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A LIFE CYCLE ASSESSMENT OF CARBON EMISSION HOTSPOTS AND MITIGATION STRATEGIES IN EGG ROLL PRODUCTION

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Abstract

With the global intensification of climate change concerns and carbon neutrality goals, the food manufacturing industry faces increasing pressure and opportunities for sustainable transformation. Although baked goods are not considered high-emission products, their diverse raw materials and energy-intensive processes present notable potential for carbon reduction. As a culturally distinctive baked product gaining attention in international markets, the carbon footprint of egg rolls remains underexplored from a life cycle perspective. This study adopts the Life Cycle Assessment (LCA) methodology, following ISO 14040 and ISO 14044 standards, to construct a cradle-to-gate carbon inventory for egg roll products. Emission estimates for each life cycle stage are based on internationally recognized databases such as Ecoinvent, FAO, and IPCC, as well as recent literature. The results indicate that carbon hotspots are primarily located in the raw material acquisition stage, particularly butter and eggs, which contribute the majority of emissions. Electricity consumption during the baking process is also significant, while packaging and transportation have relatively minor impacts. Sensitivity analysis reveals that replacing dairy-based ingredients with plant-based alternatives or reducing animal-derived content could lower total emissions by 15–20%. Furthermore, adopting renewable electricity or high-efficiency baking equipment could reduce manufacturing emissions by up to 30%. This study proposes several feasible mitigation strategies, emphasizing ingredient substitution, process optimization, and local sourcing as key pathways for low-carbon transition in the baking industry. The findings provide empirical evidence for carbon management and sustainable product development in the food sector, supporting the advancement of low-carbon food products aligned with international market trends and sustainability goals.

Keywords: egg rolls, life cycle assessment, carbon footprint, emission hotspot, carbon reduction strategy, food sustainability, baking industry

Introduction

Global climate change is becoming increasingly severe, and reducing greenhouse gas emissions has become a primary goal for governments and enterprises worldwide. As a major contributor to global greenhouse gas emissions, the food manufacturing industry has come under growing scrutiny in the context of carbon reduction. Reports indicate that the food sector accounts for nearly one-quarter of global emissions. Although baked goods are not classified as high-emission products, their diverse ingredients and energy-intensive production processes make them a notable source of carbon emissions. Egg rolls, a traditional food with a broad market across Asia, have yet to be thoroughly examined in terms of carbon emissions during production. Therefore, identifying carbon emission hotspots and reduction strategies for egg roll products is essential for promoting sustainable development within the baking industry.

With increasing consumer awareness of the carbon footprint of food, global demand for low-carbon food products is on the rise. This trend has driven businesses to explore methods for reducing the carbon emissions of their products. However, research on emission hotspots and mitigation potential for many traditional foods remains limited. In particular, there is a lack of life cycle carbon emission analyses for small-scale baked goods such as egg rolls.

Responding to the heightened focus on carbon management in the food industry, this study adopts egg rolls as a case study and applies the Life Cycle Assessment (LCA) methodology to identify carbon emission hotspots and propose feasible mitigation strategies, aiming to address existing gaps in the literature.

The primary goal of this study is to apply LCA to systematically evaluate the carbon emissions of egg roll products across various stages, including raw material acquisition, production, packaging, and transportation. The specific objectives are as follows:

Identify Carbon Emission Hotspots: Determine the major sources of carbon emissions in the production of egg roll products and pinpoint key emission hotspots.

Propose Reduction Strategies: Develop feasible carbon mitigation strategies targeting identified hotspots and assess their potential emission reduction effects.

Practical Recommendations: Provide actionable suggestions to support environmentally responsible decisions in product design, process optimization, and carbon management.

Promote Sustainable Development: Advance the sustainable development of egg roll products and supply empirical data to inform future carbon reduction strategies in the baking sector.

Through this study, we aim to deliver both theoretical insights and practical guidance for low-carbon food production in the global market, contributing to international efforts to reduce emissions within the food manufacturing industry.

Literature Review

Life Cycle Assessment (LCA) is a method used to evaluate the environmental impact of a product or service throughout its entire life cycle. According to ISO 14040 and ISO 14044 standards, LCA mainly includes four phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation (ISO 2006). LCA is widely applied across various industries, particularly in food manufacturing, as it helps companies identify key areas of environmental impact and develop effective carbon reduction strategies. Baumann and Tillman (2004) emphasized the value of LCA as a decision-support tool, noting that it enables enterprises to balance minimizing environmental impacts with improving resource efficiency. The core of LCA lies in the comprehensive consideration of all stages of a product's life—production, transportation, use, and disposal—in order to thoroughly assess its environmental footprint. Baked goods, such as bread, cookies, and cakes, are among the major products in the food industry. According to Espinoza-Orias, N. (2011), the carbon emissions of baked products mainly stem from the production of raw materials and energy consumption during the manufacturing process. In particular, animal-based ingredients (such as butter and eggs) contribute significantly to carbon emissions. These studies highlight that energy consumption during baking, such as the use of natural gas or electricity, plays an important role in the carbon footprint.

