Thai Environmental Engineering Journal Vol. 39 No. 1 (2025) : 1-11
www.eeat.or.th

Life Cycle Assessment of Plant-Based Milk Incorporating Functional Ingredients

Panusorn Hunsub[1], Kamonthip Nilmat[2], Nut Thephuttee[1], Pitchaya Pothinuch[1], Tarit Apisittiwong[1] and Nattapong Prichapan[1*]

[1]Faculty of Food Technology, College of Agricultural Innovation and Food Technology, Rangsit University, Pathum thani 12000, Thailand
[2]Institute of Biotechnology and Genetic Engineering, Chulalongkorn University, Bangkok 10330, Thailand
[*]E-mail : nattapong.p@rsu.ac.th

Article History; *Received: 30 June 2024, Accepted: 27 January 2025, Published: 30 April 2025*

Abstract

As a sustainable source, the plant-based product has gained popularity in the food industry over the last decade. This study adopted a life cycle assessment (LCA) to evaluate the environmental impacts and identify critical points of plant-based milk incorporating functional ingredients, addressing the existing gap in understanding their incorporation from an environmental perspective. The cradle-to-gate analysis encompassed raw material acquisition, including the agricultural stage, functional ingredient procurement, processing-stage resource consumption (emission, water, steam, and electricity), and waste treatment in manufacturing. Six investigated scenarios were formed by combining three types of plant-based milk (soybean, rice, and pea) with two sources of additional alternative protein (pea protein concentrate and insect powder), mangosteen peel extract as antioxidant, and fructo-oligosaccharide (FOS) as dietary fiber, defining 1 L of milk without packaging as a functional unit (FU). The modeling was conducted using Simapro software 9.0, and the assessment was implemented via the IMPACT 2002+ method. The results showed that pea milk had a lower environmental impact in 8 out of 15 categories, followed by rice and soybean milk in 3 and 4 out of 15 categories. The fortification of plant-based milk with FOS should not be utilized in formulation due to the potential for problem shifting and the occurrence of significant adverse environmental impacts. The major hotspot comes from energy consumption in processing and freeze-drying. The adoption of insect powder exhibited a lower impact than pea protein concentrates in carcinogens, non-carcinogens, aquatic ecotoxicity, terrestrial ecotoxicity, land occupation, aquatic eutrophication, and mineral extraction. The results also indicated that producing functional ingredients, especially FOS, generated a substantial environmental impact. Improvement solutions are also discussed. A large amount of generated biowaste from plant-based milk production could be promising feed to insects due to their residue nutritional value. Therefore, the credits of biowaste for the avoided animal feed mitigated the environmental impact. The incorporation of functional ingredients for nutritional fortification in plant-based milk could be assessed through a comprehensive life cycle assessment to prevent problem shifting.

Keywords : plant-based milk; life cycle assessment; pea protein concentrate; insect powder; mangosteen peel extract

Introduction

The plant-based product and alternative sources of protein play crucial roles in the rapidly expanding global market, as consumers increasingly opt for plant-based alternatives over dairy milk. Mainly, health-conscious consumers prioritize environmental awareness, nutrition, and ethical considerations. Furthermore, there is a growing environmental consciousness and responsibility, aiming to reduce environmental impacts such as eutrophication, ecotoxicity, fossil fuel depletion, and carcinogenicity compared to dairy milk [1]. The market for dairy alternatives is experiencing rapid growth within the plant-based food sector, gaining traction worldwide. It is anticipated to increase by over 439.43 billion THB between 2018 and 2023 [2]. Aligned with sustainable development goals (SDGs), this trend fosters encouragement within the food sector [3].

Plant-based milk originates from diverse sources, including cereals, legumes, nuts, oilseeds, pseudo-cereals, and others [4]. The rise and expansion of plant-based milk can be attributed to several factors, including milk protein allergies, lactose intolerance, and dietary preferences such as veganism and vegetarianism. Generally, plant-based milk exhibits lower protein quality and available calcium, but higher glycemic index values compared to bovine milk. However, it contains various health-beneficial components such as dietary fiber, essential fatty acids, vitamin E, and antioxidants that are lacking in bovine milk [5, 6]. Despite offering certain health benefits and mitigating allergy risks associated with cow's milk protein and lactose intolerance, plant-based milk often lacks essential micronutrients in adequate quantities. Therefore, the nutritional fortification of plant-based milk alternatives presents an effective solution.

