Life Cycle Assessment of Greenhouse Gas Emissions and Fossil Energy Demand for Coconut Milk Ice Cream: A Case Study from an Ice Cream Factory

Prakaytham Suksatit[1], Suchada Ukaew[2,*], Nontawan Pitakwinai[2], and Supissara Jindamanee[2]

ARTICLE INFO

Article history:
Received: 1 April 2024
Revised: 5 June 2024
Accepted: 23 August 2024
Online: 30 June 2025

Keywords:
Plant-based ice cream
Greenhouse gas emissions
Environmental impact
Coconut milk

ABSTRACT

Nowadays, consumers are not only looking for food that is beneficial to their health but also seeking options to minimize environmental impacts. Plant-based ice cream, including coconut milk ice cream, has recently gained popularity worldwide and is becoming a favored dessert choice in the global ice cream industry. The goal of this study is to evaluate the greenhouse gas (GHG) emissions and fossil energy demand (FED) of coconut milk ice cream using a cradle-to-gate approach, including waste disposal from the production stage. This research was conducted as a case study of an ice cream factory in Northern Thailand. The results showed that the GHG intensity of coconut milk ice cream was 1.17 kg CO_2 eq/kg, while the FED was 6.37 MJ/kg. The analysis highlighted coconut waste disposal as the main source of GHG emissions, whereas the production stage was the primary contributor to FED. Implementing sustainable waste management through composting, incineration, and combined methods (waste-to-energy and animal feed) could reduce GHG emissions by 49.42% to 88.77%. Strategies to reduce both GHG emissions and FED include regularly maintaining the deep freezer, insulating refrigerant pipes, adopting solar panels, switching from refined sugar to coconut sugar or raw sugar, sourcing coconuts from locations closer to the factory, and shifting from inorganic fertilizers to organic fertilizers.

1. INTRODUCTION

The global food and beverage sector plays an important role in the global economy as it supplies food for a growing population, which has a significant influence on the environment. This sector is a large source of greenhouse gas (GHG) emissions, emitting approximately 18 Gigaton CO_2 equivalent per year, accounting for 34% of total global emissions [1]. GHG emissions are produced throughout the supply chain during farm production, from the farm gate, through transport, food manufacturing, retail, household consumption, and waste disposal [2].

Within the food sector, ice cream is a popular food item worldwide because it is cool and refreshing, especially in hot weather, and comes in many flavors to suit everyone's taste. Globally, approximately 15 billion liters of ice cream are consumed each year, valued at US$62.8 billion [3]. In Thailand, the value of the ice cream market was estimated at US$396 million growing by 11% annually. The production of ice cream was reported at 12,775 tonnes in 2018 [4]. Thailand is also one of the world's top ice cream exporters, ranking 4th after the EU, the US, and the UK, as well as ranking 1st in ASEAN, with a value of around US$148.21 million in 2023 [5].

Coconut milk ice cream is a plant-based dessert with the main ingredient being coconut milk, which is not only delicious but also suitable for vegetarians and people who are allergic to cow's milk. Coconut milk ice cream has recently gained popularity internationally, and is becoming a favorite dessert choice for vegan diners [6]. Ice cream made without dairy products has grown in popularity since 2016 and has significantly increased its market share [6, 7]. In 2018, the dairy-free ice cream market was valued at $455.90 million and is expected to reach $1.20 billion by 2025, growing at approximately 14.8% annually from 2018 to 2025. [8]

The assessment of the environmental impact of the supply chain of the food industry is essential. The life cycle assessment (LCA) method is an effective tool, which is widely used to assess the environmental impacts of products and services throughout their entire life cycle, from raw material extraction, product manufacturing, product use, to end-of-life processes [9].

Previous studies that conducted LCA analysis of dairy-based ice cream using a cradle-to-grave approach reported that the emissions ranged from 3.36 to 4.00 kg CO_2 eq/kg of product [10-12]. Konstantas, Stamford [11] identified that

[1]*National Metal and Materials Technology Center (MTEC), Thailand Science Park, Pathumthani, 12120, Thailand.*
[2]*Department of Industrial Engineering, Faculty of Engineering, Naresuan University, Phitsanulok 65000, Thailand.*
**Corresponding author:* Suchada Ukaew; Phone: +66-918-385-829; Email: suchadau@nu.ac.th.

raw materials, especially from raw milk production, were the main GHG contributors to ice cream, accounting for 42%-63%, while the Scottish Government [12] reported 70%. Meanwhile, Garcia-Suarez, Sim [10] evaluated the GHG emissions of Ben & Jerry's ice cream, excluding waste disposal and transport from retailer cold storage to retail outlets. They concluded that refrigeration at the retail outlets was the largest GHG contributor at 46%, followed by ingredients at 33%, half of which came from dairy ingredients. Studies by Foster [13] and Wróbel-Jędrzejewska and Polak [14] variously reported low values of GHGs at 0.23 - 0.25 and 0.97 kg CO_2 eq/kg.

