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Quality Evaluation and Shelf-Life Study of Ready-to-Eat Panang Curry Reformulated with Plant-Based Milk

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Abstract

This study was conducted to evaluate the microbial stability, physicochemical characteristics, and nutritional quality of Dusita ready-to-eat (RTE) beef Panang curry reformulated with corn-based plant milk as a healthier alternative to coconut milk. The objectives of this study were to: (1) evaluate microbial shelf-life under chilled (4 °C), frozen (−18 °C), and retort pouch sterilization conditions; and (2) investigate physicochemical properties (L*, a*, b*, pH, and total soluble solids) together with nutritional quality. Microbiological quality was evaluated using total plate count (TPC) and yeast and mold counts for chilled products, TPC and coliform enumeration for frozen products, and thermal lethality (F_0) validation for retort-processed products. Physicochemical characteristics and nutritional labeling were also determined. Results indicated that (1) under chilled storage, TPC exceeded the acceptable limit of 10^5 CFU/g by day 9, defining a practical shelf-life of approximately 8–9 days; (2) frozen storage effectively maintained microbial stability for at least three months, with no coliforms detected throughout storage; and (3) retort pouch sterilization achieved a thermal lethality (F_0) value of ≥6 min, ensuring product safety while inducing moderate physicochemical changes, including a color difference ($\Delta E \approx 9.91$), increased pH, and reduced soluble solids. Nutritional analysis demonstrated that replacing coconut milk with plant-based milk significantly reduced total and saturated fat by approximately 65–75% while maintaining comparable protein and energy levels. Overall, the findings demonstrate that a plant-based milk reformulation improves nutritional quality, while frozen storage and retort processing provide effective preservation strategies for extending shelf-life and ensuring product safety. These findings highlight the potential of plant-based reformulation and optimized preservation technologies for developing healthier and commercially viable Thai ready-to-eat products.

Keywords: Panang curry, Plant-based milk, Shelf-life, Retort processing

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Introduction

Ready-to-eat (RTE) foods represent one of the fastest-growing sectors of the global food market, driven by increasingly time-constrained lifestyles, urbanization, and growing consumer demand for convenient, safe, and nutritious meals (Jaeger et al., 2021). In addition to convenience, modern consumers increasingly seek foods that offer improved nutritional value while maintaining high standards of safety and quality. Consequently, the development of healthier ready-to-eat products using alternative ingredients has become an important research focus within the food industry.

Panang curry is one of Thailand's best recognized traditional dishes, distinguished by its rich aroma, balanced spiciness, creamy texture, and harmonious combination of herbs and spices. Traditionally, coconut milk is an essential ingredient that contributes to its characteristic flavor and mouthfeel. However, coconut milk is also a major source of saturated fatty acids, and excessive consumption has been associated with an increased risk of cardiovascular disease (Mensink, 2016). In response to growing health awareness, plant-based milk has emerged as a promising alternative because it generally contains lower levels of saturated fat together with higher proportions of unsaturated fatty acids and other beneficial nutrients (Sethi et al., 2016; Aschemann-Witzel et al., 2020). Despite these nutritional advantages, replacing coconut milk with alternative plant-based milk presents several technological challenges. Plant-based milk differs from coconut milk in emulsion stability, viscosity, and lipid composition, which may influence the physicochemical properties, microbial stability, and overall quality of the finished product. In particular, the absence of medium-chain fatty acids, such as lauric acid, may reduce the natural antimicrobial properties commonly associated with coconut milk. Therefore, evaluating the quality and

