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Effects of heat treatment on nutritional profiles and antioxidant activity of peanuts

Einfluss von Wärmebehandlungen auf Nährstoffprofile und antioxidative Aktivität von Erdnüssen

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Summary

This study explores the effects of heat treatment on the nutritional components and antioxidant activity of peanuts, aiming to optimize the utilization of phenolics and key nutrients in peanuts. The peanuts available in the market are categorized into those with red skins and those without. They underwent three different heat treatments: boiling, frying, and baking. The effects of these treatments on the nutritional components (protein, fat, carbohydrates, and moisture), total phenolic content (TPC), and DPPH free radical scavenging ability of the peanuts were measured and compared with those of untreated peanuts. The results indicated that three heat treatments differentially affected the nutritional components of peanuts, particularly causing significant losses in protein, carbohydrates, and minerals. Boiling had an inhibitory effect on the TPC and antioxidant activity of peanuts, causing reductions of TPC by 39.85% and 25.25% for peanuts with and without skins, respectively. Conversely, frying and baking had a promoting effect on the TPC and antioxidant activity (increasing TPC by 8.30%, 19.43% and 6.08%, 44.14% for peanuts with and without skins, respectively). This research provides valuable insights into the processing conditions and consumption methods of peanuts.

Keywords: peanut, red skin, heat treatment, nutrient, antioxidant activity

Introduction

Peanut, a high-yielding and high-quality raw material for food and edible oil production in China (Wang et al., 2023), is available in two forms in the Chinese market: with and without red-skins (Nyangena et al., 2020). Despite the red skin of peanuts constituting only 3% of the whole peanut kernel (Zhao et al., 2017), it contains a high concentration of phenolics, making it a rich source of antioxidant bioactive substances. Extensive research, conducted both domestically and internationally, has substantiated the promising potential of the red skin of peanuts in various sectors, including food, animal feed, and pharmaceuticals (Redhead et al., 2022; Fernandes et al., 2021; Lorenzo et al., 2018; Sanders et al., 2014). These studies primarily focus on investigating the active components present in the red skin of peanuts, shedding light on their functional properties and exploring their beneficial implications across different industries. Despite these valuable findings, there remains a gap in research, with few comparative studies on the overall nutritional value of peanuts with and without skins. Closing this gap can provide a comprehensive understanding of the nutritional benefits offered by both types of peanuts.

Home cooking methods, such as boiling, deep-frying, and baking, significantly influence the nutritional quality of peanuts. These heat treatments can denature proteins and dissolve nitrogenous substances like amines and amine-based compounds, resulting in protein loss (Xu et al., 2014). Additionally, minerals and soluble sugars, such as reducing sugars, may dissolve into the cooking medium (Zeng et al., 2024). Xiao et al. (2022) conducted a metabolomics study on peanuts subjected to various cooking methods, revealing both gains and losses in metabolite content after cooking. Notably, the most significant differences in metabolite content were observed in organic acids, nucleotides, glycerophospholipids, and carbohydrates.

Furthermore, heat treatment facilitates the release of low molecular antioxidants from polymer subunits (Francisco and Resurreccion, 2009). Products of the Maillard reaction, formed under high-temperature conditions, exhibit antioxidant properties by scavenging oxygen radicals or chelating metals. This enhances the antioxidant properties of peanuts. Win et al. (2011) found that baking at 160 °C significantly enhanced the antioxidant activity of peanut flour. Despite the existing body of research, there remains a significant gap in the comparative study of the impact of heat treatment conditions on the nutritional quality of both regular peanuts and red-skinned peanuts. This deficiency underscores the imperative need for further, more comprehensive research. Such studies are essential to thoroughly understand the extent to which different cooking methods influence the nutritional value of peanuts, both with and without their red skin. Elucidating these effects is crucial for optimizing cooking practices and maximizing the health benefits of these widely consumed nuts.

The objective of this study is to investigate the alterations in nutrient composition and antioxidant activity in peanuts with and without skins subjected to three distinct heat treatments (boiling, baking, and frying) relative to their raw counterparts. The outcomes of this study are anticipated to have substantial implications in enhancing the utilization of peanuts‘ nutritional and bioactive constituents. Additionally, the findings are expected to provide pivotal insights and guidance in the enrichment of peanut products with nutrients, thereby contributing to the optimization of their health benefits and potential therapeutic applications.

Materials and methods

Chemicals and materials

Fresh peanuts with red skin and soybean oil were purchased from a local supermarket. Petroleum ether (30–60 °C), copper sulfate, potassium sulfate, sulfuric acid, sodium hydroxide, methyl red, bromocresol green, boric acid, methanol, Folin-ciocalteu phenol reagent, sodium carbonate, and ethanol were obtained from Sinopharm Chemical Reagent Co., Ltd. (Shanghai, China). Gallic acid and 2,2-diphenyl-1-picrylhydrazyl (DPPH) were obtained from Macklin Biochemical Co., Ltd. (Shanghai, China). All chemicals were analytical reagent grade.

Cooking treatments

Half of the peanut kernel samples were manually decorticated, with both peeled and unpeeled halves subsequently divided into four equal parts. One part remained untreated, while the other three were subjected to different treatments:

a) Boiling: Samples were boiled for 15 min and then air-dried naturally.
b) Baking: Samples were baked at 170 °C for 8 min.
c) Frying: Samples were immersed in soybean oil preheated to 175 °C, with the amount of oil equal to the weight of the peanuts, fried for 2 min, and then promptly removed and dried with absorbent paper.

