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Optimization and Accelerated Shelf-Life Testing of Caramelized Crushed Cashew Nut Ball

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Abstract

Crushed cashew nuts are often simplified as a lower-grade byproduct from cashew processing that has less value in the market than whole kernels. With the same rich nutritional profile, these broken pieces can be transformed into ingredients as new products to enhance their value. This study aimed to develop a value-added product, a nutritious caramelized ball from crushed cashew nuts combined with caramel from coconut sugar and date syrup, as a healthier alternative to refined sugar. The formulation for producing caramelized crushed cashew nut ball (CCB) was optimized using response surface methodology (RSM). The shelf-life of CCB packaged in different materials, including cast polypropylene (CPP), linear low-density polyethylene (LLDPE), and metalized aluminum (MA), was also analyzed through the accelerated shelf-life test (ASLT) to determine the suitable packaging for preserving CCB quality. The CCB samples with crushed cashew nut (100-200 g), caramel sauce (50-200 g), and cooking time (1-2 min) were then evaluated for moisture content (%), water activity (aw), hardness, and overall score for consumer acceptability (n=50). The optimum conditions were identified with 2 targets, including

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hardness and overall acceptability score (9-point hedonic scale) obtained at crushed cashew nuts: 190 g, caramel sauce: 200 g, and cooking time: 2 min, resulting in the overall acceptability score of 6.2 and hardness of 36.03 N. The ASLT method and the Arrhenius kinetics model evaluated their acceptance score and rancidity (thiobarbituric acid reactive substances; TBARS). These factors fit the Arrhenius plots (R2>0.87) and follow the first-order kinetics model. Among tested packaging, MA enhanced the shelf-life of CCB samples based on overall sensory acceptability for 25.90 weeks and TBARS values for 26.34 weeks at 35 °C. Furthermore, predictive equations were established for the shelf-life of CCB packeged in various packaging based on storage temperature (R2 = 0.97-0.99). The developed predictive equations and degradation kinetics study results have the potential to assist in utilizing packaging based on storage conditions to maintain the eating quality and predict the expiration shelf-life of CCB samples.

Introduction

Cashew (*Anacardium occidentale* L.) is a tropical nut of socioeconomic importance worldwide. Commercial processing of cashew nuts consists of a series of procedures, including roasting, cracking, shell removal, peeling, and grading.[1] After these processes, approximately 60% of high-quality and 40% of defective cashew nuts are obtained.[2] The number of defective crushed cashew nuts can significantly reduce the overall commercial price of the cashews.[3] However, crushed cashew nuts can be used as ingredients in various products such as butter,[3] edible oil[4,5] snacks,[6] and flour for bakery.[7] In recent decades, global consumption of cashew nuts has steadily increased, from 599.03 thousand metric tons in 2012 to 959.49 thousand metric tons in 2021.[8] As a result, the global cashew nuts market growth is projected to reach $11 billion in 2030.[9] These significant growths in the production and consumption of cashew nuts can be attributed to their rich nutritional profile. Cashew nuts have a high content of monounsaturated fatty acids (27.3%), polyunsaturated fatty acids (7.8%), and total dietary fiber (5.9). They are also an excellent source of protein (18.2%) and contain an optimal nutritional density of essential minerals, including calcium, copper, iron, magnesium, and potassium.[10,11] Due to these nutrients, cashew nuts provide beneficial health effects and potentially reduce cardiovascular risks.[12,13] Furthermore, the increasing demand for plant-based foods and the growing popularity of vegan diets have elevated cashew nuts to one of the most important and highly sought-after nuts worldwide. Their versatility and nutritional content have made them a popular choice for those seeking healthy snacks, and plant-based alternatives.

The demand for sustainable, tasty, and healthy snack foods has increased rapidly in recent years. With growing demand for the connection between diet and health, consumers actively seek snacks that provide nutritional benefits and support overall well-being. People are increasingly mindful of their snacks, prioritizing those with a balanced mix of protein, carbohydrates, healthy fats, and fiber. One popular choice is the energy ball, a nutritious snack in the shape of a ball with various flavors, including dried fruit, nuts, seeds, and other wholesome ingredients. This provides nutritional value as a good energy source and healthy fat, carbohydrates, protein, and fiber.[14,15] In 2022, the global energy balls market was valued at $336.72 million, and it is expected to reach $624.39 million over the next decade.[16] A key trend in the snack and confectionery industry is the rising popularity of caramel, a flavor and color used in a wide range of products. Food manufacturers are developing new products by infusing caramel with color, flavor, inclusion, or topping. The process that produces caramel, called caramelization, occurs when sugar is heated and undergoes a chemical reaction. During this process, the sugar molecules break down and go through a series of reactions known as pyrolysis. This leads to the formation of caramel compounds, like caramelan and caramelene, which give caramel its unique flavor, aroma, and rich brown color.[17] Regarding consumer demand for high-quality confectionery, fueling the growing demand for caramel-flavored treats. At the same time, the rise in clean-label and transparency-focused products has boosted interest in organic caramel ingredients. Health-conscious consumers are drawn to caramel's natural sweetness as an alternative to artificial sweeteners, aligning with the broader shift toward healthier eating. However, excessive sugar consumption is linked to health risks such as obesity, diabetes, and cardiovascular diseases. To address this, natural sweeteners like coconut sugar and dates are healthier alternatives to refined sugars. Additionally, several studies have demonstrated that incorporating natural sugar caramel into snacks lowers the consumption of refined sugar and improves product quality. Many studies have found that date syrup has a high potential for being made into snack products and satisfying the desires of consumers who prioritize health regarding color, texture, and sensory attributes.[18] Ajayi and Ikechukwu[19] reported that date syrup can replace glucose syrup in producing granola bars. Using date syrup increases the carbohydrate and fiber content of the bars, and this has been accepted by consumers. However, there has not been a report on using coconut sugar combined with date syrup as the ingredients to produce caramel and crushed nuts to create an energizing snack. Additionally, several studies have demonstrated that adding natural sugar caramel to snack products could enhance their overall quality.[20]

