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Effects of Technological Factors on The Properties and Structure of the Mini Oil Stick (Youtiao)

Tran Cong Danh, Duy H. Truong, Nguyen Thi Mai Huong*

Institute of Biotechnology and Food Technology, Industrial University of Ho Chi Minh City, Ho Chi Minh City, 70000, Vietnam

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ABSTRACT

Oil stick (youtiao) is a traditional deep-fried snack widely consumed in Asia but typically produced in large sizes with a hard texture, which limits its appeal to modern consumers. This research was designed to develop a mini version of traditional youtiao through adjustments in formulation and frying conditions that improve crispness and overall quality. Particular attention was given to the role of modified starch as a partial substitute for wheat flour, the selection of suitable leavening agents, and the optimization of frying temperature and time. By examining their combined effects on texture, expansion, color, fat content, and consumer perception, the study seeks to provide a scientific approach for upgrading the conventional, handmade product into a standardized, industrially producible snack that retains traditional sensory appeal. A stepwise experimental design was employed. Modified starch (E1414) was incorporated at 0 - 15% to replace wheat flour, while three leavening systems such as 0.2% baking powder, 0.2% ammonium bicarbonate, and a 50:50 combination were tested. Frying temperatures ranged from 180 °C to 200 °C and times from 60 to 120 seconds. Statistical analysis (one-way ANOVA, $p < 0.05$) revealed significant effects of formulation and frying parameters on product hardness, expansion, and moisture. The final formulation, fried at 190 °C for 90 seconds, showed balanced crispness, color, and oil content (moisture 4.2%, fat 18.7%), achieving the highest sensory score (7.24/9). These findings provide a scientific foundation for industrial-scale production of high quality, modernized youtiao snacks.

Keywords: Mini oil stick, Youtiao, Snack, Modified starch, Texture

Introduction

Oil stick also known as the youtiao, a type of fried bread, is a long strip of dough that is deep-fried and widely enjoyed as a breakfast item in China, Indonesia, Malaysia, Myanmar, Singapore, Laos, and various South Asian nations.[1] It is typically prepared using wheat flour, water, a leavening agent, and cooking oil.[2] These ingredients are combined into a dough, which is then allowed to rise, shaped, and fried until golden and crisp. It is characterized by a golden brown, crispy exterior and a light, porous interior structure, typically achieved through deep frying of chemically leavened dough.[3, 4] Snack foods can be classified according to their primary raw materials (cereals, tubers, legumes), processing methods (frying, baking, roasting, drying, extrusion), and sensory profiles (savory, sweet, sour, spicy).[5] In industrial production, post frying seasoning is frequently applied while the product surface remains coated with residual frying oil, which promotes adhesion of powdered or liquid flavorings and enhances sensory appeal.[6] The inherent flexibility in flavor customization, often achieved through post-frying seasoning, has led to a diverse and increasingly popular range of oil stick products. Unlike the traditional products that were usually coated with a hard sugar layer, the smaller and crispier products offer greater freedom to incorporate different flavor profiles such as sweet, savory, or spicy seasonings. This flexibility enhances their attractiveness and positions them as modern snacks that appeal strongly to younger consumers.[5, 6] Globally, the snack industry is moving toward smaller, portion-controlled products that combine traditional appeal with modern convenience. The development of compact, texturally optimized products such as mini oil sticks reflects this global trend toward innovation in traditional fried snacks.[7, 8] Upgrading traditional production practices for industrial application requires extensive experimentation involving raw materials, seasonings, and processing techniques. For fried snack products, achieving a crispy yet stable porous structure, an appealing color, and controlled oil absorption during frying are essential quality attributes.[2] Recent studies on fried foods have shown that the use of alternative flours and even dry gluten supplementation can improve structural properties such as porosity and hardness, increase dietary fiber content, and reduce oil uptake.[9-12] Other investigations have highlighted the role of suitable modified starches, particularly acetylated distarch phosphate (E1414), in enhancing product expansion, improving hardness related to gluten protein networks, stabilizing the structure, and ensuring compatibility with high-temperature deep-frying processes.[13-15]
However, the substitution or supplementation of these ingredients must be tailored to each snack product to address the inherent structural limitations caused by wheat flour. This reflects a targeted approach to ingredient selection based on the desired product characteristics and processing conditions, moving beyond simple substitution toward functional ingredient engineering.[13, 14] In addition, the selection of an appropriate leavening agent should also be considered and evaluated to achieve the desired expansion and surface quality. A higher expansion volume contributes to a lighter, crispier texture and a more appealing appearance in fried snacks.[16-18] To achieve this modernization, developing mini ready-to-eat versions of traditional products requires adjusting formulations and processing conditions to align with the specific characteristics of the product. Current research on miniaturized oil stick products remains limited and did not provide a systematic

*Corresponding author. E mail: nguyenthimaihuong@iuh.edu.vn
Tel: +84903348174

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understanding of how raw materials, supplementary ingredients, and processing parameters influence physical structure and sensory quality.[2] This study aims to investigate the use of modified starch as a partial replacement for wheat flour to create a crispier texture compared to traditional oil sticks, along with processing parameters such as leavening agent type and frying conditions including temperature and time. The analysis focuses on texture, expansion volume, color, fat content, and consumer preference. The objective is to transform traditional small-scale oil stick production into an industrially feasible process by identifying the appropriate combination of formulation and processing factors that produce mini oil sticks with desirable crispness, color, and consumer acceptability while maintaining the characteristic qualities of the original product.

Materials and Methods

Raw materials
The raw materials utilized in this investigation were sourced from specific suppliers to ensure consistency and quality. These included: wheat flour No. 11, supplied by Interflour Vietnam Company, characterized by a gluten content of 10.5-11.5%; 80% gluten powder from Viet Duc Production Trading Co., Ltd.; modified starch (E1414) procured from Nam Bao Tin Import-Export Co., Ltd.; ammonium bicarbonate from Kim Long facility in Ho Chi Minh City; baking powder from Ab Mauri Vietnam Company; cooking oil from An Long Food Joint Stock Company; salt from SOSAL Group Southern Salt Joint Stock Company; powdered sugar from Bien Hoa Sugar Joint Stock Company. All raw materials were meticulously stored under dry and airy conditions to maintain their integrity throughout the research period.