The poor nutritional value of plant-based milk, particularly its low protein content, is a significant concern. Therefore, fortification with protein concentrates and isolates could effectively address this issue. However, in terms of nutrition, rice, and pea milk present disadvantages due to its lower protein content compared to soybean milk. The FOS are non-digestible carbohydrates that could be used as a low-calorie alternative sweetener or sugar substitute. It could also improve the texture of food products. For health benefits, FOS exhibits prebiotic activity, boosts immunity, improves mineral absorption, and reduces the absorption of triacylglycerols and cholesterol [7]. The mangosteen peel extract could be utilized to fortify antioxidant and anti-inflammatory properties. Previous studies have demonstrated that it contains xanthones, anthocyanins, tannins, phenolic acids, flavonoids, and other polyphenolic compounds, particularly α-mangostin, at approximately 69% [8]. Furthermore, nutrients in mangosteen peel extract exhibit antibacterial, anti-aging, anti-hyperpigmentation, anti-obesity, antidiabetic, and antitumor activities [9]. Pea is one of the most popular sources of vegetable proteins due to its accessibility, superior returns, and cost-effective manufacturing. Additionally, pea protein is generally considered a non-food allergen with notably high nutritional content and no genetic modification, presenting a clean label for food manufacture. Moreover, pea protein is rich in lysine, which is deficient in cereals [10]. Therefore, rice milk fortified with pea protein could complement the protein quality and balance this deficiency. Finally, cricket powder was used in this research owing to its high protein content, phenolic content, antioxidant, and anti-inflammatory activities. Additionally, cricket protein also exhibits high gastrointestinal digestibility. Moreover, cricket powder is safe, and its production is environmentally sustainable [11]. Therefore, cricket powder is one of the most popular alternative animal protein sources.

The LCA methodology, in accordance with ISO 14040/44 standards, is widely used to evaluate environmental performance and to identify and compare different scenarios for the design of optimally sustainable systems. It consists of the purpose and scope definition, the life cycle inventory, the life cycle impact assessment, and the life cycle interpretation. Furthermore, the term 'cradle-to-gate' encompasses the stages of agricultural production and raw material extraction, transportation to manufacturing facilities, and product processing, including cleaning, grinding, extraction, filtration, pasteurization, and fortification along with energy consumption, emissions, and waste treatment and management [2].

The environmental impacts of milk production have contributed significantly to global warming potential, accounting for 48-65% due to methane emissions, and to acidification potential, accounting for 78-97% due to ammonia volatilization. While transitioning to organic milk production may reduce pesticide use, it is associated with increased land requirements [12]. On another aspect, oat milk demonstrated an 80% reduction in greenhouse gas emissions compared to traditional cow's milk. Additionally, oat milk exhibited significantly lower water consumption compared to almond milk [13]. A comparative LCA of dairy milk and plant-based milk, based on 1 liter of milk, revealed the following impacts: dairy milk exhibited eutrophication potential of more than 0.005 kg N, ecotoxicity of more than 100 comparative toxic units (CTUe), approximately 3 MJ surplus of fossil fuel depletion, 10 liters of water intake, and nearly 40 MJ of cumulative energy demand. In contrast, soy milk showed eutrophication potential of less than 0.0001 kg N, ecotoxicity of less than 10 CTUe, approximately 1.7 MJ surplus of fossil fuel depletion, nearly 10 liters of water intake, and more than 40 MJ of cumulative energy demand. Overall, dairy milk demonstrated the highest impacts on ozone depletion, eutrophication, smog, ecotoxicity, fossil fuel depletion, and carcinogenic potential [1]. In addition, the environmental advantages of plant-based milk, including almond, oat, soy, pea, and coconut milk over dairy milk are evident, with lower levels of global warming potential, land use, eutrophication, ozone depletion, ecotoxicity, and fossil fuel depletion [14]. Notably, as reported by Winans et al. [2], the global warming potentials (GWPs) of dairy milk ranged from 1.80 to 1.97 kg CO_2 equivalent per 48 oz. of milk, which exceeded those of almond, pea, soy, coconut, and oat milk, ranging from 0.39 to 0.58, 0.44, 0.24 to 1.21, 0.58, and 0.54, respectively. Therefore, transitioning to plant-based milk could represent the most effective strategy for reducing greenhouse gas emissions. However, the environmental benefits of incorporating plant-based milk regarding human health, ecosystem quality, global warming, and resource conservation remain uncertain. Further analysis and interpretation of product development are necessary to clarify these aspects and eco-design new products to minimize environmental impact.