Typically, nutritious snacks must have a low moisture content (<14%) and aw (<0.65) to prevent the growth of foodborne and food spoilage microorganisms. For this reason, nutritious snacks were categorized as dried food, which makes them susceptible to deterioration due to water uptake from the environment. This moisture uptake is influenced by the type of packaging used and the storage temperature.[21] Food packaging is crucial in extending shelf life by serving as a barrier to oxygen and moisture. Excessive oxygen and moisture can lead to rancidity and loss of crispness during storage.[22] Thus, the choice of packaging is critical to provide a water vapor barrier during storage. In particular, oxidative rancidity becomes more likely as water activity increases, making moisture control critical for maintaining product quality.[23] Due to this, packaging choice is crucial since it acts as a water vapor barrier during storage time.

The cast polypropylene plastic (CPP) packaging offers excellent protection against moisture and odors while keeping the product visible inside the package. On the other hand, linear low-density polyethylene (LLDPE) is widely used as a key packaging material due to its high flexibility, impact resistance, and chemical.[24] Metalized aluminum (MA) plastic is another affordable option for food packaging, where a thin layer of aluminum foil improves the barrier properties, providing strong protection against moisture, air, and odors. The accelerated shelf-life test, using the Arrhenius equation, is a powerful tool for estimating shelf-life because temperature significantly impacts product deterioration. Furthermore, the Arrhenius equation is a key tool for understanding how temperature affects food reaction rates. This model also offers insights to enhance storage systems by maintaining product quality and minimizing losses. Inadequate packaging can trigger unwanted changes in the physical and sensory properties of products, impacting their final quality.[25] To accurately predict how product quality evolves during transportation, distribution, and shelf-life, it's crucial to consider shelf-life indicators.[26]

Consequently, the current research focused on adding value to crushed cashew nuts by producing CCB. The suitable formulation for making CCB was optimized using response surface methodology (RSM) to provide a high-quality final product with nutritional and health advantages. Notably, the technology involved in CCB production is simple, allowing small producers to use it to improve their income. The chemical and sensory characteristics of CCBs packaged in CPP, LLDPE, and MA pouches were investigated in this study, and their stability at different temperatures was evaluated using kinetic models. The Arrhenius-based kinetics models were used to determine CCB stability under different temperature conditions. Degradation kinetic parameters and shelf-life indicators, which were well-fitted to the kinetic model, were also calculated to establish how temperature impacts CCB quality and storage stability.

Materials and Methods

Materials

The crushed cashew nut sample was purchased from the Grand Mom Aead (Strut Profession Ltd.; Thailand). Coconut sugar was purchased from the Mitr Phol Sugar Corp., Ltd., Thailand. Date syrup was purchased from the Kru Yu Cottage Co., Ltd., Thailand. Maltodextrin was purchased from Chemipan Corporation Co., Ltd., Thailand. Baking soda was purchased from Continental food co., ltd., Thailand. Hydrochloric acid (HCl) and glacial acetic acid were bought from Merck, Germany, while 2-thiobarbituric acid (TBA) and malondialdehyde (MDA) were bought from Sigma-Aldrich, USA.

Preparation of CCB

In this study, we are interested in caramel sauce added to date syrup to develop the CCB. The basic formulation of caramel sauce produced from alternative natural sugar was 65% coconut sugar, 26% date syrup 7% maltodextrin, and 2% of baking soda. Each batches of caramel sauce were produced and caramelized at approximately 115–120°C. After that, crushed cashew nuts were added and then mixed thoroughly, evenly formed, and then cooled on a heat-resistant silicone spherical mold at room temperature with a constant weight of 10 g per ball.

Evaluation of Physical characteristics of CCB

The moisture content of various CCB samples was determined using the Association of Official Analytical Chemists method. The water activity (aw) value of CCB was measured by a water activity meter (4TE; Aqualab; USA) as recommended in the manufacturer's instructions. The hardness of CCB was determinedusing texture analyzer (TA-XT2; Stable Micro Systems; UK). The probe used was craft knife blade (A/CKB) with testing parameters as a pre-test speed 1.5 mm/s, a post-test speed of 10 mm/s, a distance of 4 mm, and a maximum load 50 kg. 27

Evaluation of Thiobarbituric Acid Reactive Substances of CCB

Thiobarbituric acid reactive substances (TBARS) values of the CCB samples were evaluated using a modification of the method described by Malarut and Vangnai.[28] In brief, 10 g aliquots of each CCB were homogenized in 50 mL of distilled water (DW). Following the addition of the homogenate, 47.5 mL DW, and 2.5 mL 4N HCl to a distillation flask, the mixture was distilled, and 50 mL of the distillate was collected. Next, the 5 mL of 0.02 M TBA in 90% acetic acid was then added to a test tube that contained 5 mL of the collected distillate, and after 15 minutes of incubation at 90°C, the mixture was cooled to room temperature and turned pink. The absorbance of the solution was measured at 538 nm compared to a blank made with a 1:1 mixture of DW and TBA reagent. The TBARS value was calculated using an MDA standard curve, and the results were expressed in milligram of MDA per kilogram of CCB.