Tools and equipment
The principal equipment deployed for this study included: a XinFeng dough mixer (China) for dough preparation; a Hoang Long fryer (Vietnam) for the deep fat frying process; a CT3-Brookfield Ametek rheometer (USA) for texture analysis; and a Konica CR-400/CR 410 colorimeter (Japan) for color measurements. Additional equipment, such as moisture and fat analyzers, were also utilized for comprehensive product characterization.

Experiment design
The mini oil stick products in this study were prepared following a standardized formulation, as detailed in Table 1.
Unless otherwise specified for a given trial, the standard experimental conditions were as follows: 100% wheat flour as the base, a 1:1 ratio of baking powder to ammonium bicarbonate (totaling 0.2% when used), dough sheets shaped to a thickness of 4 mm, frying at 190 °C for 90 seconds. The Taiwanese Xiao Mahua oil stick served as the control sample for comparison in all experiments.

The mini oil stick production process was adapted from Penfold (2008) [19], with modifications to suit the specific structural and textural properties desired for the product. The process commenced with the thorough mixing and sieving (through a 200 micron sieve) of dry ingredients: wheat flour, gluten powder, modified starch, and sugar. Subsequently, the mixture was combined with the selected leavening agents at a low mixing speed, as determined by the experiment. This was followed by a wet mixing stage, where dissolved water and salt were incorporated. Oil was then added to the dough. The dough underwent slow mixing for 3 minutes, transitioning to fast mixing for an additional 12 minutes. After mixing, the dough was allowed to rest for 10 minutes before being rolled to a uniform thickness of 4 mm. The rolled dough was then cut into strands, each measuring 4 mm in width and 5 cm in length. These semi-finished products were deep fried within the surveyed ranges of 60-120 seconds and 180-200 °C. Finally, the finished oil stick products were seasoned before packaging.

Experiment 1
Investigating the effect of modified starch replacement ratio on oil stick structure
This experiment investigated the effects of replacing wheat flour with different proportions of modified starch at levels of 0%, 5%, 10%, and 15%. The aim was to identify the formulation that achieved hardness comparable to the control sample, a Taiwanese Xiao Mahua oil stick. To ensure consistency, all processing parameters and baseline ingredients were kept constant as summarized in Table 1, while only the proportion of wheat flour substituted with modified starch was varied, following the method of Hung and Morita (2004)[20]. Structural characteristics and microstructural changes were analyzed through texture measurements and scanning electron microscopy (SEM), and the overall experimental design is presented in Table 2.

Table 1: Mini oil stick formulation

Ingredient	% by weight
Wheat flour	100%
Gluten powder	5%
Modified starch	10%
Sugar	10%
Leavening agent	0.20%
Water	60%
Salt	2%
Oil	8%

Table 2: Experimental design for investigating the effect of modified starch replacement

Sample code	MB1	MB2	MB3	MB4
Wheat flour: modified starch ratio	100:0	95:5	90:10	85:15
Measurement indicators	Hardness, SEM			
Measurement equipment	Scanning Electron Microscope JSM-IT200, CT3 4500 Brookfield Ametek Texture Analyzer			
Objective function	Select a sample with hardness similar to the control Mahua oil stick from Taiwan (M0)			

Experiment 2
Investigating the effect of leavening agent type on mini oil stick structure
Experiment 2 was carried out following Experiment 1, using the appropriate percentage of modified starch determined in the first phase. This stage aimed to evaluate the effects of different leavening agents, each applied at a total concentration of 0.2%. The formulations consisted of 0.2% baking powder, 0.2% ammonium bicarbonate, and a mixed formulation containing 0.1% of each agent. The purpose was to identify the most suitable leavening agent based on its influence on product characteristics. All other processing parameters remained identical to those described in Table 1, and the same optimized starch

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level from Experiment 1 was maintained. The only variable examined was the leavening agent type, following the approach of Peranginangin (1997)[21]. The detailed experimental design for this stage is summarized in Table 3.

Table 3: Experimental design for investigating the effect of leavening agent type

Sample	MN1	MN2	MN3
Leavening agent	0.2% ammonium bicarbonate	0.2% baking powder	0.1% baking powder + 0.1% ammonium bicarbonate
Measurement indicators, measurement equipment, and objective function are similar to Experiment 1			

Experiment 3

Investigating the effect of frying temperature and time on oil stick structure

Experiment 3 was designed as a combined study to investigate the interactive effects of frying temperature and time on product quality. Frying temperatures ranged from 180°C to 200°C in 10°C increments, while frying times varied from 60 to 120 seconds in 15-second intervals. The evaluation parameters were consistent with those in Experiments 1 and 2, with the addition of color analysis and a comprehensive sensory evaluation. The objective was to determine the processing conditions and ingredient combinations that yield a product whose hardness, color, and sensory characteristics most closely resemble those of the control. This stepwise experimental approach, where findings from one stage guided the next, provided a systematic and efficient framework for optimizing product quality in food development. All fixed parameters were kept consistent with those listed in Table 1, using the appropriate modified starch percentage from Experiment 1 and the selected leavening agent from Experiment 2. The independent variables examined were frying temperature and time, following the methodology described by Vélez-Ruiz and Sosa-Morales (2003)[22]. The full experimental design for this study is summarized in Table 4.

