

Article

Variety and Processing Effects on the Structure–Function Properties of Upcycled Durian Seed Flours

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Abstract

Durian (*Durio zibethinus* Murray) seeds, an underutilized by-product of durian processing, were upcycled into functional flours to elucidate how varietal origin and processing govern structure–function relationships. Durian seed flours from local *Bang Nara* (L) and *Monthong* (M) varieties were prepared using three methods: native durian seed flour (NDSF; control), boiled durian seed flour (BDSF), and hydrated durian seed flour (HDSF), and benchmarked against commercial mung bean flour (MBF) and almond flour (ALF). Proximate composition, total phenolic content (TPC) and DPPH•-scavenging activity, structural characteristics (Fourier transform infrared, FTIR; X-ray diffraction, XRD), thermal behavior, and microstructure were assessed alongside functional properties including water/oil absorption, emulsion performance, and gelation. M flours contained higher protein (8.46–10.73%), dietary fiber (6.26–9.37%), ash (3.59–4.38%), TPC (53.17–87.40 mg gallic acid equivalent/g), and DPPH•-scavenging activity (92.39–94.54%) than L flours, whereas L flours had higher carbohydrate content (78.87–82.54%) than M flours (68.32–72.21%). Crude fat remained below 1% across all samples. FTIR and XRD profiles were comparable to MBF, confirming starch-based similarities, but distinct differences in color, bulk density, crystallinity, gelatinization behavior, and granule morphology reflected processing-driven structural modification. Functionally, NDSF exhibited the highest water absorption capacity (4.28 g/g); all durian seed flours showed low oil absorption (0.58–0.88 g/g) and gelation at 10–12%. Most samples demonstrated good emulsion activity and stability, except HDSF. Overall, NDSF and BDSF provided the best balance of yield, hydration capacity, and structural stability, demonstrating that both variety and processing determine the performance of upcycled durian seed flours. These findings support the valorization of durian seeds as sustainable, value-added functional ingredients aligned with circular economy and zero-waste food processing.

Keywords: starch properties; processing effects; functional properties; flour modification; by-product



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1. Introduction

Durian (*Durio zibethinus* Murray) is one of Southeast Asia's most valuable tropical fruits, contributing significantly to Thailand's agri-food economy. However, only about

30% of the fruit—the edible pulp—is consumed, while the remaining comprises inedible by-products such as rinds and seeds [1]. With Thailand producing approximately 2.4 million metric tons of durian in 2022, seed waste alone is estimated at nearly 487,000 metric tons [2]. This large volume of underutilized biomass represents both an environmental challenge and a valuable opportunity for sustainable resource utilization. In the context of the circular bioeconomy and food waste reduction, durian seeds are emerging as an interesting raw material for food innovation.

Durian seeds are rich in starch and mucilage, the latter giving them a distinctive viscous character. The starch granules (4–5 μm) resemble those of rice starch [3], but starch represents only about 10% of the seed's dry weight due to the high mucilage fraction that complicates extraction [4]. The mucilage, accounting for roughly 56% of the seed's dry weight, is composed mainly of lactose (49–60%) and glucose (37–45%), along with minor sugars and proteins containing 12 amino acids [5]. Functionally, durian seed mucilage exhibits high water- and oil-holding capacities (140–274 g and 147 g per 100 g mucilage, respectively) and can act as a natural hydrocolloid and emulsifier, as demonstrated in vegan mayonnaise formulations [6]. Previous studies have shown that the presence of gum or mucilage in durian seed flour improves moisture retention, emulsion stability, and texture, while degummed flour tends to form weaker gels and shows higher syneresis [7,8].

Despite these promising attributes, research on durian seed flour processing and its physicochemical properties remains limited. Most studies have focused on seed composition or varietal characteristics rather than how different preparation methods influence flour functionality. Moreover, comparisons across durian varieties are rare, even though cultivation environment and postharvest handling can significantly alter seed quality [7,9,10]. The present study investigates durian seeds from two Thai varieties with high commercial value: the local Bang Nara durian from Cho-Airong District, Narathiwat Province—recognized under a Geographical Indication (GI) designation [11]—and the *Monthong* variety from Tha Sala District, Nakhon Si Thammarat Province, which dominates domestic and export markets [12]. While both varieties are typically processed into high-value products such as durian paste, desserts, and dried durian, their seeds remain underutilized. Previous reports have explored limited applications such as biscuits [13], Thai desserts (Krong-Krang and Thong-Pub) [14], and meat fillers [15], but comprehensive characterization of durian seed flour remains scarce.