Several ice cream entrepreneurs in Thailand have been producing large amounts of coconut milk ice cream for sale either locally or in other provinces for a long time. However, there have been limited studies on the environmental impact and energy demand for plant-based ice cream. To address this knowledge gap, this study evaluated GHG emissions and fossil energy demand (FED) of coconut milk ice cream products as well as identified the processes associated with the most significant impacts along the pathway. The usage or disposal of coconut waste was addressed in a sensitivity analysis.

2. MATERIALS AND METHODS

2.1 Goal and scope

The goal of this study was to evaluate the GHG emissions and fossil energy demand (FED) for coconut milk ice cream, while also identifying the processes that contribute the most significant impacts within the supply chain. This research was conducted as a case study of an ice cream factory located in Phrae province. The selection of Phrae province as the study site was based on the factory's willingness to allow full access and disclosure of information rather than the abundance of raw materials like coconuts found in the southern provinces. The ability to collect data effectively and constantly was essential for conducting LCA analysis. Sensitivity analyses of the disposal of coconut waste, including coconut husk, shell, and pulp, were conducted to determine the influence of waste management methods on the overall GHG emissions of ice cream products.

2.2 System boundary and functional unit

The system boundary was the logistics and supply chain of cradle to gate, starting from the cultivation and harvesting of coconuts through to the production of ice cream, including the supply, transportation of raw materials and factory production processes, finishing with the waste disposal stage, as seen in Fig. 1. This study included waste disposal from the production stage in our cradle-to-gate analysis to provide a more accurate assessment of the environmental impacts associated with the production of coconut milk ice cream. This approach was conducted to ensure that all significant factors within the production boundary were accounted for, in accordance with ISO 14044 guidance [15]. The functional unit (FU) was one kilogram of ice cream. However, the amount of washing agents used in cleaning utensils and equipment was excluded from this study due to the lack of available data across production batches, its minor impact compared to other stages, and its insignificant effect on the overall results.

2.3 Life cycle inventory analysis and assumptions

The life cycle inventory data for the upstream processes of materials, chemicals, and energy were obtained from the ecoinvent database V3.6 [16]. The GHG impact assessment was conducted using the IPCC (2013) GWP 100a V1.03 methods, while the FED was evaluated using the cumulative energy demand V1.11 methods, which was obtained from the Simparo 9.1.0.11. Although the study focused only on GHG emissions and FED, resulting in a limited view on environmental performance by excluding other impacts such as ozone depletion, these categories were chosen due to their significance in the ongoing climate and energy demand debate. These issues are crucial for climate change mitigation and energy efficiency, both of which are important for the ice cream industry. The main GHGs considered were carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), of which 100-year global warming potential (GWP) values are 1, 28, and 265, respectively. The details of each stage and the assumptions are described below.

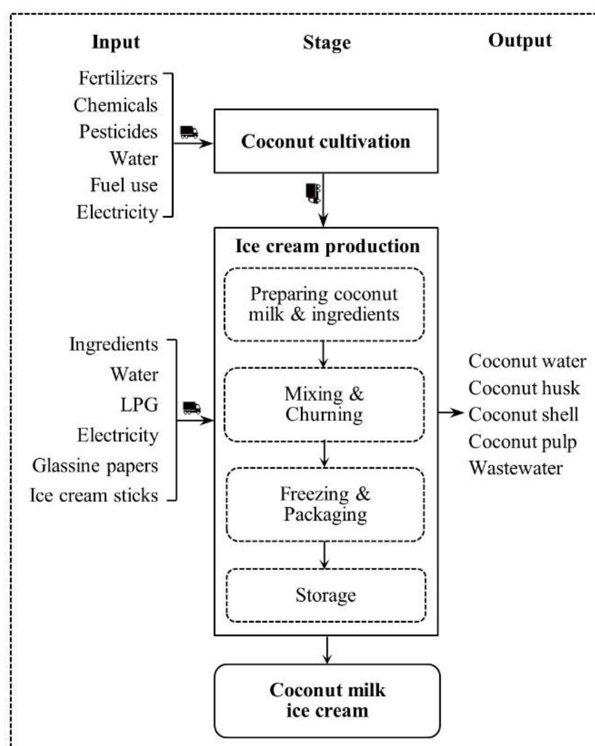

Fig. 1. The system boundary of coconut milk ice cream life cycle.