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stability of plant-based ready-to-eat curry products is essential before commercial application. Previous work by the authors investigated the substitution of coconut milk with corn-based plant milk in Panang curry and demonstrated that replacing 75% of the coconut milk produced the most acceptable formulation while reducing total fat content by more than 70% (Khunsee et al., 2026). However, that study primarily focused on formulation development and did not investigate product stability, preservation methods, or nutritional characteristics during storage. Consequently, additional research is required to determine the suitability of the developed formulation for commercial ready-to-eat applications. Ready-to-eat curry products are highly perishable because of their high moisture content and nutrient-rich composition, which favor microbial growth and physicochemical deterioration during storage (Fellows, 2017). Chilled storage can delay microbial proliferation but generally provides only a limited shelf-life of approximately 7–10 days (Koutsoumanis & Taoukis, 2005). Frozen storage substantially extends shelf-life by suppressing microbial and enzymatic activities; however, prolonged frozen storage may affect texture and product quality (Tan et al., 2020). Retort pouch sterilization offers another preservation approach by achieving commercial sterility, allowing ambient storage and facilitating long-distance distribution. Nevertheless, severe thermal processing may alter color, pH levels, soluble solids, and other quality attributes (Ramaswamy & Marcotte, 2006). Therefore, systematic evaluation of these preservation methods is necessary to determine their effects on microbial safety, physicochemical characteristics, and nutritional quality. Although previous studies have reported the nutritional benefits of plant-based ingredients and the effectiveness of various food preservation techniques, limited information is available regarding the combined effects of chilled storage, frozen storage, and retort processing on plant-based ready-to-eat Panang curry. Furthermore, comprehensive data describing microbial stability, physicochemical changes, and nutritional quality throughout these preservation methods remain limited.

Therefore, the objectives of this study were to: (1) evaluate the microbial shelf-life and safety of ready-to-eat Panang curry reformulated with plant-based plant milk under chilled (4 °C), frozen (−18 °C), and retort pouch sterilization conditions; and (2) investigate changes in physicochemical properties (L*, a*, b*, pH, and total soluble solids) together with nutritional quality in comparison with the conventional coconut milk formulation. The findings of this study are expected to provide scientific evidence supporting the development of healthier, safe, and commercially viable ready-to-eat Thai food products through appropriate formulation and preservation technologies.

Materials and methods

1. Materials

Fresh beef, Panang curry paste, herbs, spices, and plant-based milk were procured from certified local suppliers in Lampang Province, Thailand, to ensure ingredient freshness and uniform quality. The plant-based milk used in this study was derived from corn (Zea mays), selected from preliminary formulation trials and obtained from a certified commercial supplier. Stand-up aluminum foil retort pouches (12×18×3.0 cm) with high oxygen and moisture barrier properties were used as primary packaging for thermal processing and storage studies. All chemicals, reagents, and microbiological media used for physicochemical and microbiological analyses were of analytical grade and prepared according to standard laboratory procedures.

2. Sample preparation

Ready-to-eat (RTE) beef Panang curry was prepared following a standardized Thai culinary process under hygienic conditions. Beef was blanched prior to formulation to reduce surface microbial load. Each package consisted of blanched beef (90 g), curry sauce prepared with plant-based milk (45 g), red chili (2.5 g), kaffir lime leaves (2.5 g), and basil leaves (0.5 g), resulting in a net product weight of approximately 141 g/package. The prepared curry was filled into stand-up aluminum foil retort pouches and hermetically sealed using a heat-sealing machine. All samples were allowed to equilibrate to uniform temperature before being subjected to pasteurization, freezing, or sterilization treatments for shelf-life evaluation.

3. Pasteurization and chilled shelf-life study

Pasteurized samples were stored at 4 °C for 12 days. Sampling was carried out at 0, 3, 6, 9, and 12 days to evaluate microbiological quality and physicochemical properties. Microbiological analyses included Total plate count (TPC) and yeast and mold enumeration. Physicochemical analyses included color parameters (L*, a*, b*), pH, and total soluble solids (°Brix).

4. Frozen storage study

For frozen storage evaluation, sealed curry samples were stored at −18°C for three months. Sampling was conducted at 0, 1, 2, and 3 months. Microbiological quality was assessed by determining Total Plate Count (TPC) and coliforms, to evaluate hygienic status and microbial stability during frozen storage.