Table 4: Experimental design for investigating the effect of frying temperature and time

Time (seconds)	Frying temperature 180 °C	190 °C	200 °C
60s	MT1	MT6	MT11
75s	MT2	MT7	MT12
90s	MT3	MT8	MT13
105s	MT4	MT9	MT14
120s	MT5	MT10	MT15
Measurement indicators	Hardness, % moisture, % fat, SEM, color, sensory evaluation		
Measurement equipment	Similar to previous experiments		
Objective function	Select a sample with hardness similar to the control Mahua oil stick from Taiwan		

Analysis methods

Color measurement

Color indices were determined using a Minolta Chroma Meter CR-410 (Japan) which was calibrated with a white standard. Samples were finely ground and tightly pressed into a petri dish, with the sensor head positioned on the sample surface. Measurements were taken at three distinct positions, and the average value of these three readings was reported. Color readings were displayed as L* a* b* values, where L* indicates lightness/darkness, positive and negative a* values represent redness and greenness, respectively, and positive and negative b* values denote yellowness and blueness, respectively. Lab color coordinate values are converted to RGB coordinates to simulate the color of the sample using Adobe illustrator 2020 software.[23]

Structure measurement (hardness)

A Brookfield CT3 texture analyzer (AMETEK Brookfield, USA) was utilized to measure the hardness of product. Samples, with a diameter of 8.5 mm and a length of 5 cm, were placed horizontally on the platform and cut in half. A TA7 blade probe, an accessory of the texture analyzer, was used with a pre-test speed and test speed of 2 mm/s, a trigger force of 1.0 N, and a penetration distance of 5 mm. The cutting force exerted by the blade was recorded as the hardness value.[24]

Measurement of volume (V)

The volume of the mini oil stick was determined using the specific gravity method, which involved the use of millet seeds and a four-digit analytical balance. The reported value represents the average of three replicate measurements. [20]

Determination of porous structure (SEM)

The internal and surface microstructure of the oil stick samples was analyzed using a Joel, JSM-6460LV Scanning Electron Microscope (Japan). Sample preparation involved drying the oil stick samples with a CPD 030 "Critical Point Dryer" (BAL-TEC AG, Principality of Liechtenstein). Subsequently, the dried samples were mounted on metal stubs using double-sided tape and then gold-coated in a vacuum using a BAL-TEC-SCD 005 device (180s/30mA/50mm distance) (BAL-TEC AG, Principality of Liechtenstein). Images of the analyzed samples were captured under high vacuum conditions at an accelerating voltage of 25 kV.[25]

Sensory evaluation

A consumer preference test was conducted involving 70 participants aged 18 to 23 years old. The evaluation took place in a controlled laboratory environment under white light. Samples were prepared one day prior to the test and identified with random three-digit codes to prevent bias. Participants assessed their level of preference for the product using a 9-point hedonic scale, evaluating attributes such as taste, texture, and appearance. The test included three samples: the control sample, the developed mini oil stick sample, and a Korean oil stick sample. A score of 5 on the scale was considered the threshold for overall acceptability, as established by Roze (2021).[26]

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Data analysis

All experiments conducted in this study were meticulously repeated three times. Data were analyzed using one-way ANOVA, and values are reported as mean ± standard deviation (SD). Differences among means were considered statistically significant at $P < 0.05$. Analyses were conducted in Statgraphics Centurion XV (version 15.1.02; Statgraphics Technologies, Inc., USA).

Results and Discussion

Effect of modified starch replacement ratio on dough structure

Modified starch plays an important role in stabilizing the crispy and porous structure of fried products. Replacing wheat flour with modified starch has been reported to improve hardness, surface characteristics, and oil absorption behavior, which are strongly influenced by the gluten network of wheat-based formulations during deep-frying.[27] To determine the appropriate amount of modified starch for the mini oil stick product, the hardness and volume of various samples was measured and compared against a control. The results of the hardness and volume measurements, illustrating the impact of modified starch replacement, are presented in Table 5. The hardness of the oil stick samples progressively decreased as the proportion of modified starch replacement increased. Specifically, sample MB1, containing 0% modified starch (i.e., pure wheat flour), exhibited the highest hardness at 41.8 N. Conversely, sample MB4, with 15% modified starch replacement, recorded the lowest hardness at 20.3 N. This observation aligns with previous research by Sajilata and Singhal (2005)[28] on crispy snack products, which reported similar effects of modified starch. In addition to hardness, the replacement of wheat flour with modified starch also affected the expansion volume of the mini oil stick samples. A clear inverse relationship was observed between hardness and volume such as samples with higher hardness, such as MB1 (41.8 N), exhibited the lowest expansion (1.37 cm^3), whereas softer samples like MB4 (20.3 N) showed the highest volume (2.85 cm^3). This result suggests that increased modified starch content weakens the gluten network, allowing greater gas retention and expansion during frying. The resulting porous structure contributes to a lighter, less dense texture and consequently lower hardness values.

This phenomenon can be attributed to the unique properties of dual modified starch, which undergoes both cross linking and acetylation. These modifications strengthen hydrogen bonds within the flour matrix, effectively acting as bridges between starch molecules. This structural reinforcement has been shown to reduce the rate of starch retrogradation and increase gelatinization temperature. [29] Consequently, dual-modified starch forms cross-links between starch chains, enhancing structural integrity, water retention, and controlled expansion. It exhibits lower retrogradation tendency and greater thermal stability, while forming a continuous gel network that improves surface smoothness and acts as a barrier to oil absorption. However, as the concentration of modified starch increases, it proportionally dilutes the gluten network, leading to a reduction in overall protein content. This dilution causes the gluten matrix to become less cohesive, resulting in looser bonds. The modified starch then occupies the spaces within this relaxed network, leading to greater extensibility, reduced chewiness, diminished elasticity, and ultimately, a more porous and less hard cake structure. This observed decrease in hardness with increasing modified starch is a direct consequence of the modified starch's interaction with the gluten network, leading to a more porous and less rigid structure.[30]

Figure 1 illustrated images of samples with modified starch replacement. Based on the comparison with the control sample, sample MB2, which incorporated a 5% modified starch replacement, demonstrated a hardness profile deemed suitable for the product. Consequently, this 5% modified starch replacement level was selected for utilization in the subsequent experimental phases.