Sensory Evaluation of CCB

The sensory evaluation of the various CCB samples were based on an overall acceptance score determined by 50 panelists (36 females, 14 males) aged 19–48 years. Each panellist rated the sensory acceptance scores of the CCB samples in terms of colour, taste and flavour, texture, and overall appearance, using a 9point hedonic scale ranging from "liked extremely" (scoring 9) to "extremely disliked" (score 1).

In this study, an overall acceptance score of 5.0 on a 9-point hedonic scale (indicating 'neither liked nor disliked') corresponding to a TBAR value was used as the threshold limit for acceptable quality. To reduce weariness and carryover effects, the panelists were instructed to cleanse their mouths with 50–60 mL of drinking water in between evaluating two separate samples.[29] The legal and ethical aspects of the project were approved by the Ethics Committee of Naresuan University (No. 028.64) (Exemption Review), in accordance with the Declaration of Helsinki. Each individual participant in the study provided informed consent.

Experimental Design and Optimization of CCB

In order to establish a suitable formulation for the production of CCB, the models were developed using a central composite design. The experimental design used three variables (crushed cashew nut, caramel sauce and cooking time) and three levels, as described in Table 1. Response surface plots were used to create tests for the moisture content, aw, hardness, and overall acceptance score of the sensory evaluation. Each of these variables (Y) was fitted with a second-order polynomial model based on equation (1):

$$Y = \beta_0 + (\beta_1 \times X_1) + (\beta_2 \times X_2) + (\beta_3 \times X_3) + (\beta_4 \times X_1^2) + (\beta_5 \times X_2^2) + (\beta_6 \times X_3^2) + (\beta_7 \times X_1 X_2) + (\beta_8 \times X_1 X_3) + (\beta_9 \times X_2 X_3) \quad ...(1)$$

where X_1, X_2, and X_3 are the levels of additional crushed cashew nut, caramel sauce, and cooking time, respectively, and β_0, β_1, $\beta_2 \ldots \beta_9$. refer to the estimated regression coefficients.

Shelf-Life Evaluation

In this experiment, the shelf-life of CCB was investigated in different plastic pouches, including CPP, LLDPE, and MA. The Arrhenius-based kinetics models were used to determine CCB stability under different temperature conditions. Degradation kinetic parameters and shelf-life indicators, which were well-fitted to the kinetic model, were also calculated to determine how temperature affects the quality and storage stability of CCBs. The CCB samples (60 g) were stored in three types of packaging: CPP, LLDPE, and MA pouches. The water vapor transmission rates of the CPP, LLDPE, and MA pouches were 0.0030, 0.0024, and 0.0012 g/m^2.day, respectively, and their permeability coefficients were 5.77 x 10^{-6}, 5.47 x 10^{-6}, and 1.88 x 10^{-6} g.m/m^2.d.mm Hg, respectively. The thicknesses of the CPP, LLDPE, and MA pouches were 0.082, 0.098, and 0.067 mm, respectively. The effect of oxidation was controlled by adding an oxygen absorber (BestKept®; Alpine Foods Co., Ltd.; Thailand) with a capacity of 100 mL. The shelf-life study of the CCB with the various packaging types was evaluated at 35, 45, and 55 °C for 6 weeks and samples were collected once every week.

Kinetics Model

First-order reaction kinetics were discovered to be correlated with the TBARS value in CCB. The first-order reaction rate constants (k) were calculated using equation (2)

$$\ln (C/C0) = kt \quad ...(2)$$

where C is the TBARS value at time 't', C_0 is the initial of the TBA, t is the storage time and k is the reaction rate constants (slope).

Arrhenius Equation

The temperature dependency of 'k' was characterized using the Arrhenius equation. The temperature dependency of the degradation rate of TBAR with the different types of packaging was calculated using Arrhenius equations based on equation (3):

$$\ln k = \ln k_0 - (E_a / R) * (1 / T) \quad ...(3)$$

where k_0 is the rate constant of the degradation of the respective quality index at a reference temperature, k is the reaction rate constant, E_a is the activation energy of the studied action (kJ/mol), R is the universal gas constant (8.314 J.mol^{-1}. K^{-1}), and T is the temperature in kelvin units.

The shelf-life of the CCB packed in CPP, LDPPE, and MA stored at various temperatures was calculated using the ASLT methods based on changes in k. A direct equation was employed to estimation of the expiration of CCB as described by Al-Zubaidy and Khalil[30] for quantifying degradation as shown in equation (4):

$$Ex = e^{-\left\{\frac{S}{T} + I - ln\left(-ln\left(\frac{p\%}{100}\right)\right)\right\}} \quad ...(4)$$

where Ex is the shelf-life of CCB (in weeks) which varies depending on the unit of the first-order rate constant; S and I represent the slope and intercept, respectively, acquired from the application of the Arrhenius equation by plotting the logarithm of the k versus 1/T, T denotes the absolute or Kelvin temperature, and p% is the percentage of remaining levels of any identified substance. In order to estimate the time required to reduce levels by 50%, this study employed p% (p%=50).