5. Sterilization process and heat penetration study

Thermal sterilization was carried out using a steam retort autoclave system (LAC-5040SD, Daihan Labtech Co., Ltd., South Korea). Temperature profiles during processing were monitored at the cold spot of the product using a needle thermocouple (Type 401, TechniCAL LLC, USA) connected to a CALPlex 32-channel datalogger (CALPlex, TechniCAL LLC, USA). Thermal data were recorded and analyzed using CALSoft5 software

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(TechniCAL LLC, USA). Sterilization was conducted at a process temperature of 118°C for 36 min to achieve a sterilization value (F_0) of not less than 6 min. Heat penetration testing was performed to validate the adequacy of thermal lethality and ensure uniform heat distribution within the retort pouch. Microbiological shelf-life testing for retort-processed samples was not performed; therefore, product safety and process adequacy were interpreted based on thermal lethality (F_0) and heat penetration validation. Although microbiological analysis was not conducted for retort-processed samples, product safety was ensured through validation of thermal lethality (F_0) and heat penetration analysis, which are internationally accepted indicators of commercial sterility in retort processing.

6. Physicochemical and nutritional analysis

Physicochemical properties of the curry samples were analyzed following AOAC International (2000) methods. Color values (L*, a*, and b*) were measured using the CIE Lab system with a colorimeter (CR-400, Konica Minolta, Inc., Japan). pH was determined using a calibrated digital pH meter (SevenCompact S220, Mettler-Toledo GmbH, Switzerland), and total soluble solids (°Brix) were measured using a digital refractometer (PAL-1, Atago Co., Ltd., Japan). Nutritional labeling was calculated per serving and per 100 g in accordance with Thai food and drug administration (FDA) regulations, enabling comparison among chilled, frozen, retort-processed, and control (coconut milk-based) formulations.

7. Statistical analysis

A completely randomized design (CRD) was employed for physicochemical and microbiological analyses to minimize systematic bias among treatments. All experiments were conducted under controlled laboratory conditions, and all analytical determinations were performed in triplicate to ensure reproducibility and reliability. Mean values obtained from triplicate determinations were used for statistical comparison. All experimental data were expressed as mean±standard deviation (SD). Statistical analysis was performed using one-way analysis of variance (ANOVA). Differences among treatment means were determined using Duncan's multiple range test (DMRT) at a significance level of $p \leq 0.05$. Prior to ANOVA, data were tested for normality using the Shapiro–Wilk test and for homogeneity of variance using Levene's test to verify that the assumptions for parametric analysis were satisfied.

Results and discussion

1. Chilled storage (4°C)

During chilled storage at 4 °C, microbial proliferation became evident from day 3 onwards. The total plate count (TPC) increased slightly during the first 6 days from below the detection limit at day 0 to 5.32×10^1 CFU/g (day 3) and 1.84×10^2 CFU/g (day 6)—indicating good initial microbiological stability. No significant increase ($p \geq 0.05$) in microbial load was observed during the initial storage period (day 0–6), suggesting effective microbial control under chilled conditions. After day 6, microbial growth accelerated markedly, reaching 2.38×10^5 CFU/g at day 9 and 3.31×10^7 CFU/g at day 12 (Table 1). A significant increase ($p \leq 0.05$) in TPC was observed after day 6, indicating the onset of exponential microbial growth. Yeast and mold were not detected throughout the study period, confirming that bacterial proliferation was the dominant spoilage mechanism under refrigeration (Table 1).

Table 1 Microbial counts in chilled Panang curry with plant-based milk

Storage time (days)	Microbial counts (CFU/g)	
	Total plate count	Yeast & mold
0	<10	<10
3	5.32×10^1	<10
6	1.84×10^2	<10
9	2.38×10^5	<10
12	3.31×10^7	<10

Remark: Data are mean values from triplicate analyses. "<10" indicates counts below detection limit (10 CFU/g). The product exceeded 10^5 CFU/g by day 9, defining a chilled shelf-life of about 8–9 days.