Despite the considerable research on plant-based milk, there remains a lack of understanding regarding incorporating functional ingredients from an environmental perspective. Therefore, this study aimed to conduct a comparative assessment of plant-based milk fortified with different functional ingredients using the life cycle assessment (LCA) methodology, focusing on environmental impacts to facilitate further improvements.

Methodology

Production of plant-based milk

For functional ingredients, the insect powder (100% house cricket, *Acheta domesticus* L., containing 70% protein, 10% fat, 2.6% carbohydrate, 3.57-5.10% ash) was supplied by Protanica Co., LTD., Thailand, whereas mangosteen peel (*Garcinia mangostana* L.) powder was purchased from Healthy Hills Farm Co., LTD., Thailand. Pea protein (80% protein, 6.9% fat, 5.6% carbohydrate, 4.4% dietary fiber) and FOS (90% dietary fiber) were purchased from Krungthepchemi, Thailand.

Plant-based milks were prepared using the following methods: dry soybeans or rice were soaked separately in water for 6 hours, drained, and washed. Subsequently, soybeans, rice, or peas were blended with water at a ratio of 1:7 using a blender for 5 minutes, followed by filtration through a straining cloth. The plant-based milks were then boiled at 90°C for 10 minutes. Next, 5% pea protein concentrate, or cricket powder, was added to the plant-based milk, followed by 5% FOS. The resulting plant-based milk was homogenized using the IKA T25 ULTRA-TURRAX® homogenizer for 5 minutes. Afterward, the plant-based milks were boiled at 72°C for 10 minutes. Additionally, 0.5% mangosteen peel extract obtained through hot water extraction was added to the plant-based milk. Finally, the plant-based milks were cooled down for approximately 30 ± 5 minutes in an ice-water bath and stored at 4°C.

Life cycle assessment

The LCA study was conducted following ISO 14040/44. The goal of this study is to investigate and compare the environmental impacts associated with each plant-based milk production incorporating functional ingredients from cradle-to-gate. The system encompasses the life cycle stages, including the agricultural production of raw materials (soybean, rice, and pea), the production of pea protein concentrate, insect powder, FOS, and mangosteen peel extract as functional ingredients, transportation to the processing facility, and the manufacturing of plant-based milk. This includes processes such as raw material utilization, water consumption, energy use, emissions, and waste treatment. For waste management, seed residue waste was treated as biowaste, and wastewater from the production chain was subjected to wastewater treatment. The analysis was conducted within a cradle-to-gate system boundary, as illustrated in Figure 1. The boundary excludes milk packaging, transportation to retail stores, consumer use, end-of-life disposal, facility construction, capital equipment, and infrastructure from the life cycle. The functional unit (FU) is defined as 1 L in (a) soybean milk, (b) rice milk, and (c) pea with functional ingredients in various scenarios associated with the production. The fortification comprised FOS as a prebiotic, an antioxidant agent, and an alternative protein. Data were collected from experimental data, used in the Ecoinvent 3.5 database by using the cut-off system model, Agri-footprint 4.0 database, and compiled from existing literature presented in Table 1. Inventory data for each scenario is shown in Table 2.

The modeling was conducted using the LCA SimaPro 9.0 software, employing the IMPACT 2002+ methodology. It included the following four damage categories: human health, ecosystem quality, climate change, and resource depletion. Midpoint categories consisted of carcinogens (CG), non-carcinogens (NCG), respiratory inorganics (RI), ionizing radiation (IR), ozone layer depletion (OLD), respiratory organics (RO), aquatic ecotoxicity (AEC), terrestrial ecotoxicity (TE), terrestrial acid/nutrition (TA), land occupation (LO), aquatic acidification (AA), aquatic eutrophication (AE), global warming (GWP), non-renewable energy (NRE), and mineral extraction (ME) that all aligned with the comprehensive impact of the food industry. The drying data of mangosteen peels was obtained from García et al. [8], and Rodríguez-Meizoso et al. [16]. The LCI of FOS was obtained from Gerbino et al. [15]. Briefly, the production used yacon potato with autohydrolysis without allocation. The 100% Cricket powder (*Acheta Domesticus*) was harvested from 1,176.5 tons/ 10,000 m^3 of farmland. The Life cycle inventory data of 1 L of each plant-based milk production is shown in Table 2.

