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Effects of Pretreatment and Frying Temperature on Oil Content, Acrylamide Formation, Color, Texture, and Sensory Acceptance of Kerupuk Sanjai Cassava Chips from Bukittinggi, West Sumatra

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Abstract

Kerupuk sanjai is a thin cassava (Manihot esculenta Crantz) chip that is a traditional culinary specialty of Bukittinggi, West Sumatra, produced by deep-frying uniformly sliced cassava in palm oil at high temperatures. As a high-carbohydrate starch-based fried product, kerupuk sanjai is susceptible to two principal quality and safety concerns: excessive oil uptake and the formation of acrylamide a probable human carcinogen (IARC Group 2A) generated via the Maillard reaction between asparagine and reducing sugars above 120°C. This study systematically evaluated the effects of four pretreatment strategies control (no pretreatment), blanching (85°C, 2 min), soaking in 3% NaCl solution (40°C, 20 min), and pre-drying (60°C oven, 45 min) combined with two frying temperatures (150°C and 170°C) on oil content, color (L* and a*), acrylamide concentration, textural hardness, and sensory acceptability of kerupuk sanjai. A 4 × 2 factorial Completely Randomized Design with three replicates was employed. Results demonstrated that both pretreatment and frying temperature significantly affected all measured parameters ($p < 0.001$), with significant interactions for acrylamide ($p < 0.05$). Pre-drying yielded the lowest oil content (22.3 ± 0.5% at 170°C), while blanching produced the lowest acrylamide concentration (180 ± 12 µg/kg at 150°C) and best colorimetric attributes. Increasing frying temperature from 150°C to 170°C increased acrylamide by approximately 3.0–3.5-fold across all pretreatments. The a* colorimetric parameter (redness) exhibited a strong positive Pearson correlation with acrylamide content ($r = 0.97$, $p < 0.001$), validating it as a non-destructive process control indicator applicable at the artisan production level. Blanching combined with 150°C frying is recommended as the safest processing combination, while pre-drying combined with 170°C provides the optimal balance between oil reduction and consumer acceptability (overall sensory score 4.1/5.0).

Keywords: Kerupuk sanjai; cassava chips; acrylamide; oil content; blanching; pre-drying; frying temperature; food safety; Maillard reaction; West Sumatra

Introduction

Kerupuk sanjai also known locally as keripik sanjai or keripik singkong sanjai is a traditional snack food originating from Bukittinggi, West Sumatra, representing one of the most commercially significant culinary heritage products of the Minangkabau region. Produced from thinly sliced fresh cassava (Manihot esculenta Crantz) deep-fried in palm or coconut oil until crispness is achieved, kerupuk sanjai is frequently coated with a characteristic sweet-spicy balado chili glaze and sold as a premium local souvenir product commanding higher retail prices than generic commercially produced cassava chips. The product sustains a significant cottage industry sector in the Bukittinggi area, providing livelihoods for hundreds of artisan producers [1].

Despite its cultural and economic importance, kerupuk sanjai like all high-carbohydrate starch-based deep-fried products is potentially susceptible to two interrelated food safety concerns that have attracted

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increasing regulatory and scientific attention globally. First, the high fat content resulting from oil absorption during deep-frying contributes to dietary fat intake, with implications for cardiovascular disease risk in populations that consume such snacks regularly. Second, and of greater toxicological significance, the elevated temperatures (typically 160–190°C) employed during deep-frying of cassava slices can promote the formation of acrylamide via the Maillard condensation reaction between free asparagine and reducing sugars [2, 3].

Acrylamide (prop-2-enamide, CAS 79-06-1) was identified in thermally processed starchy foods by Swedish food safety authorities in 2002, triggering an intense global research response [4]. The International Agency for Research on Cancer (IARC) has classified acrylamide as a Group 2A probable human carcinogen based on sufficient evidence of carcinogenicity in animal studies and mechanistic evidence in humans, with epoxidation to glycidamide as the principal activation pathway [5]. In carbohydrate-rich thermally processed foods, acrylamide concentrations typically range from 150 to 4,000 µg/kg, with fried potato and cassava products representing some of the highest-exposure food categories [6]. The European Food Safety Authority (EFSA) and joint FAO/WHO committees have established margin of exposure (MOE) calculations indicating that dietary acrylamide exposure is of concern for public health.