After treatment, all samples, encompassing untreated controls, were pulverized, transferred into labeled bags, and refrigerated at 4 °C for subsequent analyses.

Fat content

The determination of fat content in peanut samples was carried out in accordance with the Soxhlet extraction method in GB5009.6-2016. Briefly, 2.5 g of peanut powder, wrapped in filter paper, was accurately weighed and loaded into the extraction cylinder. Before connection to the extractor, the receiving bottle was dried to a constant weight. Subsequently, an amount of petroleum ether was added. This setup was then subjected to a water bath maintained at 80 °C, where it underwent repeated extraction for a duration ranging between 6 to 10 h. The receiving bottle was carefully detached, and the petroleum ether was allowed to evaporate completely, leaving the contents dry. The bottle was then repeatedly weighed until a constant weight was achieved, ensuring the complete removal of the solvent.

Protein content

Protein content in peanut samples was quantified following the Kjeldahl method as outlined in the GB5009.5-2016. Peanut flour (0.8 g), copper sulfate (0.4 g), and potassium sulfate (6 g) were weighed and combined with 20 mL of sulfuric acid in a digestion tube. Digestion was conducted until the mixture turned into a clear and transparent solution. Afterward, 20 mL of distilled water was added to cool the mixture to room temperature. For nitrogen determination, the mixture was transferred to a conical flask containing 20 mL of boric acid solution and a pre-prepared indicator. Alkali was added until all the solution in the digestion tube turned black, followed by distillation. Finally, the solution was titrated with a standard hydrochloric acid solution.

Moisture content

The moisture content in peanut samples was determined using the direct drying method. Peanut powder (2 g) was accurately weighed and dried in a vacuum oven at 101–105

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°C for 1 h. The sample was then placed in a desiccator to cool for 0.5 h before weighing, and this drying process was repeated until a constant weight was achieved.

Ash content

The ash content in peanuts was measured following the crucible ashing method as specified in GB5009.4-2016. Peanut powder (2.5 g) was accurately weighed and placed into a crucible of constant weight. The crucible was initially charred on an electric furnace, then transferred to a muffle furnace set at 550 °C for 4 h of combustion. Subsequently, the crucible was cooled in a desiccator for 0.5 h before weighing, and this combustion process was repeated until a constant weight was achieved.

Carbohydrate content

The carbohydrate content in peanuts was determined using a subtractive method (BeMiller, 2017). Specifically, the total carbohydrate content was calculated by subtracting the sum of the fat, protein, ash, and moisture contents from 100.

Mineral content

The determination of minerals in peanuts was conducted with reference to the experimental method of Karpiuk et al. (2016), with slight modifications. Peanut powder (0.5 g) was weighed and mixed with 20 mL of nitric acid and then digested at 155 °C for 50 min until the solution became clear and transparent. The solution was then heated on an electric furnace to evaporate the nitric acid until the residue was reduced to 1-2 mL. After cooling, the solution was transferred to a 10 mL plastic centrifuge tube that had been rinsed with deionized water. A PinAAcle 900F flame atomic absorption spectrometer (PerkinElmer, USA) was used to determine the minerals. The standard solutions of calcium and iron were diluted with 0.5 mol/L nitric acid solution to create a concentration gradient for measuring, and to obtain standard curves for the two minerals. The digested samples were then measured, and the results were calculated according to Equation (1):

$$\text{Element content (mg/g)} = \frac{(c - c_0) \times v \times f \times 100}{m \times 1000} \quad (1)$$

where c is the mineral concentration of the specimen solution (mg/L); c_0 is the mineral concentration of the blank reagent (mg/L); v is the volume of the solution (mL); f is the dilution factor, and m is the mass of peanut powder (g).

Total phenolic content

The total phenolic content (TPC) of peanuts was determined by modifying the method described by Liu et al. (2022b). Peanut powder was weighed and mixed with 6 mL of 60% methanol aqueous solution. The mixture was then extracted by stirring in a 50 °C water bath for 30 min, followed by centrifugation at 8000 r/min for 5 min. The upper methanol aqueous was collected. This extraction process was repeated three times, and the extract was combined. To remove proteins from the extract, an equal volume of trichloroacetic acid (6%) solution was added. The mixture was subjected to ultrasonic agitation for 30 min, allowed to settle for 1 h, and then centrifuged at 4000 r/min for 15 min to remove insoluble substances. Subsequently, the extract was rotary-evaporated to eliminate methanol-water, reducing the volume to 2 mL or less. Methanol-water was then added to restore the volume to 2 mL, yielding the total phenolic extract of peanuts.

