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Effect of Drying Pre-Treatment on Nutritional Composition, Fatty Acid Profile, and Antioxidant Properties of Bambangan (*Mangifera pajang*) Seed and Its Fat

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ABSTRACT

This study investigates the effects of five different drying methods (sun, oven, cabinet, microwave, and freeze-drying) on the nutritional composition, fatty acid profile, and antioxidant properties of bambangan seed powder and its extracted fat. Proximate analysis revealed that freeze drying preserved the highest crude fat content (6.94%), while sun drying resulted in higher crude fiber levels (4.51%). Cabinet drying achieved the lowest moisture content (5.57%), thereby enhancing shelf stability. Fatty acid profiling showed stearic (37.29 - 44.68%) and oleic acids (38.71 - 45.53%) as dominant in bambangan seed fat, with freeze drying and cabinet drying retaining higher saturated fatty acids, whereas oven drying and microwave drying promoted unsaturated fatty acid. Total phenolic content (62.43 - 83.90 mg GAE/g) and ferric reducing antioxidant power (102.41 - 129.52 mM/100g) were highest in freeze drying samples, particularly in seed powder, indicating superior retention of antioxidant compounds. A strong positive correlation (r>0.800) between TPC and FRAP was observed. Freeze drying is the most effective method for preserving nutritional and bioactive components, followed closely by cabinet drying, which offers a practical balance between quality retention and processing feasibility.

Keywords: Antioxidant activity, drying methods, fatty acid profile, *Mangifera pajang*, phenolic content

INTRODUCTION

Underutilized plant species are used because they are considered less important than staple foods in terms of global production and market value (Gosh *et al.*, 2023). However, many of these underutilized foods have high nutrient density and can be grown with minimal agricultural inputs. In addition, fruit by-products, such as seeds and peels, are naturally rich in antioxidants due to their phenolic components. The peel and seed of the bambangan fruit (*Mangifera pajang*) are rich in antioxidants and phytochemicals such as polyphenols, flavonoids, carotenoids, and anthocyanins, which help neutralize free radicals and have the potential for nutraceutical and functional food applications (Jahurul *et al.*, 2019a & 2019b). Bambangan seeds contain 7.67 - 11.00% fat, 3.08 - 4.10 % protein, and 38.68 - 72.90% carbohydrates, making them a nutritious food source (Jahurul *et al.*, 2018a; Norazlina *et al.*, 2021). The seeds are a potential ingredient for nutraceutical and functional foods. Due to their nutritional content and antioxidant properties, bambangan seeds can be used in the development of functional foods by incorporating them into foods, which can enhance their health-promoting properties (Kalsum & Mirfat, 2014; Jahurul *et al.*, 2018b).

However, post-harvest preservation is essential to maintain their quality, and drying is a common method used for this purpose. While various drying processes have been extensively studied in other fruits, their effects on the composition of bambangan seeds are still unexplored. Drying is a common preservation technique that reduces moisture content and transforms perishable fruits and vegetables into stable, shelf-stable powders suitable for functional food applications (Lalita & Jiradech, 2016; Abebe & Gesessew, 2021; Fernandes *et al*., 2025). While drying improves storage, transportation, and year-round availability, it can also significantly impact the retention of bioactive compounds and nutrients. Common drying methods include sun drying (SD), oven drying (OD), cabinet drying (CD), microwave drying (MD), and freeze-drying (FD). Each method differs in heat transfer mechanisms, energy efficiency, and effects on food matrices.

Among these, SD is cost-effective and widely used in tropical regions such as Malaysia (Nazirah *et al*., 2024). The drying process is through natural solar radiation and ambient air flow. OD and CD offer reliable moisture reduction at relatively low cost. OD uses hot air convection in a controlled chamber to uniformly remove moisture, whereas CD employs a controlled chamber with forced air circulation and adjustable airflow. MD provides faster drying rates and more uniform energy distribution (Özkan *et al.,* 2018). This is achieved by electromagnetic waves that generates internal heating through molecular vibration of water, promoting rapid moisture removal while minimizing nutrient and antioxidant loss due to shorter exposure time. FD is often considered the most effective method for preserving nutrients and bioactive components (Lalita & Jiradech, 2016). It involves freezing the sample followed by sublimation of ice under vacuum, bypassing the liquid phase. This process is gentle, preserving heat-sensitive compounds, resulting in a porous, lightweight product with excellent rehydration properties.