Results and Discussion.

Life cycle assessment

For interpretation, the process comprises seven steps: soaking, extraction (using a disintegrator), separation (via a filter press), formulation, nutrient fortification, homogenization, and heat treatment, which are discussed in detail below for each stage. The environmental impact of the materials, as assessed by the IMPACT 2002+ method, is depicted in Figure 2.

In agricultural production, when comparing the same amount of rice, soybeans, and peas, it was found that peas exhibited the lowest contribution to 7 out of the 15 midpoint impacts, including CG, RI, IR, OLD, RO, LO, AE, and GWP. For endpoints, peas showed the lowest impact on human health and climate change, while soybeans exhibited the lowest impact on resource depletion. The environmental impact of 1 kg of pea seed includes; (1) human health: 66.2% of the impact is attributed to pea production processes such as combined harvesting, application of phosphate fertilizer (P_2O_5), and harrowing tillage, with an additional 11.6% attributed to transport via sea transoceanic ship, (2) ecosystem quality: this is influenced by activities related to pea seed for sowing, application of plant production via field sprayer, and combined harvesting, (3) climate change: 67.9% of the impact arises from pea production activities, including combined harvesting, application of phosphate fertilizer, and pea seed for sowing, with an additional 10.4% attributed to freight transportation, (4) resource: 59.4% of the impact is due to pea production processes and freight transportation. On the other hand, the environmental impact of 1 kg of soybeans includes; (1) human health: arising from land use change in annual crops due to land tenure and diesel burned in building machine processing, (2) ecosystem quality: influenced by activities related to seed for sowing, application of plant production via field sprayer, and combined harvesting, (3) climate change: stemming from land use change in annual crops due to land tenure, (4) resources: resulting from combined harvesting and freight transportation. In contrast, the environmental impact of 1 kg of rice is primarily attributed to irrigation processing and drying of the grain. This stage typically requires high quantities of water and electricity consumption.

In terms of functional ingredients are depicted in Figure 3, focusing on sustainable sources. FOS, as a prebiotic, resulted in climate change from freeze-drying and extracting processes [15]. The freezing of the supernatant for storage emerged as the primary hotspot, making the highest contribution to 10 out of the 15 midpoint impacts, followed by substrate extraction, which contributed to 4 out of the 15 midpoint impacts, along with RO in the purification stage due to freeze-dried in water solution. Moreover, antioxidant extract was extracted and analyzed for LCA, as described in [8]. Using agricultural waste as a raw material would not contribute to environmental burdens in the cultivation stage and previous stage. Therefore, more attention should be paid to leaves and peels [16]. The result in Figure 3 (b) shows that electricity for drying mangosteen peels could be the main environmental impact.