This study therefore aims to characterize the physicochemical and functional properties of durian seed flours produced using three different processing methods—native durian seed flour (NDSF; control), boiled durian seed flour (BDSF), and hydrated durian seed flour (HDSF)—from two varieties, local Bang Nara and Monthong, and to compare these properties with those of mung bean and almond flours, which have attracted attention as alternative flours due to their protein, fiber, and bioactive compound contents that contribute to functional and health-promoting food formulations [16,17]. Through this comparison, the study seeks to identify the influence of variety and processing on flour quality, and to evaluate the feasibility of using durian seed flour as a functional ingredient in sustainable food formulations. It is hypothesized that varietal differences and processing conditions significantly modify the starch–mucilage network, thereby affecting hydration behavior, emulsification capacity, and gelation characteristics. The findings are expected to provide valuable insight into the structure–function relationships of durian seed flour and its potential role in valorizing agricultural by-products for future food product development.

2. Materials and Methods

2.1. Chemicals

Folin–Ciocalteu reagent, sodium carbonate (Na_2CO_3), 95% ethanol, and 2,2-diphenyl-1-picrylhydrazyl (DPPH) were purchased from Sigma-Aldrich Co. (St. Louis, MO, USA). All chemicals and reagents used in this study were of analytical grade.

2.2. Durian Seed Samples

Durian seeds from two varieties were obtained from local orchards that primarily sell durian flesh. Seeds of the local Bang Nara variety (L) were collected from Cho-Airong District, Narathiwat Province (6.20167° N , $101.84167^\circ \text{ E}$), and seeds of the Monthong variety (M) were collected from Tha Sala District, Nakhon Si Thammarat Province (8.66503° N , 99.92248° E), both in Southern Thailand. In general, L seeds exhibited a larger size than M seeds (Figure 1).



Figure 1. Visual appearance of durian seeds from local Bang Nara (L) and Monthong (M) varieties.

2.3. Preparation of Durian Seed Flours

The collected seeds were processed into three durian seed flours using different chemical-free pretreatments: native durian seed flour (NDSF; control), boiled durian seed flour (BDSF), and hydrated durian seed flour (HDSF). For comparison, commercial mung bean (*Vigna radiata* L.) flour (MBF; Pine Brand, Sitthinan Co., Ltd., Pathum Thani, Thailand) and almond (*Prunus dulcis*) flour (ALF; Sierra Valley Almonds, Madera, CA, USA) were used as reference flours. Unless otherwise stated, all drying steps were carried out in a forced-convection hot-air oven (Binder FED400, Tuttlingen, Germany) at 55° C overnight to a final moisture content below 12%. A hot-air oven was selected because it provided controlled and uniform drying conditions suitable for laboratory-scale sample preparation and ensured consistent dried samples for subsequent analyses. The dried samples were then ground in a blender (Panasonic, Model MX-898N, Berkshire, UK) for 2 min, sieved through a 100-mesh screen, and stored in sealed polyethylene bags at -20° C until further analysis.

2.3.1. Native Durian Seed Flour (NDSF)

NDSF, used as the control with no thermal or hydration pretreatment, was prepared following Baraheng and Karrila [7] with slight modifications. Fresh seeds were washed, manually dehulled to remove the brown seed coat, and thinly sliced (2–3 mm thickness) before drying, grinding, and sieving as described above to obtain NDSF (Figure 2). Samples obtained from the local Bang Nara and Monthong varieties were designated L-NDSF and M-NDSF, respectively.