Table 5: Hardness and volume of the oil stick samples when replacing modified starch

Sample code	Hardness (N)	Volume (cm^3)
M0	32.1 ± 1.90^c	2.64 ± 0.10^c
MB1	41.8 ± 3.0^d	1.37 ± 0.14^a
MB2	33.8 ± 1.5^c	2.14 ± 0.08^b
MB3	27.3 ± 2.9^b	2.37 ± 0.06^b
MB4	20.3 ± 3.9^a	2.85 ± 0.09^c

M0 is the control sample, MB1, MB2, MB3, MB4 are samples with 0%, 5%, 10%, 15% modified starch replacement, respectively. Letters on each data point indicate significant differences within the same column at $p < 0.05$. Mean ± standard deviation.

Figure 1: Mini oil stick with modified starch replacement (MB1, MB2, MB3, MB4 were samples with 0%, 5%, 10%, 15% modified starch replacement, respectively)

Effect of leavening agent type on mini oil stick structure

The characteristic porous, crispy, and firm structure of oil stick is directly influenced by leavening agents, despite their relatively low concentration in the overall formulation. Therefore, a thorough investigation into different types and quantities of leavening agents was essential to identify the most suitable option, primarily through comparative analysis of hardness and volume against the control sample. The results detailing the hardness and volume of the mini oil stick samples, as affected by the type of leavening agent, are presented in Table 6.

Table 6: Hardness and volume of mini oil stick

Sample code	Hardness (N)	Volume (cm^3)
M0	32.1 ± 1.90^{ab}	2.60 ± 0.10^{c}
MN1	29.4 ± 0.85^{a}	2.70 ± 0.26^{c}
MN2	33.8 ± 1.96^{b}	1.30 ± 0.15^{a}
MN3	30.3 ± 0.96^{a}	2.10 ± 0.10^{b}

M0 is the control sample, MN1, MN2, MN3 correspond to 0.2% ammonium bicarbonate, 0.2% baking powder, and 50:50 combination of ammonium bicarbonate and baking powder, respectively. Letters on each data point indicate significant differences within the same column at $p < 0.05$. Mean ± standard deviation.

Table 6 and Figure 2 reveals that among the three mini oil stick samples utilizing different leavening agents (0.2% ammonium bicarbonate, 0.2% baking powder, and 0.1% baking powder + 0.1% ammonium bicarbonate combination), sample MN2 (with 0.2% baking powder) exhibited the highest hardness at 33.8 N, while sample MN1 (with 0.2% ammonium bicarbonate) had the lowest at 29.4 N. Notably, there was no statistically significant difference in hardness among these three samples when compared to the control sample. Further analysis of volume, however, showed a distinct pattern: sample MN1 achieved the highest expansion at 2.7 cm^3, whereas MN2 displayed the lowest expansion at 1.3 cm^3.

Figure 2: Mini oil stick using different leavening agents type (MN1, MN2, MN3 correspond to 0.2% ammonium bicarbonate, 0.2% baking powder, and 50:50 combination of ammonium bicarbonate and baking powder, respectively)

When baking powder is incorporated into dough, it typically undergoes a reaction between sodium bicarbonate and H^+ ions, leading to the release of carbon dioxide gas, generally represented by the equation $NaHCO_3 + H^+ \rightarrow Na^+ + CO_2\uparrow + H_2O$. Research indicates that baking powder reactions can produce over 12% CO_2 by weight [31]. However, only approximately 25% of the baking powder typically reacts, and its use can lead to localized alkalization, potentially causing undesirable brown spots and a bitter taste in the finished product [32]. The generation of Na^+ ions during this reaction also contributes to an increase in dough pH, which, paradoxically, can indirectly stiffen the dough.[21, 32]

In contrast, ammonium bicarbonate, when added, decomposes during the frying process, releasing both ammonia and carbon dioxide without requiring a reaction with an acid, unlike baking powder.[32] This reaction is represented as $NH_4HCO_3 \rightarrow NH_3\uparrow + CO_2\uparrow + H_2O$. While highly effective in gas production, the use of ammonium bicarbonate can introduce an undesirable ammonia odor to the product. To mitigate this, a pre-reaction of ammonium bicarbonate with acetic acid (CH_3COOH) can be employed, yielding a weak acid salt and CO_2 through the reaction:

$$NH_4HCO_3 + CH_3COOH \rightarrow CH_3COONH_4 + CO_2\uparrow + H_2O$$

This proposed prereaction of ammonium bicarbonate with acetic acid to mitigate ammonia odor demonstrates a practical and innovative approach to overcoming a common sensory challenge with this leavening agent. It highlights that successful product development often requires not just choosing the right ingredient, but also understanding and mitigating its potential drawbacks through process modifications or pre-treatments, ensuring consumer acceptance.

Comparing the reaction equations, it is evident that ammonium bicarbonate generates a greater volume of gas than baking powder. According to Neeharika (2020)[32], the decomposition reaction of ammonium bicarbonate is characterized by an increasing, less spreading gas release that effectively retains gas, leading to a substantial increase in cake volume. A significant advantage of ammonium bicarbonate is that its thermal decomposition in the product does not leave behind salt residues, thus maintaining the pH of dough. This makes ammonium bicarbonate particularly recommended for low-moisture products such as crispy biscuits and dry cookies.[32]

The sample combining 0.1% baking powder and 0.1% ammonium bicarbonate resulted in a smaller volume compared to the sample with 0.2% ammonium bicarbonate, though it was larger than the sample with 0.2% baking powder. This combination did not achieve the desired effect, as the amount of CO_2 gas produced was insufficient to create a volume comparable to the control sample. When comparing the volumes of the three samples to the control, the sample with 0.2% ammonium bicarbonate was deemed the most suitable. Consequently, 0.2% ammonium bicarbonate was selected for use in the next experiment.

