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Thermal Stability of Antioxidant Compounds and Nutritional Profile of Functional Crackers Based on Surian Leaves

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ABSTRACT

Kerupuk or cracker, a popular snack in Indonesia, is typically high in carbohydrates but low in functional components. Surian leaves (*Toona sureni*), which are rich in antioxidant compounds, have the potential to enhance the functional value of these crackers. However, the stability of these compounds during thermal processing remains largely unknown. This study aims to evaluate the effect of surian leaves addition and each processing stage (raw, boiling, drying, frying) on the proximate composition and antioxidant activity (IC₅₀) of the crackers. This study utilized a factorial Completely Randomized Design (CRD) with two factors: the addition of surian leaves (0% and 16%) and four processing stages. The analyses included proximate composition and the DPPH antioxidant assay. The results showed that the addition of surian leaves significantly increased antioxidant activity ($p < 0.001$). The processing stages exerted a dominant influence on all parameters: boiling caused the leaching of water-soluble compounds; drying significantly increased protein and ash concentrations; while frying drastically elevated the fat content and was simultaneously the most detrimental stage for antioxidant activity. Despite the degradation, the surian leaves-fortified crackers consistently exhibited significantly higher antioxidant activity compared to the control at every processing stage. It can be concluded that surian leaves are an effective functional ingredient for crackers; however, the processing method is a critical determinant of the final product quality.

Contribution to Sustainable Development Goals (SDGs):

SDG 3: Good health and well-being

SDG 9: Industry, Innovation, and Infrastructure

SDG 12: Responsible consumption and production

1. INTRODUCTION

1.1. Research Background

As global health consciousness grows, there has been a significant shift in food consumption toward products that are not only palatable but also provide health benefits. This phenomenon

has positioned health as one of the most relevant trends driving innovation in the global food and beverage market [1] [4]. Rather than focusing solely on caloric intake, modern consumers increasingly demand high-quality foods with enhanced nutritional and functional properties [2]. In response to this demand, fortification, or the addition of natural ingredients rich in bioactive compounds to popular food products, has become a key strategy to improve their nutritional and functional value



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[25]. In this context, *kerupuk* (Indonesian crackers), a highly popular snack in Indonesia and various Southeast Asian countries, can serve as an ideal medium for fortification innovation to support the shift towards healthier and more sustainable consumption patterns.

Despite their immense popularity, conventional crackers generally possess limited nutritional and functional value, as they are primarily starch-based products that generally provide carbohydrate energy and lack meaningful levels of bioactive compounds. This limitation presents a substantial opportunity for innovation: transforming crackers into a functional food by adding natural ingredients [3] [28]. This strategy focuses on enriching the product with active compounds such as antioxidants, phenolics, and flavonoids, which are known to have health benefits. This practice of functional fortification has become an active area of research, with numerous studies exploring the addition of ingredients such as anthocyanin-rich purple sweet potato [21], isoflavone-containing tempe [1] [13] [24], and even the utilization of various fish types as a source of omega-3 fatty acids to enhance the health potential of this popular snack [2] [3] [8].

In the quest for natural functional ingredients, the utilization of local natural resources emerges as a highly promising solution. Surian leaves (*Toona sureni*), a plant widely found in Indonesia, represent one such prospective natural ingredient that remains largely underutilized for functional enrichment in the food industry. The literature indicates the significant advantages of surian leaves, particularly their high content of bioactive compounds such as phenolics and flavonoids [6] [15] [20]. These compounds contribute to the strong antioxidant activity of surian leaves, which is attributed to flavonoid compounds such as quercetin and kaempferol [16]. The traditional use of surian leaves in herbal medicine further supports their potential as functional food ingredients to enhance the health benefits of crackers.

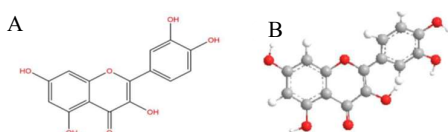


Fig. 1. Structure and bibliometric results of quercetin: (A) Chemical structure of quercetin, and (B) 3D conformer of quercetin [29].

However, the great potential of surian leaves as a functional agent is faced with a critical challenge: the sensitivity of its bioactive compounds to thermal processing. The traditional cracker-making process involves several intensive thermal stages, including boiling the dough at approximately 100°C, drying at 50-60°C, and finally deep-frying at high temperatures up to 180°C or more [28]. This series of heat treatments can significantly degrade antioxidant compounds in surian leaves, thereby reducing or even eliminating their functional effectiveness in the final product [15]. Therefore, a thorough understanding of the thermal stability of these bioactive compounds at each processing stage is crucial for successful product development. To date, no comprehensive study has systematically evaluated the cumulative effects of individual thermal processing stages on the nutritional composition and antioxidant stability of surian leaf-enriched crackers.