According to the microbiological acceptability limit of 10^5 CFU/g for ready-to-eat (RTE) foods recommended by International Commission on Microbiological Specifications for Foods (2011), the chilled product exceeded the threshold by day 9. Linear interpolation between day 6 and day 9 suggested a practical shelf life of approximately 8.5 days, which corresponds with the typical 5–10 day range reported for chilled RTE meals (Koutsoumanis & Taoukis, 2005). The growth curve indicated a clear lag phase (day 0–6), exponential phase (day 6–9), and early stationary phase (day 9–12), consistent with the kinetic behavior of psychrotrophic bacteria such as *pseudomonas spp*., *Brochothrix thermosphacta*, and certain *Enterobacteriaceae* that dominate in high moisture, protein rich foods stored under refrigeration. This growth pattern is consistent with microbial kinetics observed in

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high-moisture ready-to-eat (RTE) foods, where psychrotrophic bacteria adapt to low-temperature conditions before entering exponential growth. The absence of yeast and mold growth may be attributed to three factors: (i) limited oxygen availability within the sealed containers and under the surface fat layer, (ii) the antifungal properties of essential oils and phenolic compounds derived from Thai herbs and spices (e.g., chili, kaffir lime, and basil), and (iii) matrix conditions with high water activity (a_w>0.95) and moderately acidic pH (5.0–6.0) that favor bacterial rather than fungal growth. Furthermore, replacing coconut milk with plant-based milk may have reduced intrinsic antimicrobial activity due to the absence of medium chain fatty acids such as lauric acid, which possess strong bacteriostatic effects. This finding highlights the functional role of coconut milk lipids in microbial inhibition, which may be diminished in plant-based formulations lacking medium-chain fatty acids. These findings indicate that bacterial spoilage is the primary determinant of the chilled shelf life of Panang curry with plant-based milk. From an industrial perspective, this suggests that chilled storage alone may be insufficient for extending shelf-life beyond 7–9 days without additional preservation strategies. To extend product life beyond 9 days without compromising fresh like quality, several hurdle technologies can be applied. Modified atmosphere packaging (MAP) using CO_2/N_2 mixtures (30–60% CO_2) could inhibit psychrotrophic bacteria by lowering oxygen levels. High-pressure processing (HPP) at 400–600 MPa for 1–3 min may inactivate vegetative cells while preserving sensory attributes. Additionally, incorporating natural antimicrobials (e.g., spice extracts rich in citral or eugenol, or organic acid salts such as sodium lactate and sodium acetate) could provide additional microbial control. Optimization of pH and soluble solids, together with rapid chilling and strict cold-chain management, could further improve microbial safety and extend shelf-life by 2–3 days. Overall, these results are consistent with previous reports indicating the limited shelf-life of chilled RTE meals (Koutsoumanis & Taoukis, 2005), the increasing consumer demand for minimally processed chilled foods (Ragaert et al., 2011), and the effectiveness of MAP, HPP, and natural preservatives in extending refrigerated shelf-life while maintaining sensory and nutritional quality (Pereira & Vicente, 2010). The present findings further confirm that microbial growth remains the primary limiting factor in chilled RTE curry products, particularly when reformulated with plant-based ingredients.

2. Frozen storage (−18°C)

Frozen storage effectively suppressed microbial growth throughout the 3-month storage period. Total Plate Count (TPC) remained extremely low, increasing only slightly from 54 CFU/g at day 0 to 152 CFU/g at month 3. No significant increase ($p \geq 0.05$) in microbial load was observed throughout the storage period, indicating strong microbial stability under frozen conditions. No coliforms were detected in any sample, confirming the hygienic quality of the frozen product. The negligible microbial increase highlights the effectiveness of −18°C storage in extending shelf-life without significant microbial risk (Table 2).

Table 2 Microbial counts in frozen Panang curry with plant-based milk

Storage time (months)	Microbial counts (CFU/g)	
	Total plate count	Coliform
0	54	Not Detected
1	102	Not Detected
2	148	Not Detected
3	152	Not Detected

Remark: Data are presented as mean values from triplicate analyses. "Not detected" indicates values below 10 CFU/g.