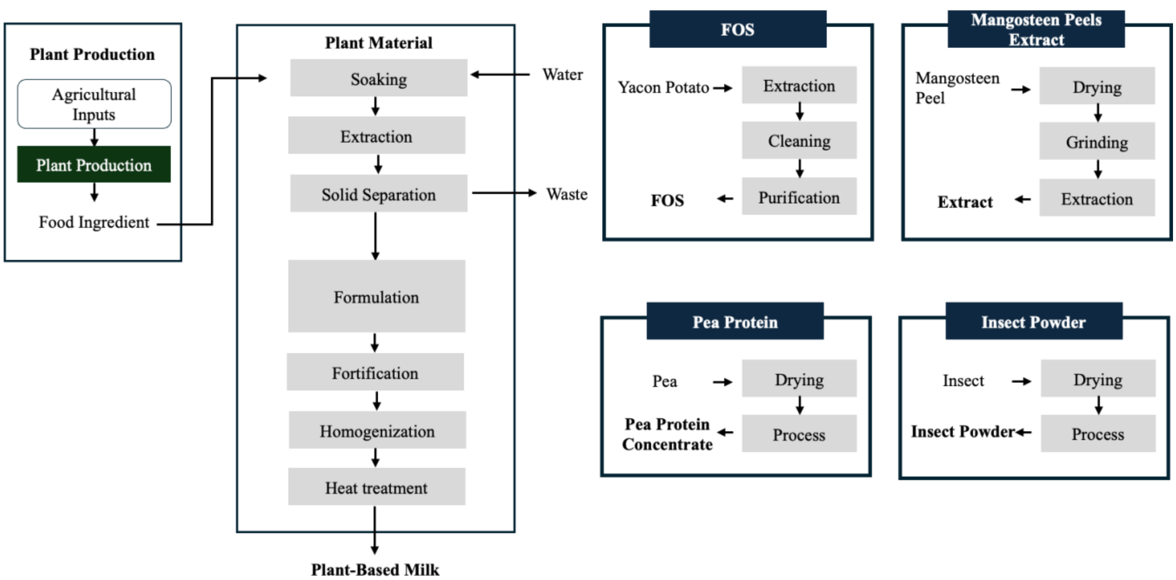

Figure 1 System Boundary

Table 1 Functional ingredients used for fortification

Name	Specification	Reference
1. FOS	Prebiotics, fiber, and alternative sweeteners	[15]
2. Mangosteen peel extract	Antioxidant and anti-inflammatory activities	[8, 16]
3. Protein		
a) Pea protein concentrate	75% protein, 5% fat, and 3% carbohydrate	Agri-footprint
b) Insect powder	70% protein, 10% fat, <10% carbohydrate, 0.3% Cholesterol, and 0.4% Sodium	[17]

Table 2 Life cycle inventory of 1 L of plant-based milk production

		Soybean milk (S1)		Rice milk (S2)		Pea milk (S3)	
Inputs	**Unit**	**Pea protein concentrate (S1.1)**	**Insect powder (S1.2)**	**Pea protein concentrate (S2.1)**	**Insect powder (S2.2)**	**Pea protein concentrate (S3.1)**	**Insect powder (S3.2)**
- Seeds	g	336.28	340.14	342.17	339.07	186.22	181.87
- Tap Water	L	2.35	2.38	2.40	2.37	1.30	1.27
- Electricity	kWh	0.0583	0.0583	0.0583	0.0583	0.0583	0.0583
- Steam [a]	kg	0.30	0.30	0.30	0.30	0.30	0.30
- FOS	g	67.3	68.0	59.88	59.34	50.55	49.36
- Pea protein concentrate	g	67.3	-	59.88	-	50.55	-
- Insect powder	g	-	68.0	-	59.34	-	49.36
- Extract	g	6.7	6.8	5.99	5.93	5.05	4.94
Outputs							
- Product	L	1.00	1.00	1.00	1.00	1.00	1.00
- Solid waste (Biowaste) [b]	g	768.64	777.45	1075.40	1065.66	292.63	285.79
- Wastewater [c]	cm^3	955.47	967.66	975.79	963.60	528.56	516.36

Note: (a) data from Ecoinvent database, (b) Biowaste {RoW}| market for | Cut-off, U, and (c) Wastewater, average {RoW}| market for wastewater, average | Cut-off, U