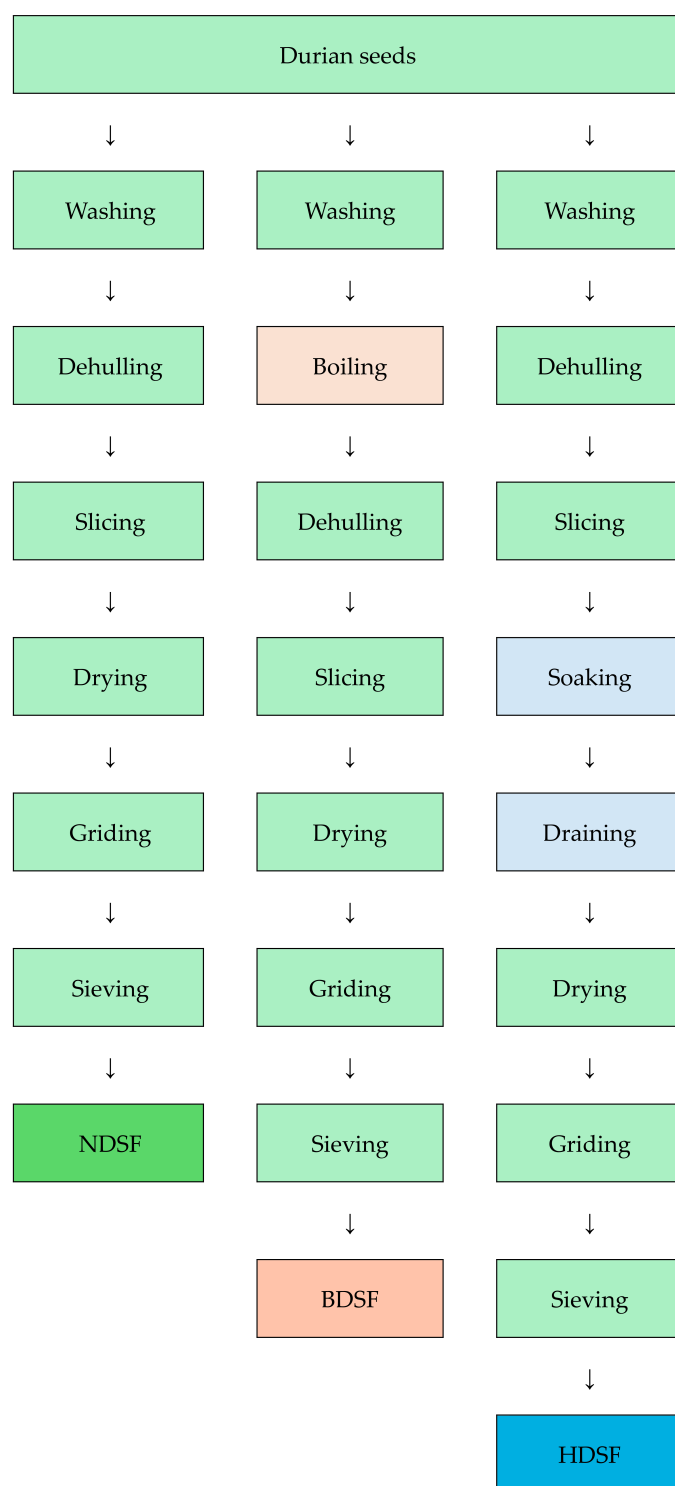


Figure 2. Flowchart of the preparation of durian seed flours: native durian seed flour (NDSF; control), boiled durian seed flour (BDSF), and hydrated durian seed flour (HDSF).

2.3.2. Boiled Durian Seed Flour (BDSF)

BDSF was produced according to Varichanan et al. [9] with modifications. Fresh seeds were washed and boiled in water at a seed-to-water ratio of 1:3 (w/v) for 30 min. The boiled seeds were then dehulled and thinly sliced (2–3 mm thickness), followed by drying, grinding, and sieving as described above to obtain BDSF (Figure 2). Samples prepared from the local Bang Nara and Monthong varieties were designated L-BDSF and M-BDSF, respectively.

2.3.3. Hydrated Durian Seed Flour (HDSF)

HDSF was prepared following Varichanan et al. [9] with slight modifications. Fresh seeds were washed, dehulled, thinly sliced (2–3 mm thickness), and mixed with distilled water at a ratio of 1:1 (*w/v*) for 2 min. The short hydration time was considered sufficient because the thin seed slices allowed rapid and uniform water penetration, while longer soaking could increase the leaching of soluble components. The hydrated mixture was filtered through muslin cloth, and the retained seed slices were then dried, ground, and sieved as described above to obtain HDSF (Figure 2). Samples prepared from the local Bang Nara and Monthong varieties were designated L-HDSF and M-HDSF, respectively.

2.4. Yield and Proximate Composition

The yields (%) of NDSF, BDSF, and HDSF were determined based on the weight of the initial fresh seeds. The whole durian seed flour with brown seed coat (WDSF) was also produced following the NDSF method without dehulling, and its yield was compared with those of the dehulled flours.

Moisture, protein, fat, ash, and crude fiber contents were analyzed following the AOAC methods [18]. Protein content was determined using a nitrogen conversion factor of 6.25, and carbohydrate content was calculated by difference. The WDSF was also analyzed for proximate composition to compare with the dehulled flours produced by the three methods—NDSF, BDSF, and HDSF.