Statistical Analysis

Three duplicates of each physicochemical property measurement and sensory assessment were performed. To fit each experimental data model, the coefficient of determination (R2) was calculated using the MINITAB software (version 12; Minitab Inc.; USA), which was used for statistical analyses. The SPSS for Windows application (version 16; SPSS Inc.; USA) was used to examine mean differences at a significance level of $p \leq 0.05$ using Analysis of variance (ANOVA) and Duncan's multiple range test. Arrhenius plot and shelf-life prediction linear regressions were computed using Microsoft Excel 2019 (Microsoft Corp.; USA).

Results

Optimization of CCB on Physical characteristics and Sensory Analysis

The standards for CCB samples were followed according to the standard of coated cashew nut products by the Ministry of Public Health of Thailand (No.332/254) including a moisture content not exceeding 4% and receiving a good overall acceptance score from the sensory panelists.

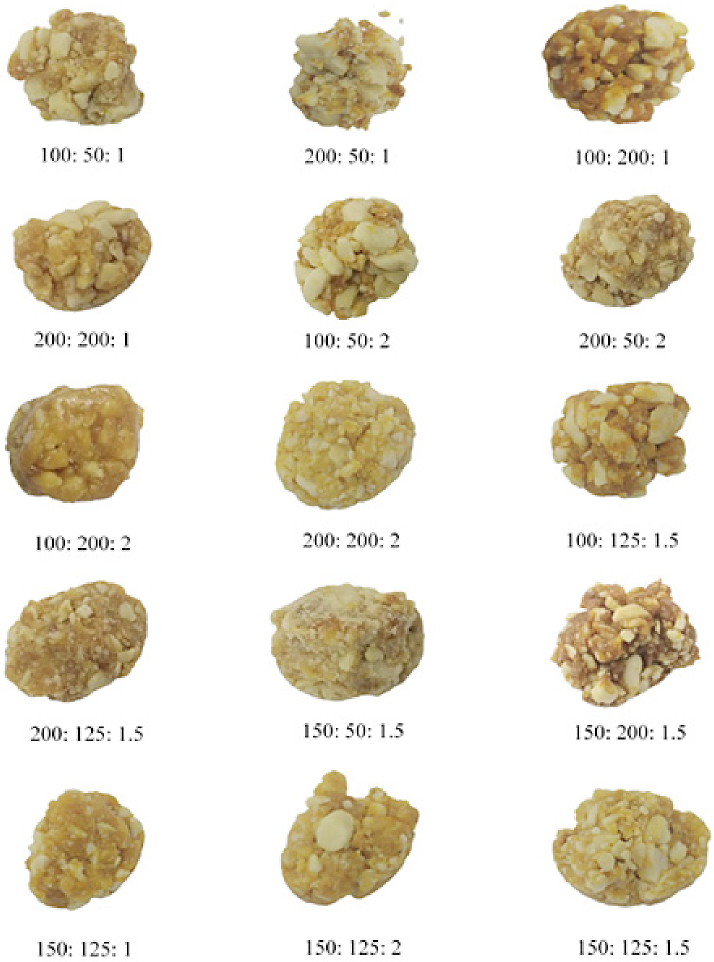

Fig. 1 Appearance of CCB from experimental design and levels of factors of crushed cashew nut (g): caramel sauce (g): cooking time (min) from the central composite design

All CCB samples had a lower moisture content than the maximum allowable (less than 4%), while the a_w values were less than 0.34. The texture profile and overall acceptance based on sensory evaluation are very important parameters for product acceptance quality. The utilization of sensory analysis is an analytical process that offers insight into the perspective of products for future commercialization. The overall acceptance score (based on the 9-point hedonic scale) was used to represent the sensory parameters of CCB for color, taste and flavor, texture, and overall appearance and are presented in Table 1. Moreover, the appearance of all CCB samples is shown in Fig. 1.

Based on the response surface methodology experimental results, regression analysis was used to model the significant effects of the amount of crushed cashew nut (X_1), amount of caramel sauce (X_2), and cooking time (X_3) on the overall acceptance scores from sensory evaluation and texture quality. The greatest R^2 and R^2_{adj} values with no statistically significant lack of fit ($p>0.05$) were used to evaluate the goodness-of-fit of the regression analysis models.

Table 1: Levels of factors in central composite design of hardness, overall acceptance, moisture content (%) and aw of CCB