During frozen storage, TPC values remained far below the international acceptability limit of 10^5 CFU/g for ready-to-eat (RTE) foods (International Commission on Microbiological Specifications for Foods, 2011), confirming that the freezing process efficiently maintained microbial safety for at least three months. The minimal increase in TPC is attributed not to bacterial multiplication but to the possible resuscitation of sublethally injured cells during thawing and plating. These findings are consistent with previous studies reporting that freezing at −18°C arrests metabolic activity, inhibits enzyme systems, and induces osmotic stress by ice-crystal formation (Rahman, 2007; Fellows, 2017). The formation of ice crystals reduces water availability and disrupts cellular structures, thereby limiting microbial activity and enzymatic reactions. Mechanistically, freezing does not destroy all microorganisms but keeps them in a dormant state by lowering water activity (a_w<0.8) and reducing diffusivity in the food matrix. This reduction in molecular mobility significantly limits nutrient diffusion and microbial metabolism. As a result, microbial metabolism ceases, and population increases are negligible during storage. The absence of coliforms across all test intervals indicates that post processing contamination was effectively prevented, confirming that the production and packaging procedures met hygienic standards. In comparison with chilled storage, where bacterial counts rapidly exceeded 10^5 CFU/g within nine days, the frozen treatment demonstrated outstanding microbiological stability. This clearly demonstrates that freezing is significantly more effective than chilled storage in controlling microbial growth in RTE curry systems. Therefore, in the frozen state, shelf life is not limited by microbial spoilage but rather by physicochemical and sensory quality degradation.

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According to Tan et al. (2020) and Leygonie et al. (2012), long-term freezing can alter food quality through protein denaturation, drip loss, or lipid oxidation, especially in meat-based or spice-rich formulations.

In this study, Panang curry with plant-based milk contained higher proportions of unsaturated fatty acids compared with coconut milk, offering nutritional advantages but greater susceptibility to oxidation. This highlights a key trade-off in plant-based reformulation, where improved nutritional quality may increase susceptibility to oxidative deterioration. To mitigate oxidative changes, low oxygen permeability packaging (e.g., multilayer films containing EVOH or polyamide) and vacuum or inert gas filling are recommended. Moreover, spice and herb volatiles, such as eugenol, citral, and limonene, may act as natural antioxidants, contributing to flavor stability and oxidative protection. These intrinsic components, together with consistent −18 °C storage, help maintain both microbiological and nutritional quality. From a nutritional perspective, freezing is recognized as one of the gentlest preservation methods, maintaining macronutrient integrity (Rong et al., 2018). The comparable energy, protein, and fat contents observed between chilled and frozen products in this study confirm that freezing preserves proximate composition with minimal loss of nutritive value. Overall, frozen storage at −18 °C ensured microbiological safety and nutritional stability of Panang curry with plant-based milk for at least three months. From an industrial perspective, frozen storage represents a reliable preservation strategy for extending shelf-life while maintaining product safety and nutritional quality. Any further shelf-life extension should focus on controlling oxidative rancidity and maintaining textural integrity rather than microbial safety. The combination of stable freezing conditions, appropriate packaging barriers, and antioxidant formulation represents an optimal strategy for long-term preservation of ready-to-eat Thai curry products. In addition, optimization of packaging systems and antioxidant strategies is essential for long-term quality retention in plant-based RTE curry products.

3. Retort pouch sterilization

Thermal sterilization of the plant-based milk beef Panang curry achieved an F_0 value of at least 6 min, exceeding the FDA-recommended minimum of 3 min for low-acid foods (Stumbo, 2013), which indicates sufficient thermal process lethality for the production of shelf-stable ready-to-eat (RTE) products. This F_0 value confirms that the applied thermal process was sufficient to achieve commercial sterility, ensuring the destruction of pathogenic and spoilage microorganisms in low-acid food systems. Although microbiological analysis was not performed for retort-processed samples, process adequacy was validated through F_0 determination and heat penetration analysis, which are internationally accepted indicators of product safety.