2.3.1 Coconut farming

Coconuts, the raw material of coconut milk ice cream, are widely cultivated in the southern region of Thailand. Coconuts are typically cultivated at the beginning of the wet season and are harvested after five years of growth, yielding produce throughout their 40-year lifespan [17]. Coconut cultivation begins with preparing land before the planting, followed by the application of fertilizer. Once the coconuts reach maturity, they are harvested manually [17, 18]. For the 40 years of cultivation, the application of synthetic nitrogen (N) fertilizer was 3,128 kg ha^{-1}. Urea is commonly used as a form of N fertilizers in Thailand [19]. The amount of phosphorus (P_2O_5), and potassium (K_2O) were applied at rates of 3,128 kg ha^{-1} and 5,053 kg ha^{-1} [18], respectively. Animal manure fertilizer was also applied about 298,438 kg ha^{-1} [18]. A borax rate of 867 kg ha^{-1} was applied as an additional nutrient recommended for coconut cultivation to address boron deficiencies, which significantly impact root growth, fruit yield, cell wall strength, promote nutrient transport within the plant [20]. Diesel fuel usage at the farm was 286 kg ha^{-1}, which was calculated based on land preparation for planting as suggested by DLD [21]. Electricity usage for pumping water was determined based on water requirement for coconut cultivation as suggested by Puspaningrum, Indrasti [22]. The annual coconut yield averaged about 3,256 kg ha^{-1} [23], resulting in a total of 712,289 kg ha^{-1} over 40 years of cultivation.

The default values of 0.01325, and 0.01425 from the 2006 IPCC guidelines were used to estimate the total N_2O emissions from N fertilizer and organic N applied to soil. While the default value of 0.13 was used to calculate CO_2 emission from dolomite [24]. The data inputs for the coconut cultivation were mostly obtained from the Department of Agriculture [18], except for the amounts of diesel fuel and electricity consumption, details of which were provided above in section 2.3.1, as shown in Table 1.

2.3.2 Ice cream production

The factory produced an average of 223 kg of coconut milk ice cream daily, with a range of 200 to 246 kg per day. Meanwhile, the production of ice cream in Thailand was reported at 12,775 tonnes in 2018 [4]. The production of the ice cream started with the preparation of coconut milk, which involved splitting the coconut shell into two parts and then using a coconut grater to shred it to obtain coconut meat. The coconut meat was then mixed with hot water and squeezed to extract the coconut milk. One coconut contained about 0.80 kg of coconut meat, which yielded about 2.13 kg of coconut milk. The next step was the preparation of the ingredients, which involved boiling water, sugar, tapioca starch, and corn starch together. Liquefied petroleum gas (LPG) was used as a heat source for boiling water. The boiled mixture and the remaining ingredients, such as coconut milk, salt, sweetened condensed milk, and others, were then poured into a churner and blended until the mixture became fluffy. The fluffy ice cream mixture was poured into ice cream molds which were placed in the blast freezer for a specific time, after which time the chilled ice cream was removed from the mold, wrapped in glassine papers, and ice cream sticks were inserted. Finally, the ice cream was stored in a deep freezer at a temperature of -20 °C to -25 °C for three days for 223 kg batch to allow it to harden. The data input and output of ice cream production were obtained from the factory, as shown in Table 2.

Table 1. Inventory data for the coconut cultivation over a period of 40 years*, based on 1 kg of coconut

Detail	Amount	Data sources
Input		
Synthetic N fertilizer (g)	4.39	[18]
Organic N fertilizer (g)	0.59	[18]
P fertilizer (g)	4.39	[18]
K fertilizer (g)	7.09	[18]
Magnesium sulfate (g)	0.35	[18]
Sodium chloride (g)	12.68	[18]
Dolomite (g)	33.56	[18]
Pesticides (g)	0.01	[18]
Calcium sulfate (g)	1.62	[18]
Ferrous sulfate (g)	1.22	[18]
Zinc sulfate (g)	1.22	[18]
Borax (g)	1.22	[18]
Water (L)	88.03	[18]
Fuel use at farm (g)	0.40	Our study
Electricity (kwh)	0.01	Our study
Output		
Coconut (kg)	1.00	
N_2O emissions (g N_2O)	0.10	Our study
CO_2, dolomite (g CO_2)	1.46	Our study
CO_2, fuel combustion (g CO_2)	4.36	Our study