Runs	Independent factors			Hardness (N)	Overall Acceptance	Moisture content (%)	a_w
	Crushed cashew nut (g)	Caramel sauce (g)	Cooking Time (min)				
1	100	50	1	14.03 ± 0.87[f]	5.8 ± 1.21[abc]	1.91 ± 0.08[c]	0.23 ± 0.01[b]
2	200	50	1	17.11 ± 0.96[f]	5.9 ± 0.58[abc]	1.93 ± 0.06[c]	0.23 ± 0.01[b]
3	100	200	1	49.39 ± 5.74[a]	4.9 ± 0.91[bc]	3.36 ± 0.12[a]	0.34 ± 0.01[a]
4	200	200	1	37.28 ± 2.40[c]	6.9 ± 0.70[a]	3.37 ± 0.04[a]	0.33 ± 0.02[a]
5	100	50	2	15.15 ± 1.08[f]	5.0 ± 0.86[bc]	2.03 ± 0.03[c]	0.24 ± 0.02[b]
6	200	50	2	18.09 ± 1.30[f]	5.9 ± 0.73[abc]	1.95 ± 0.10[c]	0.23 ± 0.02[b]
7	100	200	2	45.09 ± 4.39[b]	4.2 ± 1.26[c]	3.40 ± 0.07[a]	0.32 ± 0.02[a]
8	200	200	2	33.42 ± 0.97[d]	6.3 ± 0.60[ab]	3.32 ± 0.06[a]	0.33 ± 0.03[a]
9	100	125	1.5	27.07 ± 0.57[e]	5.6 ± 1.09[abc]	2.62 ± 0.07[b]	0.24 ± 0.01[b]
10	200	125	1.5	25.38 ± 0.49[e]	6.0 ± 0.35[abc]	2.62 ± 0.12[b]	0.25 ± 0.02[b]
11	150	50	1.5	15.05 ± 1.53[f]	5.3 ± 0.11[abc]	1.96 ± 0.16[c]	0.23 ± 0.03[b]
12	150	200	1.5	40.95 ± 2.05[c]	5.4 ± 1.39[abc]	3.31 ± 0.16[a]	0.31 ± 0.01[a]
13	150	125	1	25.05 ± 1.30[e]	5.3 ± 1.48[abc]	2.63 ± 0.18[b]	0.26 ± 0.03[b]
14	150	125	2	26.36 ± 1.36[e]	5.1 ± 0.73[abc]	2.63 ± 0.10[b]	0.25 ± 0.01[b]
15-20	150	125	1.5	24.44 ± 1.59d[e]	5.3 ± 0.84[abc]	2.64 ± 0.19[b]	0.25 ± 0.01[b]

Values indicate three replicates ± standard deviations.
a-f Different lowercase letters in the same column indicate significant ($p \le 0.05$) differences between means based on Duncan's test.

Regression analyses for the hardness, overall acceptance scores from sensory evaluation, moisture content and a_w, value revealed that the models generated statistically significant fits (based on R^2 and R^2_{adj}), accounting for more than 75% of the difference in the data obtained from the experiments. The desirability function can be used to analyze the optimal level of independent factors, demonstrating that the models were reliable and appropriate to explain the effect of the amount of crushed cashew nuts (X_1), amount of caramel sauce (X_2), and cooking time (X_3) for CCB as:

Hardness (N) = $5.75 - 0.0283X_1 + 0.2491X_2 - 1.79X_3 + 0.000371X_1^2 + 0.000480X_2^2 + 1.63X_3^2 - 0.000993X_1X_2 + 0.0015X_1X_3 - 0.03420X_2X_3$ (R^2 = 0.9941, R^2_{adj} = 0.9888, Lack of fit = 0.064)

Overall acceptance = $9.55 - 0.0622X_1 - 0.01394X_2 + 1.14X_3 + 0.000179X_1^2 + 0.000002X_2^2 - 0.695X_3^2 + 0.000103X_1X_2 + 0.0045X_1X_3 - 0.00147X_2X_3$ (R^2 = 0.8824, R^2_{adj} = 0.7765, Lack of fit = 0.356)

Moisture content (%) = $1.112 + 0.229X_1 + 0.984X_2 + 0.230X_3 - 0.035X_1^2 + 0.0134X_2^2 + 0.0044X_3^2 - 0.0016X_1X_2 - 0.0987X_1X_3 - 0.0565X_2X_3$ (R^2 = 0.9979, R^2_{adj} = 0.9959, Lack of fit = 0.068)

$a_w = 0.2924 + 0.0076X_1 - 0.0348X_2 - 0.0860X_3 - 0.0083X_1^2 + 0.04253X_2^2 + 0.0289X_3^2 + 0.00467X_1X_2 + 0.00685X_1X_3 - 0.01073X_2X_3$ (R^2 = 0.9820, R^2_{adj} = 0.9659, Lack of fit = 0.1

Optimization of Conditions for CCB

According to the result of moisture content and aw of all CCB samples were found to be lower than standard of coated cashew nut. Given the importance of texture and overall acceptance in determining product quality. Therefore, the optimized formulation of CCB was focused on achieving the ideal hardness and overall acceptance score, as these were the target criteria for consumer acceptance. A multiple-response optimization method was used to calculate the optimal conditions. The CCB formulation was optimized in order to predict results with improved reliability based on two target criteria: hardness (40 N) and overall acceptance score (7). The optimization was studied within the limitations of selected parameters in order to forecast the results with more reliability.

