optimize processes, design sustainable products, and comply with regulations [14]. Its user-friendly features enable companies to explore greener materials, improve production efficiency, and meet sustainability goals. For example, LCA FE helps the automotive industry reduce waste and emissions by optimizing materials and production methods for sustainable vehicle designs [15].

1.3 Packaging Industry

Packaging is divided into primary (e.g., bottles, blister packs), secondary (e.g., bubble wraps, cartons), and tertiary (e.g., pallets, containers), each ensuring product safety, logistics efficiency, and branding [16]. Bubble wrap, as one of the popular choices of secondary packaging made from LDPE or LLDPE, cushions fragile items during transit but raises environmental concerns, prompting sustainable alternatives [17].

The bubble wrap manufacturing process begins with melting LDPE or LLDPE pellets at high temperatures (450°F to 512°F) to form thin plastic sheets through extrusion [18]. One sheet is pressed onto a roller with bubble-shaped cavities, where air is injected to form the bubbles, then sealed with another flat plastic layer. The material is cooled, tensioned for consistency, and cut to size before being rolled for transport [19]. This streamlined process combines advanced machinery and precise engineering to produce lightweight, durable bubble wrap with minimal material waste.

Overall, the bubble wrap manufacturing process is a precise and efficient operation that transforms LDPE or LLDPE pellets into lightweight, durable protective material. Through extrusion, bubble formation, sealing, cooling, and cutting, advanced machinery ensures consistent quality while minimizing material waste, making bubble wrap reliable for cushioning fragile items during transport.

1.4 Previous Research on LCA in Packaging Industry

Previous LCA studies, following ISO14040: Environmental Management-Life cycle assessment-Principles and framework [20], and ISO14044: Environmental Management-Life cycle assessment-Requirements and guidelines standards [21] reveal significant environmental impacts of corrugated box production, such as acidification, global warming, and toxicity, driven by landfilling and energy use [22]. Research on 3D concrete printing (3DCP) highlights the environmental burden of Portland cement, prompting exploration of sustainable alternatives [23]. Table 1 tabulates previous research particularly in the packaging industry, together with the findings of the research. Limited LCA studies on bubble wraps indicate a gap in understanding their environmental impact, calling for further research to enhance sustainable packaging.

Table 1 *Previous research work-related*

No.	Title	Findings	References
1.	Life Cycle Assessment of Corrugated Box	Optimization of machine shop layout (eliminated dispatcher and modified arrangement of various machines)	Verma et al., 2019
2.	Life cycle assessment (LCA) and environmental sustainability of cementitious materials for 3D concrete printing: A systematic literature review	A literature review on the use of cementitious materials for 3D printing applications in the context of environmental sustainability	Tinoco et al., 2022
3.	A Systematic Literature Review on Environmental Sustainability Issues of Flexible Packaging	Reviews the environmental sustainability issues of flexible packaging that provide integrated insights for scholars, practitioners and policymakers.	Farrukh et al., 2022
4.	Chapter 2 - Life Cycle Assessment of Waste Management Systems	This chapter introduces Life Cycle Assessment (LCA) as a tool for evaluating and comparing the environmental impacts of various waste management strategies—such as prevention, collection, recycling, anaerobic digestion, composting, combustion, and landfilling—in response to growing global waste and stricter environmental regulations, highlighting its role in supporting policy and business decisions through integrated environmental, economic, and social assessments.	Brancoli & Bolton, 2019
5.	Total Life Cycle of Polypropylene Products: Reducing Environmental Impacts in Manufacturing Phase	This paper uses Life Cycle Assessment (LCA) with GaBi 8.0 software to evaluate the environmental impacts of a polypropylene product—focusing on the injection-moulding stage—by analyzing energy use, emissions, and recyclability across its full life cycle, revealing that 91% of the environmental burden occurs during production.	Mannheim & Simenfalvi, 2020

2. Methodology

The methodology to achieve the research objectives involves using LCA FE software to simulate and analyze the environmental impact in a systematic and structured manner. The flow of the methodology is illustrated using a flowchart. All the content in the method outlines a step-by-step procedure for assessing the environmental impact of the LLDPE bubble wrap. Figure 1 presents a flowchart of the methodology discussed in this paper.