Despite the growing body of research on functional cracker fortification, most studies have primarily focused on single-level incorporation and end-product evaluation, with limited attention to dose-dependent responses and compound stability throughout processing stages. Furthermore, there is a lack of studies that integrate phytochemical quantification with mechanisms of processing-induced degradation.

Therefore, this study aimed to evaluate the effects of incorporating surian leaf (5-20%) and processing stages on the nutritional profile and antioxidant stability of the crackers. Furthermore, this study investigated the interactions between surian leaf formulation and processing stages in preserving the functional quality of the final product. Additionally, this study explores alternative processing approaches to enhance bioactive retention, thereby bridging the gap between food processing and horticultural utilization of underexplored plant resources.

1.2. Literature Review

Functional foods have attracted increasing attention due to their potential to provide health benefits beyond basic nutrition. These foods are commonly enriched with bioactive compounds such as phenolics, flavonoids, carotenoids, and dietary fibre, which contribute to antioxidant, anti-inflammatory, and disease-preventive effects [25]. Snack products, including crackers are considered suitable carriers for functional ingredients because of their widespread consumption and long shelf life [3].

Crackers are traditionally produced from starch based ingredients, particularly tapioca flour which mainly contribute carbohydrates but contain limited micronutrients and antioxidant compounds [26]. Fortification using natural plant materials has become an important strategy to improve their nutritional and functional quality.

Surian leaves represent a promising but underutilized plant material. Several studies have reported that Surian leaves contain substantial levels of phenolic and flavonoid compounds with strong antioxidant activity [20]. The antioxidant potential of Surian leaves is associated with bioactive compounds, such as quercetin, which are known for their radical-scavenging properties [16]. In addition, Surian leaves have been traditionally used in herbal medicine, supporting their safety and potential use in functional food products.

Antioxidant compounds in plant based materials are highly sensitive to thermal processing. Food processing techniques such as boiling, drying and frying may induce degradation of phenolics and thermal decomposition [23]. Frying at high temperatures is particularly associated with substantial losses of antioxidant compounds and increased lipid oxidation [28]. Boiling can reduce antioxidant levels due to the migration of water soluble compounds into the cooking medium [32].

Phenolic compounds structural degradation during thermal treatment, resulting in reduced antioxidant capacity [11]. Drying methods significantly influence the retention of bioactive compounds in plant materials.

1.2.1. Functional food and antioxidant enrichment in Crackers

Functional foods are defined as food products that provide physiological benefits beyond basic nutritional functions due to the presence of bioactive compounds [25]. Increasing public awareness regarding healthy lifestyles has accelerated the

development of functional snack product with improved nutritional and antioxidant properties [4]. Crackers represent a promising food matrix for functional fortification because they are widely consumed, affordable, and possess a relatively long shelf life [26]. The relationship between processing conditions and antioxidant stability is essential for developing functional crackers with retained bioactive properties.

1.2.2. Potential of Surian leaves as a functional ingredient

Surian leaves (*Toona sureni* Merr.) are among the underutilised plant resources in Indonesia, with significant potential as a functional food ingredient. Several phytochemical studies have demonstrated that Surian leaves contains substantial amount of phenolic compounds and other secondary metabolites that contribute to strong antioxidant activity [20]. Bioactive compounds are known to play important roles in scavenging free radicals and reducing oxidative stress.

1.3. Research Objective

This study aims to evaluate the effect of Surian leaf (*Toona sureni* Merr.) incorporation and thermal processing stages on the nutritional profile and antioxidant stability of functional crackers.

2. MATERIALS AND METHODS

2.1. Research Design

This study employed a Completely Randomized Design (CRD) with a factorial arrangement of two treatment factors. The first factor was the addition of surian leaves (Factor A), consisting of two levels: A1 (control, 0% addition) and A2 (16% addition). The second factor was the processing stage (Factor B), during which samples were collected for analysis. This factor consisted of four levels: B1 (Raw Dough, before heat treatment), B2 (After Boiling), B3 (After Drying), and B4 (After Frying). The combination of these two factors resulted in eight treatment combinations. All analyses for each treatment combination were performed in duplicate as analytical replicates for each processing stage.