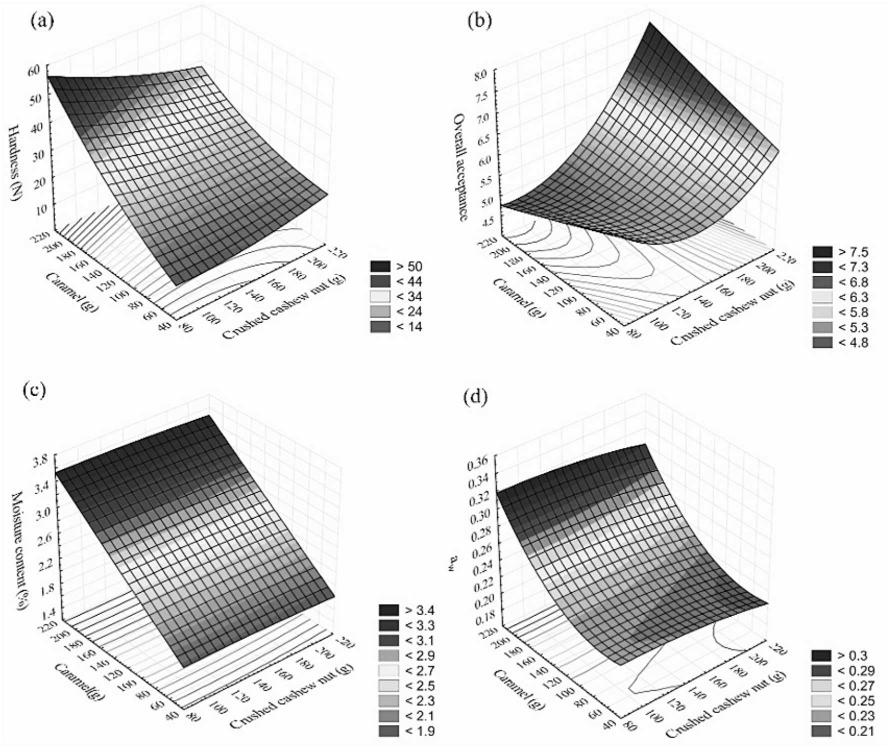

Fig. 2: Response surface plots of CCB production on hardness (a), overall acceptance score (b), moisture content (%) (c) and water activity (d) by the amount of crushed cashew nut (X1), amount of caramel sauce (X2), and cooking time (X3) at 1.5 min

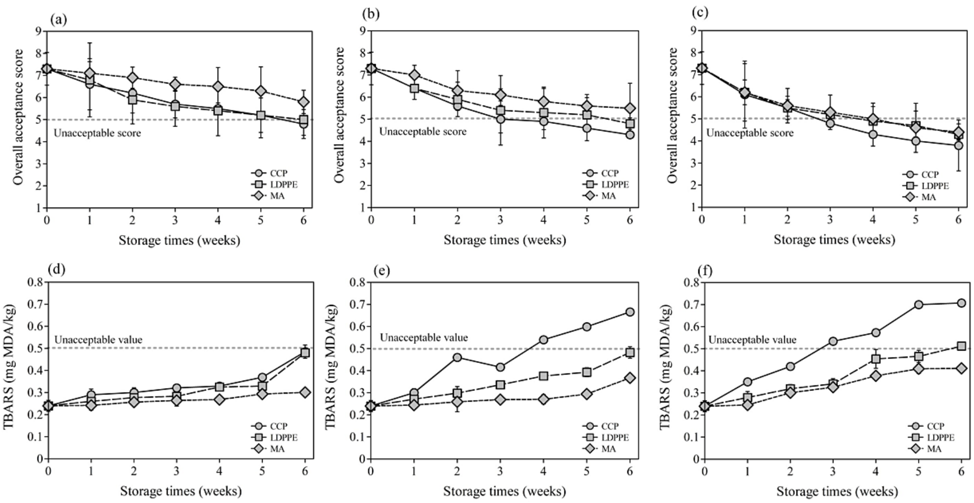

Fig. 3: Overall acceptance score and TBARS values at 35 °C (a, d), 45 °C (b, e), and 55°C (c, f) of the caramelized crushed cashew nut balls packed in CPP (●), LDPPE (■), and metalized aluminum (◆) for 6 weeks

Evaluating Lipid Oxidation and Overall Sensory Quality Changes

Changes in the overall acceptance scores and TBARS values of the CCBs tested using various types of packaging and storing at 35, 45, and 55°C are shown in Fig. 2. The results showed that storage temperature and different types of packaging had a significant effect on the overall acceptance score and TBARS values of CCB.

Kinetics Study

The quality loss of CCB was investigated based on the overall acceptance scores and TBARS values for the ASLT of CCB packed in CPP, LLDPE, and metalized aluminum at 35, 45, and 55°C. These parameters represent deterioration factors in snack products and are used to predict the expiration date in correlation with the actual expiration date that the producer claims.[36] For the ASLT, the acceptability scores and TBARS value were evaluated using the Arrhenius model. This model can describe the reaction rate of food because temperature is the primary factor in food quality change.[37]

The reaction order was determined by comparing the R^2 value for each linear regression equation at the same temperature, where a high R^2 value indicates a better fit of the regression model to the data. The change in overall acceptance and TBARS values of CCB were modeled and mostly found to be a first-order reaction with $R^2 > 0.84$ for all experiments. The rate of overall acceptance scores and TBARS production were substantially dependent on temperature and packaging type, as described by Arrhenius kinetics. Fig. 4 shows the Arrhenius plotted of ln k versus 1/T for the rate of overall acceptance and TBARS at constant temperature. The estimated values of Ea and k for the overall acceptance scores and TBARS values are reported in Table 2.

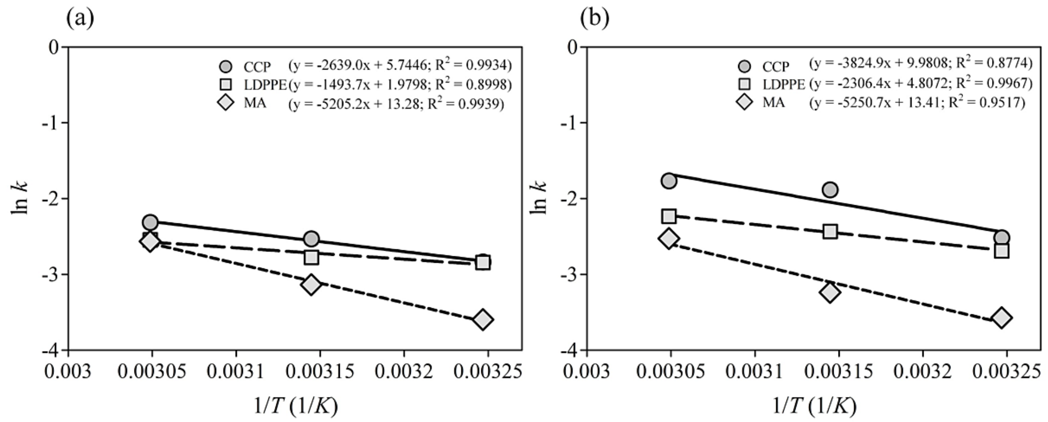

Fig. 4: Arrhenius plot (In k versus 1/T) for overall acceptance (a) and TBARS (b) constant of caramelized crushed cashew nut balls in different packaging during storage