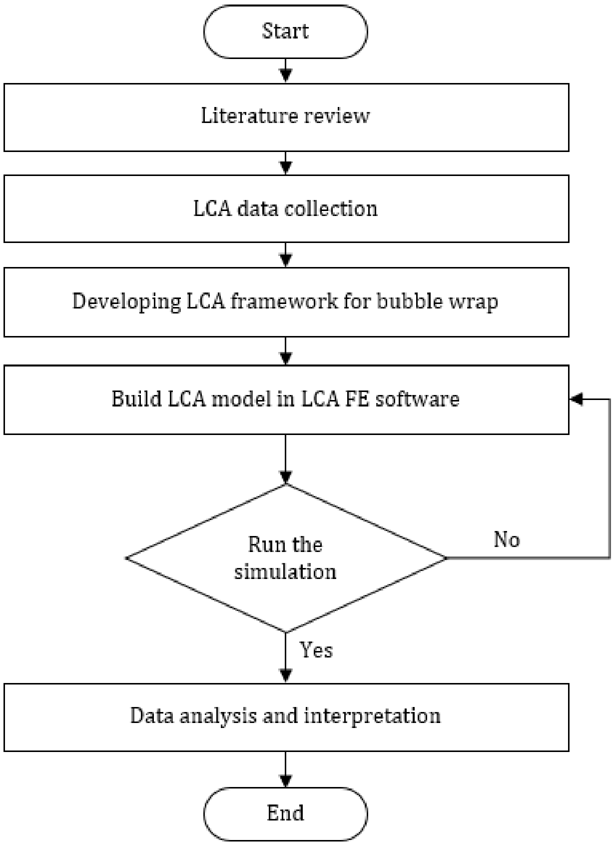

Fig. 1 *Flowchart of methodology*

2.1 Identification of LCA Parameter Framework

This research identified the parameters of Life Cycle Assessment (LCA) to evaluate the environmental impacts of bubble wrap using a cradle-to-grave approach [24]. Key inputs included raw materials, energy, and transportation, while outputs focused on waste emissions across all stages. Process flow diagrams defined system boundaries per ISO 14044 standards. Table 2 presents the inputs and outputs for LLDPE bubble wraps in LCA FE software.

2.2 Development of LCA Model in LCA FE Software

The development of the Life Cycle Assessment (LCA) model for bubble wrap was carried out using LCA FE software to analyze its environmental impacts. In this research, LCA FE educational version is used. The process involved creating a detailed framework that captured all relevant inputs, such as materials, energy, transportation, and outputs, including emissions and waste.

Table 2 *The inputs and outputs for LLDPE bubble wraps*

No.	Inputs	Outputs
1	**Raw materials** – Ethylene (C_2H_4) monomer – Additives (e.g., antioxidants, slip agents) – Catalysts for polymerization	**The LLDPE bubble wrap product** – LLDPE (Linear Low-Density Polyethylene) bubble wrap rolls (50 cm × 100 m × 100 pcs) **Material losses:** – Polymer scraps, edge trims
2	**Energy consumption** - Electricity for extrusion, bubble formation, cooling, and cutting (e.g., kWh/process) – Fuel (e.g., natural gas or diesel) for heaters or compressors	**Emissions:** – Air: CO_2, CH_4, NO_x, VOCs – Water: Cooling water discharge, potential microplastics – Soil: Solid polymer waste (non-recyclables), filter residues
3	**Water usage** – Cooling water in extrusion and bubble formation – Water for cleaning equipment (if applicable	**By-products/effluents:** – Heated wastewater (cooling discharge) – Sludge or residues (from filtration or cleaning systems)
4	**Air encapsulation** – Compressed air introduced during bubble formation (in flat film extrusion process)	– Air-filled cavities in bubble wrap (impact cushioning) – Potential release of compressed air or leaks during manufacturing

2.2.1 Material Selection

This research uses LLDPE/PE-LLD to produce bubble wraps, valued for their strength, flexibility, and puncture resistance. Key properties like weight and energy consumed are summarized in Table 3, with a focus on optimizing durability and recyclability for sustainable packaging.