All analyses for each treatment combination were performed in duplicate (n=2). The study employed a factorial completely randomised design (CRD) with two factors: suria leaf addition (0% and 16%) and four processing stages (raw dough, boiling, drying, and frying).

2.2. Cracker Formulation and Preparation

2.2.1. Raw materials and cracker processing

This study utilized two cracker formulations, adapted from [22], a control formulation (0% surian leaves) and a treatment formulation (16% surian leaves), as detailed in Table 1.

preparation and cooking. All dry ingredients, consisting of tapioca flour, minced garlic, coriander powder, and salt, were mixed until homogeneous. Subsequently, hot water (90°C) was gradually added while the dough was kneaded until it reached a smooth, pliable consistency. For the treatment formulation, finely chopped surian leaves were incorporated during the final stage of kneading. The resulting dough was then shaped into cylinders (approximately 5 cm in diameter) and boiled in water (100°C)

until fully cooked, as indicated by the dough floating to the surface.

Table 1. Cracker formulation

No	Ingredients	Formulation	
		Control (0%) (grams)	Experiment (16%) (grams)
1	Surian Leaves	0	80
2	Tapioca Flour	500	500
3	Garlic	4	4
4	Coriander	15	15
5	Salt	15	15
6	Water	300	300

The cracker preparation process began with dough After cooking, the boiled dough was removed from the water, cooled, and then refrigerated at 10°C for 8 hours to solidify its texture for easier slicing. The firm dough was subsequently thinly sliced into uniform pieces approximately 2 mm thick. These raw cracker slices were then dried in a food dehydrator at 60°C for 6 hours until the moisture content was reduced to below 12%. The final stage was deep-frying, in which the dried crackers were cooked in hot oil at 170°C for 30 seconds, until fully expanded and crisp.

2.3. Chemical and functional analysis

Proximate analysis was performed to determine the nutritional composition of the crackers at each processing stage, following AOAC International official methods. Moisture content was determined using the gravimetric oven method (AOAC 925.10) at 105°C, while ash content was measured via the dry ashing method in a muffle furnace (AOAC 923.03) at 550°C. Protein content was determined using the Micro-Kjeldahl method (AOAC 960.52) with a conversion factor of 6.25, whereas fat content was extracted using the Soxhlet method (AOAC 920.39) with n-hexane as the solvent. Carbohydrate content was calculated by difference according to AOAC guidelines, using the following formula: Carbohydrate (%) = 100% - (% moisture + % ash + % protein + % fat).

To evaluate the functional capacity, the antioxidant activity of the crackers was measured using the DPPH (2,2-diphenyl-1-picrylhydrazyl) free radical scavenging assay. For each measurement, 0.5 mL of sample extract was mixed with 2.5 mL of DPPH solution, and the mixture was incubated in the dark at room temperature for 30 minutes. The decrease in absorbance resulting from the reaction between the sample extract and the DPPH solution was measured using a UV-Vis Spectrophotometer at a wavelength of 517 nm. The results were expressed as IC50 values, defined as the concentration of the extract required to inhibit 50% of free radicals. Vitamin C was used as the positive control for comparison; a lower IC50 value indicates stronger antioxidant activity.

3. RESULT AND DISCUSSION

3.1. Effect of processing stages on proximate composition

This section presents the effect of surian leaf addition and the processing stage on the proximate composition of the crackers. The changes in each parameter are presented in Figure 2 to visualize the observed trends.