2.5. Total Phenolic Content (TPC) and DPPH-Radical Scavenging Activity (RSA)

Total phenolic content (TPC) of durian seed flours and commercial MBF and ALF was determined using the Folin–Ciocalteu method, following Charoenphun and Klangbud [19] with minor modifications. Flour extracts were prepared by mixing flour with 95% ethanol (10 g/100 mL) and shaking for 1 h at room temperature (26–28 °C). The mixture was filtered through Whatman No. 1 filter paper, and the residue was re-extracted twice under the same conditions (three extraction cycles in total). All filtrates were combined for analysis.

For the assay, 500 µL of the combined extract was mixed with 2 mL of 10% (*v/v*) Folin–Ciocalteu reagent and vortexed. Then, 4 mL of 7.5% (*w/v*) Na₂CO₃ was added, vortexed, and the reaction mixture was incubated in the dark at room temperature for 30 min. Absorbance was measured at 765 nm using a Shimadzu UV-2100 spectrophotometer (Shimadzu Scientific Instruments Inc., Columbia, MD, USA). TPC was calculated from a gallic acid calibration curve and expressed as mg gallic acid equivalents (GAEs)/g extract ($y = 0.0086x + 0.0219$; $R^2 = 0.9896$).

Antioxidant capacity was determined following Chaijan et al. [20]. Extracts (0.08 mL) were mixed with 0.32 mL distilled water and 2 mL 0.6 mM 2,2-diphenyl-1-picrylhydrazyl radical (DPPH) solution, incubated in the dark (30 min), and absorbance was read at 517 nm. In Equation (1), “A” denotes the absorbance measured at 517 nm, where A_{control} and A_{sample} represent the absorbance values of the control and sample, respectively. Radical scavenging activity (RSA, %) was calculated as follows:

$$\%RSA = \frac{A_{\text{control}} - A_{\text{sample}}}{A_{\text{control}}} \times 100 \quad (1)$$

2.6. Physical Properties

2.6.1. Color

Color of durian seed flour and commercial flours (MBF and ALF) was measured using a portable Hunter Assoc. Laboratory Miniscan/EX instrument (10° standard observers, illuminant D65, Reston, VA, USA). The color parameters were recorded as L* (lightness; 0 = black, 100 = white), a* (− = green, + = red), and b* (− = blue, + = yellow). Flour

was placed in a glass sample cup, positioned over the light source, and covered prior to measurement. The L^* , a^* , and b^* values were recorded in triplicate.

The whiteness index (WI) was calculated according to Chaple et al. [21] using the following equation:

$$\text{Whiteness index} = 100 - \sqrt{(100 - L^*)^2 + a^{*2} + b^{*2}} \quad (2)$$

2.6.2. Bulk Density

Bulk density was measured according to Kaur et al. [22]. A known mass of flour was transferred into a pre-tared graduated cylinder and gently tapped until no further change in volume was observed. Bulk density was calculated as the ratio of sample weight (g) to the settled volume (mL) and expressed as g/mL.

2.7. Structural Characterization

2.7.1. Thermal Properties

Thermal properties were determined using a differential scanning calorimeter (DSC; PerkinElmer DSC 6000, Waltham, MA, USA) following Chumsri et al. [23]. Approximately 3 mg of sample was weighed into an aluminum DSC pan and mixed with 9 μ L of distilled water. The pan was hermetically sealed and equilibrated at room temperature overnight. Samples were then heated from 30 to 120 °C at a rate of 10 °C/min, using an empty sealed pan as the reference. The onset (T_o), peak (T_p), and conclusion (T_c) temperatures, as well as the enthalpy change (ΔH) of the transition, were recorded.

2.7.2. Crystalline Properties

X-ray diffraction (XRD) patterns of the samples were obtained using an X-ray diffractometer (Rigaku Oxford Diffraction, Manchester, UK) following Li et al. [24] with minor modifications. Prior to analysis, each flour sample was gently packed into a standard powder sample holder and the surface was leveled to obtain a smooth, flat specimen. Measurements were performed using Cu K α radiation ($\lambda = 0.154$ nm), with the diffractometer operated at 40 kV and 30 mA. Diffractograms were recorded over a 2θ range of 3–40° using at room temperature.

Relative crystallinity was calculated from the diffractograms by separating the crystalline and amorphous contributions using the Peak Fit software (ver. 4.12; Sea Solve Software, Inc., Framingham, MA, USA). The crystallinity index was calculated as

$$\text{Crystallinity (\%)} = \frac{A_c}{A_a + A_c} \times 100 \quad (3)$$

where A_c is the crystalline area and A_a is the amorphous area.