Table 3 *The characteristics of LLDPE bubble wraps consideration*

Items	Characteristics	Value
Material	• Low Density Granulate (LLDPE/PE-LLD)	2.5 kg
Type of Process	• Extrusion	920.9 kWh (50%)
	• Bubble Formation	368.3 kWh (20%)
	• Cooling Process	276.3 kWh (15%)
	• Cutting Process	276.3 kWh (15%)

This research used 100% LLDPE granulate to produce bubble wrap, with energy and power consumption data for extrusion and bubble formation based on LCA FE software and continuous operation. From the calculation of area of the functional unit (FU) as 50 cm × 100 m = 0.5 m × 100 m = 50 m^2, and by considering typical grammage for single-layer bubble wrap as 50 g/m^2 [25], the estimation of total mass is calculated as Area × Grammage = 50 m^2 × 50 g/m^2 = 2500 g = 2.5 kg.

The table details that 1 kg of LLDPE granulate is used per roll, and the production process (extrusion, bubble formation, cooling, and cutting) consumes a total of 1841.7 kWh of energy per roll [26].

2.2.2 Manufacturing Phase

The bubble wrap manufacturing process involves extrusion, bubble formation, lamination, and cutting. LLDPE granulate is melted during extrusion, consuming significant energy. In the bubble formation stage, compressed air creates bubbles, with energy efficiency being crucial to minimize waste. Lamination may be applied for durability, requiring additional energy. The final step is cutting the bubble wrap to size, with proper handling during packaging and storage to prevent damage and reduce waste. Efficient resource use in each stage is key to minimizing environmental impact.

2.2.3 End of Life (EOL) Phase

The cradle-to-grave analysis of bubble wrap includes its entire lifecycle, with a focus on the EOL phase, which covers material waste disposal through landfill and incineration. In LCA FE software, input and output parameters were carefully recorded, tracing the process from raw materials to EOL. Significant waste contributions were identified, including polyethylene waste from landfills, incineration by-products, and steam conversion.

3. Result and Discussion

This section presents the key findings from the Life Cycle Assessment (LCA) of 50cm x 100m LLDPE single-layer bubble wrap. It focuses on understanding the environmental impacts at each stage of the product's life—from raw material extraction and manufacturing to transportation and disposal. By analyzing the data from LCA FE software, this section highlights the major contributors to the product's environmental footprint, providing insights into where improvements can be made. Ultimately, the goal is to identify opportunities for making bubble wrap production more sustainable and reducing its overall impact on the environment

3.1 LCA Framework

This research evaluates the environmental impacts of 50cm x 100m LLDPE single-layer bubble wrap using the cradle-to-grave LCA method with LCA FE software. The analysis covers raw material sourcing, extrusion, bubble formation, cooling, cutting, and disposal, highlighting the need for sustainable practices in e-commerce to address bubble wrap waste. The LCA model is shown in Figure 2.