Various pretreatment strategies have been documented to reduce acrylamide formation by depleting the Maillard precursors (asparagine and reducing sugars) from the food surface prior to frying. Blanching with hot water or steam leaches soluble asparagine and glucose from the starch matrix, reduces surface moisture, and denatures surface enzymes collectively limiting the availability of Maillard reactants [7]. Pre-drying before frying forms a surface crust that physically impedes oil penetration while simultaneously reducing the duration of high-temperature exposure needed to achieve the target moisture content, thereby limiting acrylamide formation window [8]. Salt soaking has been reported to partially reduce acrylamide through ion exchange and competitive inhibition of Maillard reactions, though with less consistent efficacy [9]. A critical gap in the existing literature is the absence of systematic data for cassava chip products from West Sumatra, where cassava cultivars, chip thickness, frying oil type, and frying practices differ from the potato-chip-based systems that dominate the international literature.

The objectives of this study were: (i) to systematically evaluate four pretreatment strategies combined with two frying temperatures on oil content, color, acrylamide, texture, and sensory acceptance of kerupuk sanjai; (ii) to validate the utility of the a* colorimetric parameter as a real-time acrylamide predictor; and (iii) to provide evidence-based process recommendations for artisan kerupuk sanjai producers seeking to minimize health risks while maintaining product quality.

Literature Review

2.1. Acrylamide Formation Mechanism in Starchy Foods

Acrylamide formation in thermally processed foods proceeds primarily via the Maillard reaction pathway, in which the free amino group of asparagine (the most reactive amino acid precursor) condenses with carbonyl groups of reducing sugars to form N-glycosyl asparagine intermediates, which undergo Schiff base formation, cyclization, and decarboxylation to yield acrylamide as a quantitatively important degradation product [2, 3]. The reaction rate follows Arrhenius kinetics with strong temperature dependence a 10°C temperature increase approximately doubles acrylamide formation rate and proceeds optimally at low water activity (aw < 0.6), explaining why surface-dehydrated zones of fried chips are the

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primary sites of acrylamide generation [6]. Cassava is particularly susceptible because some cultivars have been reported to contain relatively high free asparagine concentrations (80–400 mg/100 g fresh weight), and because the high amylose content of cassava starch promotes surface drying patterns that create extended low-aw zones during frying [1].

2.2. Oil Absorption During Deep Frying

Oil absorption in deep-fried starchy products occurs predominantly during the post-frying cooling phase, when condensation of water vapor from the hot product creates a partial vacuum that draws surface oil into the cellular pore structure vacated by evaporated moisture. The degree of oil absorption is therefore principally governed by the surface microstructure, moisture content at the time of frying completion, and the duration of high-temperature oil contact [8, 10]. Pre-drying creates a surface crust with reduced porosity and initiates partial dehydration before oil contact, substantially reducing both oil uptake and the duration of Maillard-favorable low-aw conditions during frying. This dual benefit reduced oil and reduced acrylamide makes pre-drying particularly attractive as a simple, low-cost intervention for artisan producers.

2.3. Color as a Predictor of Acrylamide

The colorimetric a* parameter (redness/greenness on the CIE L*a*b* color scale) has been established as a reliable, non-destructive predictor of acrylamide content in fried potato products, with correlation coefficients reported in the range r = 0.92–0.98 [11, 12]. This correlation exists because both a* redness increase and acrylamide formation are downstream consequences of the same Maillard reaction cascade: brown pigments (melanoidins) that increase a* and acrylamide are formed through the same reaction network from the same precursors under the same temperature-time conditions. The a* parameter is therefore mechanistically linked to acrylamide rather than merely empirically correlated, supporting its use as a rapid in-line quality indicator in processing environments where LC-MS/MS acrylamide analysis is not feasible.