Effect of frying temperature and time on dough structure

Frying temperature and time are two critical parameters in the deep-fat frying process, profoundly influencing the product's hardness and color.[32] Therefore, a comprehensive survey was conducted to identify the optimal frying temperature and time by comparing the hardness and color of the experimental samples with the control. The hardness measurement results from this experiment were depicted in Figure 3.

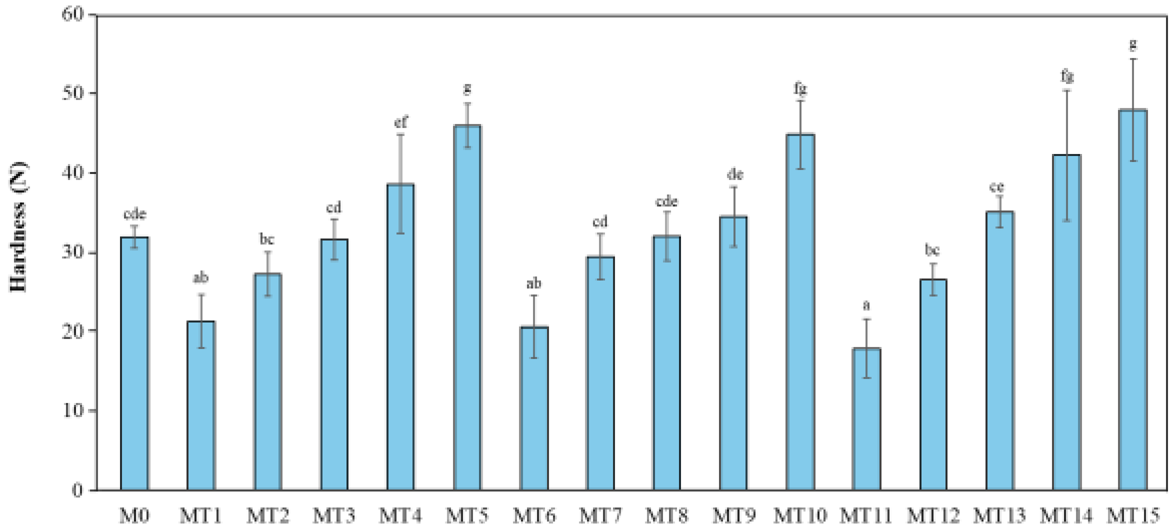

Figure 3: Hardness of mini oil stick s as a function of frying temperature and time (M0 is the control; MT1 - MT5 were fried at 180 °C, MT6 - MT10 at 190 °C, and MT11 - MT15 at 200 °C, with frying times ranging from 60s to 120s. Different letters above the bars indicate significant differences at $p < 0.05$).

The results clearly demonstrate that the hardness of the oil stick tends to increase progressively with both increasing frying temperature and extended frying time. This observation is consistent with prior research indicating that the texture of fried products is significantly affected by these frying conditions.[16] Specifically, sample MT15, fried at 200 °C for 120 seconds, exhibited the highest hardness at 47.9 N, while sample MT11, fried at 200 °C for 60 seconds, showed the lowest hardness at 17.9 N.

During the deep-frying process, a series of complex chemical and physical transformations occur, including starch gelatinization, protein denaturation, water evaporation, and the formation of a distinct crust.[33] The more water that escapes as vapor, the greater the porosity of the oil stick. The formation of these internal pores, resulting from water evaporation, facilitates increased oil penetration into the product. This conclusion aligns with the findings of Thanatuksorn (2005)[34]. When comparing the control sample (M0) to all experimental samples, sample MT8, fried at 190°C for 90 seconds, showed no statistically significant difference in hardness (32.0 ± 3.1 N) from the control.

Figures 4 illustrate changes in moisture and fat content of oil stick fried at different temperatures and times. The results indicate an approximately linear relationship between oil uptake and water evaporation during frying: higher temperatures and longer frying times cause greater moisture loss, which in turn increases oil absorption. This suggests that while higher temperatures and longer times can achieve the desired hardness, they also lead to higher fat content.

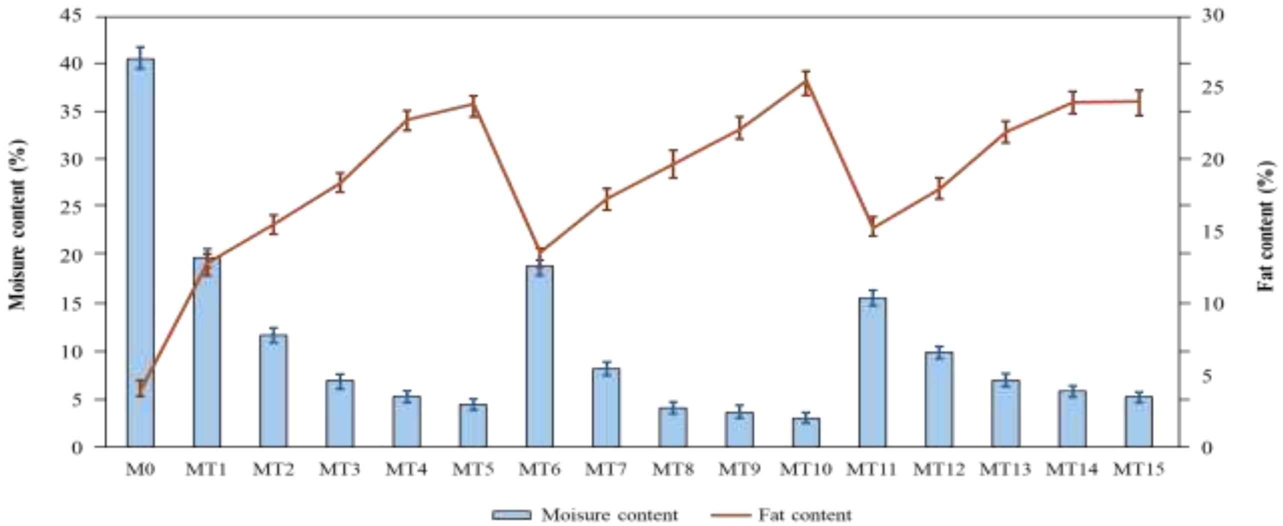

Figure 4: Moisture content and fat content of mini oil stick s as a function of frying temperature and time (M0 is the control; MT1 - MT5 were fried at 180 °C, MT6 - MT10 at 190 °C, and MT11 - MT15 at 200 °C, with frying times ranging from 60s to 120s)