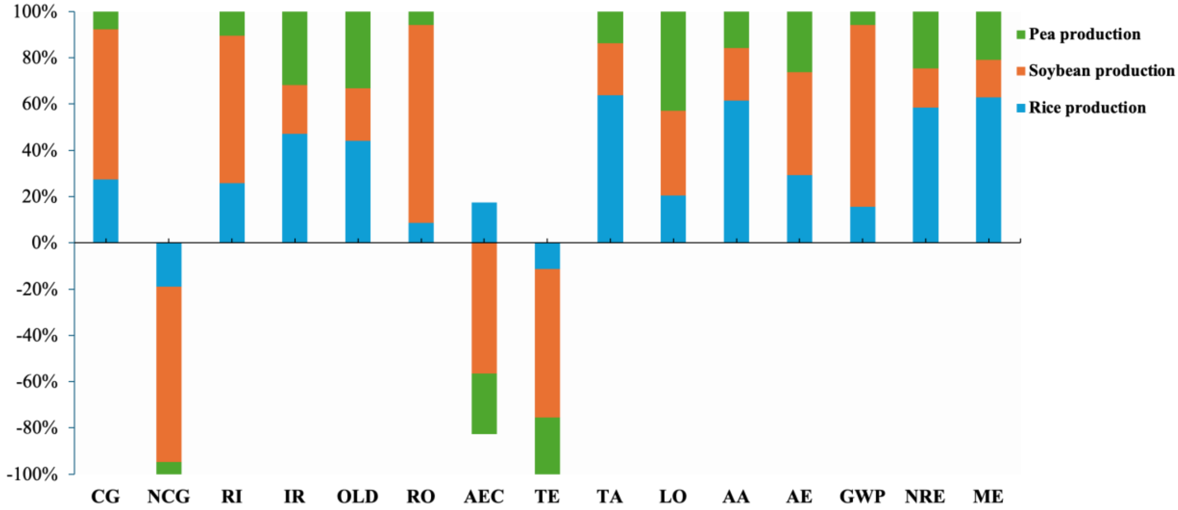

Figure 2 Environmental Impact of Materials

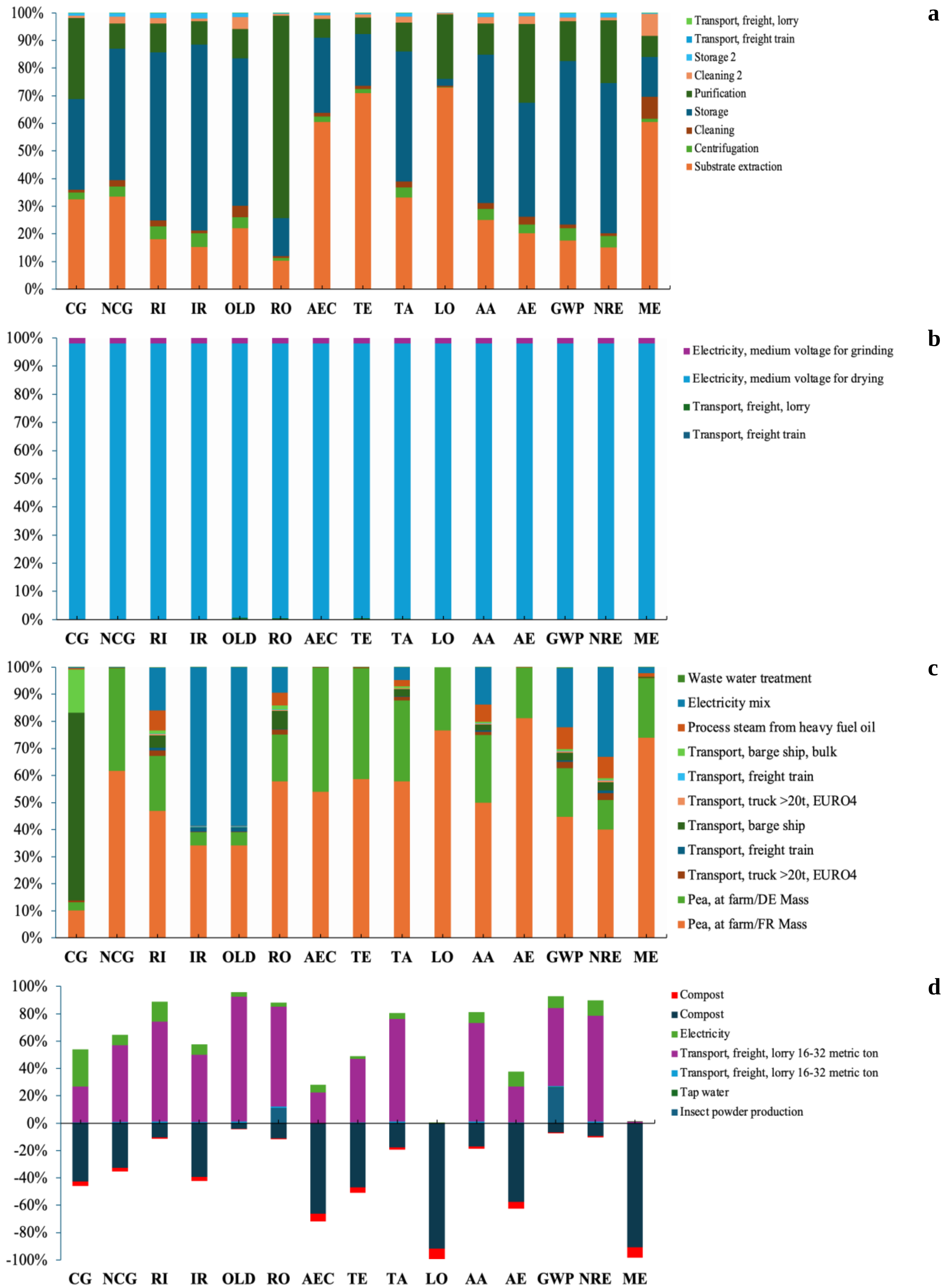

Figure 3 Environmental Impact of Functional Ingredients of (a) FOS, (b) Mangosteen Peel Extract, (c) Pea Protein Concentrate, and (d) Insect Powder

There are two scenarios for alternative protein fortification, which are being compared regarding their environmental impact. First, pea protein concentrate primarily originates from pea production at the farm, contributing to 12 out of 15 midpoint impacts. The exceptions include carcinogens in barge ship transportation, ionizing radiation, and ozone layer depletion in electricity production. In the second alternative, insect powder provides lower because it avoids biowaste treatment. In Thailand, approximately 7,500 metric tons of crickets are produced annually from 20,000 farms [17]. The environmental impact of insect powder was lower than pea protein concentrates in CG, NCG, AEC, TE, LO, AE, and ME. However, pea protein concentrates exhibit differences in RO, IR, OLD, RO, TA, AA, GWP, and NRE. Therefore, selecting alternative proteins could be considered in detail before utilization. The result corresponds to Heusala et al. [18], which shows that legume protein concentrate was lower by 50% compared to animal protein sources per kg protein.

During the process, steam and medium-voltage electricity are utilized in the chemical industry. Additionally, the process generates a substantial amount of biowaste and wastewater. The environmental impact affects human health and ecosystem quality due to production, while global warming and resource depletion primarily stem from chemical industry streams. It also generated biowaste from this product of 2.47 g and wastewater of 4.978 L. The use of FOS led to an environmental impact. Global warming increased from 0.46 to 12.78 kg CO_2 equivalent, and aquatic ecotoxicity increased from 77.72 to 3286.46 kg TEG water in scenario S1.1. The overall