Given the growing demand for high-quality, nutrient-rich foods, improving drying methods has become a key focus in food processing research. Although numerous studies have reported the effects of various drying methods on the quality of fruits and vegetables (Özkan *et al*., 2018; Adugna *et al*., 2020; Abebe & Gesessew, 2021; Sundar *et al*., 2024), there is a lack of research on the drying behavior of bambangan seed and its implications for functional food development. This study addresses that gap by evaluating how different drying techniques influence the nutritional and antioxidant properties of bambangan seed and its fat. Specifically, it aims to assess the effects of the five drying methods (SD, OD, CD, MD, and FD) on the proximate composition, fatty acid content, TPC, and antioxidant capacity of bambangan seed and its fat. This study reports the effects of different drying methods on the nutritional composition and antioxidant properties of bambangan seed and its fat, offering valuable insights for optimizing its processing into value-added functional ingredients.

MATERIALS AND METHODS

Materials

Ripe bambangan fruits were collected from Tuaran, Sabah (Malaysia). Chemicals and reagents used for the analyses included ferric chloride, gallic acid, hexane (analytical grade), n-hexane (GC-grade), hydrochloric acid, Kjedahl tab, methanol (analytical and LC-MS grade), sodium carbonate, sulphuric acid, sodium hydroxide, sodium acetate trihydrate and 2,4,5-tripridyl-s-triazine (TPTZ) were sourced from Sigma (USA) and were of the highest purity available.

Preparation of Bambangan Seed Powder (BSP) from Various Drying Methods

The peel and flesh of the bambangan fruit (Figure 1) were manually removed using a stainless-steel household knife. The seeds were thoroughly rinsed with distilled water to remove residual flesh and then cut into uniform pieces (1 cm × 2 cm × 0.2 cm). The seeds were dried according to the method described by Banerjee *et al.* (2016), Dorta *et al.* (2012), and Jahurul *et al.* (2019). The dried seeds were ground into powder form using a grind mill (MX898M, Panasonic, Malaysia) and sieved to obtain uniform particle size (<250 µm). The drying treatments applied were as follows:

Sun Drying (SD) Treatment

The seeds were spread in a single layer on stainless steel trays and covered with a fine mesh to protect them from insects and debris. Drying was conducted under ambient outdoor temperature (28-35 ºC) for 72 hours with 8 hours of direct sun exposure per day. Samples were turned twice daily to ensure uniform drying and prevent fungal growth.

Cabinet Drying (CD) Treatment

Drying was conducted using a cabinet dryer (TD-1200, Thermoline, AUS) at a set temperature of 60 °C for 24 hours. Seed pieces were placed in a single layer on the stainless-steel trays. The drying continued until the samples reached constant weight

Oven Drying (OD) Treatment

Samples were dried in a convection oven (Binder ED 115, Binder, Germany) at 60 °C for 24 hours. Seed samples were spread evenly in a single layer on aluminum trays. The oven provided natural air circulation, and samples were not disturbed during the process. Moisture content was monitored to ensure drying was complete once constant weight was obtained.

Microwave Drying (MD) Treatment

Drying was carried out in a domestic microwave oven (Samsung ME9114, South Korea; 900 W maximum power). Seed pieces were arranged in a single layer on a microwave-safe glass plate and exposed to microwave energy at 180 W (20% power level) for 10 minutes. The seeds were turned manually at the 5-minute mark to improve drying uniformity. The microwave had no rotating turntable. Drying was stopped once the sample reached constant weight based on pre-calibrated moisture testing.

Freeze Drying (FD) Treatment

Fresh seed samples were frozen at –20 °C for 24 hours before being freeze-dried in a freeze dryer (Alpha 2-4 LSC plus, CHRIST, Germany) at –40 °C under a vacuum of 0.04 mbar for 48 hours. Dried samples were stored in airtight containers at 4 °C until analysis. Freeze-dried samples were not ground until analysis to minimize oxidation.