The gallic acid standard was dissolved in a small amount of methanol and then diluted with distilled water to prepare a 100 µg/mL standard solution. This solution was further diluted with distilled water to obtain standard solutions of 5, 10, 20, 30, 40, 50, and 60 µg/mL concentrations. For the assay, 0.5 mL of the above standard solutions was mixed with an equal volume of distilled water and twice the volume of Folin-ciocalteu reagent. Then, 3 mL of 7.5% sodium carbonate solution was added, and the mixture was shaken well. The reaction was carried out in the dark for 1 h, after which the absorbance was measured at 765 nm. A standard curve for gallic acid was constructed, and the fitted linear equation yielded a correlation coefficient of 0.997. This indicates a strong linear relationship between the mass concentration of gallic acid and absorbance within the tested range. A 0.5 mL of the total phenol extract from peanuts was taken and analyzed for total phenol content using the aforementioned method. The TPC of peanut was calculated using the standard curve and the result was expressed as mg (gallic acid equivalent) per kg (peanut mass).

DPPH radical scavenging activity

This experiment, modified from the method developed by Liu et al. (2022a), involved preparing dilutions of the total phenolic extract of peanuts at 4, 5, 10, 15, 30, and 45 times, along with a 0.1 mmol/L DPPH solution. For the assay, 1 mL of DPPH solution was mixed with 1 mL of the diluted total phenolic extract. This mixture was then left to react in the dark at room temperature for 0.5 h. The absorbance of the samples was measured at a wavelength of 517 nm using a UV-visible spectrophotometer. The DPPH radical scavenging activity was calculated using Equation (2):

$$\text{DPPH radical scavenging rate (\%)} = \left(1 - \frac{A_1 - A_2}{A_0}\right) \times 100\ \% \quad (2)$$

where A_0 is the absorbance of DPPH solution; A_1 is the absorbance after the reaction of adding DPPH solution, and A_2 is the absorbance of the sample.

Statistical analysis

Statistical analysis was performed using SPSS 26.0 software, and statistically significant was tested using Duncan‘s multiple comparisons and t-tests at $p < 0.05$. Data were expressed as the mean ± standard deviation from three measurements.

Results and discussion

Effect of heat treatment on the color of peanuts

The color of peanuts is an essential factor determining their appeal to the appetite and contribution to health benefits. Different heat treatment methods affect the appearance of the final peanut product, which in turn influences consumer choices of peanut products. It can be observed from Figure 1 that different heat treatments significantly affect the color of peanuts. The red-skinned peanuts darken after frying (Figure 1A) may be due to the Maillard reaction occurring during the heating process (Francisco and Resurreccion, 2009). The peanuts without skins turn yellow after frying (Figure 1B) possibly due to the absorption of some oil or the dissolution of some pigmented substances into the surface oil. Boiled red-skinned peanuts show noticeable fading (Figure 1G), and the water appeared reddish-brown, which indicated that most pigmented substances dissolve into the water. The boiled peanuts without skins lead to a

FIGURE 1: *Color changes of untreated and three heat-treated peanuts with and without skins: Fried peanuts with (A) and without skins (B); Baked peanuts with (C) and without skins (D); Untreated peanuts with (E) and without skins (F); Boiled peanuts with (G) and without skins (H).*

light green color in the water, suggesting a certain degree of color fading in the peanuts (Figure 1H). In contrast, the color change in the baked peanuts was relatively subtle (Figure 1C, D). The color of baked red-skinned peanuts is similar to that of untreated peanuts (Figure 1E), which could be attributed to the fact that they were only exposed to air during baking, resulting in the pigments in the skin not easily leaching out. The edges of peanuts without skins turn slightly yellow after baking (Figure 1D), possibly due to the exudation of internal oils from the peanuts.

Effect of heat treatment on fat content of peanuts

The fat content of peanuts is a critical indicator of their nutritional and health benefits, relating directly to their processing characteristics, processing efficiency, and storage stability. These factors are essential determinants of the market competitiveness of peanuts and their processed products (El Idrissi et al., 2023). The fat content of peanuts with and without skins was found to be in the range of 41.50 g/100 g to 50.16 g/100 g and 47.22 g/100 g to 51.82 g/100 g, respectively, which is consistent with the results of other researchers (Bishi et al., 2015; Yu et al., 2021).

According to Figure 2, it can be concluded that under different heat treatments, the fat content of peanuts without skins was significantly higher than that of red-skinned peanuts, indicating that red skin contains less fat. Given the high fat content of peanuts, there was no statistically significant difference in fat content between peanuts with and without skins under the same treatment conditions. In addition, we observed significant variations in the fat content of peanuts through different heat treatments. After boiling, the fat content of peanuts without skins slightly decreased, which may be due to the degradation of partial lipids at high temperatures and the loss of the protective barrier provided by red skin, resulting in fat leaching into the water. The fat content of peanuts with and without skins considerably increased after frying, by 9.40% and 20.86%, respectively. This increase is because of the transfer of lipids between soybean oil and peanuts during frying, along with the formation of floating oil on the surface of the peanuts, resulting in an increase in measured fat content. Additionally, the dehydration of peanuts during frying results in a reduced mass, thereby elevating the measured fat content. After baking, the fat content of peanuts with and without skins increased by 3.96% and 10.96% respectively, which was consistent with the research results of Wang et al. (2014), who found that the oil yield of peanuts gradually increased during the first 30 min of baking.