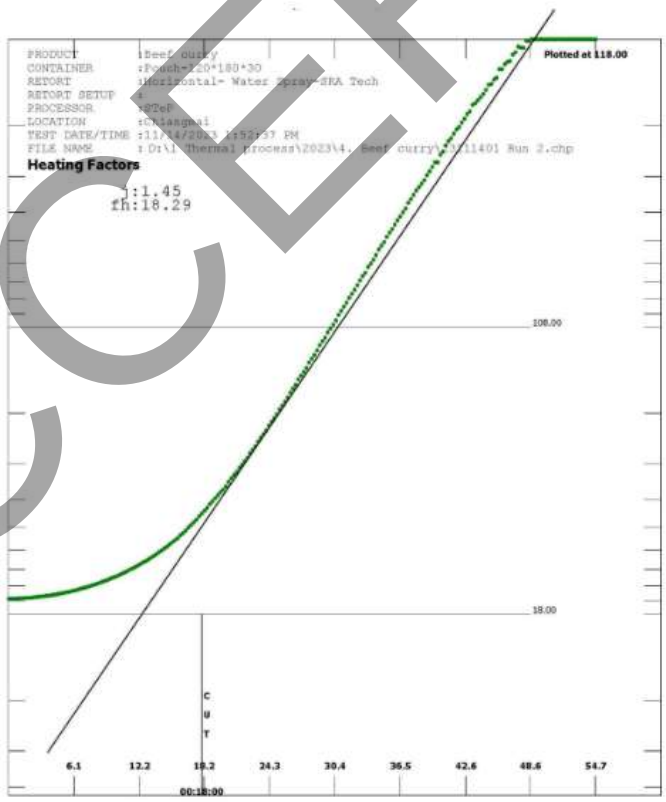


Fig. 1 Temperature profile (heat penetration test) of plant-based milk beef Panang curry in stand-up aluminum foil pouch (120×180×30 mm, including sealing area) processed in a horizontal retort

Remark: The temperature profile demonstrated effective heat transfer to the cold spot of the product, confirming uniform thermal distribution within the retort pouch. The identification of the cold spot is critical in retort processing, as it represents the slowest heating region and determines the overall process lethality.

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Physicochemical analyses revealed statistically significant ($p \leq 0.05$) changes in several quality parameters after sterilization (Table 3). Color degradation was evident through decreases in *lightness (L), *redness (a), and *yellowness (b)**, with a total color difference (ΔE) of approximately 9.91, indicating visible darkening and loss of brightness. The increase in pH from 5.32 to 5.76 may be attributed to protein denaturation and the release of buffering compounds such as amino acids and mineral salts from ingredients during heating. Meanwhile, the significant reduction in soluble solids (°Brix) from 23.70 to 16.60 suggested thermal breakdown or precipitation of soluble carbohydrates and sugars under high temperature conditions. Despite these physicochemical changes, the sterilization process ensured microbiological safety and rendered the product shelf-stable at ambient temperature for long-term storage. The observed changes may be more pronounced in plant-based formulations due to differences in lipid composition compared with coconut milk, particularly the higher proportion of unsaturated fatty acids.

Table 3 Physicochemical quality of ready-to-eat beef Panang curry before and after sterilization

Physicochemical quality	Ready-to-eat beef Panang curry	
	Before sterilization	**After sterilization**
L* value	34.35^{a}±0.04	29.63^{b}±0.50
a* value	24.21^{a}±0.07	17.36^{b}±0.38
b* value	37.73^{a}±0.14	32.38^{b}±0.29
ΔE	–	9.91±0.22
pH	5.32^{b}±0.00	5.76^{a}±0.00
Soluble solids of curry sauce (°Brix)	23.70^{a}±0.00	16.60^{b}±0.10

Remark: Data are presented as mean±standard deviation. Different superscript letters within the same row indicate significant differences between means ($p \leq 0.05$).



(a) (b)

Fig. 2 Sterilized ready-to-eat beef Panang curry product: (a) before sterilization and (b) after sterilization

The F_0 value exceeding 6 min demonstrated sufficient thermal lethality, consistent with commercial sterilization requirements for low-acid ready-to-eat (RTE) foods. However, as commonly observed in retort processed foods, heat exposure induced physicochemical alterations that can affect sensory quality. The decrease in L, a, and b* values* corresponds to Maillard browning reactions and pigment degradation caused by extended heating. This reaction is accelerated at high temperatures and is influenced by the composition of plant-based milk, which may alter sugar–protein interactions during heating. This browning phenomenon involves interactions between reducing sugars and amino compounds, leading to the formation of melanoidins, which deepen the color of the product (Patras et al., 2010). Moreover, the reduction in °Brix suggests that non enzymatic caramelization and precipitation of soluble solids occurred, consistent with the findings of Varzakas and Tzia (2015), who noted significant decreases in soluble solids in retort sterilized sauces. The observed increase in pH likely results from amino acid deamination and buffering during heating, reflecting protein unfolding and the loss of acidic compounds (Fellows, 2017). These changes, while modifying flavor intensity and viscosity, do not compromise product safety. From a food science perspective, such physicochemical shifts represent and highlight the trade-off between microbial safety and sensory preservation and quality, particularly in reformulated plant-based RTE products. Although retort sterilization inevitably causes some degradation of color and flavor, it remains the most reliable preservation method for ensuring long-term shelf stability, especially for export-ready Thai ready-to-eat meals that require ambient storage. The use