(a) Bambangan fruit (b) Bambangan cross section

Figure 1. Picture of bambangan fruit (a) and its seed cross-section (b)

Extraction of Bambangan Seed Fat (BSF)

The crude BSF was extracted using Soxhlet extraction, following the AOAC (2003) official analysis method with slight modification. 80.00 ± 0.01 g of BSP was extracted in the Soxhlet extractor, using hexane as a solvent at a 1:5 (w/v) ratio, for 8 hours (40 °C). The residual solvent in the extracted BSF was evaporated at 40 °C using a rotary evaporator (4001, HEIDOLPH LABORTA, Germany). The fat was dried in an oven (Binder ED 115, Binder, Germany) at 40 °C for 2 hours. The weight of the extracted BSF was recorded to determine the total fat yield.

Proximate Analysis

The proximate analysis of BSP, including moisture, ash, fat, protein, crude fiber, and carbohydrates, was determined according to the official method of the Association of Official Analytical Chemists (AOAC, 2016). The moisture content was determined using the oven (Binder ED 115, Binder, Germany) drying method (official AOAC method 984.25). In contrast, the fat and ash content were determined using the standard methods of Soxhlet extraction and ashing. The protein content was calculated by determining the nitrogen content and multiplying it by the conversion factor of 6.25. Crude fibre was determined by acid and alkali digestion. The total carbohydrate content was calculated by difference by subtracting the combined percentages of moisture, ash, fat, protein, and fibre from 100 %.

Fatty Acid Composition of BSF

The fatty acid analysis was conducted following the IUPAC 2.301 method. For the preparation of samples, 0.50 ± 0.01 g of BSF was dissolved in 2.5 ml n-hexane and 0.5 ml of 2N potassium hydroxide in methanol. The resulting mixture was vortexed for 1 minute at 1200 rpm, followed by 10 10-minute settling period. The transparent upper layer was then extracted for analysis. The fatty acid methyl ester (FAMEs) profiles of the blends were analyzed using a DB-23 column (30 m x 0.32µm x 0.25: ID) in a gas chromatography (GC), equipped with a flame ionization detector (GC-2-10, Shimadzu, Japan). Fatty acids were identified under the following conditions: an initial temperature of 90 °C (maintained for 5 minutes), increased at 8 °C/ minute to 185 °C (maintained for 1 minute), and then increased at 2 °C/minute to a final temperature of 250 °C (maintained for 5 minutes). The injector and detector temperatures were set at 250 °C using a split mode (1:20). The elution of the fatty acid methyl ester was determined based on the standard.

Determination of Total Phenolic Content (TPC) and Ferric-Reducing Antioxidant Power (FRAP)

The TPC in BSP and BSF was determined following the Follin-Ciocalteau and FRAP assay described by Jahurul *et al*. (2018b) and Khairy *et al*. (2015). FRAP was measured using the TPTZ reagent and expressed as mmol Fe(II)/100g. Methanol:hexane partitioning was utilized to extract phenolics from seed powder and BSF. The methanolic extract of BSP and BSF was prepared prior to analysis. A total of 2.50 ± 0.01 g of BSF was dissolved in 5 ml of hexane and 5 ml of 60% methanol. The resulting mixture was thoroughly stirred for 1 minute using a vortex. Subsequently, the mixture was centrifuged at 3500 rpm for 10 minutes at 4 °C. The supernatant was collected for further analysis. The TPC of BSP and BSF was expressed as Gallic Acid Equivalents (GAE) per gram of fresh weight. For FRAP, the antioxidant activity of the extracts was assessed based on a calibration curve generated using $FeSO_4.7H_2O$. The results were expressed as the concentration of antioxidants with ferric-reducing ability per gram of bambangan seed extract (µM/g).

Statistical analysis

Analyses were performed in triplicate, with results expressed as means (±) and standard deviations (SD). SPSS version 29 was used for statistical analysis. A one-way ANOVA was used to test for differences between means, followed by a Tukey's test for comparison. Pearson correlation was used to measure the relationship between TPC and FRAP, with a significance of $p<0.05$.