** The average productive lifespan of coconuts is 40 year [17]*

2.3.3 Waste disposal

The solid waste from the production stage, such as coconut husk, shell, and pulp, was usually disposed of in a managed landfill. Sometimes local people requested the waste to feed their animals, to use it as fertilizer, or for other purposes. Although the landfill was classified as a managed landfill with the emission factor of 0.79 kg CO_2 eq/kg waste [25], this research calculated waste emissions based on the specific types of waste disposed of, using the emission factor of 3.27 kg CO_2 eq/kg waste for coconut husk and shell, and 2.53 kg CO_2 eq/kg waste for pulp [25]. The purpose of this approach was to gain a better understanding of the emissions associated with different waste materials. The wastewater from the production process was collected and treated through the waste treatment system. The amounts of waste are shown in Table 3.

Table 2. Inventory data for the ice cream production, based on 1 kg of coconut milk ice cream

Detail	Amount
Input	
Coconut (g)	269.04
Refined sugar (g)	170.30
Tapioca Starch (g)	34.06
corn starch (g)	10.22
Salt (g)	4.09
Sweetened condensed milk (g)	12.94
Whey powder (g)	34.06
Gelatin (g)	2.04
Tap water (L)	25.00
Filtered water (L)	0.72
Glassine papers (g)	5.29
Ice cream sticks (g)	2.42
LPG (g)	0.21
Electricity (kWh)	0.24
Output	
Coconut milk ice cream (kg)	1.00
Coconut water (g)	45.93
Coconut husk (g)	85.31
Coconut shell (g)	36.09
Coconut pulp (g)	85.15
Wastewater (L)	25.00

Table 3. The inventory data for the waste disposal, based on 1 kg of coconut milk ice cream

Waste	Amount
Coconut husk (g)	85.31
Coconut shell (g)	36.09
Coconut pulp (g)	85.15
Wastewater (L)	25.00

2.3.4 Transportation

The transportation consisted of four stages: 1) transportation of initial inputs such as fertilizers from sellers to coconut farm, 2) transportation of coconuts from the farm to the factory (i.e., from southern to northern Thailand), 3) transportation of other ingredients to the factory, and 4) transportation of coconut waste to a municipal waste disposal site. Transportation in stages one to three used four-wheel pickup trucks with a 7-tonne loading capacity, while transportation from stage four was carried out using a six-wheel garbage truck with a 11-tonne loading capacity. The details of the transportation stage are illustrated in Table 4.

Table 4. The inventory data for the transportation, based on 1 kg of coconut milk ice cream

Detail	tkm
1) Transport inputs from sellers to the farm	
Synthetic N fertilizer	1.42×10^{-5}
Organic N fertilizer	1.89×10^{-6}
P fertilizer	1.42×10^{-5}
K fertilizer	2.29×10^{-5}
Magnesium sulfate	1.13×10^{-6}
Sodium chloride	4.09×10^{-5}
Dolomite	1.08×10^{-4}
Pesticide	1.63×10^{-8}
Calcium sulfate	5.24×10^{-6}
Ferrous sulfate	5.24×10^{-6}
Zinc sulfate	3.93×10^{-6}
Borax	3.93×10^{-6}
2) Transport coconuts from the farm to the factory	
Coconut	2.37×10^{-1}
3) Transport ingredients to the factory	
Refined sugar	6.19×10^{-4}
Tapioca Starch	1.24×10^{-4}
Corn starch	3.71×10^{-5}
Salt	1.49×10^{-5}
Sweetened condensed milk	4.70×10^{-5}
Whey powder	2.12×10^{-2}
Gelatin	1.27×10^{-3}
Glassine papers	1.92×10^{-5}
Ice cream sticks	8.79×10^{-6}
4) Transport solid waste to the disposal site	
Coconut waste	2.17×10^{-3}

2.4 Calculation of GHG emissions and fossil energy demand

The methodology to calculate GHG emissions was based on activity data, emission factors, and global warming potential (GWP) [26], as illustrated in Equation 1. Meanwhile, Equation 2 showed the calculation of FED, where activity data represented the amount of energy consumed from fossil sources, and the energy factor indicated the efficiency of the energy conversion process for each fossil energy source [27].

$$\underset{[kgCO2eq]}{GHG} = \underset{[unit]}{\text{Activity data}} \times \underset{[kgGHG/unit]}{\text{Emission factor}} \times \underset{[kgCO2eq/kgGHG]}{GWP} \quad (1)$$

$$\underset{[MJ]}{FED} = \underset{[unit]}{\text{Activity data}} \times \underset{[MJ/unit]}{\text{Engergy factor}} \quad (2)$$

3. RESULTS AND DISCUSSION

3.1 The GHG emissions of coconut milk ice cream

Fig. 2 presents the life cycle GHG emissions of coconut milk ice cream. The results showed that the GHG intensity of ice cream was 1.17 kg CO_2 eq/kg, in which waste disposal was the largest source of GHG emissions, accounting for 53.73% of total emissions. The production stage produced 29.63%, transportation contributed 13.32%, and the cultivation stage contributed 3.32%.