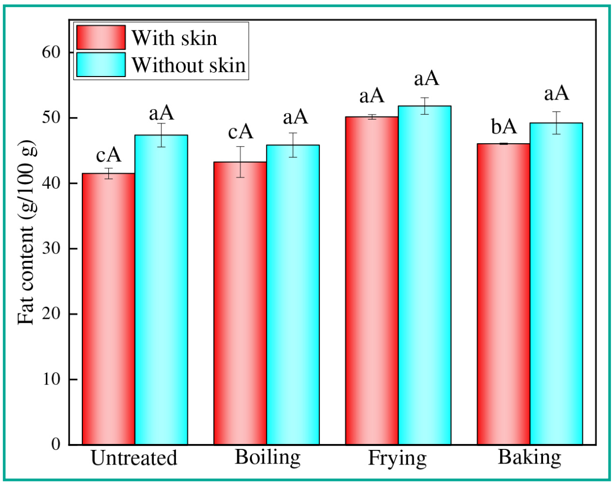

FIGURE 2: *Fat content of untreated and three heat-treated peanuts with and without skins. Different uppercase letters indicate significant differences between peanuts with and without skins under the same treatment; Different lowercase letters (a, b, and c) represent significant differences among the same peanuts across the three types of heat treatments.*

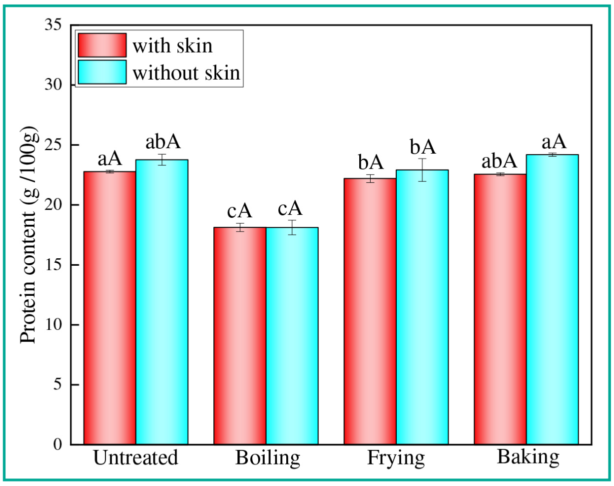

FIGURE 3: *Protein content of untreated and three heat-treated peanuts with and without skins. Different uppercase letters indicate significant differences between peanuts with and without skins under the same treatment; Different lowercase letters (a, b, and c) represent significant differences among the same peanuts across the three types of heat treatments.*

Effect of heat treatment on the protein content of peanuts

Peanut protein is valued for its high-quality amino acid composition and excellent nutritional value, serving as an economically viable source of plant protein with potential significance for enhancing global nutritional security. Additionally, its favorable functional properties, such as emulsification and gelation capabilities, broaden its application prospects in the food industry (Arya et al., 2016). The protein content of untreated peanuts with and without skin was 22.78 g/100 g and 23.77 g/100 g, respectively, which was close to the protein content measured in other studies (Arya et al., 2016; Yu et al., 2021). According to Figure 3, the protein content of peanuts decreased after boiling and frying, which was in agreement with the research results of Adeyeye (2010), possibly due to the Maillard reaction

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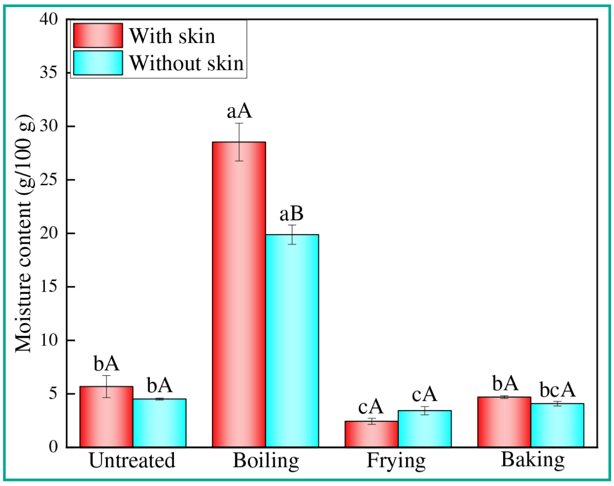

FIGURE 4: *Moisture content of untreated and three heat-treated peanuts with and without skins. Different uppercase letters (A and B) indicate significant differences between peanuts with and without skins under the same treatment; Different lowercase letters (a, b, and c) represent significant differences among the same peanuts across the three types of heat treatments.*

between free amino groups in protein and carbonyl groups in reducing sugar during heating, resulting in a decrease in protein content. The protein content of raw, boiled, baked, and fried peanuts without skins was higher than that of peanuts with skins, which was consistent with the findings of Ejigui et al. (2005). We believe this may be due to the lower protein content in red skins compared to peanut kernels, resulting in a decrease in overall protein content in peanuts with skins at the same mass.

Effect of heat treatment on the moisture content of peanuts

Moisture content is a crucial quality factor in assessing the storability of food, and its measurement is of great significance for the storage, cost, and processing of food products. As illustrated in Figure 4, the water content of peanuts increased after boiling, because the high content of protein in peanuts absorbs water and exhibits excellent water-holding capacity. Notably, peanuts with skins show a significantly higher moisture content than those without skins, indicating that the skins have good water absorption and retention properties. The skins are rich in dietary fiber (approximately 45% of the dry skins) (Ahmed et al., 2016) and their barrier function helps retain moisture in peanuts with skins. Conversely, other heat treatment methods result in a decrease in moisture content for both peanuts with and without skins, with frying resulting in a decrease of 57.15% and 17.23%, and baking leading to a decrease of 24.14% and 9.57%, respectively.