RESULTS AND DISCUSSION

Effect of Drying Methods on the Proximate Compositions of Bambangan Seeds

The proximate analysis in Table 1 revealed that the moisture, crude fat, and crude fiber content were significantly ($p<0.05$) affected by the drying methods. Moisture content was lowest in cabinet drying (CD) (5.57%) and highest in sun drying (SD) (8.63%), indicating that CD is highly effective in moisture removal due to the controlled temperature and consistent air circulation. Moisture content is a crucial parameter that influences the quality and shelf life. The results showed CD exhibited a consistent heating effect, effectively eliminating humid air from the seed surface and facilitating moisture loss, resulting in the lowest moisture content. The lower moisture content is due to controlled heat and air circulation. In contrast, SD prolonged exposure to ambient conditions may result in less effective drying and moisture reabsorption from the environment. However, the slightly high moisture in FD (7.40%) is acceptable given the preservation of heat-sensitive compounds.

These values are generally lower than the 8.90% reported moisture by Jahurul *et al.* (2018a), possibly due to differences in variety, growing conditions, or post-harvest treatment. The results obtained in this study are in agreement with those of Siddiqui *et al*. (2024), who reported that controlled drying environments such as CD and OD effectively reduce moisture content and improve drying efficiency. FD, while resulting in slightly higher moisture content than CD or OD, is known to preserve heat-sensitive compounds and maintain structural integrity. A trend similarly observed in studies by Mina *et al*. (2024) on carrot slices. In addition, the moisture content found here is consistent with the value of 6.13% reported by Norazlina *et al*. (2020) for bambangan seeds. Compared to other tropical fruit seeds such as jackfruit (10.78%) and avocado (13.09 – 15.10%) (Egbuonu *et al*., 2018; Ejiofor *et al*., 2018), bambangan seeds exhibit relatively low moisture levels, which may contribute to better shelf stability and reduced microbial risk.

Crude fat content was highest in freeze drying (FD) (6.9%), followed by CD (6.70%) and SD (6.18%). Oven drying (OD) (5.17%) yielded the lowest crude fat. The high fat retention in FD samples promotes the ability of the method to preserve thermolabile and volatile lipids without using high temperatures. The fat loss observed in OD samples was presumably due to oxidation or volatilization of fats under prolonged heating. These results align with the findings of Dadhaneeya *et al*. (2023), who reported that FD preserved more lipids in dragon fruit due to the absence of high-temperature exposure, which helps retain sensitive compounds. Similarly, Belwal *et al*. (2022) reported significant lipid degradation in plant-based products subjected to hot air drying. In addition to expressing the fat content as a percentage of the proximate composition, the actual fat yield was determined based on 80 g of the dried seed powder used for extraction. The total fat extracted ranged from 4.14 g (OD) to 5.55 g (FD), corresponding to a fat yield of 5.17% to 6.94% of the lowest and highest fat mass, respectively. Crude fiber content was highest in SD (4.51%), while FD (2.13%) resulted in the lowest fiber content. The higher fiber content in SD samples resulted from the partial degradation or removal of non-fiber components, concentrating the fiber fraction.

On the other hand, FD may retain more intact cellular structures, resulting in slightly lower measurable crude fiber after defatting. This observation aligns with Dadhaneeya *et al*. (2023), who reported that FD preserves cell wall integrity, potentially affecting fiber determination. Ash content showed no significant differences, which is consistent with the general understanding that minerals are non-volatile and resist degradation during thermal processing (Silva *et al*., 2020). However, CD and MD yielded slightly higher ash content compared to OD, FD, and SD. This variation may be due to differences in heat intensity and exposure duration, where rapid dehydration in CD and MD could lead to greater retention of inorganic matter. Siddiqui *et al*. (2024) similarly reported that while ash content generally remains stable, drying conditions can influence the retention of specific minerals depending on the food matrix and method used.