Table 2. Proximate composition of crackers at different processing stages

Parameter	Processing Stage	Control (0%)	Surian (16%)
Moisture Content (%)	Raw Dough	38.2 ± 1.1 ^d	39.8 ± 1.3 ^d
	After Boiling	62.4 ± 1.8 ^a	64.1 ± 1.5 ^a
	After Drying	8.6 ± 0.4 ^e	9.2 ± 0.5 ^e
	After Frying	2.8 ± 0.3 ^f	3.4 ± 0.4 ^f
Ash Content (%)	Raw Dough	1.8 ± 0.2 ^e	2.6 ± 0.2 ^d
	After Boiling	2.1 ± 0.2 ^{de}	3.1 ± 0.3 ^c
	After Drying	3.2 ± 0.3 ^c	4.5 ± 0.4 ^a
	After Frying	2.4 ± 0.2 ^d	3.8 ± 0.3 ^b
Fat Content (%)	Raw Dough	0.3 ± 0.1 ^d	0.4 ± 0.1 ^d
	After Boiling	0.4 ± 0.1 ^d	0.5 ± 0.1 ^d
	After Drying	0.6 ± 0.1 ^d	0.7 ± 0.1 ^d
	After Frying	28.4 ± 2.1 ^a	24.6 ± 1.8 ^b
Protein Content (%)	Raw Dough	2.4 ± 0.3 ^{bc}	2.6 ± 0.3 ^{bc}
	After Boiling	1.8 ± 0.2 ^c	2.0 ± 0.3 ^c
	After Drying	3.8 ± 0.4 ^a	3.9 ± 0.4 ^a
	After Frying	2.8 ± 0.3 ^b	2.9 ± 0.3 ^b
Carbohydrate Content (%)	Raw Dough	57.3 ± 1.5 ^b	54.6 ± 1.6 ^{bc}
	After Boiling	33.3 ± 2.0 ^d	30.3 ± 1.9 ^d
	After Drying	83.8 ± 2.2 ^a	81.2 ± 2.1 ^a
	After Frying	63.6 ± 2.3 ^b	65.3 ± 2.2 ^b

Note: Values are presented as mean ± standard deviation (n=2). Different superscript letters within the same parameter indicate significant differences ($p < 0.05$) based on Duncan's Multiple Range Test (DMRT).

The addition of surian leaves, the processing stage, and their interaction all influenced the crackers' moisture content. The highest moisture content (Figure 1a) was observed in the samples after boiling, then decreased sharply during the drying and frying stages. The increase in moisture during boiling is attributed to starch gelatinisation, in which starch granules absorb water from the cooking medium [18] [30]. Conversely, the drying and deep-frying processes involved high temperatures, leading to extensive water evaporation. Interestingly, the addition of surian leaves tended to increase water absorption during boiling and retain slightly higher moisture content after frying compared to the control. This effect may be associated with the presence of fiber in the surian leaves, which can influence water retention. Duncan's Multiple Range Test (DMRT) as a post hoc analysis. A significance level of $p < 0.05$ was applied for all statistical tests.

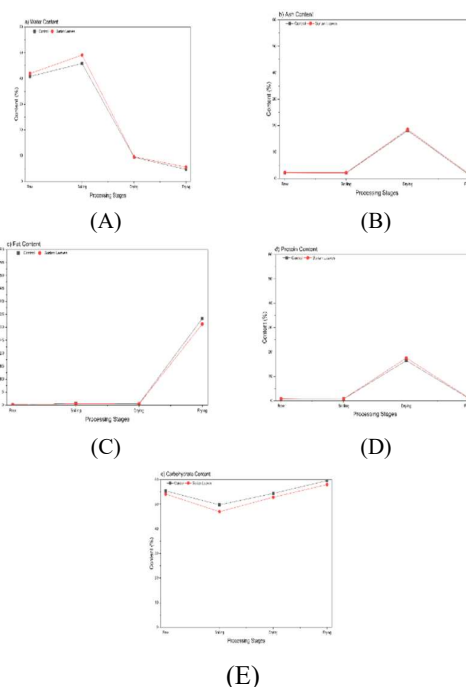


Fig. 2. The effect of processing stages on the proximate composition of crackers, showing changes: (a) moisture content, (b) ash content, (c) fat content, (d) protein content, and (e) carbohydrate content.

The ash content of the crackers was influenced by the addition of surian leaves, the processing stage, and the interaction between the two factors. The trend in Figure 2B indicates that the addition of surian leaves consistently increased the ash content at every processing stage. This increase is attributed to the natural mineral content in the surian leaves. The ash content reached its peak after drying, as the loss of water mass increased the concentration of non-volatile mineral components. Conversely, during frying, the relative ash content decreased due to oil absorption, thereby increasing the total product mass and diluting the mineral concentration.

The fat content of the crackers was significantly affected by the processing stage. Figure 2C clearly demonstrates that the fat content in the raw, boiled, and dried dough was very low, almost negligible. However, a drastic increase in fat content occurred after deep-frying, due to the absorption of hot oil into the cracker matrix. A key finding of this study is that crackers fortified with surian leaves consistently exhibited a lower final fat content than the control crackers after being fried. This suggests that components within the surian leaves, most likely the fibre, may form a barrier that inhibits oil absorption during deep-frying.