Effect of heat treatment on the ash content of peanuts

Ash content is an indicator of the amount of inorganic components (inorganic salts and oxides) in food. According to Figure 5, the ash content of peanuts with skins and without skins before treatment was 2.30 g/100 g and 2.36 g/100 g, respectively, with no significant difference in ash content. The ash content of boiled peanuts was significantly lower than that of untreated peanuts, at 1.79 g/100 g and 1.69 g/100 g, respectively. Coupled with the observation that water turned reddish-brown after boiling peanuts with skins and green after boiling peanuts without skins, it is hypothesized that a large number of inorganic components were lost to the water through boiling during the heat treatment process, resulting in a decrease in ash content. The increase in ash content after frying may be related to the adhesion of oxidation products generated during the frying process on the peanuts. The ash content of baked peanuts was close to that of untreated peanuts, with baked peanuts with and without skins having ash contents of 2.42 g/100 g and 2.44 g/100 g, respectively, which was close to the results of Ejigui et al. (2005).

Effect of heat treatment on the carbohydrate content of peanuts

Carbohydrates in peanuts play a pivotal role in providing energy and dietary fiber, contributing to a balanced diet and supporting digestive health. Additionally, the presence

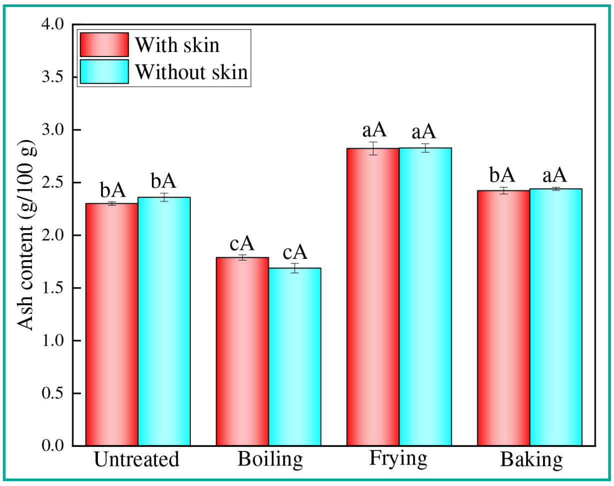

FIGURE 5: *Ash content of untreated and three heat-treated peanuts with and without skins. Different uppercase letters indicate significant differences between peanuts with and without skins under the same treatment; Different lowercase letters (a, b, and c) represent significant differences among the same peanuts across the three types of heat treatments.*

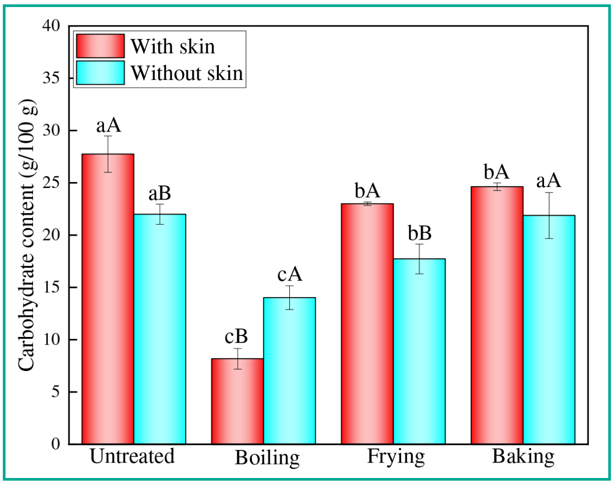

FIGURE 6: *Carbohydrate content of untreated and three heat-treated peanuts with and without skins. Different uppercase letters indicate significant differences between peanuts with and without skins under the same treatment; Different lowercase letters (a, b, and c) represent significant differences among the same peanuts across the three types of heat treatments.*

of carbohydrates in peanuts enhances their sensory attributes, such as sweetness and texture, making them a desirable ingredient in various culinary applications and food products. The carbohydrate content of untreated peanuts with skins was 27.75 g/100 g, while that of untreated peanuts without skins was 21.99 g/100 g. As shown in Figure 6, the carbohydrate content of peanuts with skins reduced by 70.54% after boiling; for peanuts without skins, it decreased by 36.36%; After frying, the carbohydrate content of peanuts with skins decreased by 11.23%, and peanuts without skins showed a 0.53% reduction in carbohydrates. After baking, the carbohydrate content of peanuts with skins decreased. Heat treatment can lead to a reduction in carbohydrate content due to several mechanisms (Puddington, 1948; Fagerson, 1969; Banožic´ et al., 2020). High temperatures may induce the decomposition of carbohydrates, with thermal degradation resulting in the breakdown of these compounds into smaller molecules. The Maillard reaction, which occurs during heating, consumes reducing sugars and leads to the formation of complex, non-carbohydrate compounds. Hydrolysis can also fragment larger carbohydrate molecules into smaller sugars. Additionally, volatile loss may occur, where volatile carbohydrates evaporate at elevated temperatures. Finally, structural changes induced by heat may alter the detection of carbohydrates during analysis. These factors collectively contribute to the observed decrease in carbohydrate content following heat treatment.