Materials and Methods

3.1. Raw Materials

Fresh cassava tubers (Manihot esculenta Crantz, local variety 'Mentega') of uniform maturity (8–9 months post-planting), free from blemishes or mechanical damage, were sourced from a single farm in Agam Regency, West Sumatra, and processed within 6 hours of harvest. Refined palm olein (iodine value 56 g I2/100 g, free fatty acid < 0.1%, peroxide value < 1.0 meq O2/kg) from a single commercial batch was used as the frying medium. All chemical reagents sodium chloride (food grade), acrylamide standard (Sigma-Aldrich, ≥ 99%), [2,3-$^{2}H_{2}$]-acrylamide isotope-labeled internal standard, formic acid (HPLC grade), acetonitrile (HPLC grade), and methanol (HPLC grade) were of analytical grade.

3.2. Cassava Chip Preparation and Pretreatments

Cassava tubers were peeled, washed, and sliced to a uniform thickness of 1.0 ± 0.05 mm using a calibrated mandoline slicer. Sliced chips were randomly distributed to four pretreatment groups: (P0) control no pretreatment, chips fried immediately after slicing; (P1) blanching slices immersed in water at 85°C for 2 minutes, drained, and surface blotted before frying; (P2) NaCl soaking slices immersed in 3% (w/v) NaCl solution at 40°C for 20 minutes, rinsed with distilled water, drained, and blotted; (P3) pre-drying slices dried in a forced-air oven at 60°C for 45 minutes to achieve partial dehydration (target moisture 50–55% of fresh weight), then allowed to equilibrate to room temperature for 5 minutes before frying. Each

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pretreatment group was further divided for frying at 150°C and 170°C, yielding eight experimental treatment combinations (P0–P3 × T150–T170) each replicated three times (n = 24 experimental units).

3.3. Deep Frying Process

Frying was conducted in a temperature-controlled laboratory deep fryer (capacity 4 L, equipped with PID temperature controller ± 1°C) using fresh palm olein for each experimental batch. The chip-to-oil mass ratio was maintained at 1:30 to ensure minimal temperature perturbation upon chip addition. Frying was continued until chip moisture content reached 3.0 ± 0.5% (monitored by rapid moisture determination). Fried chips were removed, drained on stainless-steel mesh for 60 seconds, blotted with absorbent paper for standardized post-frying drainage, cooled to room temperature (25 ± 2°C), and transferred to sealed amber containers for analysis within 4 hours.

3.4. Analytical Methods

Moisture content was determined by oven drying at 105°C (AOAC Method 925.10) [13]. Oil content was determined by Soxhlet extraction with n-hexane for 6 hours (AOAC Method 920.85) and expressed as percentage of total chip mass (wet basis). Color measurements (L*, a*, b*) were made using a calibrated reflectance colorimeter (Konica Minolta CR-400, Japan) on five measurement points per sample. Acrylamide was quantified by LC-MS/MS (Shimadzu LCMS-8060, Japan) using the isotope dilution method with [2,3-$^{2}H_{2}$]-acrylamide as internal standard, following SPE cleanup on Oasis HLB cartridges; quantification limit was 15 µg/kg [14]. Textural hardness was determined as peak fracture force (N) using a texture analyzer (TA.XT Plus, Stable Micro Systems, UK) with a 5 mm cylindrical probe at 1 mm/s test speed. Sensory evaluation was conducted by 30 semi-trained panelists using a 5-point hedonic scale for color, crispiness, flavor, and overall acceptability. All analyses were performed in triplicate.

3.5. Statistical Analysis

A 4 × 2 factorial Completely Randomized Design was used. Two-way ANOVA was applied to assess main effects of pretreatment and frying temperature, as well as their interaction, using SPSS 27.0. Mean separation was performed by Duncan's Multiple Range Test (DMRT) at 5% significance. Pearson correlation coefficients were calculated between a* and acrylamide across all 24 experimental units.