2.7.3. Molecular Properties

Fourier transform infrared (FTIR) spectroscopy was used to characterize the molecular structure and functional groups of durian seed flours compared with commercial MBF and ALF, following Chumsri et al. [23]. Spectra were acquired using a Bruker Vector 33 FTIR spectrometer (Bruker Co., Ettlingen, Germany) equipped with an attenuated total reflectance (ATR) diamond crystal. ATR mode was selected because it enables direct measurement of flour samples with minimal sample preparation and provides rapid and reliable spectral analysis of functional groups. Measurements were recorded over 500–4000 cm^{-1} at a resolution of 4 cm^{-1} , averaging 32 scans per sample. Spectral processing and analysis were performed using OPUS software (version 8.5; Bruker Optik GmbH, Ettlingen, Germany).

2.8. Morphology of Starch Granules

Starch granule morphology was examined using scanning electron microscopy (SEM) following Chumsri et al. [23]. Samples were mounted on circular aluminum stubs using double-sided adhesive tape and sputter-coated with gold–palladium. Micrographs were obtained using a scanning electron microscope (Gemini SEM; Carl Zeiss Microscopy, Jena, Germany) operated at an accelerating voltage of 5 kV.

2.9. Functional Properties

2.9.1. Water Absorption Capacity (WAC) and Oil Absorption Capacity (OAC)

WAC and OAC were determined using a centrifugation method adapted from Kaur et al. [22]. For WAC, flour (3.0 g) was dispersed in 25 mL of distilled water in a pre-weighed centrifuge tube. The suspension was allowed to stand for 30 min at room temperature with occasional stirring, then centrifuged at $3000 \times g$ for 25 min. The supernatant was decanted, and the tube containing the hydrated sediment was placed in a hot-air oven (Binder FED400, Tuttlingen, Germany) at 50 °C for 25 min to remove excess surface moisture. The tube containing the hydrated sediment was reweighed.

For OAC, flour (0.5 g) was mixed with 6 mL of soybean oil in a pre-weighed centrifuge tube and vortexed for 1 min. After standing for 30 min at room temperature, the mixture was centrifuged at $3000 \times g$ for 25 min. The unbound oil was removed, and the tube was inverted for 25 min to drain before reweighing.

WAC and OAC were expressed as g water or oil bound per g flour (dry basis) and calculated as

$$\text{WAC} = \frac{W_{\text{sed,WAC}} - W_{\text{dry,WAC}}}{W_{\text{dry,WAC}}} \quad (4)$$

$$\text{OAC} = \frac{W_{\text{sed,OAC}} - W_{\text{dry,OAC}}}{W_{\text{dry,OAC}}} \quad (5)$$

where W_{dry} is the initial dry sample weight (g) and W_{sed} is the weight (g) of the tube contents after draining.

2.9.2. Emulsion Activity (EA) and Emulsion Stability (ES)

Emulsion activity (EA) and emulsion stability (ES) were determined using a modified method of Naczek et al. [25]. Flour (1.0 g) was dispersed in 50 mL of distilled water and homogenized for 30 s at room temperature using an IKA homogenizer (T25 digital Ultra-Turrax, Staufen, Germany). Soybean oil (25 mL) was then added and homogenized for 30 s. An additional 25 mL of soybean oil was added and the mixture was further homogenized for 90 s. The resulting emulsion was divided equally into two centrifuge tubes for EA and ES determination.

To determine EA, one tube was centrifuged at $1100 \times g$ for 5 min using an RC-5B plus centrifuge (Sorvall, Norwalk, CT, USA), and the volume of the emulsified layer was recorded. To determine ES, the second tube was heated in a W350 Memmert water bath (Schwabach, Germany) at 85 °C for 15 min, cooled to room temperature, and centrifuged under the same conditions; the volume of the remaining emulsified layer was recorded. EA and ES were calculated as

$$\text{EA (\%)} = \frac{V_2}{V_1} \times 100 \quad (6)$$

$$\text{ES (\%)} = \frac{V_3}{V_1} \times 100 \quad (7)$$

where V_1 is the initial emulsion volume in the tube before centrifugation, V_2 is the emulsified layer volume after centrifugation, and V_3 is the emulsified layer volume after heating and centrifugation.