Protein content is better preserved in SD and FD due to the lower temperatures involved. The chemical reaction between amino acids and reducing sugars typically occurs at elevated temperatures and leads to loss of available protein through complex formation, thus minimizing thermal denaturation and Maillard reactions. In contrast, CD, OD, and MD, which involve high temperatures, showed reduced protein levels. This trend is in line with Siddiqui *et al*. (2024), who emphasized that high-temperature drying methods can lead to protein denaturation and compromised nutritional quality. Although the protein content of the bambangan seed is lower than that of other fruit seeds such as avocado and rambutan, it still offers high-quality protein, as evidenced by its rich amino acid profile (Jahurul *et al*., 2018b). Carbohydrates represented the largest nutrient fraction in bambangan seeds, ranging from 74.82% to 80.00%. This high carbohydrate content plays a key role in influencing the functional and sensory characteristics of the seed-based product, including texture, sweetness, and energy density. Carbohydrates contribute to desirable qualities such as mouthfeel and palatability, which are essential for consumer acceptance in food applications.

Oven Drying (OD) (80.00%) samples had the highest carbohydrate content, likely due to the concentration effect following the removal of other components during drying. SD (74.82%) samples exhibited the lowest carbohydrate content, possibly due to slower dehydration and partial sugar degradation. While prolonged heat exposure can concentrate carbohydrates, excessive heat may alter their structure and digestibility (Siddiqui *et al*., 2024). Overall, CD was effective in reducing moisture content, FD was optimal for fat retention, and SD contributed to higher fiber content, albeit with higher residual moisture, possibly reducing microbial safety. The choice of drying methods should therefore be tailored to the desired nutritional properties of the final product.

Table 1. Effect of drying on the proximate composition of bambangan seed on a dry basis

Proximate composition	Sun Drying	Cabinet Drying	Oven Drying	Microwave Drying	Freeze Drying (FD)
Moisture (%)	8.63±0.30^{a}	5.57±0.45^{c}	7.19±0.12^{b}	7.49±0.0^{b}	7.40±0.13^{b}
Fat (%)	6.18±0.06^{c}	6.70±0.05^{b}	5.17±0.06^{d}	6.07±0.05^{c}	6.94±0.02^{a}
Fat (g per 80 g of dried seeds)	4.94±0.17^{c}	5.36±0.09^{b}	4.14±0.36^{d}	4.86±0.27^{c}	5.55±0.33^{a}
Ash (%)	2.20±0.37^{a}	2.57±0.15^{a}	2.45±0.14^{a}	2.52±0.22^{a}	2.32±0.03^{a}
Protein (%)	3.75±0.06^{a}	2.87±0.04^{c}	2.96±0.06^{c}	2.87±0.01^{c}	3.34±0.01^{b}
Fibre (%)	4.51±0.26^{a}	3.06±0.08^{b}	2.30±0.15^{c}	2.59±0.36$^{b,\ c}$	2.13±0.05^{c}
Carbohydrate (%)	74.82±0.37^{d}	79.26±0.06^{b}	80.00±0.42^{a}	78.60±0.25$^{b,\ c}$	77.88±0.13^{c}

Data are mean value ± standard deviation. Different letter(s) within the row are significant differences according to One-way ANOVA ($p<0.05$).

Effect of Drying Pretreatment on Fatty Acid Compositions of BSF

Nine fatty acids were identified in bambangan seed fat (BSF) (Table 2), with stearic acid (37.29 - 44.68%) and oleic acid (38.71 - 45.53%) being predominant, followed by palmitic, linoleic, and arachidic acids. Long-chain saturated fatty acids (SFAs), such as lignoceric acid, were detected only in SD, CD, OD, and FD samples, with FD and CD showing higher levels of stearic acid. In contrast, oleic and linoleic acid concentrations were lower in heat-based treatments, with CD exhibiting the lowest values. This suggests that prolonged heat exposure likely accelerates oxidation of unsaturated fatty acids (USFAs), resulting in fat degradation (Mokhtar *et al*., 2018). FD samples exhibited nearly equal proportions of stearic (41.49%) and oleic (42.49%) acids, whereas CD samples exhibited a stearic acid (44.68%) dominance, indicating a shift toward a more saturated profile. This is reflected in the total SFA content, which was highest in CD, followed by FD.