The reduced oil absorption observed in surian-enriched crackers may be associated with structural modifications in the starch matrix. However, further studies quantifying dietary fibre and conducting microstructural analysis (e.g., SEM) are required to confirm this mechanism. The addition of surian leaves, the processing stage, and their interaction did not have a significant effect on the protein content of the crackers (Figure 2D). The inclusion of surian leaves did not result in a significant increase in protein content at any stage compared with the control. Regarding the process, a slight decrease in protein content was observed after boiling, likely caused by the leaching of some water-soluble proteins into the boiling medium.

Protein content slightly decreased after boiling due to the leaching of water-soluble proteins into the cooking medium. However, the protein concentration increased significantly after drying due to reduced moisture, with the highest protein percentage observed at the dried stage. Concentrated the solid components. Finally, the protein content of the fried product was lower than that of the dried product; this was due to the added mass from absorbed oil, which decreased the relative protein concentration.

Unlike the other parameters, the carbohydrate content of the crackers (Figure 2E) was significantly affected only by the processing stage, whereas the addition of surian leaves did not have a meaningful effect. The carbohydrate content tended to decrease after boiling, presumably because a portion of the starch dissolved and leached into the boiling water. A relatively high carbohydrate content was recorded in the final product after frying. The addition of surian leaves at 16% was insufficient to significantly alter the carbohydrate composition, as the crackers' primary matrix is still dominated by tapioca starch. This confirms that the main role of surian leaves is to serve as a source of micronutrients and functional compounds, rather than to change the primary macronutrient composition.

3.2. Effect of Processing Stage on Antioxidant Activity

The addition of surian leaves significantly enhanced the antioxidant activity of the crackers, as indicated by lower IC_{50} values than the control at every processing stage (Figure 3). The surian leaf addition, the processing stage, and the interaction between the two factors all had a highly significant effect on antioxidant activity ($p < 0.001$).

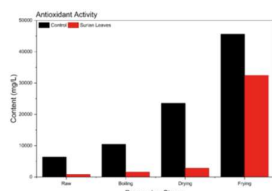


Fig. 3. Mean IC_{50} (µg/mL) ± SD values of the crackers for each treatment. A lower IC_{50} value indicates stronger antioxidant activity.

The positive effect of the surian leaf addition was most evident in the raw dough. The raw dough fortified with surian leaves exhibited the strongest antioxidant activity, showing the lowest IC_{50} value (818.23 µg/mL). This occurs because the bioactive compounds, such as phenolics and flavonoids, contained in surian leaves remained intact and had not yet been degraded by thermal processing. The presence of these compounds is responsible for the high functional potential of surian leaves. However, this antioxidant activity systematically decreased at each thermal processing stage, which was indicated by an increase in the IC_{50} value. The boiling process caused a portion of the water-soluble antioxidant compounds to leach into the cooking medium. Subsequently, the drying and, in particular, the high-temperature deep-frying processes led to significant thermal degradation of the heat-sensitive bioactive compounds. Deep-frying was the most destructive stage, resulting in the highest IC_{50} values (i.e., the weakest activity) for both the surian-fortified and the control products.

The key and most significant finding of this study is that although the antioxidant activity decreased, the crackers fortified with surian leaves still exhibited far superior antioxidant activity at every processing stage compared to the control products at the same stage. For example, the fried crackers fortified with surian leaves exhibited an IC_{50} of 32,462 µg/mL, whereas the fried control crackers showed an IC_{50} of 45,620 µg/mL. These results indicate that crackers fortified with surian leaves retained higher antioxidant activity throughout processing than the control.

Table 3. Antioxidant activity (IC_{50} values) of crackers at different processing stages

Processing Stage	Control (0%)	Surian (16%)
Raw Dough	6,520 ± 380 ^e	818.23 ± 45.6 ^f
After Boiling	10,240 ± 550 ^d	2,485 ± 135.2 ^e
After Drying	23,480 ± 1,250 ^c	3,240 ± 180 ^e
After Frying	45,620 ± 2,280 ^a	32,462 ± 1,650 ^b

Note: Values are presented as mean ± standard deviation (µg/mL, n=2). Lower IC_{50} values indicate stronger antioxidant activity.

The most substantial decline in antioxidant activity was observed after the frying stage, as evidenced by the highest IC_{50} values. This can be explained by the extreme thermal conditions ($\approx 170^{\circ}\text{C}$), which accelerate the degradation of heat-labile bioactive compounds, such as flavonoids. High-temperature frying not only induces thermal decomposition but also promotes the oxidation and polymerisation of phenolic compounds, rendering them less effective as antioxidants. Additionally, the presence of hot oil may further exacerbate oxidative reactions, contributing to the loss of antioxidant functionality. Overall, these findings emphasize that processing conditions play a critical role in determining the functional quality of food products. Optimising processing parameters, particularly reducing exposure to high temperatures and minimising water-based losses, is essential to preserving antioxidant compounds. The use of alternative processing techniques, such as vacuum frying or low-temperature drying, may offer promising strategies to improve antioxidant retention in functional cracker products.