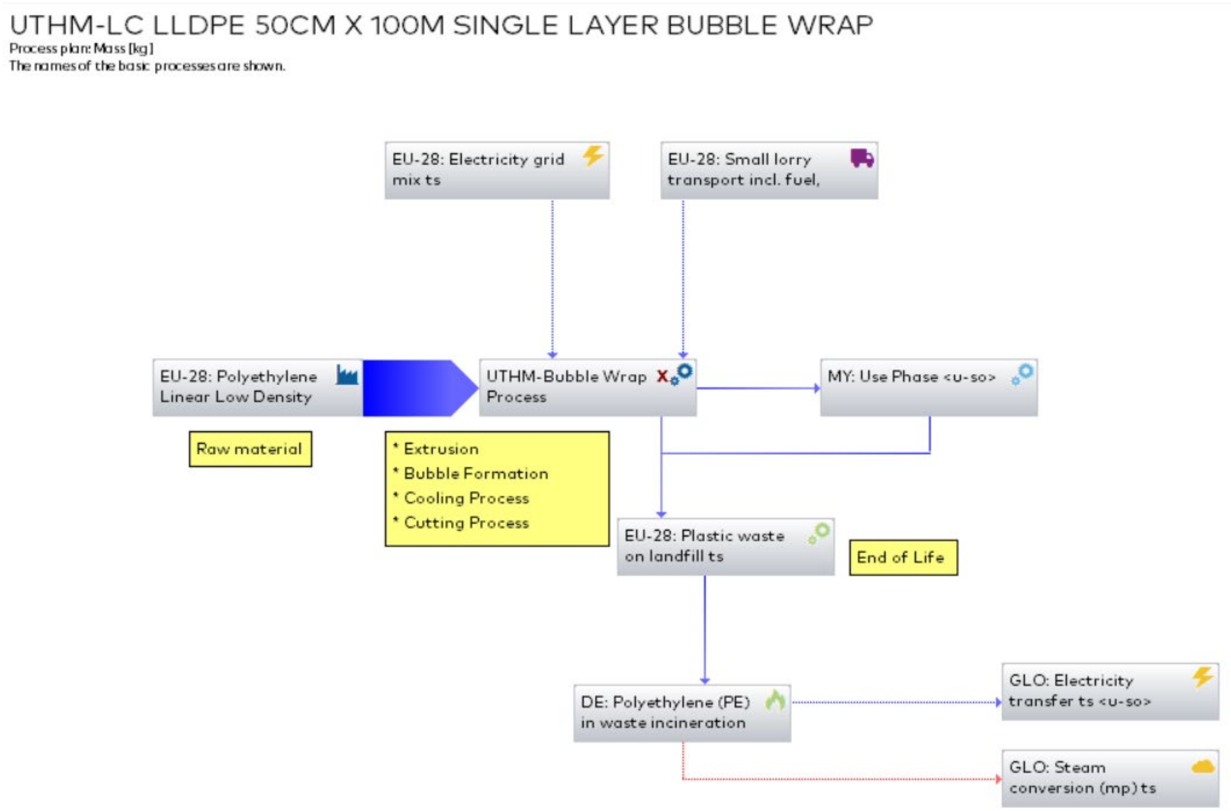

Fig. 2 *LCA model constructed in LCA FE software*

3.2 Emissions Profile

Table 4 shows the environmental impact of LLDPE bubble wrap is mainly driven by air and water emissions throughout its lifecycle. The highest contribution to Global Warming Potential (GWP) comes from air emissions (1.29×10^5 kg CO_2 eq.), while Acidification Potential (AP) and Photochemical Ozone Creation Potential (POCP) are also heavily impacted by air emissions. Freshwater and industrial soil emissions significantly contribute to Eutrophication Potential (EP) and Freshwater Aquatic Ecotoxicity Potential (FAETP).

Table 4 *Emissions profile for GWP, AP, EP, ADP Fossil, POCP and FAETP*

Values of Potential Environment al Impacts	GWP	AP	EP	ADP fossil	POCP	FAETP
	kg CO_2 eq.	kg SO_2 eq.	kg Phosphate eq.	MJ	kg Ethene eq.	kg Dichlorobenzene eq.
Emissions to air	1.29×10^5	225	19.6	-	25.5	45.3
Emissions to fresh water	-	0.00151	5.93	-	5.12×10^{-12}	625
Emissions to sea water	-	-	0.0714	-	3.07×10^{-13}	0.00124
Emissions to agricultural soil	-	1.45×10^{-19}	1.93×10^{-10}	-	-	2.81
Emissions to industrial soil	-	3.85×10^{-9}	0.271	-	-	0.121
Total	1.29×10^5	2.25×10^2	25.8724	-	25.5	6.73×10^2

These emissions, particularly CO_2 and phosphates, drive climate change, degrade air quality, and harm aquatic ecosystems. To mitigate the environmental footprint, efforts should focus on reducing emissions during production and disposal phases through cleaner technologies, improved energy efficiency, and better waste management practices, including recycling and the reduced landfill waste.

3.3 Potential Environmental Impacts

Table 5 listed the distribution of values for each potential environment impact, generated from LCA FE software. Overall, the production process and energy use were the main contributors to these impacts, while transportation and waste disposal had much smaller effects.

Table 5 *Distribution of values for each potential environmental impact*

Values of Potential Environmental Impacts	GWP	AP	EP	ADP fossil	POCP	FAETP
	kg CO_2 eq.	kg SO_2 eq.	kg Phosphate eq.	MJ	kg Ethene eq.	kg Dichlorobenzene eq.
Polyethylene Low Linear Density	3.92×10^4	71.222	8.48	1.59×10^6	15.202	510.814
Electricity Grid mix	7.3×10^4	152.539	16.879	8.05×10^5	10.862	160.673
Small lorry transport include fuel	275.97	1.337	0.337	3.77×10^3	-0.574	1.468
Polyethylene in waste incineration plant	4.14×10^{-5}	3.75×10^{-9}	8.44×10^{-10}	0.00	2.72×10^{-10}	8.82×10^{-10}
Plastic waste on landfill (end phase)	68.3	0.186	0.195	1.02×10^3	0.021	0.321
Total	1.13×10^5	225.285	25.891	2.4×10^6	25.511	673.275