environmental impact results followed the same pattern across all scenarios, showing an increase of over 95%. Therefore, adding FOS in plant-based milk should not added to the formula in terms of environmental impact. For the overall life cycle assessment of each plant-based milk formula, the environmental impact of plant-based milk fortified with different functional ingredients was analyzed and shown in Figure 4. The result showed that pea milk fortified with insect power had the lowest environmental impact with the lowest environmental impact in 8 out of 15 categories. On the contrary, soybean milk fortified with insect power had the highest environmental impact with the highest environmental impact in 8 out of 15 categories.

Daily milk contributes significantly to global greenhouse gas due to methane emissions produced by approximately 2.4-3.6 kg of CO_2 equivalents per liter, water use for growing feed crops, land use for feed crops, and eutrophication from fertilizers and manure. In plant-based milk generally has a lower environmental impact (cradle to gate without electricity at retail and transportation from factory to retail) in terms of eutrophication, ecotoxicity, fossil fuel depletion, and cumulative energy demand compared to dairy milk. However, plant farming can contribute to deforestation, it still requires energy and water, particularly during processing and pasteurization [1]. In this finding, fortified plant-based milk may have slightly higher emissions than unfortified versions due to processing and ingredient sourcing. Plant-based milk is fortified with different functional ingredients to enhance the nutritional profile of plant-based milk but slightly increases its environmental impact. The production and transportation of nutrients require energy and resources, increasing the overall carbon footprint. For instance, calcium fortification has been shown to contribute approximately 10-15% more emissions to the total environmental footprint [19].