Results and Discussion

4.1. Oil Content

Oil content was significantly affected by both pretreatment ($p < 0.001$) and frying temperature ($p < 0.001$), without significant interaction. Pre-drying (P3) consistently produced the lowest oil content across both frying temperatures24.6 ± 0.6% at 150°C and 22.3 ± 0.5% at 170°C representing a 20–21% reduction relative to the untreated control (Table 1). This finding confirms the mechanism described by Moyano and Pedreschi [8]: the partially dehydrated crust formed during pre-drying reduces inter-pore connectivity, limiting the capillary suction of oil during the post-frying cooling phase. Blanching (P1) produced a modest 5–7% oil reduction relative to control, likely due to partial gelatinization of surface starch reducing porosity. NaCl soaking (P2) showed negligible oil reduction. The counter-intuitive observation that higher frying temperature (170°C) produced slightly lower oil content than 150°C is consistent with the capillary model: higher temperatures generate more vigorous moisture evaporation, maintaining positive internal vapor pressure for a longer period of the frying cycle and thereby delaying oil penetration [10].

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Table 1. Oil content (%) of kerupuk sanjai under different pretreatment × frying temperature combinations (mean ± SD, n = 3).

Pretreatment	150°C	170°C
P0: Control	31.2 ± 0.8d	28.4 ± 0.7c
P1: Blanching (85°C, 2 min)	29.8 ± 0.7cd	27.1 ± 0.7bc
P2: NaCl soaking (3%, 20 min)	30.5 ± 0.8cd	27.8 ± 0.7c
P3: Pre-drying (60°C, 45 min)	24.6 ± 0.6ab	22.3 ± 0.5a

Different superscript letters across all cells indicate significant differences ($p < 0.05$, DMRT).

4.2. Acrylamide Formation and Color Parameters

Acrylamide content and colorimetric a* values are presented in Table 2. Acrylamide concentrations across all treatments ranged from 180 ± 12 µg/kg (P1 at 150°C) to 1,480 ± 60 µg/kg (P0 at 170°C) a 8.2-fold range demonstrating the profound influence of pretreatment and temperature on acrylamide generation. The increase from 150°C to 170°C frying increased acrylamide by 3.0–3.5-fold across all pretreatment groups, confirming the exponential temperature dependence of Maillard kinetics [6]. Blanching was the most effective pretreatment, reducing acrylamide by 57% at 150°C and 62% at 170°C relative to control, consistent with the dominant mechanism of asparagine and glucose leaching from the chip surface during water immersion [7].

Table 2. Acrylamide (µg/kg), colorimetric a*, and textural hardness (N) of kerupuk sanjai (mean ± SD, n = 3).

Pretreatment	Acrylamide 150°C	Acrylamide 170°C	a* 150°C	a* 170°C	Hardness 150°C (N)	Hardness 170°C (N)
P0 Control	420 ± 25d	1480 ± 60h	3.2 ± 0.2c	6.8 ± 0.3f	8.2 ± 0.4b	9.1 ± 0.4c
P1 Blanching	180 ± 12a	560 ± 30e	2.1 ± 0.2a	4.3 ± 0.2d	7.4 ± 0.3a	8.0 ± 0.4b
P2 NaCl	390 ± 22d	1260 ± 55g	2.8 ± 0.2bc	5.9 ± 0.3e	8.0 ± 0.4b	8.8 ± 0.4bc
P3 Pre-dry	300 ± 18c	980 ± 45f	2.6 ± 0.2b	5.2 ± 0.3e	9.4 ± 0.5c	10.3 ± 0.5d

Different superscript letters within each parameter group indicate significant differences ($p < 0.05$, DMRT).

Pre-drying (P3) reduced acrylamide by 29–34% relative to control a meaningful but less dramatic reduction than blanching through a different mechanism: shortened effective frying duration (lower-aw surface zones reached faster) and reduced availability of soluble sugars released from the pre-dried surface crust. The significant pretreatment × temperature interaction for acrylamide ($p < 0.05$) reveals that blanching efficacy increases disproportionately at higher temperature: the absolute acrylamide difference between P0 and P1 was 240 µg/kg at 150°C but 920 µg/kg at 170°C, indicating that blanching is especially valuable when elevated temperatures cannot be avoided for operational reasons.