Additionally, for untreated, fried, and baked peanuts, the carbohydrate content of peanuts with skins was higher than that of peanuts without skins, which is related to the high proportion of dietary fiber in the skins. During boiling, the carbohydrate content in peanuts with skins was lower than that in peanuts without skins, possibly due to the presence of soluble fiber in the dietary fiber of the skins (Shimizu-Ibuka et al., 2009), which dissolves in water during the boiling process, resulting in a decrease in content. Carbohydrates exist in various forms in food and undergo complex changes during processing. This study only explores their total content, while the changes in various forms of sugars in peanuts during heat treatment require further detailed analysis.

Effect of heat treatment on mineral content of peanuts

Peanuts are rich in essential minerals, which play crucial roles in bone health, energy production, immune function, and antioxidant defense. This mineral composition not only contributes to the nutritional value of peanuts but also supports various metabolic processes, making peanuts a beneficial component of a healthy diet. A macroelement (calcium) and a trace element (iron) commonly found in peanuts were selected to assess the variations in mineral content levels in peanuts under different heat treatments.

The measured mineral contents of peanuts are shown in Table 1, with peanuts with skins containing 1.193 mg/g of calcium and 0.207 mg/g of iron, and peanuts without skins containing 0.934 mg/g of calcium and 0.131 mg/g of iron. This indicates that red skins contain minerals, especially iron. Heat treatment caused significant losses in both calcium and iron in peanuts. After boiling, frying, and baking, the calcium content in peanuts with skins decreased by 31.10%, 32.28%, and 36.30% compared to untreated peanuts, while the iron content decreased by 76.33%, 59.90%, and 63.77%, respectively. Baking caused the greatest loss of calcium in peanuts with skins and boiling resulted in the greatest loss of iron. After boiling, frying, and baking, the calcium content in peanuts without skins decreased by 26.77%, 22.06%, and

TABLE 1: *The calcium and iron content of untreated and three heat-treated peanuts with and without skins.*

Peanuts		Calcium content (mg/g)	Iron content (mg/g)
With skin	Untreated	1.193 ± 0.119^{aA}	0.207 ± 0.030^{aA}
	Boiling	0.822 ± 0.036^{bA}	0.049 ± 0.003^{bA}
	Frying	0.796 ± 0.039^{bA}	0.083 ± 0.052^{bA}
	Baking	0.760 ± 0.027^{bA}	0.075 ± 0.027^{bA}
Without skin	Untreated	0.934 ± 0.204^{aA}	0.131 ± 0.006^{aA}
	Boiling	0.684 ± 0.095^{aA}	0.060 ± 0.008^{cA}
	Frying	0.728 ± 0.173^{aA}	0.085 ± 0.005^{bA}
	Baking	0.783 ± 0.013^{aA}	0.038 ± 0.010^{dA}

Different uppercase letters indicate significant differences between peanuts with and without skins under the same treatment; different lowercase letters (a, b, c, and d) represent significant differences among the same peanuts across different treatments ($p<0.05$).

16.17% compared to untreated peanuts, respectively, while the iron content decreased by 54.20%, 35.11%, and 70.99% respectively. For peanuts without skins, boiling and baking were the heat treatment methods that caused the greatest loss of calcium and iron, respectively.

The Effect of heat treatment on the total phenol content of peanuts

Phenolic compounds, which are plant-based secondary metabolites, are predominantly found in the external layers, including the peel, hull, and shell, serving to safeguard the materials of the inner kernel material. Various factors, both internal and external, including genetic makeup, conditions of the environment, the process of germination and maturation, as well as methods of processing and preservation, significantly affect the variety and concentration of phenolic compounds present in plants (Ma et al., 2014). According to Figure 7, the TPC in untreated peanuts without skins was 2.83 mg/g, with peanuts retaining their skins exhibiting a higher TPC, indicating that phenolic compounds are primarily concentrated within the skins. After boiling, the TPC in peanuts with skins decreased by 39.85%, while in peanuts without skins, it reduced by 25.25%. Considering the color change of the water after boiling as observed in the experiment, it can be inferred that the destruction

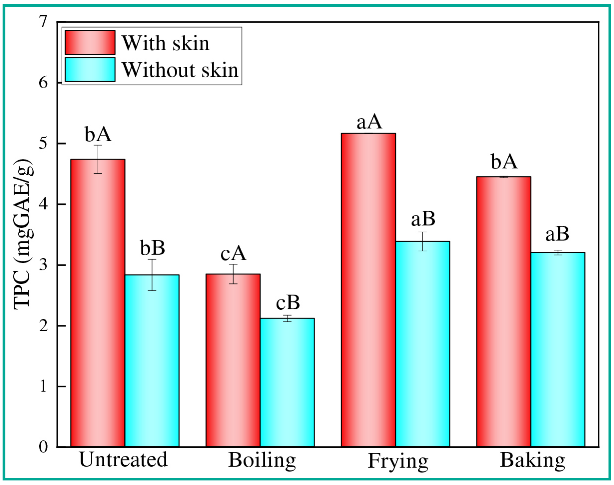

FIGURE 7: *Total phenol content (TPC) of untreated and three heat-treated peanuts with and without skins. Different uppercase letters (A and B) indicate significant differences between peanuts with and without skins under the same treatment; Different lowercase letters (a, b, and c) represent significant differences among the same peanuts across the three types of heat treatments.*