The high IC_{50} values observed indicate relatively low antioxidant potency compared to pure extracts, suggesting that matrix interactions and thermal degradation significantly reduce bioactive availability [11].

4. CONCLUSION

The addition of surian leaves to the crackers did not significantly alter their macronutrient profile. Although there was a statistical increase in ash content, attributed to the natural mineral content of the leaves, the primary contribution of this fortification appears to lie not in major changes to the macronutrient composition, but in the enhancement of the crackers' functional potential. This was reflected in the significantly higher antioxidant activity observed in the surian leaf-fortified crackers compared to the control. These findings suggest that the role of surian leaves extends beyond micronutrient supplementation, as they primarily serve as a source of bioactive compounds that enhance antioxidant capacity.

The results of this study highlight the distinct impact of each processing stage on the cracker's composition. Boiling was shown to cause leaching, a process where some water-soluble components, such as phenolic compounds [19] and a small

fraction of proteins [7], migrated from the dough into the boiling water. This mechanism likely contributes to the observed reduction in antioxidant activity and protein content after the boiling stage. Conversely, drying exerted a concentrating effect; the drastic loss of water mass significantly increased the percentage of solid components, such as protein [12] and minerals, making this stage crucial for enhancing nutritional density [14]. The deep-frying stage, while essential for creating a crispy texture, had two primary negative impacts: an exponential increase in fat content from oil absorption and substantial degradation of antioxidant compounds from high-temperature exposure [28].

Alternative processing methods, such as vacuum frying and air frying, have been reported to significantly improve bioactive compound retention while reducing oil absorption [5]. These approaches offer promising strategies for producing healthier functional snack products. One of the most interesting findings was the interaction between the surian leaves and the processing method. Crackers fortified with surian leaves consistently had lower fat content after frying than the control. This phenomenon suggests that components within the surian leaves, particularly dietary fiber, may contribute to the formation of a matrix that inhibits oil absorption during frying by creating a network on the product's surface [30]. Furthermore, although antioxidant activity decreased drastically due to the heat, the crackers with surian leaves still exhibited far superior antioxidant activity at every processing stage compared to the control product. These results indicate that surian leaf fortification increases retained antioxidant activity across processing stages, thereby enhancing the functional value of the final product, even after it undergoes a series of intensive thermal processing steps [10] [27].

The findings of this study have important implications, both practical and scientific. From a practical standpoint, these results provide insights for optimizing the frying process in commercial applications. Although high-temperature frying was shown to decrease antioxidant activity, careful control of frying temperature may help balance desirable textural properties with antioxidant retention. Furthermore, to address fat absorption, oil-free final cooking methods warrant exploration. Alternative methods, such as puffing machines, microwave heating, or traditional techniques like sand roasting, could be sustainable options for creating functional, crispy crackers without added fat. Scientifically, this research provides new insights into the stability of bioactive compounds from Indonesian local flora (Toona sureni) when applied in a complex, starch-based food matrix and subjected to a series of high-temperature thermal processes.

Although this study provides valuable insights, it has several limitations, notably the use of a single concentration of surian leaves (16%) and a fixed temperature for each processing stage. Building on these limitations, future research could focus on optimizing the concentration of surian leaves to achieve the best balance between enhancing functional benefits and ensuring consumer sensory acceptance. Furthermore, in line with the implication to optimize cooking methods, the exploration of alternative processing technologies is crucial. Given the significant degradation of antioxidants and fat absorption during conventional deep-frying, future studies could explore lower-temperature methods, such as vacuum frying, to maximise the retention of bioactive compounds, as well as oil-free methods,

such as sand roasting or the use of a puffing machine, to produce a healthier final product.

Future studies should include shelf-life evaluation, particularly focusing on lipid oxidation and antioxidant stability during storage, as these factors critically determine product applicability. From a horticultural perspective, *surian leaf* is a promising, underutilised species with significant phytochemical potential. Variability in phenolic content may be influenced by environmental factors, leaf maturity, and geographical origin, suggesting opportunities for further agronomic and phytochemical studies [15].

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