On the other hand, OD, MD, and SD samples retained higher USFA concentrations (Figure 2). This variation in fatty acid profiles likely arises from oxidative degradation of USFAs, which generates volatile by-products and reduces nutritional value (Wang *et al*., 2020). These findings are consistent with Hurtado-Ribeira *et al*. (2023a), who reported significant changes in fat integrity due to drying and defatting techniques in BSF. Their study found that OD preserved fat stability better than FD, while FD caused increased free fatty acid levels due to enhanced lipolysis. They also noted that thermal drying reduced both moisture and free fatty acid levels, thereby improving fat stability. This supports the current findings, where CD and FD, despite contrasting thermal mechanisms, led to higher SFA and lower USFA contents, reflecting modified fat quality.

Moreover, Hurtado-Ribeira *et al*. (2023b) also reported that freeze-drying combined with mechanical pressing, although efficient for fat extraction, increased free fatty acid and moisture content, potentially compromising fat stability. This aligns with our observation that FD samples retained some USFAs but showed signs of oxidative deterioration. Compared to mango seed fat, which contains 6.67 – 7.71% palmitic acid, 42.27 – 48.23% stearic acid, 32.91 – 41.41% oleic acid, and 5.51 – 5.97% linoleic acid (Jahurul *et al*., 2018c; Jin *et al*., 2017), BSF fat exhibits a higher oleic acid and lower stearic acid content. These differences demonstrates the influence of both botanical origin and post-harvest processing on fatty acid profiles.

Table 2. Effect of drying on the fatty acid composition of bambangan seed fat.

Fatty acid (%)	Sun Drying	Cabinet Drying	Oven Drying	Microwave Drying	Freeze Drying
Saturated fatty acids (SFAs)					
Palmitic (C_{16})	7.74 ± 0.03^{a}	$8.17 \pm 0.02^{c,d}$	8.13 ± 0.02^{c}	8.23 ± 0.00^{d}	7.86 ± 0.05^{b}
Stearic (C_{18})	38.60 ± 0.00^{c}	44.68 ± 0.01^{e}	37.29 ± 0.05^{a}	37.80 ± 0.00^{b}	41.49 ± 0.01^{d}
Arachidic (C_{20})	1.83 ± 0.02^{a}	2.38 ± 0.01^{c}	1.93 ± 0.02^{b}	$1.87 \pm 0.03^{a,b}$	$1.87 \pm 0.03^{a,b}$
Behenic (C_{22})	0.31 ± 0.00^{a}	0.41 ± 0.01^{d}	0.34 ± 0.00^{c}	$0.32 \pm 0.00^{a,b}$	$0.33 \pm 0.00^{b,c}$
Lignoceric (C_{24})	0.53 ± 0.03	0.84 ± 0.00	0.65 ± 0.00	-	0.57 ± 0.00
Unsaturated fatty acids (USFAs)					
Oleic ($C_{18:1}$)	45.53 ± 0.02^{e}	38.71 ± 0.02^{a}	45.07 ± 0.02^{d}	44.03 ± 0.03^{c}	42.49 ± 0.01^{b}
Linoleic ($C_{18:2}$)	5.07 ± 0.01^{b}	4.51 ± 0.01^{a}	6.08 ± 0.01^{d}	6.82 ± 0.01^{e}	5.14 ± 0.00^{c}
Linolenic ($C_{18:3}$)	0.23 ± 0.02^{a}	0.21 ± 0.00^{a}	0.32 ± 0.00^{c}	0.28 ± 0.00^{b}	0.27 ± 0.04^{b}
Paullinic acid ($C_{20:1}$)	0.14 ± 0.00^{c}	0.93 ± 0.00^{a}	0.15 ± 0.00^{d}	0.14 ± 0.00^{c}	0.13 ± 0.02^{b}

Data are mean value ± standard deviation. Different letter(s) within the row are significant differences according to One-way ANOVA ($p<0.05$).