of the cell wall structure in peanuts during high-temperature treatment led to the dissolution and substantial loss of water-soluble phenolic compounds into the water (Lin and Chang, 2005). After frying, the TPC increased by 9.05% in peanuts with skins and 19.43% in peanuts without skins, possibly due to the high temperatures of frying in soybean oil facilitating the dissolution of some lipophilic substances, reducing polyphenol oxidase activity, or protecting phenolic compounds from degradation (Maisuthisakul et al., 2007). The TPC in peanuts without skins increased by 13.01% after baking, likely because the heating process caused the release of phenolic compounds with larger molecular weights in bound forms into simple free forms, thereby enhancing the TPC of the samples (Win et al., 2011). This process may be related to the Maillard reaction (Yu et al., 2005).

Effect of heat treatment on the antioxidant activity of peanut total phenols

As the TPC of peanuts increases, the DPPH radical scavenging rate gradually increases, as shown in Figure 8. By measuring the IC_{50} values for DPPH radical scavenging activity in different groups, we investigated the effect of various heat treatments on the antioxidant activity of peanuts (Table 2). Without heat treatment, the IC_{50} value of peanuts with skins (1.36 mg/g) was lower than that of peanuts without skins (1.88 mg/g), indicating that peanuts with skins have a stronger scavenging ability compared to those without skins. The IC_{50} value for peanuts with skins increased after boiling due to the loss of total phenols, leading to a decrease in free radical scavenging ability. After frying and baking, the IC_{50} values of peanuts with skins were similar and both lower than those of untreated peanuts with skins. This suggests that the DPPH radical scavenging ability of total phenols in peanuts is enhanced after frying and baking, consistent with the results of TPC. The higher the TPC, the stronger the scavenging ability, thereby enhancing antioxidant capacity (Balasundram et al., 2006; Dasgupta and De, 2007). For peanuts without skins, the IC_{50} values of scavenging rates after different heat treatments were in the order of boiling > baking > frying, indicating their antioxidant activity increased in this order.