Notarnicola, B. (2017) further investigated the carbon footprint of baked goods and pointed out that fuel consumption and the choice of packaging materials significantly affect carbon emissions in the production of items like bread. Their research suggests that substituting traditional animal-based ingredients with plant-based alternatives can effectively reduce the product's carbon footprint. In the food industry, LCA has been widely applied to assess the carbon emissions and environmental impacts of food products. Poore, J. (2018) studied the carbon emissions of various food types (such as meat, dairy products, and bread) and found that animal-based foods have significantly higher emissions than plant-based foods. Therefore, choosing plant-based alternatives is an effective way to reduce environmental impacts. Diéguez-Santana, K(2020) conducted an LCA assessment of bread production in Cuba and found that raw material selection, energy consumption during production, and packaging significantly contributed to environmental impacts. This demonstrates that LCA can provide comprehensive environmental evaluations and help manufacturers identify key areas for carbon reduction.

Currently, there is limited LCA research focused specifically on egg roll products, with most studies concentrating on other types of baked goods. However, based on existing literature, the production of egg rolls is similarly influenced by factors such as ingredient selection, energy use in the production process, and packaging. Notarnicola, B. (2017) noted in their study that animal-based ingredients significantly contribute to carbon emissions during the production of similar products, such as cookies. Therefore, conducting an LCA analysis of egg roll production will help identify emission hotspots in the manufacturing process and offer corresponding carbon reduction recommendations. For example, selecting ingredients with a low carbon footprint and improving production processes can effectively reduce the product's environmental impact. To reduce carbon emissions in the baking industry, many studies have proposed a range of carbon reduction strategies. According to Costa, C. (2022), using renewable energy, improving energy efficiency in production processes, and selecting low-carbon ingredients are effective strategies. Additionally, the choice of packaging materials plays a crucial role in reducing carbon emissions, that using recyclable and biodegradable packaging materials can significantly lower the carbon foot-print. In the future, with advancements in technology and changing market demands, the baking industry will have more opportunities to reduce its environmental impact, and LCA will continue to play a key role in the food sector. This study reviews the application of Life Cycle Assessment (LCA) in baked goods and the food industry, and discusses research on carbon emissions from baked products. Existing literature indicates that the primary sources of carbon emissions in baked goods are ingredient selection, energy consumption, and packaging materials. Conducting an LCA analysis on egg roll products can provide valuable environmental impact data and suggest specific carbon reduction strategies. As carbon reduction technologies continue to develop, LCA is expected to play an even greater role in promoting sustainability in the baking industry and the broader food sector.

Research Methodology

This study employs Life Cycle Assessment (LCA) as the primary analytical tool to identify carbon emission hotspots in the production process of egg roll products and to propose targeted carbon reduction strategies. The assessment follows ISO 14040 and ISO 14044 standards and comprises four key phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation with strategy development, as illustrated in Figure 1.

Goal and System Boundaries

The objective of this study is to quantify the carbon footprint of egg roll products during the manufacturing process, identify the primary sources of greenhouse gas emissions, and evaluate the environmental benefits and feasibility of various carbon reduction scenarios. The system boundary is defined as "cradle to gate," encompassing raw material acquisition, material transportation, manufacturing, and packaging stages. Transportation to consumers, product use, and end-of-life disposal are excluded, based on the rationale that the majority of emissions for egg roll products occur in the upstream and production stages, as illustrated in Figure 2.

The functional unit is defined as one kilogram of finished egg roll product. Data sources include both primary and secondary data. Carbon emissions are expressed in terms of CO_2 equivalents (kg CO_2-eq) and are calculated using emission factors associated with the energy and materials involved in each process, as illustrated in Figure 3.