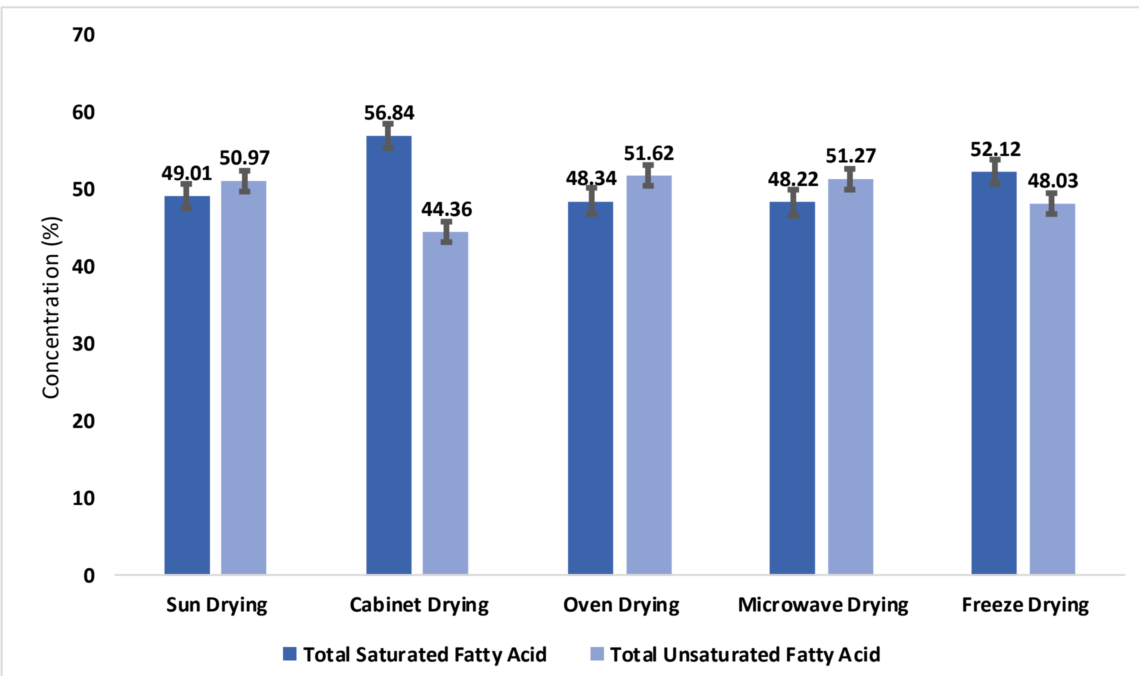

Figure 2. Effect of drying method on total saturated fatty acid and unsaturated fatty acids of bambangan seed fat

Effect of Drying Pretreatment on the Phenolic Content and FRAP

Polyphenolic compounds are key contributors to the antioxidant capacity of fruits and vegetables, protecting against oxidative stress (Borlace *et al*., 2024). In this study, FD samples exhibited the highest phenolic content, with values of 83.90 mg GAE/g for BSP and 62.43 mg GAE/g for BSF. CD retained moderate phenolic levels, whereas OD, MD, and SD led to significantly ($p<0.05$) lower TPC values (Table 3). The reduced TPC in MD samples was due to the rapid and intense heat exposure, causing degradation or polymerization of thermolabile compounds. Similarly, SD resulted in low TPC, attributed to enzymatic degradation and potential microbial activity during prolonged exposure to ambient conditions (Mansour, 2016; Zeidvand *et al*., 2024). OD, although more economical, showed limited phenolic retention, especially compared to FD, which is known for preserving heat-sensitive bioactives. Across all treatments, TPC values were consistently lower in BSF than BSP, indicating that Soxhlet extraction may degrade some heat-sensitive phenolics (Jouki *et al*., 2014). The Soxhlet method requires prolonged heating (8 hours at 40 °C), which can promote oxidation or polymerisation of sensitive compounds, contributing to the lower antioxidant levels observed in BSF. In future work, the use of gentler extraction methods, such as enzyme-assisted, cold-press or supercritical CO_2 methods, could help to better preserve antioxidants and unsaturated fatty acids.