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of retort pouches constructed with aluminum foil and polymer laminates contributed to effective heat transfer and oxygen barrier protection, thereby minimizing oxidative degradation during storage. The high barrier properties of multilayer retort pouches are especially important for plant-based formulations, which are more susceptible to oxidative deterioration. Compared with traditional cans, the flexible pouch structure allows faster heat penetration and lower thermal gradients, which help preserve nutrients and reduce process time (Rahman, 2007). In summary, the retort processed Panang curry achieved commercial sterility with acceptable physicochemical quality, validating its potential as a shelf stable, ready-to-eat Thai curry suitable for domestic and international markets. From an industrial perspective, retort processing offers a robust solution for producing shelf-stable Thai RTE meals suitable for large-scale production and international distribution. Future optimization may focus on refining thermal process parameters or applying mild pretreatments (e.g., high pressure or vacuum deaeration steps) to mitigate color and flavor degradation while maintaining the necessary microbiological safety standards. Further studies may investigate optimization of thermal profiles and formulation strategies to minimize quality degradation while maintaining required lethality.

4. Nutritional labeling

Four formulations of beef Panang curry were evaluated for their nutritional composition: (1) control sample beef Panang curry with coconut milk (220 g), (2) chilled sample beef Panang curry with plant-based milk (220 g), (3) frozen sample beef Panang curry with plant-based milk (220 g), and (4) retort pouch sample beef Panang curry with plant-based milk (140 g). Nutritional values were calculated based on standardized Thai FDA nutrition labeling guidelines and verified using food composition databases. The control sample exhibited the highest energy (360 kcal) and total fat (20 g, including 14 g saturated fat), which was attributed to the high lipid content of coconut milk. In contrast, the chilled plant-based milk variant demonstrated a marked reduction in both total and saturated fat (10 and 5 g, respectively) and a lower energy content (260 kcal), while maintaining comparable protein (22 g) and carbohydrate levels. When normalized per 100 g, similar trends in fat reduction and energy decrease were observed across all plant-based formulations, confirming that the differences were not solely due to portion size variation. Similarly, the frozen variant presented a nearly identical nutritional profile to the chilled formulation (260 kcal, 9 g total fat, 5 g saturated fat, 22 g protein), suggesting that frozen storage effectively preserved macronutrient stability. No significant differences ($p \geq 0.05$) in macronutrient composition were observed between chilled and frozen samples, indicating that freezing effectively preserved nutritional quality. The retort pouch product, due to its smaller portion size (140 g), contained the lowest energy (200 kcal), total fat (4.5 and 2 g saturated fat), and sodium (580 mg), though its protein content (20 g) remained consistent with the other plant-based formulations. The lower nutrient values observed in the retort product are primarily attributed to the smaller serving size rather than substantial nutrient degradation. Overall, substituting coconut milk with plant-based milk significantly reduced total and saturated fat contents across all product formats, while maintaining stable protein and carbohydrate values. These findings support the classification of the developed product as a healthier ready-to-eat (RTE) Thai curry option, aligning with current consumer demand for nutritious and lower fat traditional meals.

Table 4 Nutritional composition of different Panang curry formulations

Product type	Portion (g)	Energy (kcal)	Total fat (g)	Saturated fat (g)	Protein (g)	Sodium (mg)	Remarks
Control (coconut milk)	220	360	20.0	14.0	22	700	high lipid from coconut milk
Chilled (plant-based milk)	220	260	10.0	5.0	22	640	reduced fat, good protein retention
Frozen (plant-based milk)	220	260	9.0	5.0	22	640	stable macronutrient profile
Retort pouch (plant-based milk)	140	200	4.5	2.0	20	580	small portion, mild nutrient loss

Remark: Data are based on standardized nutrition labeling (per serving). Nutrient values may vary slightly due to processing differences.