2.9.3. Least Gelation Concentration (LGC)

LGC was determined following Kaur et al. [22]. Flour dispersions were prepared at 2–20% (*w/v*) (2, 4, 6, 8, 10, 12, 14, 16, 18, and 20% *w/v*) in distilled water to a final volume of 5 mL in test tubes. Tubes were heated in a boiling water bath for 1 h, rapidly cooled under running tap water, and then held at 4 °C for 2 h. LGC was defined as the lowest concentration at which the gel did not flow when the tube was inverted.

Gelation strength was qualitatively scored as no gelation (–), gel (+), firm gel (++), and very firm gel (+++).

2.10. Statistical Analysis

All experiments were conducted in triplicate. Data were analyzed by one-way analysis of variance (ANOVA), and mean differences were determined using Duncan's multiple range test. Statistical analyses were performed using SPSS software (version 17.0 for Windows; SPSS Inc., Chicago, IL, USA), and significance was accepted at $p < 0.05$.

3. Results and Discussion

3.1. Yield

The yield of food products is an essential parameter for assessing industrial feasibility, as it reflects both material efficiency and potential economic return. As shown in Figure 3, the yields of durian seed flours varied among processing methods and varieties, with the order: L-NDSF (49.29%) > L-BDSF (46.65%) > M-NDSF (31.36%) > M-BDSF (26.03%) > L-HDSF (19.71%) > M-HDSF (17.88%). When compared to the WDSF, all dehulled flours exhibited lower yields. For instance, L-WDSF (50.54%) and M-WDSF (36.91%) produced slightly higher recoveries than their respective dehulled counterparts, suggesting that seed coat removal and aqueous processing (boiling or hydration) resulted in the loss of soluble starch and protein fractions. However, dehulling enhanced flour purity and homogeneity, yielding a finer and more functional powder suitable for ingredient applications. Such yield variations have also been attributed to compositional differences and the extent of processing-induced leaching, as reported for tropical seed flours by Baraheng and Karrila [7].

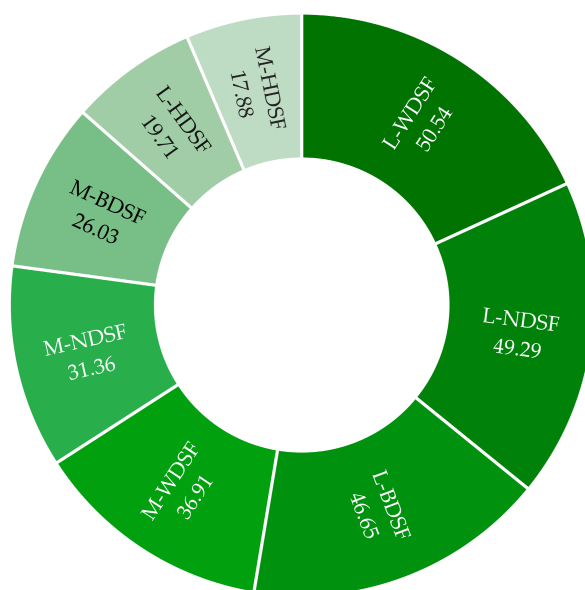


Figure 3. The yield of durian seed flours from local Bang Nara (L) and Monthong (M) varieties prepared using different processing methods: native durian seed flour (NDSF; control), boiled durian seed flour (BDSF), and hydrated durian seed flour (HDSF), compared with whole durian seed flour with the brown seed coat (WDSF).

3.2. Proximate Composition

The proximate composition of durian seed flours prepared with different processing methods is presented in Table 1. Moisture content among the durian seed flours ranged from 5.29% to 8.15%, whereas the WDSF samples (6.84–10.88%) exhibited higher values. The elevated moisture content in WDSF likely results from the hygroscopic nature of the fibrous seed coat, which retains more bound water. In contrast, dehulled flours showed lower and more uniform moisture levels, contributing to better storage stability and reduced microbial susceptibility—important factors for flour-based food systems. All the durian seed flours had moisture contents below 12%, meeting the general standard for flours and starches, which typically contain about 12% moisture [26]. Moisture content varies depending on the source, storage conditions, and climatic factors. Reported values include approximately 9% for native tapioca and corn starches, around 10% for plantain and corn starches, and 11–17% for potato starch [27]. Overall, the low moisture contents observed in durian seed flours in this study indicate favorable storage stability.