These findings are in line with recent studies. An investigation on *Capparis spinosa* L. (caper fruit) reported that FD was most effective in preserving phenolic content and antioxidant activity (Babaei Rad *et al*., 2025). In addition, a study on *Moringa oleifera* leaf waste found that tray drying, a method comparable to CD, preserved more phenolics and flavonoids than SD, with strong correlation to antioxidant activity (Irwansyah *et al*., 2020). Research on agarwood (*Aquilaria malaccensis*) also concluded that controlled drying techniques (dehydrator and air-drying) were better than SD for retaining phenolic compounds (Delica-Balagot *et al*., 2024), reinforcing the advantage of CD and FD over uncontrolled methods. The ferric reducing antioxidant power (FRAP) values also followed a similar trend and were significantly different across drying methods ($p<0.05$). FD yielded the highest antioxidant activity (129.52 ± 0.67 mmol Fe (II)/100 g extract), followed by CD, SD, OD, and MD.

Notably, BSF samples had lower FRAP (73.62 - 102.41 mM/100g) values than BSP (116.86 - 129.52 mM/100g), supporting the hypothesis that the fat matrix undergoes greater oxidative degradation during drying and extraction, especially under thermal conditions. A strong positive correlation ($r>0.800$) between TPC and FRAP in BSP confirms the central role of phenolics as contributors to antioxidant activity. Across drying methods, BSP consistently retained more phenolic and antioxidant compounds than BSF. This can be explained by the inherently higher concentration of polyphenolics in the seed powder matrix, which offers greater protection compared to the fat fraction that is more prone to oxidative deterioration. FD proved most effective in preserving antioxidant properties in both BSP and BSF. However, the high energy demands and operational costs limit its scalability for industrial applications. Cabinet drying, which demonstrated moderate yet stable retention of bioactive compounds, presents a more viable alternative for large-scale processing due to its balance between performance and cost-efficiency.

Table 3. Effect of drying on the antioxidant parameters of bambangan seed powder (BSP) and bambangan seed fat (BSF).

Drying methods	BSP		BSF	
	Total phenolic contents (mg GAE/g)	FRAP values (mM/100g)	Total phenolic Contents (mg GAE/g)	FRAP values (mM/100g)
Sun Drying	79.27±0.01^a	117.17±1.63^b	48.45±1.24^b	86.70±0.11^c
Cabinet Drying	80.43±0.38^b	126.44±0.31^c	56.12±0.19^d	94.23±0.61^d
Oven Drying	79.18±0.22^a	116.89±3.13^a	45.62±0.14^a	85.29±0.04^b
Microwave Drying	79.27±1.32^b	116.86±1.92^a	54.70±6.67^c	73.62±0.57^a
Freeze Drying	83.90±0.09^c	129.52±0.67^d	62.43±0.11^e	102.41±0.06^e

Data are mean value ± standard deviation. BKP: bambangan kernel powder, BKF: bambangan kernel fat, GAE: gallic acid equivalent. Different letters (a-e) within the column are significant differences according to One-way ANOVA (*p<0.05*).

CONCLUSIONS

This study examined the effects of different drying methods on the nutritional composition, fatty acid profile, and antioxidant properties of bambangan (*Mangifera pajang*) seed powder (BSP) and bambangan seed fat (BSF). FD was the most effective method for preserving nutrients, phenolic compounds, and antioxidant capacity, followed closely by CD. Both FD and CD caused minimal thermal degradation, resulting in better retention of fat and protein content. Although SD yielded the highest crude fibre content and is economically viable, it showed reduced antioxidant activity and total phenolic content. OD and MD were less favourable due to greater nutrient losses caused by prolonged or intense heat exposure. The BSF was found to be rich in stearic and oleic acids, indicating its potential as a functional fat source. A strong positive correlation between total phenolic content and antioxidant capacity (FRAP) supports the use of bambangan seed-derived products as natural antioxidant ingredients. These results demonstrate that bambangan seeds can serve as a nutrient ingredient for functional food development, particularly when processed using FD or CD to retain nutritional and bioactive properties. Further research is recommended to optimize drying parameters and evaluate the performance of BSP and BSF in food formulations, including their sensory attributes and shelf-life stability. This will contribute to the value-added utilization of bambangan seeds as a functional component in food applications.

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