The color results of the mini oil stick, as influenced by frying temperature and time, were presented in Table 7. These data illustrated that as frying temperature and time increased, the L* value (lightness) of the mini oil stick decreased, while the a* (redness) and b* (yellowness) values generally increased. This indicates that the product's color progressively darkened and shifted towards reddish-yellow hues. This inverse relationship between time/temperature and lightness (L*) is a well-documented phenomenon in fried products and

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is consistent with studies on fried potato snacks by Krokida (2001)[35] and Nourian (2003)[36].

The development of color in oil stick after frying is primarily attributed to the Maillard reaction and caramelization. The Maillard reaction involves the interaction between reducing sugars and amino acids, proteins, or other nitrogen-containing compounds under heat. Caramelization, on the other hand, describes a complex series of reactions occurring from the direct heating of carbohydrates.[37] An increase in temperature accelerates both the heat transfer rate and the rate of moisture evaporation from the surface, thereby expediting these color-forming reactions. This leads to an earlier formation of the crust and a darker color, consistent with observations by Van Koerten (2015)[38]. Despite the systematic optimization, the color of the experimental samples did not achieve similarity with the control sample. It is also recognized that the color of mini oil stick can be influenced by the seasoning applied post-frying.

Given that the primary focus of this experiment was to optimize the mini oil stick structure, hardness was prioritized as the key objective for sample selection. Based on this criterion, sample MT8, with frying conditions of 190 °C and 90 seconds, was chosen as it most closely matched the hardness of the control sample.

Table 7: The color results of the mini oil stick

Sample code	Temperature (ºC)	Time (s)	L*	a*	b*	Simulated Color in MATLAB Software
M0	-	-	65.0 ± 0.10^{a}	4.90 ± 0.20^{de}	34.8 ± 0.40^{i}	
MT1	180	60	80.4 ± 1.10^{fg}	1.80 ± 0.10^{b}	23.3 ± 0.60^{a}	
MT2	180	75	80.8 ± 1.00^{g}	1.90 ± 0.10^{bc}	24.4 ± 0.20^{b}	
MT3	180	90	77.2 ± 1.00^{e}	4.80 ± 0.30^{d}	27.3 ± 0.70^{b}	
MT4	180	105	76.9 ± 0.60^{e}	4.90 ± 0.10^{de}	28.4 ± 0.30^{e}	
MT5	180	120	73.8 ± 1.00^{d}	6.40 ± 0.20^{f}	29.9 ± 0.40^{f}	
MT6	190	60	82.5 ± 0.50^{h}	1.40 ± 0.20^{a}	22.9 ± 0.20^{a}	
MT7	190	75	79.8 ± 0.90^{fg}	3.80 ± 0.40^{d}	26.8 ± 0.20^{d}	
MT8	190	90	76.2 ± 0.90^{e}	5.20 ± 0.20^{e}	28.8 ± 0.40^{d}	
MT9	190	105	72.5 ± 0.60^{cd}	7.10 ± 0.50^{g}	30.5 ± 0.50^{fg}	
MT10	190	120	71.7 ± 0.60^{c}	7.70 ± 0.10^{h}	30.7 ± 0.30^{g}	
MT11	200	60	82.5 ± 0.90^{h}	2.20 ± 0.10^{c}	25.9 ± 0.20^{c}	
MT12	200	75	79.4 ± 0.70^{f}	4.10 ± 0.30^{d}	25.8 ± 0.50^{c}	
MT13	200	90	76.2 ± 0.90^{e}	5.20 ± 0.20^{e}	28.8 ± 0.40^{e}	
MT14	200	105	72.3 ± 1.00^{c}	6.80 ± 0.20^{g}	30.1 ± 0.30^{f}	
MT15	200	120	69.1 ± 0.60^{b}	8.70 ± 0.10^{de}	32.5 ± 0.30^{h}	

M0 is the control; MT1 - MT5 were fried at 180 °C, MT6 - MT10 at 190 °C, and MT11 - MT15 at 200 °C, with frying times ranging from 60s to 120s

Comparison of differences between samples throughout the experiment process

Following the selection of optimal parameters from each sequential experiment, the microstructural characteristics of the chosen mini oil stick samples were examined using scanning electron microscopy (SEM). This microscopic analysis revealed distinct structural differences between the experimental mini oil stick samples from experiment 1, 2, and 3, and the control sample. Figure 5 visually represents the microstructure of these various samples as observed by SEM. The control sample (Figure 5a) exhibited a remarkably smooth surface with no discernible pores, indicative of a dense and tightly structured internal matrix. This suggests a highly developed gluten framework within the control dough system.[25] In contrast, the experimental samples (Figures 5b, 5c, and 5d) displayed rougher surfaces, and their cellular structures appeared to be disrupted by the high temperatures encountered during deep fat frying. The surfaces of these samples featured numerous pores, which are primarily attributed to the rapid evaporation of water during frying, and partly to the CO_2 generated by the leavening agents, which helps to support the structure of product.[39] Figure 6 presents the actual appearance of the oil stick samples from the experimental trials.

Despite the observed differences, there was a general improvement in the surface smoothness of the oil stick samples across the three sequential experiment, indicating a refinement in the product's characteristics as optimization progressed.