Table 1. Proximate composition on a wet basis of durian seed flours from local Bang Nara (L) and Monthong (M) varieties prepared using different processing methods, including native durian seed flour (NDSF; control), boiled durian seed flour (BDSF), and hydrated durian seed flour (HDSF), compared with the original whole durian seed flour with brown seed coat (WDSF).

Samples	Moisture (%)	Protein (%)	Crude Fat (%)	Crude Fiber (%)	Ash (%)	Carbohydrate (%)
L-NDSF	5.29 ± 0.12 ^d	6.75 ± 0.11 ^g	0.71 ± 0.00 ^b	1.95 ± 0.00 ^f	2.61 ± 0.18 ^e	82.54 ± 0.22 ^a
L-BDSF	6.62 ± 0.26 ^c	6.98 ± 0.16 ^f	0.28 ± 0.01 ^g	2.28 ± 0.01 ^e	2.57 ± 0.21 ^e	81.30 ± 0.56 ^a
L-HDSF	8.18 ± 0.24 ^b	7.10 ± 0.13 ^{ef}	0.36 ± 0.01 ^f	2.27 ± 0.00 ^e	2.63 ± 0.09 ^e	79.52 ± 0.30 ^b
L-WDSF	6.84 ± 0.20 ^c	7.20 ± 0.08 ^e	0.46 ± 0.02 ^e	3.64 ± 0.03 ^d	2.99 ± 0.03 ^d	78.87 ± 0.15 ^b
M-NDSF	6.95 ± 0.02 ^c	9.54 ± 0.06 ^b	0.81 ± 0.02 ^a	6.27 ± 0.11 ^c	4.22 ± 0.03 ^{ab}	72.21 ± 0.17 ^c
M-BDSF	8.15 ± 0.20 ^b	8.46 ± 0.04 ^d	0.49 ± 0.02 ^d	9.37 ± 0.09 ^a	3.59 ± 0.04 ^c	70.55 ± 0.70 ^d
M-HDSF	7.58 ± 0.32 ^{bc}	10.73 ± 0.05 ^a	0.61 ± 0.01 ^c	6.26 ± 0.11 ^c	4.38 ± 0.02 ^a	70.77 ± 0.79 ^d
M-WDSF	10.88 ± 2.18 ^a	8.92 ± 0.03 ^c	0.68 ± 0.02 ^b	7.22 ± 0.03 ^b	4.03 ± 0.12 ^b	68.32 ± 2.33 ^e

Values are presented as the mean ± standard deviation of triplicate determinations. Different letters within the same column indicate significant differences ($p < 0.05$).

Protein content differed substantially between the two durian varieties and processing forms. The local Bang Nara flours (L-series) contained 6.75–7.10% protein, whereas the Monthong flours (M-series) contained significantly higher levels (8.46–10.73%). Among these, M-HDSF exhibited the highest protein content, which may be attributed to hydration-induced structural modification that facilitates partial protein extraction and reconcentration upon drying. When compared with their corresponding whole durian seed flour (WDSF) samples (L-WDSF: 7.20%; M-WDSF: 8.92%), the dehulled flours showed comparable or slightly higher protein values, suggesting that removal of the seed coat did not reduce, and may even enhance, protein concentration due to reduced fiber dilution. These protein values are consistent with previous reports of 7.2–8.6% protein in native durian seed flours [7,28]. In comparison with other plant-based sources, the durian seed flours had lower protein contents than MBF (22.63–35.24%) [17,29], wheat flour (12%) [30], and several tree nuts, including ALF (21.2–22.5%) [16,31], Brazil nut (14.3%), walnut (15.2%), cashew (18.2%), and pistachio (20.2%), but were within the range reported for macadamia (7.7%) and pecan (9.2%), according to the USDA National Nutrient Database [31].

All durian seed flours contained low crude fat contents (<1%), supporting their classification as low-fat functional flours. This characteristic distinguishes durian seed flour from legume- or nut-based flours such as MBF and ALF, which typically contain 0.33–2.45% lipids for MBF [29] and as high as 53–57.4% lipid for ALF [16,32]. The low fat content of durian seed flours enhances shelf stability and makes them a promising base ingredient for reduced-fat formulations.