The results clearly demonstrated that the substitution of coconut milk with plant-based milk significantly improved the nutritional balance of Panang curry. Coconut milk is rich in medium chain triglycerides (MCTs) such as lauric acid, which, although metabolically beneficial, contribute to high saturated fat content (Mensink, 2016). By contrast, plant-based milk formulations derived from cereals and legumes contain unsaturated fatty

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acids that help lower total lipid and saturated fat levels without diminishing flavor intensity or creaminess. In addition, the absence of coconut-derived saturated fats contributes to a more favorable lipid profile associated with reduced cardiovascular risk. From a food science standpoint, the stability of protein and carbohydrate contents across all variants indicates that processing methods, refrigeration, freezing, and retort sterilization did not induce significant nutrient degradation. No statistically significant differences ($p \geq 0.05$) in protein and carbohydrate contents were observed among processing methods, confirming minimal macronutrient degradation. This aligns with findings by Rong et al. (2018), who reported that macronutrient composition in ready-to-eat meals remains stable under cold and frozen storage due to limited enzymatic activity. Minor differences observed in the retort pouch product can be attributed to thermal denaturation of proteins and caramelization of sugars, which may slightly reduce °Brix and alter color or flavor characteristics (Patras et al., 2010; Varzakas & Tzia, 2015). Nevertheless, the retort process ensures microbiological safety and facilitates long-term ambient storage, a major advantage for export oriented Thai RTE meals. The marked reduction in saturated fat (up to 65–75%) across the plant-based variants enhances the product's health appeal and aligns with global dietary recommendations that encourage limiting saturated fat intake as part of a balanced diet (World Health Organization, 2020), although further clinical evidence would be required to confirm specific health benefits. In addition, the caloric reduction of approximately 100–160 kcal per serving positions this reformulated Panang curry as a "better-for-you" Thai convenience food, catering to modern health-conscious consumers. Overall, the plant-based milk formulations achieved a balanced nutritional profile with reduced fat and energy values, while maintaining adequate protein levels and flavor consistency. From a product development perspective, this reformulation supports the development of functional ready-to-eat foods that meet both nutritional and market demands. This suggests that reformulating traditional Thai curries with plant-based ingredients can effectively modernize heritage foods into functional, sustainable, and globally competitive ready-to-eat products, aligning with the principles of healthy nutrition and soft power gastronomy.

Conclusion

The development of Dusita beef Panang curry with plant-based milk demonstrates the successful integration of food science innovation and nutritional reformulation to enhance product safety and nutritional quality. The results indicate that (1) chilled storage at 4°C maintained acceptable microbiological quality for approximately 8–9 days; (2) frozen storage at −18°C ensured microbial stability for at least three months; and (3) retort pouch processing achieved sufficient thermal lethality ($F_0 \geq 6$ min), supporting the production of commercially sterile shelf-stable products. Nutritional evaluation confirmed that substituting coconut milk with plant-based milk significantly reduced both total and saturated fat while maintaining comparable protein and energy levels. Overall, the findings demonstrate that plant-based reformulation combined with appropriate preservation technologies provides a promising strategy for developing healthier ready-to-eat Thai curry products. The findings also provide scientific evidence supporting the application of corn-based plant milk as a healthier alternative to coconut milk in traditional Thai ready-to-eat foods without compromising product safety or nutritional quality. This study contributes to the development of innovative Thai ready-to-eat products with improved nutritional value and practical potential for commercial production. Future studies should focus on optimizing thermal processing conditions and evaluating long-term physicochemical, microbiological, and nutritional stability during extended storage.

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Author contributions

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Utsaphong Uprarawanna – Methodology, Formal analysis, Validation, Writing – review & editing.
Sungwan Chompuja – Investigation, Data curation, Writing – review & editing.
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Conflicts of Interest

The authors declare no conflict of interest.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

The authors used AI-assisted tools to improve language clarity and readability. The final manuscript was reviewed and approved by the authors, who take full responsibility for the content.

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