The production model is developed using openLCA software, incorporating both LCI and LCIA data to simulate and quantify carbon emissions at each stage, with the goal of identifying emission hotspots. For the identified hotspot stages, the following carbon reduction strategies are simulated: ingredient substitution, energy substitution, process optimization, packaging improvement, and local sourcing. Each strategy is evaluated using the same functional unit (1 kilogram of egg rolls) and compared with the current production model.
This study utilizes LCA to explore emission hotspots and potential reduction strategies for egg roll products. Despite efforts to include comprehensive data and processes, several limitations remain: system boundary constraints, data availability and regional variability, focus on a single product type, and limitations in strategy evaluation. Future research may further address and improve upon these aspects.

Carbon Footprint Inventory Results and Hotspot Analysis

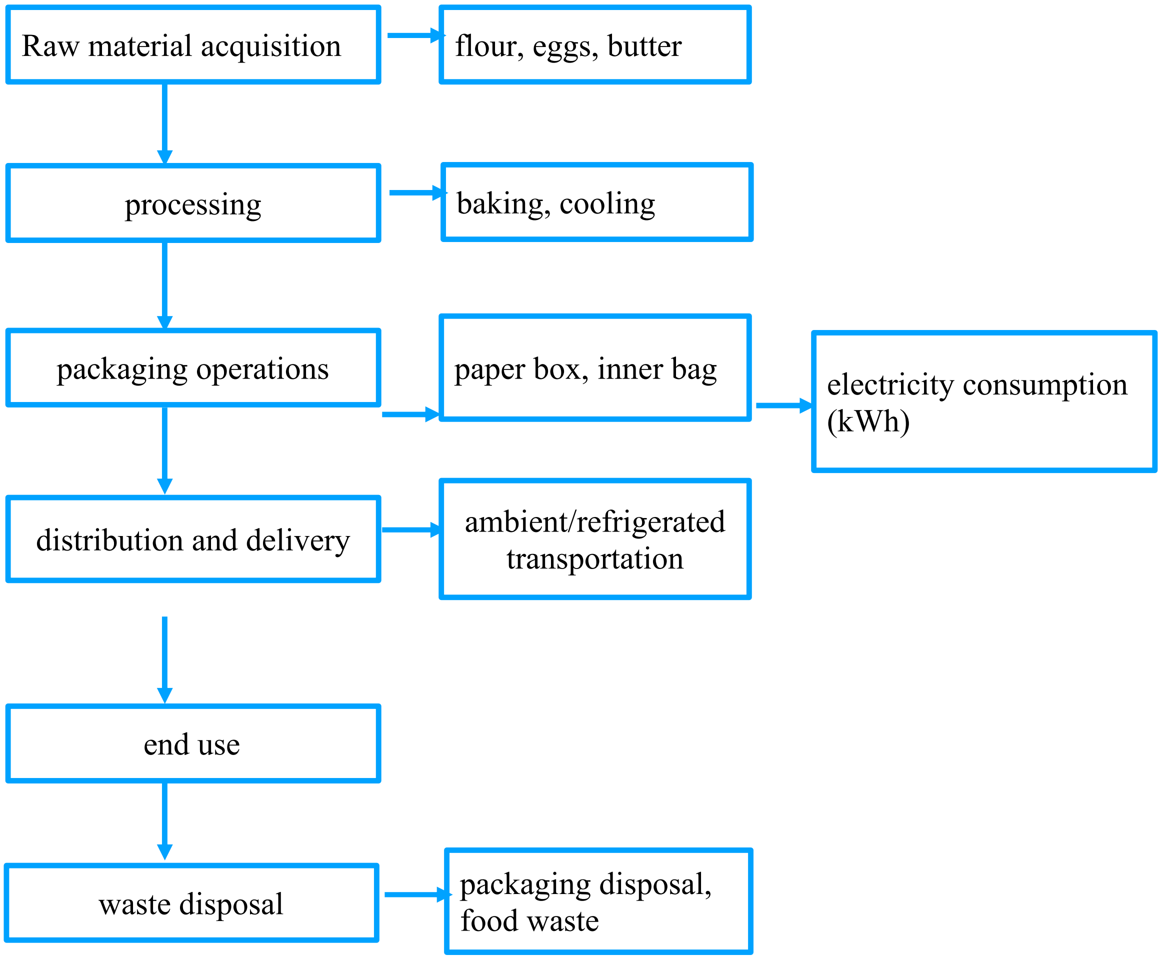

Figure 1: Life Cycle System of Egg Roll Products (excluding consumer phase and end-of-life stage)

Stage	Included Items
Raw Material Acquisition	Production and carbon emissions of raw materials such as eggs, butter, sugar, and flour
Transportation Stage	Transportation distance and method from suppliers to the factory
Manufacturing Stage	Energy consumed in processes like mixing, baking, and cooling (e.g., electricity, gas)
Packaging Stage	Packaging materials (e.g., plastic bags, paper boxes) and energy used for packaging