The disposal stage, at 0.63 kg CO_2 eq/kg, contributed the most to the net GHG emissions. These emissions were mostly attributed to CH_4 generated in the landfill [28, 29] created by the decomposition of the coconut waste: 23.93% from husk, 18.48% from pulp, and 10.12% from shell. The disposal stage had greater GHG emissions than the production and transportation stages. This was because our study considered waste emissions based on the specific types of waste disposed of, which had a higher emission factor than those of managed landfills, as mentioned in Section 2.3.3. Additionally, a large amount of coconut waste was produced, resulting in higher GHG emissions compared to electricity usage during the production and transportation stages. The GHG intensity from the production stage was 0.35 kg CO_2 eq/kg. The most dominant sources of GHG emissions were electricity (14.62%) and sugar (11.16%). The emissions associated with electricity consumption were primarily from deep freezer storage (12.40%). Sugar was a major source of GHG emissions due to the large amount of sugar required in the process and its higher emission factor compared to other ingredients. The transportation stage showed a GHG intensity of 0.16 kg CO_2/kg. This was due to the use of diesel fuel for the long-distance transport of coconuts from the farm to the manufacturing facility, which accounted for 10.51%. The cultivation stage exhibited the lowest GHG emissions at 0.04 kg CO_2 eq/kg, which was attributed to the high yield per hectare as well as the low input and maintenance requirements, resulting in low GHG emissions. The N_2O emissions resulting from the application of N fertilizer (0.60%), followed by N fertilizer production (1.09%), were the main source of GHG emissions for this stage.

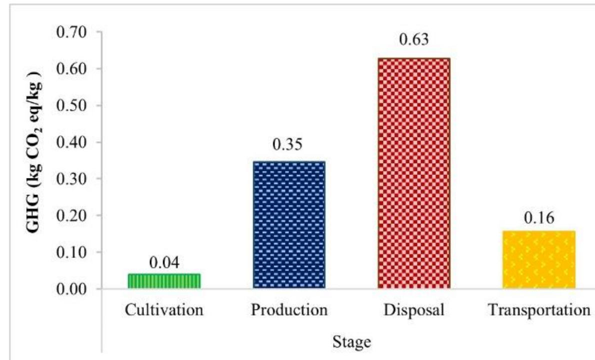

Fig. 2. The GHG emissions of coconut milk ice cream for each stage

The GHG values in our study were relatively lower at 1.17 kg CO_2 eq/kg than those in dairy-based ice cream products, which ranged from 3.36 to 4 kg CO_2 eq/kg [10-12], representing a GHG reduction of approximately 68.21%. This was due to the fact that coconut cultivation requires fewer intensive resources than dairy farming [30]. In our study, the GHG emissions of coconut milk were 0.49 kg CO_2 eq/kg or 0.50 kg CO_2 eq/liter, which was relatively close to the usual range of plant-based milk (0.7-1.18 kg CO_2 eq/liter) and about 46.81% lower than the average emissions of plant-based milk. In contrast, the GHG emissions for dairy milk were 3.15 kg CO_2 eq/liter [31]. In addition, the system boundary in our study was limited to the overall logistics and supply chain within a cradle-to-gate approach, which included waste disposal from the production stage but excluded the stages of retail, distribution, consumption, and end-of-life disposal. Our findings indicated that the disposal of coconut waste exhibited the largest source of GHG emissions in the entire process. On the other hand, other studies [10-12] conducted LCA analyses of dairy ice cream using a cradle-to-grave approach. Konstantas, Stamford [11] identified that raw materials, especially from raw milk production, were the main GHG contributors to ice cream, accounting for 42%-63%, while the Scottish Government [12] repored 70%. Meanwhile, Garcia-Suarez, Sim [10] evaluated the GHG emissions of Ben & Jerry's ice cream, excluding waste disposal and transport from retailer cold storage to retail outlets. They concluded that refrigeration at retail outlets was the largest GHG contributor at 46%, followed by ingredients at 33%, half of which came from dairy ingredients. However, the GHG emissions reported in our study were higher compared to those in the studies by Wróbel-Jędrzejewska and Polak [14], who reported the GHG emissions of dairy-based ice cream at 0.23 - 0.25 kg CO_2 eq/kg, and Foster [13], who reported 0.97 kg CO_2 eq/kg. This discrepancy may be due to variations in the scopes applied across the different studies.