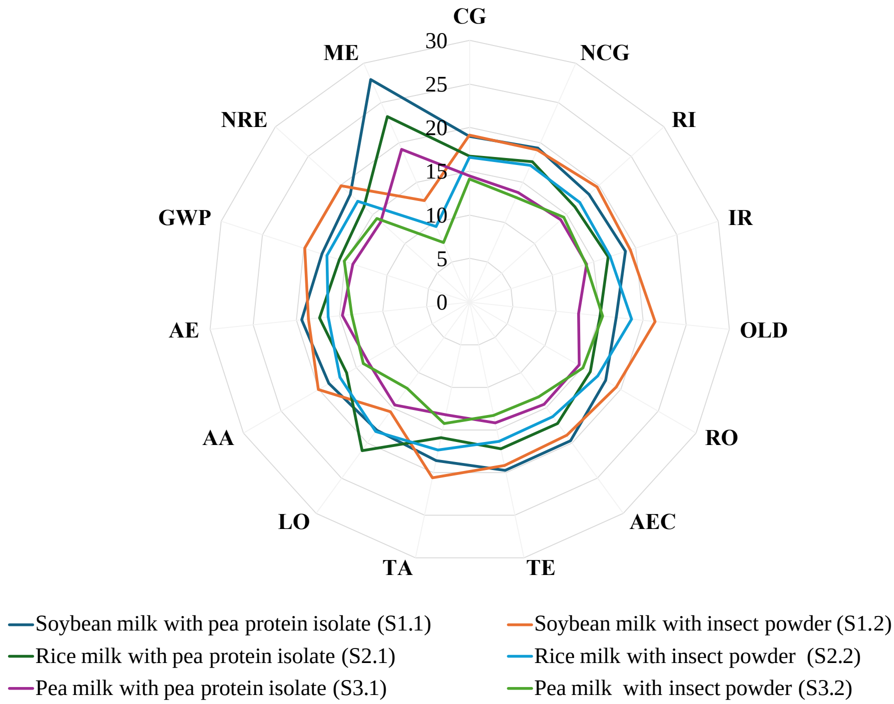

Figure 4 Environmental Impact of Plant-Based Milk

Analysis for further improvement

This work only focused on the volume of milk production as a FU. However, the comprehensive nutritional value of calories, kilogram protein, or essential amino acids should be accounted for in the allocation of environmental assessments. Extending the system boundaries to a cradle-to-grave analysis provides a more accurate and comprehensive assessment, leading to better decision-making, clearer environmental policies, and more sustainable product offerings. To mitigate environmental impact, insect powder, serving as an alternative protein, could utilize biowaste generated from plant-based production. Utilizing waste treatment to produce animal feed for insect cultivation presents a promising strategy with potential benefits. Investigating alternative processes and sources for producing prebiotics via green extraction methods could be further considered. Besides, implementing a transition to solar energy for electricity could effectively mitigate environmental impact. Further improvement could be implemented to align with sustainable practices within the food industry. To improve the reliability and relevance of LCA studies, it is crucial to consider these factors and apply sensitivity analysis to understand the robustness of the results.

Conclusions

The findings reveal that fortifying plant-based milk with functional ingredients to enhance the nutritional profile increases its environmental impact due to additional processing and sourcing of ingredients. It could be assessed in a comprehensive life cycle assessment to prevent problem shifting associated with adopting renewable sources, sustainable ingredient sourcing, and efficient production methods. Agricultural products are the primary contributors, followed by steam, water consumption, and biowaste treatment. Moreover, fortification enriches the product in terms of dietary fiber, antioxidant compounds, and protein content which is often deficient in plant-based products. The addition of pea protein concentrates and insect protein for fortification had been suggested for formulation. However, the use of FOS had not been recommended due to its significant environmental impact. In the context of sourcing and processing, apprehensions endure concerning the adoption of novel sustainable origins and eco-friendly technologies, which could be substantially alleviated through effective waste management strategies, encompassing the retrieval of valuable ingredients from waste materials. Perspectives from life cycle assessment have been identified for improvement. The nutritional fortification with processed ingredients should be reviewed to ensure consistency and alignment with life cycle assessment principles.

Acknowledgements

This research received the funding support from Rangsit Research Institute, Rangsit University, Thailand. The authors express their gratitude to the Food Processing Pilot Plant, and the Faculty of Food Technology, the College of Agricultural Innovation and Food Technology, Rangsit University, for equipment support. The authors also thank the Center of Excellence on Hazardous Substance Management, Chulalongkorn University, for their software support.

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