The values of the environmental impacts as in Table 5 are used to calculate the percentage of contributions of each environmental impact. The analysis of LLDPE 50cm x 100m single-layer bubble wrap revealed that its production had the highest environmental impact, with ADP Fossil accounting for 95.47% of the total impact. GWP was the second largest contributor at 4.49%, while POCP and EP both had the smallest impact at 0.001%. Other impacts, which are FAETP and AP contributed 0.027% and 0.009% respectively. Details of the calculation is tabulated in Table 6.

Table 6 *Percentage calculation*

Values of Potential Environmental Impacts	Value	Percentage [%]
ADP Fossil [MJ]	2,400,000.000	95.467
GWP [kg CO_2 eq.]	113,000.000	4.495
FAETP [kg Dichlorobenzene eq.]	673.275	0.027
AP [kg SO2 eq.]	225.285	0.009
EP [kg Phosphate eq.]	25.891	0.001
POCP [kg Ethene eq]	25.511	0.001
Total	2,513,949.962	100.000

The environmental impact of LLDPE bubble wrap is mainly driven by air and water emissions throughout its lifecycle. The highest contribution to GWP comes from air emissions (1.29×10^5 kg CO_2 eq.), while AP and POCP are also heavily impacted by air emissions. Freshwater and industrial soil emissions significantly contribute to EP and FAETP. These emissions, particularly CO_2 and phosphates, drive climate change, degrade air quality, and harm aquatic ecosystems. To mitigate the environmental footprint, efforts should focus on reducing emissions during production and disposal phases through cleaner technologies, improved energy efficiency, and better waste management practices, including recycling and the reduced landfill waste. The results emphasize that the depletion of fossil resources, driven by LLDPE production, dominates the environmental footprint of the bubble wrap, with energy use in production being a major factor. Transportation and waste disposal played minor roles in the overall impact.

The LCA of LLDPE bubble wrap, commonly used in e-commerce packaging, highlights its significant environmental impact due to increased demand from online shopping [27]. Major contributors to greenhouse gas emissions, including GWP and POCP, are tied to production and transportation processes powered by fossil fuels [28]. Transitioning to renewable energy in these stages could substantially reduce emissions [29]. Additionally, the production and disposal of bubble wrap discharge phosphates and pollutants into freshwater systems, leading to eutrophication and biodiversity loss, a concern that could be alleviated through recycling and sustainable disposal techniques [30].

The reliance on petrochemical-based LLDPE also depletes non-renewable fossil resources, underscoring the need for biodegradable or recycled materials to reduce waste [31]. Bubble wrap's disposal exacerbates landfill accumulation, presenting long-term environmental challenges [32]. By adopting sustainable packaging alternatives and creating a circular economy, e-commerce businesses can significantly minimize their environmental footprint [33]. Other than that, implementing alternative materials, increasing recycling, and optimizing production methods are essential strategies for reducing packaging waste and fostering a more sustainable future for the e-commerce industry [34].

4. Conclusion

In summary, this study analyzed the environmental impact of producing and using single-layer LLDPE bubble wrap, measuring 50 cm by 100 m, commonly used in e-commerce packaging, using Life Cycle Assessment (LCA) with LCA FE software. The results revealed significant concerns, including fossil resource depletion which accounts for 95.47% of the total environmental impact, and high greenhouse gas emissions caused by energy-intensive production processes. By evaluating the entire product lifecycle, from raw material source through manufacturing, extrusion, bubble formation, cooling, cutting, and end-of-life disposal, the study successfully developed a comprehensive LCA model. This model provides valuable insights into resource consumption, energy use, and emissions, enabling organizations to identify opportunities for improvement and adapt it for other packaging materials.

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Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception:*** *Muhammad Khalis Fathris, Tengku Nur Azila, Emelia Sari;* ***data collection:*** *Muhammad Khalis Fathris;* ***analysis and interpretation of results:*** *Muhammad Khalis Fathris, Tengku Nur Azila;* ***draft manuscript preparation:*** *Muhammad Khalis Fathris, Tengku Nur Azila, Yong Tze Me, Shaiful Rizal Masrol. All authors reviewed the results and approved the final version of the manuscript.*

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