3.2 The FED of coconut milk ice cream

The fossil energy demand of the coconut milk ice cream was 6.37 MJ/kg, as illustrated in Fig. 3. The results showed that the production stage was the most energy-intensive, accounting for 56.86% of the total FED. This high percentage was due to the electricity (36.18%) and sugar processing (13.40%). The transportation stage had the second highest FED contribution at 36.54%, resulting from the long-distance transport of coconuts from the farm to the ice cream factory. The fossil energy demand from coconut cultivation was 4.38%, whereby 1.61% of it was attributed to sodium chloride due to a high application rate, while 1.22% of it was from urea production. The disposal stage had the smallest contribution to FED, which contrasted with the GHG results, where it was the highest. This difference was because the coconut waste was disposed of in the landfill that did not use fossil fuels.

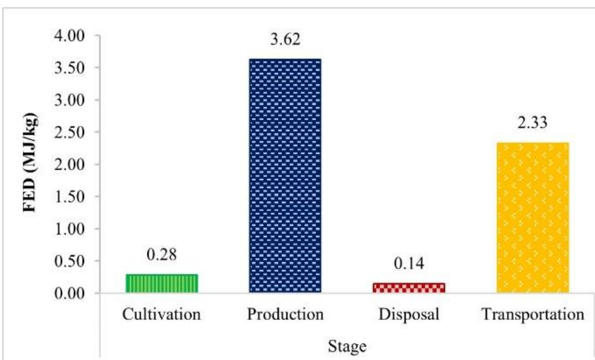

Fig. 3. The FED of coconut milk ice cream for each stage

3.3 Sensitivity analysis

From the baseline results, coconut waste disposed of in the landfill was identified as the primary contributor to GHG emissions of ice cream. To determine the influences of waste management on the final GHG emissions of ice cream products, three scenarios were conducted, assuming all other inputs were constant. The disposal of coconut waste was assumed to be reduced by: 1) incineration, 2) composting, and 3) combined methods (waste-to-energy and animal feed), using coconut husk and shell as substitute fuel to generate electricity, and substituting soybean meal with coconut pulp as animal feed. The protein content of coconut pulp was approximately 3.91% [32, 33], thus 3.29 g of coconut pulp could be used to replace soybean meal. Coconut waste management using different methods had a significant impact on the overall GHG emissions of the coconut milk ice cream, as shown in Fig. 4.

The greatest GHG savings would result from using coconut husk and shell as a substitute fuel for producing electricity and replacing soybean meal with coconut pulp for animal feed (Scenario 3), resulting in a GHG reduction of 88.77% compared to the baseline result. The disposal of coconut waste through incineration (Scenario 1) resulted in a GHG reduction of 51.39%, and composting (Scenario 2) led to a GHG reduction of 49.42%, compared to the baseline result. Although composting coconut waste could significantly reduce GHG emissions, the study did not consider the decomposition time of coconut waste, especially coconut shells, which could take several years to decompose (on average about 2 to 5 years) [34, 35] and require extensive land area for the process. This could limit the efficiency of composting as a waste management strategy to reduce GHG emissions. Furthermore, the conversion of land to composting areas could impact the overall GHG emissions of ice cream. However, this study excluded the impact of land use change on GHG emissions due to focusing on the direct emissions from waste management strategies. Including the impacts of land use change would require more extensive data and analysis, which were outside the scope of this research.

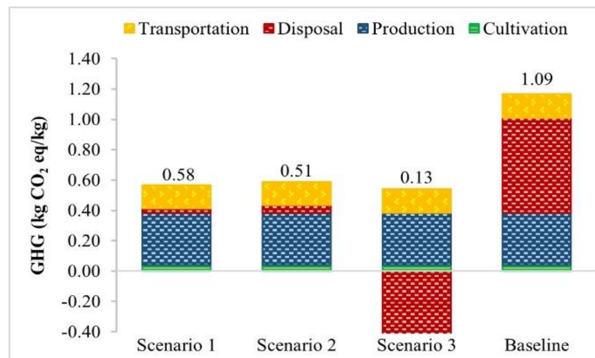

Fig.4. The GHG emissions of coconut milk ice cream from various waste utilization scenarios compared to the baseline.