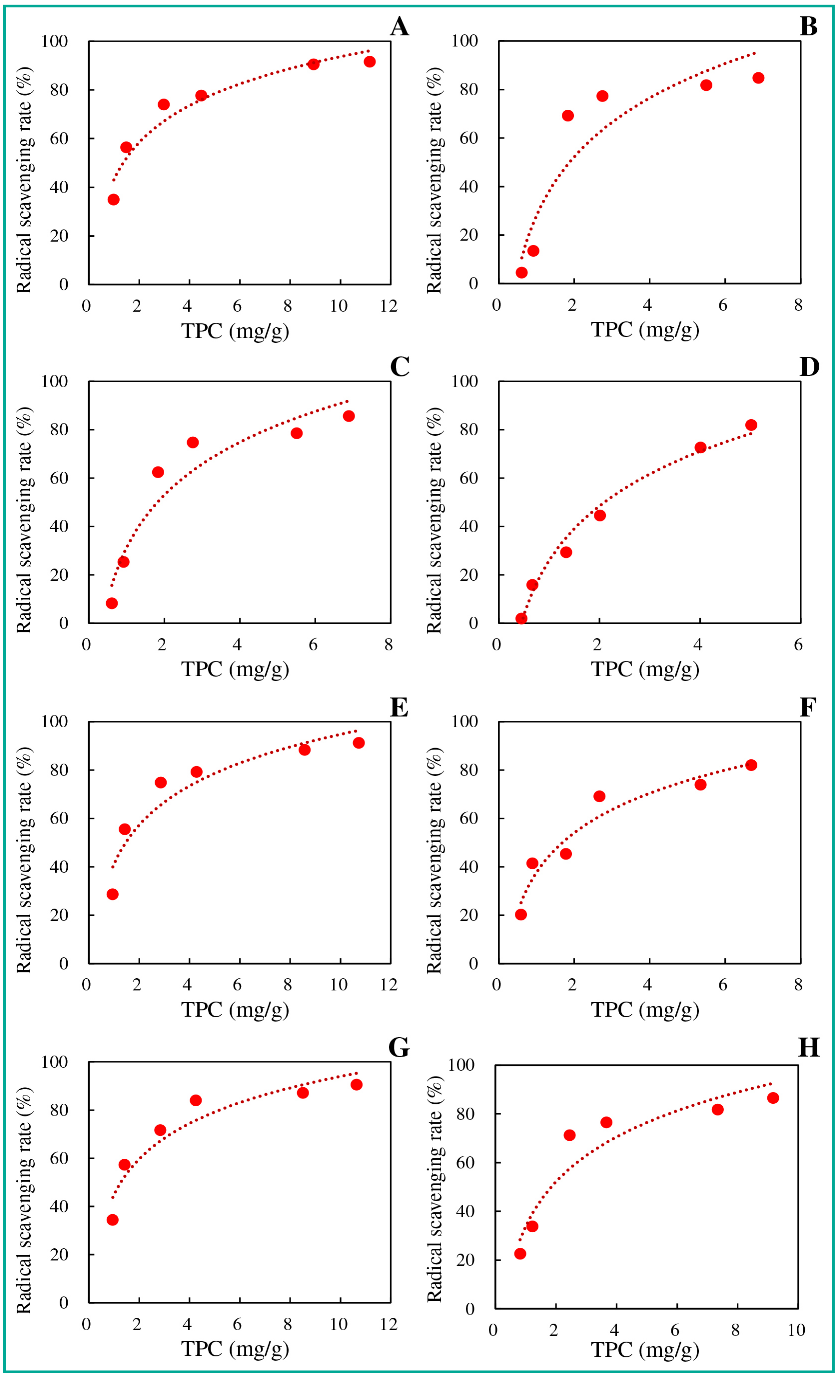

FIGURE 8: *DPPH radical scavenging of total phenols in untreated and three heat-treated peanuts with and without skins: Untreated peanuts with (A) and without skins (B); Boiled peanuts with (C) and without skins (D); Fried peanuts with (E) and without skins (F); Baked peanuts with (G) and without skins (H).*

TABLE 2: *IC_{50} of DPPH free radical scavenging rate in untreated and three heat-treated peanuts with and without skins.*

Peanuts		IC_{50} (mg/g)
With skin	Untreated	1.36
	Boiling	1.82
	Frying	1.27
	Baking	1.27
Without skin	Untreated	1.88
	Boiling	2.10
	Frying	1.69
	Baking	1.84

Changes in nutritional components and phenolics of peanuts after heat treatment

In reviewing the entire study, we have summarized the effects of different heat treatments on the nutritional components and phenolics content of peanuts. As demonstrated in Table 3, both frying and baking result in an increase in the fat content of peanuts, while boiling has inconsistent effects on the fat content of peanuts with and without skins; the fat content of peanuts with red-skins increases, whereas it slightly decreases for peanuts without skins. Boiling and

TABLE 3: *Changes in nutritional components and total phenol content of peanuts after three heat treatments.*

	Heat treatment	Peanuts with skins	Peanuts without skins
Fat content	Boiling	4.23%	−0.31%
	Frying	10.96%	3.96%
	Baking	20.86%	9.40%
Protein content	Boiling	−21.98%	−23.78%
	Frying	−0.98%	1.79%
	Baking	−2.54%	−3.59%
Moisture content	Boiling	402.70%	340.31%
	Frying	−57.15%	−24.14%
	Baking	−17.23%	−9.57%
Ash content	Boiling	−22.25%	−28.47%
	Frying	5.30%	3.39%
	Baking	22.69%	19.83%
Carbohydrate content	Boiling	−70.54%	−36.36%
	Frying	−17.09%	4.59%
	Baking	−11.23%	−0.53%
Calcium content	Boiling	−31.10%	−26.77%
	Frying	−33.28%	−22.06%
	Baking	−36.30%	−16.17%
Iron content	Boiling	−76.33%	−54.20%
	Frying	−59.90%	−35.11%
	Baking	−63.77%	−70.99%
Total phenolic content	Boiling	−39.85%	−25.25%
	Frying	8.30%	19.43%
	Baking	6.08%	44.14%

baking lead to a reduction in protein content in peanuts, while frying results in a slight decrease in protein content for red-skinned peanuts and a slight increase for peanuts without skins. Following boiling, the moisture content of peanuts significantly increases, whereas it decreases after frying and baking. The ash content of peanuts decreases after boiling but increases after frying and baking. After these three thermal treatments, a notable loss of carbohydrates in red-skinned peanuts was observed, with the greatest loss occurring during boiling. In contrast, peanuts without skins exhibited inconsistent trends, with carbohydrate content rising after frying, differing from the effects of boiling and baking. The content of calcium and iron in peanuts suffers significant losses after thermal treatments. The TPC of peanuts decreases after boiling but increases after baking and frying. In summary, boiling, frying, and baking have a greater impact on the nutritional components of red-skinned peanuts than peanuts without skins, with boiling having the most significant effect on nutritional content. The impact of thermal treatments on the TPC is less for red-skinned peanuts compared to peanuts without skins, with baking having the greatest effect.

Conclusions

This study primarily compares the nutritional components, TPC, and antioxidant activity of peanuts with and without skins under various thermal treatments. Boiling resulted in significant losses in the protein, carbohydrate, ash, mineral, and TPC of peanuts, while markedly increasing their moisture content. Frying decreased the moisture and mineral content of peanuts but increased their fat, ash, and total phenolic content, with a decrease in protein and carbohydrate content for red-skinned peanuts and an increase in peanuts without skins. Baking led to a loss of some protein, moisture, carbohydrates, and minerals in peanuts, while increasing the content of fat, ash, and total phenolics. Overall, the impact of thermal treatments on the nutritional components of red-skinned peanuts was more significant than on peanuts without skins, with boiling having the most considerable effect on nutritional properties. Furthermore, regarding TPC and antioxidant capacity, boiling had a significant negative impact on peanuts, decreasing both their TPC and free radical scavenging ability. In contrast, frying and baking were found to increase the TPC of peanuts, thereby enhancing their antioxidant capacity.

Moreover, this work only investigates the effects of three common thermal processing methods on the nutritional components and TPC of peanuts with and without red skin, without delving into the actual amount absorbed during the digestion process. Therefore, further research is required to explore the bioavailability of nutrients and phenolic compounds under different thermal treatments through in vivo or in vitro digestion studies or at the biological level.

Conflicts of interest

There are no conflicts of interest.

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