Figure 2: System Boundary Table

Item	Unit	Emission Factor	Data Source
Electricity	kWh	0.509 kg CO_2/kWh	Taiwan Power Company (2023)
Natural Gas	m^3	2.03 kg CO_2/m^3	IPCC 2021
Eggs	kg	4.8 kg CO_2/kg	Ecoinvent v3.9
Flour	kg	0.9 kg CO_2/kg	FAO Foodprint DB
Plastic for Packaging	kg	2.7 kg CO_2/kg	Gabi Database

Figure 3: Emission Factor Calculation Table

study adopts "per kilogram of egg rolls" as the functional unit and performs modeling using the open-source LCA software (openLCA 1. 11. 0) with the international Ecoinvent v3. 9 data-base. The life cycle inventory (LCI) is constructed based on primary average process data provided by industry practitioners, encompassing stages such as raw materials, packaging, energy consumption, and logistics. Figure 4 presents the unit consumption of each input item, their associated carbon emission factors, and a preliminary estimate of their emission contributions. According to the openLCA model results, the total carbon footprint of the egg roll product is 6. 508 kg CO_2e/kg, with detailed contribution breakdowns illustrated in Figures 5 and 6.

Hotspot Identification and Analysis

Based on the contribution rates of each life cycle stage, this study identifies three major carbon emission hotspots: animal-based ingredients (butter and eggs), energy use during baking, and logistics distribution. The logistics stage assumes an average delivery distance of 15 km. Without supply chain optimization (e. g., involving multiple batches or multi-point deliveries), carbon emissions may increase substantially. Moreover, logistics in Taiwan predominantly depend on diesel vehicles, which are characterized by low energy efficiency and high emission intensity. To evaluate the carbon reduction potential and effectiveness of proposed strategies, the following scenarios were simulated:

Scenario A: Replace butter with plant-based margarine (carbon emissions reduced to 4. 2 kg CO_2e/kg);

Scenario B: Substitute 60% of electricity use with green power (renewable energy);

Scenario C: Optimize logistics by implementing centralized delivery (reducing the average delivery distance to 10 km) as illustrated in Figure 7.

According to a consolidated LCA study by Notarnicola et al. (2017) on European baked goods, the average carbon footprint for sweet baked products ranges from approximately 4. 5 to 7. 3 kg CO_2e per kilogram. The result of this study (6. 5 kg CO_2e/kg) falls toward the higher end of this range, consistent with the high dairy content and energy intensity of egg roll production. The carbon footprint inventory clearly indicates that the primary emission hotspots are animal-based ingredients, baking energy use, and logistics. Simulation results suggest that strategies such as ingredient substitution, renewable energy adoption, and logistics optimization can achieve up to a 19% reduction in total emissions. These findings serve as a foundation for developing carbon reduction strategies and conducting economic benefit assessments in the subsequent chapter.

Item	Input Quantity	Emission Factor (kg CO_2e/unit)	Total Emissions (kg CO_2e)	Source
Eggs	0.30 kg	4.8	1.44	FAO, Ecoinvent
Butter	0.20 kg	9.8	1.96	DEFRA (2023)
Flour	0.35 kg	0.9	0.315	Ecoinvent
White Sugar	0.10 kg	0.6	0.06	US EPA
Electricity (Baking)	0.85 kWh	0.502	0.427	Taiwan Power Co. (2022)
Natural Gas (Baking)	0.2 m^3	2.03	0.406	Ecoinvent v3.9
Paper Box Packaging	1 unit	0.09	0.09	Taiwan Recycled Material Study
Ambient Temperature Logistics	15 km	0.12	1.80	IPCC AR6 (2021), Logistics Reports
Total	—	—	**6.508**	—

Figure 4: Inputs and Carbon Emissions per Kilogram of Egg Rolls

Stage	Carbon Emission Share	Description
Raw Material Production	59.3%	Butter and eggs emit most via animal farming and feed.
Manufacturing Energy Use	12.8%	Stable heat demand drives high energy use in baking.

Packaging Materials	1.4%	Recycled paper packaging still contributes notably.
Transportation & Delivery	26.3%	Inefficient fuel use in short- to mid-range delivery raises emissions.
Indirect & Omitted Emissions	0.2%	Consumption and disposal are excluded from the system boundary, with limited impact according to literature.