Table 2: Activation energy (Ea) and reaction rate constant (k) of overall acceptance and TBARS values at 35, 45, and 55°C of caramelized crushed cashew nut balls in different packaging

Property	Packaging type	k (per day)			Ea (kJ/mol)
		35°C	45°C	55°C	
Overall acceptance	CPP	0.059	0.078	0.100	21.941
	LDPPE	0.057	0.066	0.076	12.418
	MA	0.027	0.046	0.075	43.276
TBARS	CPP	0.087	0.129	0.186	31.800
	LDPPE	0.068	0.087	0.108	19.175
	MA	0.026	0.045	0.074	43.654

Shelf-Life of Caramelized Crushed Cashew Nutball

Sensory characteristics are the most critical decision factor that influences customer preference. Additionally, the volatile carbonyl compound generated due to lipid oxidation contributed to rancidity, negatively affecting the eating quality of the CCBs. The shelf-life estimation of the CCBs was calculated, with a requirement period for a 50% degradation of sensory acceptability scores and TBARS values, based on the first-order kinetic model. Analysis of the prediction equations for shelf-life based on storage temperature yielded R^2 values between 0.9738–0.9963, the longest shelf-life was obtained for MA (with a sensory shelf-life of 25.88 weeks and a TBARS shelf-life of 26.34 weeks at 35°C) (Table 3).

Table 3: Shelf-life of caramelized crushed cashew nut balls in different packaging at 35, 45, and 55°C, based on overall acceptance and TBARS values

Property	Packaging	Shelf-life (weeks)[a]			Predictive equation[b]	R^2
		35°C	45°C	55°C		
Overall acceptance	CPP	11.67	8.91	6.92	SL = -0.2375T + 19.854	0.9915
	LDPPE	12.22	10.49	9.09	SL = -0.1565T + 17.645	0.9963
	MA	25.88	15.21	9.23	SL = -0.8323T + 54.228	0.9742
TBARS	CPP	7.93	5.37	3.72	SL = -0.2107T +15.155	0.9845
	LDPPE	10.12	8.00	6.41	SL = -0.1855T +16.524	0.9931
	MA	26.34	15.41	9.32	SL = -0.8514T + 55.335	0.9738

[a] Shelf-life calculated based on the percentage of residual levels of any attributes (50%).
[b] T and SL in predictive equations for shelf-life indicate storage temperature and shelf-life, respectively.

Discussion

Optimization of CCB on Physical Characteristics and Sensory Analysis

A response surface plot indicated that the highest caramel sauce proportion (200 g) with the lowest amount of crushed cashew nut (100 g) was rejected based on the overall acceptant preference score (<5) from the panelists (Fig. 2b). This evaluation score was related to the highest CCB hardness values (45.09 and 49.39 N) from the texture analysis which increased as the amount of caramel sauce increased (Fig. 2a). Because sugar is the main component of caramel sauce, increasing the sugar content enhances the strength of the internal bond, resulting in a high hardness value.31 The optimum conditions were found to be 189 g for crushed cashew nuts, 200 g of caramel sauce, and 2 min cooking time. The expected values under optimal conditions were identified as a hardness value of 35.00 N and an overall acceptance score of 6.0 with a desirability of 1.00. To validate this model, a small adjustment for practicality to produce CCB was modified as follows: 190 grams of crushed cashew nuts, 200 grams of caramel sauce, and a cooking time of 2 min. This optimized condition was applied to prepare the experimental evaluation of CCB in triplicate. The results showed a hardness value of 36.03 ± 2.96 N and sensory acceptability of 6.2 ± 0.4. The predicted and experimental values of this model under the optimum conditions were not significantly different based on a t-test, which was appropriate accordance with the projected values and demonstrated that the model was suitable for optimum the conditions for producing CCBs. In addition, the nutritional composition of CCB prepared by using optimized conditions has been revealed nutrition information per ball (10 g): energy 35 Kcal, moisture content of 3.3% dry basis, carbohydrate content of 2.1 g, protein 0.8 g, total fat 2.1 g, saturated fat 0.7 g, cholesterol of 1.1 mg, dietary fiber 0.2 g, sugar 2.1 g and sodium of 23 mg.