This LCA analysis had limitations when considering the cradle-to-gate approach. Retail distribution and end-of-life disposal processes were not considered due to the lack of data on refrigerated transport, distribution to retail shops, and the electricity consumption of refrigeration in each shop. Furthermore, the emission factor values of some materials were not available, so profiles of other materials with similar chemical properties were used as substitutes. As these factors were constrained, the analyses of GHGs and FED results for coconut milk ice cream were limited accordingly.

Overall, the results concluded that waste disposal was a significant source of GHG emissions, while the production was a primary contributor to FED. The study recommended using sustainable waste management through composting, incineration, and combined methods over landfill disposal for coconut waste to mitigate GHG emissions. Other strategies to reduce GHGs and FED included maintaining freezers, insulating refrigerant pipes, adopting solar panels, using less processed sugars, sourcing coconuts locally, and switching to organic fertilizers to promote sustainable agriculture. The study estimated that the annual GHG emissions from the overall process were approximately 81,110 kg CO_2 eq, and the FED was about 443,319 MJ.

4. CONCLUSIONS

This study evaluates the GHG emissions and FED for coconut ice cream, using an ice cream factory as a case study. The study was conducted using a cradle-to-gate approach, which included all aspects of the farm to factory logistics and supply chain, as well as the waste disposal process. The functional units for both GHG emissions and FED for coconut ice cream were one kilogram of ice cream.

The analysis highlights waste disposal as a major source of GHG emissions, and identifies the production stage as a main contributor to FED. The results from the study suggest that to mitigate GHG emissions, incineration should be adopted for coconut waste management instead of landfill disposal. Other options for reducing GHGs and FED include regularly maintaining the deep freezer, insulating refrigerant pipes, adopting solar panels, switching from refined sugar to coconut sugar or raw sugar, sourcing coconuts from locations closer to the factory, and shifting from inorganic fertilizer to organic fertilizer.

The findings of this study can better inform ice cream producers and vendors to understand and manage their emissions and also provide information for consumers to make purchasing decisions. Communities and policymakers can use this information to support local businesses while promoting sustainable development of local industries and the environment.

In future studies, there is a need to improve the methods used to address the limitations and uncertainties of research. The LCA analysis of coconut milk ice cream, using a cradle-to-grave approach, is necessary to gain a more comprehensive understanding. In addition, improving the recipe by reducing sugar content or substituting with sugars that emit fewer GHGs, along with implementing specific food technology processes, should be considered to move towards sustainable production in the agri-food system. Further research is needed to assess other environmental aspects, including ozone depletion, to gain a better understanding of environmental consequences. Additionally, it is important to determine the decomposition times of various coconut waste components and evaluate the effect of land use changes caused by composting on GHG emissions. This approach can provide more comprehensive and accurate data on the environmental impacts associated with various waste management scenarios.

ACKNOWLEDGEMENT

We wish to thank the ice cream factory for allowing us to collect the required data, regarding the production of ice cream. Thanks also to Mr. Roy I. Morien of the Naresuan University Graduate School for his editing of the grammar, syntax, and general English expression in this manuscript.

REFERENCES

[1] Crippa, M., et al. 2021. Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature Food* 2(3): 198–209.

[2] Tubiello, F.N., et al. 2022. Pre- and post-production processes increasingly dominate greenhouse gas emissions from agri-food systems. *Earth Syst. Sci. Data* 14(4): 1795–1809.

[3] Lindner, J. 2023. The most surprising ice cream consumption statistics and trends in 2024. [cited 2024 February 17]; Available from: https://gitnux.org/ice-cream-consumption-statistics/

[4] CEIC. Thailand production: Ice cream. [cited 2024 June 2]; Available from: https://www.ceicdata.com/en/thailand/production-manufactured-goods-isic-rev-4/production-ice-cream

[5] Thai PBS. 2024. Thailand is Asia's leading ice cream exporter. [cited 2024 March 28]; Available from: https://www.thaipbsworld.com/thailand-is-asias-leading-ice-cream-exporter/

[6] Choudhury, N.R. 2021. Plant-based ice-creams market: Global plant-based ice-creams market snapshot (2023 to 2033).

[7] Phanphisit, S. 2023. Coconut milk ice cream—cut ice cream—invites you to follow the journey of Thai ice cream around the world. [cited 2024 February 17]; Available from: https://www.creativethailand.org/article-read?article_id=33838

[8] Kateman, B. 2020. Plant-based ice cream is flying off the shelves. [cited 2024 May 25]; Available from: https://www.forbes.com/sites/briankateman/2020/01/21/plant-based-ice-cream-is-flying-off-the-shelves/

[9] Curran, M.A. 2013. Life cycle assessment: a review of the methodology and its application to sustainability. *Current Opinion in Chemical Engineering* 2(3): 273–277.