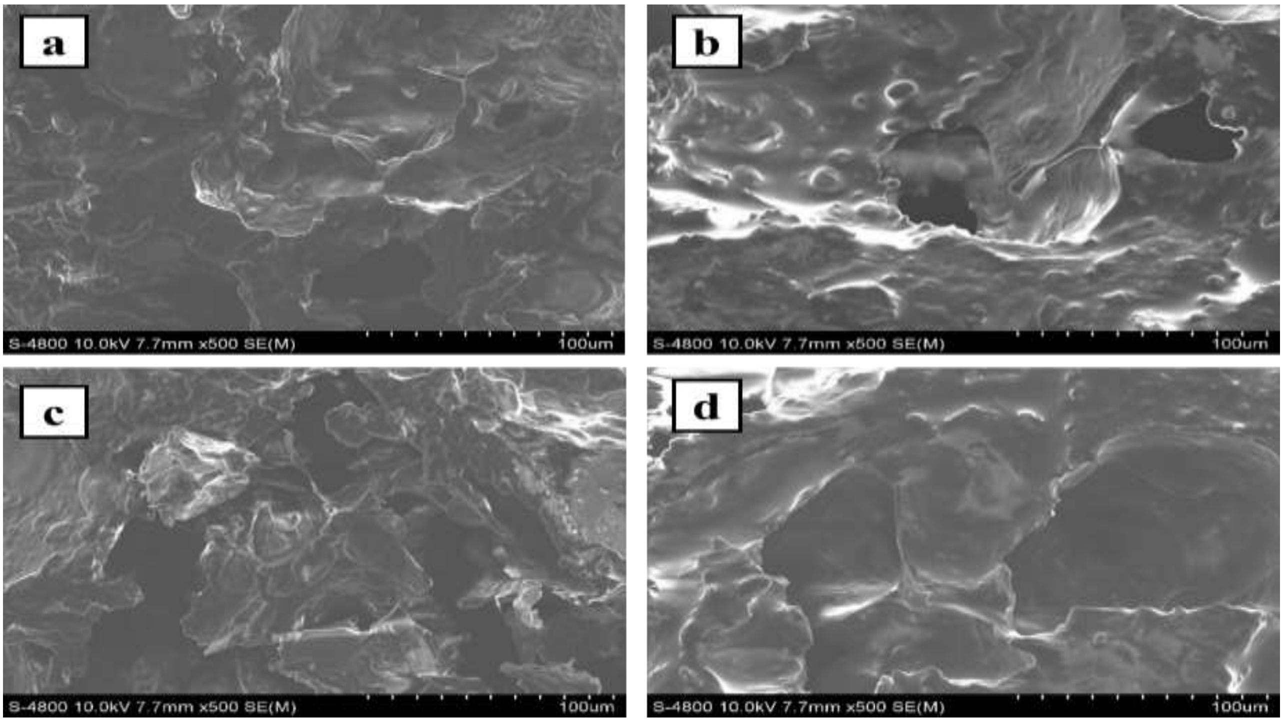

Figure 5: Scanning electron microscope images of mini oil stick (a) control sample; (b) the optimal product selected in experiment 1 (0.5 % modified starch); (c) the optimal product selected in experiment 2 (0.2 % ammonium bicarbonate); (d) the optimal product selected in experiment 3 (190 °C, 90 seconds).

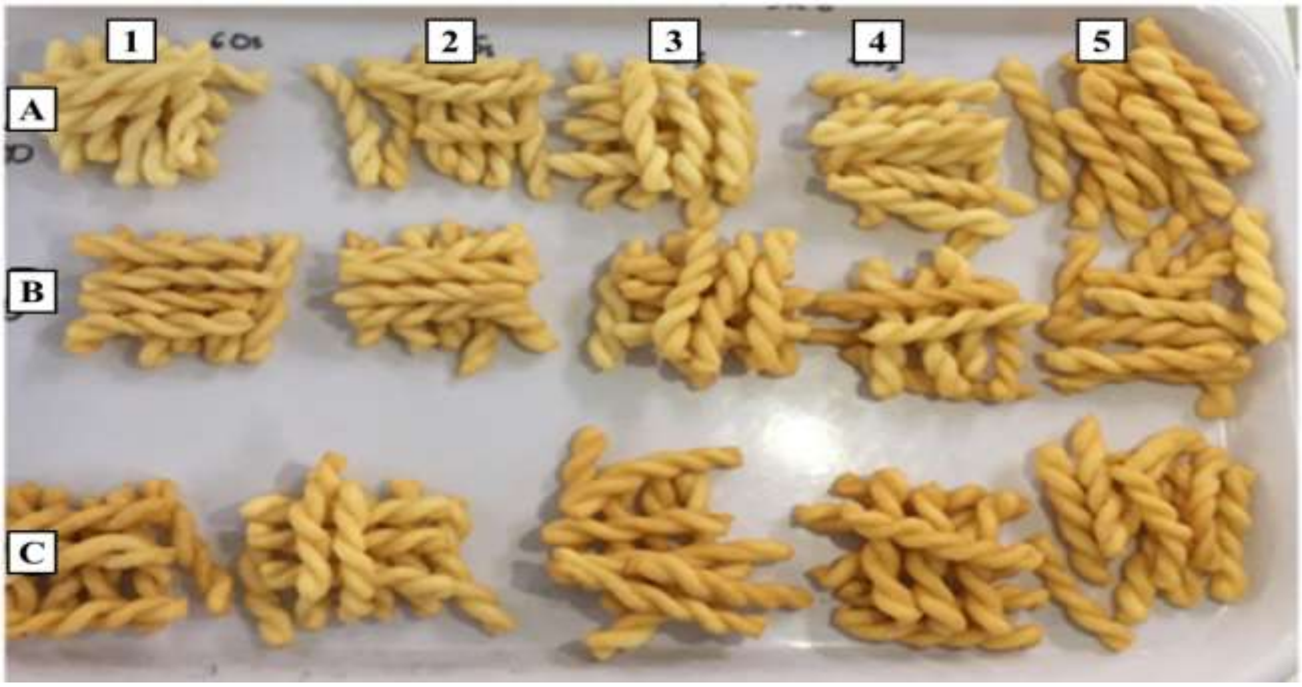

Figure 6: Mini oil stick fried at 180°C - 200°C and 60 seconds - 120 seconds (sample 1, 2, 3, 4, 5 correspond to samples fried at 60, 75, 90, 105, 120 seconds, respectively; letters A, B, C correspond to samples fried at 180 °C, 190 °C, 200 °C, respectively)