The Pearson correlation between a* and acrylamide across all 24 experimental units was $r = 0.97$ ($p < 0.001$), validating the strong mechanistic link between surface browning and acrylamide formation previously documented for potato chips [11, 12]. This high correlation has direct practical implications: artisan kerupuk sanjai producers can use visual color assessment or a low-cost colorimeter to define a target endpoint redness value that reliably predicts acceptable acrylamide levels, without requiring access to LC-MS/MS analytical infrastructure. Based on the present data, an a* endpoint target of ≤ 3.0 at 150°C or ≤ 4.5 at 170°C is suggested as corresponding to acrylamide levels below 500 µg/kg.

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4.3. Sensory Evaluation

Sensory scores (Table 3) revealed that P1 at 150°C and P3 at 170°C achieved the highest overall acceptability (4.0 and 4.1/5.0, respectively). Blanching at 150°C produced the lightest color with the best colorimetric score (4.3), while pre-drying at 170°C yielded the highest crispiness rating (4.4) due to the elevated textural hardness (10.3 N) and reduced final oil content. The untreated control at 170°C, while receiving the highest flavor score among all treatments (4.2/5.0) owing to more intense Maillard-derived flavors preferred by some panelists, received a lower overall acceptability due to its undesirably dark color, consistent with documented consumer color preferences for golden-yellow rather than dark-brown cassava chips.

Table 3. Sensory scores of kerupuk sanjai on a 5-point hedonic scale (mean, n = 30 panelists).

Treatment	Color	Crispiness	Flavor	Overall Acceptability
P0 Control 150°C	3.8	3.7	3.6	3.7
P0 Control 170°C	3.3	4.3	4.2	3.9
P1 Blanching 150°C	4.3	3.9	3.8	4.0
P1 Blanching 170°C	4.1	4.2	3.9	4.0
P2 NaCl 150°C	3.9	3.8	3.9	3.8
P2 NaCl 170°C	3.7	4.1	4.0	3.9
P3 Pre-dry 150°C	4.1	4.0	3.8	4.0
P3 Pre-dry 170°C	3.9	4.4	4.0	4.1

Hedonic scale: 1 = dislike extremely; 5 = like extremely.

4.4. Process Recommendations for Artisan Producers

Integrating the totality of results oil content, acrylamide, color, texture, and sensory acceptability two process recommendations emerge for West Sumatran kerupuk sanjai producers. For maximum food safety (minimum acrylamide): blanching at 85°C for 2 minutes followed by frying at 150°C represents the optimal strategy, yielding acrylamide of 180 µg/kg (11-fold reduction from unoptimized process), acceptable sensory scores (4.0/5.0), and a good color profile. For maximum oil reduction with acceptable safety: pre-drying at 60°C for 45 minutes followed by frying at 170°C achieves the lowest oil content (22.3%), the highest crispiness (4.4), and good overall acceptance (4.1/5.0), while producing moderately lower acrylamide than untreated control at 170°C. Producers are strongly advised against using temperature × duration combinations that produce a* > 6.0, as this colorimetric threshold corresponds to acrylamide concentrations exceeding 1,000 µg/kg in the current dataset. Frequent replacement of frying oil is also recommended, as degraded oil accelerates both oxidative deterioration and acrylamide formation [15].

Conclusion

This study provides the first systematic evaluation of acrylamide mitigation strategies for kerupuk sanjai cassava chips from West Sumatra. Both pretreatment type and frying temperature critically determined oil content, acrylamide formation, color, texture, and sensory quality. Blanching achieved the greatest acrylamide reduction (57–62%) while pre-drying produced the lowest oil content (22.3%). Temperature elevation from 150°C to 170°C increased acrylamide by 3.0–3.5-fold, representing the most impactful

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single variable. The a* colorimetric parameter showed exceptional correlation with acrylamide (r = 0.97), confirming its value as a practical, real-time process control tool.

For maximum food safety, blanching at 85°C for 2 minutes followed by frying at 150°C is recommended. For balanced oil reduction and safety, pre-drying at 60°C combined with 170°C frying represents an effective alternative. Future research should quantify precursor asparagine and reducing sugar content in different West Sumatran cassava cultivars to enable model-based acrylamide prediction, evaluate vacuum frying as a technology capable of simultaneously reducing oil and acrylamide, and investigate the stability of the a*–acrylamide relationship across different cassava varieties and chip thicknesses.

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