[10] Garcia-Suarez, T., et al. 2008. Greenhouse gas assessment of Ben & Jerry's ice-cream: Communicating their 'Climate Hoofprint'. In: *6th Int. Conf. on Life Cycle Assessment in the Agri-Food Sector*. Zurich, Switzerland.

[11] Konstantas, A., Stamford, L., Azapagic, A. 2019. Environmental impacts of ice cream. *Journal of Cleaner Production* 209: 259–272.

[12] Scottish Government. 2011. Scottish dairy supply chain greenhouse gas emissions. *Methodology Report*.

[13] Foster, C., et al. 2006. Environmental impacts of food production and consumption: A report to DEFRA. Manchester Business School, Department for Environment, Food & Rural Affairs, London.

[14] Wróbel-Jędrzejewska, M., Polak, E. 2023. Carbon footprint analysis of ice cream production. *Sustainability* 15(8).

[15] Finkbeiner, M., et al. 2006. The new international standards for life cycle assessment: ISO 14040 and ISO 14044. *Int. J. Life Cycle Assess.* 11(2): 80–85.

[16] Ecoinvent Centre. 2019. Ecoinvent Database.

[17] Dinromrum, N. 2022. *Things about coconut*, 2nd ed. Petchnaka.

[18] DOA. 2020. Coconut production. [cited 2023 May 15]; Available from: https://doa.go.th/hort/wp-content/uploads/2020/01/coconut-production.pdf

[19] Chitibut, W., Poapongsakorn, N., Aroonkong, D. 2014. Fertilizer policy in Thailand.

[20] Moura, J., et al. 2013. Applying boron to coconut palm plants: Effects on soil, plant nutritional status, and

productivity. *J. Soil Sci. Plant Nutr.* 13: 79–85.

[21] DLD. 2018. The expense of precise land preparation for planting Rayong 69 cassava. [cited 2022 February 20]; Available from: https://nutrition.dld.go.th/nutrition/images/pdf/techno61/8.br61.pdf

[22] Puspaningrum, T., et al. 2023. Life cycle assessment of coconut plantation, copra, and charcoal production. *Global J. Environ. Sci. Manage.* 9(4): 653–672.

[23] HRI. 2020. Coconut. Horticulture Research Institute, DOA. [cited 2021 March 21]; Available from: https://www.doa.go.th/hort/?page_id=11232

[24] Klein, C.D., et al. 2006. IPCC guidelines for national greenhouse gas inventories, Volume 4. [cited]; Available from: http://www.ipcc-nggip.iges.or.jp/public/2006gl/

[25] Thai National LCI. 2022. Emission factor. TIIS MTEC–NSTDA; Available from: https://thaicarbonlabel.tgo.or.th

[26] Bhatia, P., et al. 2011. Greenhouse Gas Protocol: Product life cycle accounting and reporting standard. World Resources Institute.

[27] Frischknecht, R., et al. 2015. Cumulative energy demand in LCA: The energy harvested approach. *Int. J. Life Cycle Assess.* 20(7): 957–969.

[28] Hoklis, C., Sharp, A. 2014. Greenhouse gas emission from municipal solid waste in Phnom Penh, Cambodia. *GMSARN Int. J.* 8: 73–78.

[29] Wongsoonthornchai, M., Thitanuwat, B. 2024. Carbon footprint of food waste handling and disposal: A case study of Sam Khok, Pathum Thani Province, Thailand. *GMSARN Int. J.* 18: 285–290.

[30] Poore, J., Nemecek, T. 2018. Reducing food's environmental impacts through producers and consumers. *Science* 360: 987–992.

[31] Ritchie, H. 2022. Dairy vs. plant-based milk: What are the environmental impacts? [cited 2024 February 21]; Available from: https://ourworldindata.org/environmental-impact-milks

[32] Limmanee, M., Rumpagaporn, P. 2017. Preparation of coconut residue for chemical modification. In: *Proc. 55th Kasetsart Univ. Conf.*, Bangkok, Thailand.

[33] Chupraphawan, Y., et al. 2019. Increasing protein level and decreasing fiber level of coconut meal by fungal fermentation. *Khon Kaen Agric. J.* 47(2): 635–642.

[34] Decompose Time. 2023. What is the decomposition time of coconut shell? [cited 2024 June 2]; Available from: https://decompositiontime.com/coconut-shell/

[35] Moujoud, Z., et al. 2023. Study of fired clay bricks with coconut shell waste: Technological and thermal properties. *J. Build. Eng.* 68: 106107.