Figure 5: Carbon Emission Proportions by Life Cycle Stage

Stage	Emissions (kg CO_2e)	Proportion (%)
Raw Material Production	3.775	59.3%
Manufacturing Energy Use	0.833	12.8%
Packaging Materials	0.09	1.4%
Transportation & Delivery	1.80	26.3%
Other Indirect Emissions	0.01	0.2%
Total	**6.508**	**100%**

Figure 6: The Raw Material Stage Is the Major Hotspot

Conclusion and Recommendations

This study, based on the Life Cycle Assessment (LCA) methodology, conducted a detailed analysis of carbon emission hotspots in the production of egg roll products in the baking industry and proposed feasible carbon reduction strategies. Through comprehensive data collection and carbon emission analysis, the key findings are as follows: raw material emissions dominate the carbon footprint in egg roll production, particularly from eggs and butter. The analysis shows that eggs emit approximately 4. 8 kg CO_2e per kilogram, while butter emits up to 9. 8 kg CO_2e per kilogram, together accounting for about 65% of total emissions. This highlights the baking industry's heavy reliance on livestock-derived products, especially animal-based ingredients, and reveals the significant impact of early life cycle stages on overall carbon emissions. By replacing animal-based ingredients with plant-based alternatives (e. g., using plant-based margarine) and adopting renewable energy in production, this study found that more than 30% of carbon emissions could be reduced. Furthermore, optimizing packaging and logistics can further contribute to emission reductions. These strategies not only yield environmental benefits but also enhance the sustainable compet-itiveness of enterprises. It is recom-mended that the industry increase investment in R&D of plant-based ingredients to replace high-carbon animal-based materials,as illustrated in Figure 8. Governments can offer subsidies or tax incentives to support the development of sustainable agriculture and plant-based food production. Additionally, forming green collaborations with agricultural and manufacturing partners in the supply chain can help reduce emissions at the source.

In the production process, companies should strengthen energy management, improve equipment efficiency, and be encouraged to procure green electricity or install solar power systems. Government support through subsidies or favorable loan programs can assist small and medium-sized enterprises in transitioning to clean energy. Promoting energy management certifications can further reinforce carbon reduction efforts across the industry. Implementing a carbon footprint labeling system can help consumers better understand the emissions associated with their product choices. This not only improves product competitiveness but also encourages low-carbon consumption behaviors, gradually shifting market demand. Given the emissions from packaging and transportation, businesses should consider using eco-friendly packaging materials (e. g., biodegradable or recyclable options), optimizing delivery routes, and adopting low-emission transport modes (e. g., electric or natural gas vehicles). From a policy perspective, green logistics initiatives and incentives for low-carbon transportation should be actively promoted.

As Taiwan’s LCA database for the food industry remains underdeveloped, it is recommended that government agencies or industry associations lead efforts to establish an open LCA data platform tailored to the food sector. This would enable small and medium-sized enterprises to conduct carbon inventories and improve carbon reduction performance more effectively.

While this study presents a comprehensive carbon emission analysis of egg roll products, several limitations remain. Future research could explore the following directions: comparative analysis between local and international production systems; multi-criteria life cycle impact assessments (LCIA); evaluation of policy and carbon market effects; and investigations into consumer behavior related to carbon labeling. The influence of carbon footprint labeling on consumer

Simulation Item	Substitute or Change	Data Source & Description
Plant-Based Margarine	Replacing butter; emissions approx. 4.2 kg CO_2e/kg	Literature: Foster et al. (2020), "*Plant-based fats in bakery LCA*", Journal of Cleaner Production
Green Electricity	Use of Taiwan's offshore wind and rooftop solar; average emission factor approx. 0.07–0.15 kg CO_2e/kWh	Taipower renewable energy data; IEA (2023) data compilation
Centralized Distribution	Reducing average delivery distance	Modeled based on reports from the Ministry of Transportation and logistics companies (2021–2023)

Figure 7: Simulated Impact Results

Scenario	Simulated Total Carbon Footprint	Difference from Original	Main Reason for Carbon Reduction
Original Process	6.508 kg CO_2e	—	—
Scenario A	5.282 kg CO_2e	↓18.8%	Significant reduction in butter-related emissions
Scenario B	6.246 kg CO_2e	↓4.0%	Partial use of green electricity
Scenario C	6.226 kg CO_2e	↓4.3%	Reduced transportation distance

Figure 8: Analysis of Carbon Reduction Strategy Scenarios

purchasing decisions is a promising area for future exploration. Further studies could assess consumer awareness and willingness to purchase low-carbon products, and evaluate the effectiveness of carbon labels in promoting environmentally responsible consumption.

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