Evaluating Lipid Oxidation and Overall Sensory Quality Changes

In this study, an overall acceptance score of 5.0 (neither liked nor disliked) on a 9-point hedonic scale was considered as the threshold limit for acceptable quality.[32] Additionally, a score of 5.0 or lower was identified as the point where the quality of CCB begins to decline, corresponding to a TBAR value exceeding 0.5 mg MDA/kg (Fig. 3d, 3e, 3f). Increasing the storage time and storage temperature significantly decreased the overall acceptance scores (Fig. 3a, 3b, 3c), while the TBARS values significantly increased (Fig. 3d, 3e, 3f) throughout storage times. The correlation between the overall acceptance and the TBARS values of CCB reflected the undesirable taste and odor of rancidity during storage due to the decomposition of hydroperoxides breaking down into secondary oxidation products as malonealdehyde.[33] As shown in Fig. 3f, CCB stored at 55°C had higher TBARS values for all packaging types, indicating the rapid increase in lipid rancidity and lower acceptability scores. Malonaldehyde is an aldehyde indicator produced during the breakdown of unsaturated fatty acids throughout the distribution and storage of products.[34] The lipid oxidation products in foods produce an unpleasant rancid odor, which is one of the most important attributes affecting food quality, nutrition, safety, color, and consumer acceptance.[34,35]

Kinetics Study

Regarding the Ea values, the total acceptance scores for MA, LDPPE, and CPP were 43.276, 12.418, and 21.941 kJ/mol, respectively. In particular, the Ea of the TBARS values for MA, LDPPE, and CPP were 43.654, 19.175, and 31.800 kJ/mol, respectively. The highest Ea and the lowest k values indicate that more energy was required to initiate the lipid oxidation reaction and to decrease sensory properties. The CCB packed in MA had higher Ea and lower k values for both quality parameters than the other packages, resulting in the slowest rate of increase in TBARS and sensory loss. Raising the temperature increased k for the chemical and sensory properties, demonstrating that these reaction rates had a strong temperature dependence. The k value of chemical degradation caused by TBARS production indicated a relatively faster rate at high temperature than for the overall acceptance scores with all types of packaging. Among the packaging types, CCB packed in CPP had the most significant sensitivity response to temperature change and was causally related to the highest TBAR production and lowest sensory scores, resulting in its rapid rejection by the panelists. Therefore, low-temperature storage slowed down the rancidity reaction and degradation of the sensory score in the CCBs, especially for the CCB packed in MA, resulting in a good quality level of the CCB. Based on the kinetic studies using the Arrhenius model, our findings provide a better understanding of the temperature-dependent changes in the chemical and sensory properties of CCB, as well providing guidance in designing the optimal packaging capable of preserving a good quality of CCB.

Shelf-life of Caramelized Crushed Cashew Nutball

The shelf-life of the CCBs in all packaging was extended by lower storage temperatures, resulting in a good quality of CCB being preserved. Consequently, there was an increase in TBARS values and a decrease in sensory acceptability scores of CCB at elevated temperatures due to rapid lipid oxidation, which is the primary cause of the shortening of shelf-life.[5,38]

Based on the steeper slopes of the sensory quality and the TBARS predictive equations, CCB packed in MA had a shelf-life similar to or better than the other types of packaging at all storage temperatures. The aluminum-coated layer of MA had a significantly high impact on the moisture and light barrier properties. This coating on the layer of MA transformed it into a non-transparent pouch with extremely low free volume between the polymer chains, resulting in the lowest water vapor transfer rate (WVTR) and permeability coefficient.[36,39] The oxidative and light barrier properties of MA prevented the oxidation reaction from oxygen and light exposure, delaying the lipid oxidation rate and prolonging sensory acceptability by the panelists. Therefore, packaging is crucial in preventing lipid oxidation and sensory quality deterioration caused by temperature changes during storage, with MA being suitable for maintaining the shelf-life storage stability of CCB. Furthermore, the predictive equations from the current study can be employed to estimate the lipid oxidation and sensory acceptance of CCB.

Conclusion

The caramelized nutballs were produced from crushed cashew nuts as the main ingredient. The optimal conditions for producing the value-added CCB were identified for crushed cashew nuts, caramel sauce, and cooking time (190 g, 200 g, and

2 min, respectively) and there was good acceptance from panelists of the generated product. The sensory qualities and the TBARS values reflecting the rancid odor were the most important factors influencing consumer preference and discriminating the quality of CCB. Using an Arrhenius kinetic model, these attributes could be utilized to predict the shelf-life of CCB stored in different packaging. The overall sensory acceptability scores and TBARS values were a good fit with Arrhenius plots using a first-order kinetic model. The Arrhenius model's reaction rate constant (k) and the TBARS values from various packaging types can be used to comprehend changes in overall sensory quality. Based on our results (both the overall sensory evaluation and the TBARS values), the longest shelf-life was obtained for MA (with a sensory shelf-life of 25.88 weeks and a TBARS shelf-life of 26.34 weeks at 35°C). Thus, MA should be considered as appropriate packaging to minimize undesirable changes and prolong the shelf-life of CCB.

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Conflict of Interest

The authors declare that there is no conflict of interest.

Data Availability Statement

Data will be made available on request.

Ethics Statement

The legal and ethical aspects of the project were approved by the Ethics Committee of Naresuan University (No. 028.64) (Exemption Review), in accordance with the Declaration of Helsinki.

Informed Consent Statement

This study did not involve human participants, and therefore, informed consent was not required.

Clinical Trial Registration

This research does not involve any clinical trials.

Permission to Reproduce Material from other Sources

Not appilcable.

Author Contributions

- **Chitsiri Rachtanapun:** Investigation, Methodology, Writing-original draft, Data curation, Visualization.
- **Juthamas Tantala:** Conceptualization, Investigation, Methodology, Writing-original draft, Data curation.
- **Pornchai Rachtanapun:** Conceptualization, Funding acquisition
- **Porawan Naksang:** Conceptualization, Investigation, Methodology, Data curation, Writing-original draft, Visualization, Writing-review and editing.

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