Sensory evaluation

To assess consumer acceptance, the preference level of the developed mini oil stick sample was compared with that of the Taiwanese Xiao Mahua oil stick (control) and a Korean oil stick. The results of this sensory evaluation were presented in Figure 7.

The sensory evaluation was conducted with a panel of 70 participants, aged between 18 and 23 years old. An analysis of variance (ANOVA)

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performed on the preference data yielded a p-value is less than 0.05, indicating a statistically significant difference in preference levels among the three product samples.
Among the tested products, the developed mini oil stick received the highest average preference score of 7.24, indicating it was the most preferred product by the tasters. The Korean oil stick followed with an average score of 6.87, being less preferred than the mini oil stick. Finally, the Taiwanese Xiao Mahua oil stick (control sample) recorded the lowest average preference score of 5.80, making it the least preferred among the three samples (Figure 7). The observed differences in preference levels among the samples can likely be attributed to variations in their porosity and expansion, which directly influence the eating sensation and overall consumer experience.

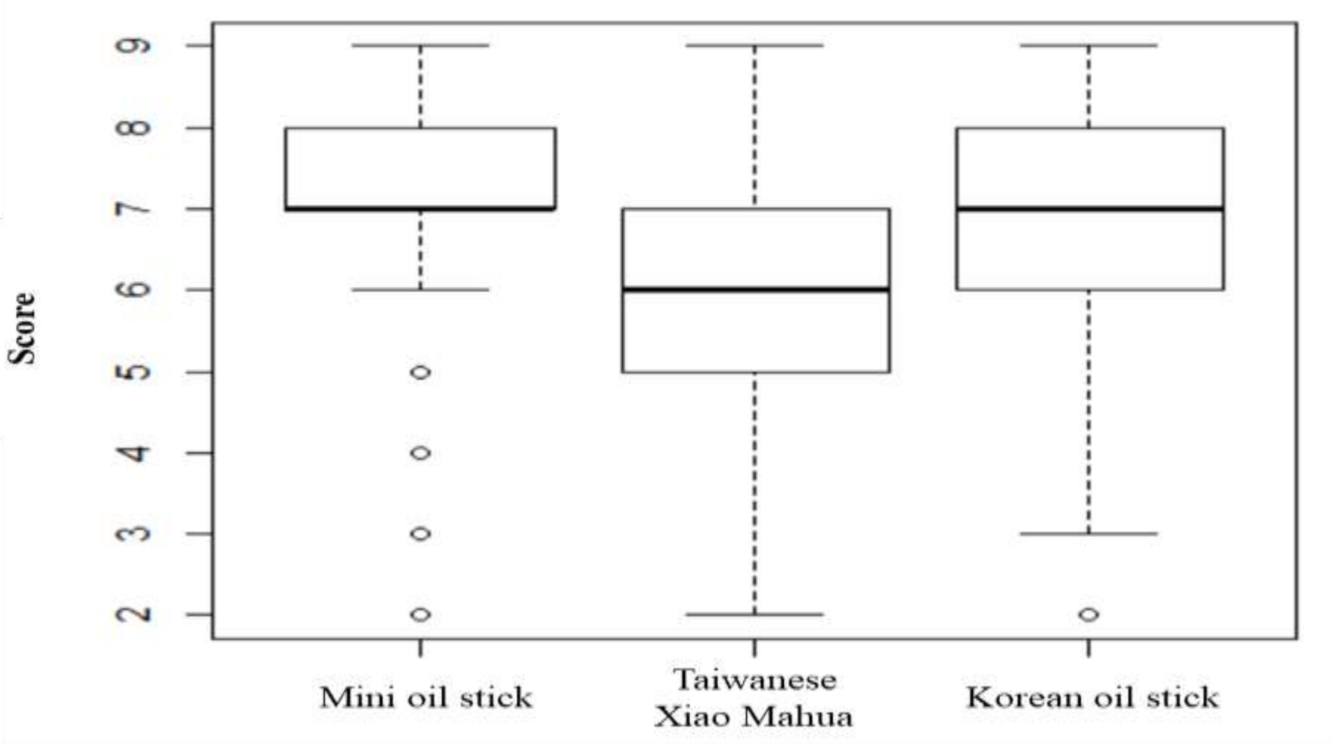

Figure 7: The preference score of oil stick products

Conclusion

The study shows that modified starch and a leavening agent act as processing additives that improve the volume expansion and textural hardness of mini oil sticks (youtiao). Frying temperature and time significantly affected structure, specific volume, color, moisture content, and fat content. Moisture loss and oil uptake exhibited a strong positive linear correlation with increases in frying temperature and duration. A formulation with 5% modified starch (replacing wheat flour) and a single leavening agent (0.2% ammonium bicarbonate) fried at 190 °C for 90 seconds achieved desirable hardness, volumetric expansion, color, and favorable sensory attributes relative to the control. Despite these achievements, microstructural analysis performed using scanning electron microscopy (SEM) revealed that further research is necessary to achieve a structure that is completely identical to the control sample, suggesting avenues for further product optimization.

Conflict of Interest

The authors declare no conflict of interest

Authors' Declaration

The authors hereby declare that the work presented in this article is original and that any liability for claims relating to the content of this article will be borne by them.

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