The crude fiber content showed marked variation depending on the processing and variety. Among L samples, fiber values ranged from 1.95% (L-NDSF) to 2.27% (L-HDSF), while the M samples exhibited much higher values (M-BDSF: 6.27%; M-HDSF: 6.26%). When compared to their respective WDSF samples (L-WDSF: 3.64%; M-WDSF: 7.22%), the dehulled flours generally showed lower fiber contents, reflecting the removal of the outer seed coat, which is a major source of insoluble fiber. However, even with this reduction, the fiber content of durian seed flours (1.9–6.3%) remained considerably higher than that of refined wheat flour (0.3–1.0%) [28], suggesting their potential as functional ingredients with health-promoting properties such as improved bowel regulation and water retention capacity. When compared with other nut and legume flours, the fiber contents of ALF and MBF have been reported as 9.7% [16] and 2.50–7.83% [29], respectively. The ash content, representing total mineral content, ranged from 2.57% to 4.38%, with the M flours showing slightly higher values than the L flours, consistent with their corresponding WDSF samples. The observed range aligns well with previous findings of 3.8–4.5% ash in durian seed flours [7,28]. This result suggests that the seed coat contributes moderately to total ash content, but the majority of mineral content is retained within the endosperm, particularly after controlled processing.

Conversely, the carbohydrate content was highest in the L flours (79.52–82.54%), followed by the M flours (70.55–72.21%), and was comparable to or slightly higher than their corresponding WDSF samples (L-WDSF: 78.87%; M-WDSF: 68.32%). The carbohydrate content of durian seed flours was in the same range as that of wheat flour (74.6%) [30] and higher than that of MBF and ALF. The carbohydrate content of MBF has been reported to be 51.92–60.09% [29], whereas a value of 16.2% has been reported for ALF [30]. The predominance of carbohydrate as the major macronutrient highlights the potential of durian seed flour as a starch-rich ingredient for bakery, confectionery, and thickening applications.

Overall, the compositional profile indicates that the dehulled durian seed flours were comparable or superior in nutritional quality to the original WDSF, with higher purity, lower moisture, and desirable macronutrient balance. The L variety generally provided higher carbohydrate and yield values, while the M variety offered higher protein, fiber, and ash contents. These results suggest that varietal and processing effects play complementary roles in defining the nutritional quality of durian seed flours. Their low-fat, moderate-fiber, and high-carbohydrate composition support their potential as cost-effective, plant-based ingredients for use in functional and value-added food formulations. Accordingly, dehulled durian seed flours obtained from different processing methods were analyzed further to gain deeper insight into their physicochemical and functional properties.

3.3. Total Phenolic Content (TPC) and DPPH-Radical Scavenging Activity (RSA)

The TPC and RSA of ethanolic extracts from durian seed flours of the L and M varieties, as well as from commercial legume and nut flours (MBF and ALF), are presented in Table 2. Among all samples, M-NDSF exhibited the highest TPC (87.40 ± 0.81 mg GAE/g), which was significantly higher ($p < 0.05$) than those of the L variety samples and commercial MBF. In contrast, ALF showed the lowest TPC (0.53 ± 0.13 mg GAE/g).

Phenolic compounds in fruit wastes, especially seeds and peels, are valuable natural antioxidants with strong radical-scavenging activity. The TPC in fruit seeds is often higher than in the pulp, suggesting that these by-products are rich sources of bioactive compounds [33]. The higher TPC observed in M flours compared with L variety samples (e.g., 32.75 ± 1.23 mg GAE/g in L-NDSF) may be attributed to varietal differences in metabolism and the effects of processing. Thermal treatment during drying or cooking can also promote the release of bound phenolics from cell wall matrices, thereby enhancing extractability and increasing the measurable free phenolic content [34–36]. However, heat

treatment may also cause the degradation of heat-sensitive polyphenols. Therefore, the net effect depends on the balance between the release of bound phenolics and their thermal degradation. In this study, thermal processing appeared to enhance the measurable free phenolic content, indicating that the release effect was more pronounced, consistent with previous reports [34–36].

Table 2. Total phenolic content (TPC) and DPPH free radical-scavenging activity (RSA) on a wet basis of durian seed flours from local Bang Nara (L) and Monthong (M) varieties prepared using different processing methods: native durian seed flour (NDSF; control), boiled durian seed flour (BDSF), and hydrated durian seed flour (HDSF), compared with commercial mung bean flour (MBF) and almond flour (ALF).

Samples	TPC (mg GAE/g)	DPPH Inhibition (%RSA)
L-NDSF	32.75 ± 1.23 ^d	92.89 ± 0.41 ^a
L-BDSF	11.87 ± 1.67 ^e	82.31 ± 1.88 ^c
L-HDSF	42.09 ± 0.00 ^c	87.47 ± 2.51 ^b
M-NDSF	87.40 ± 0.81 ^a	93.12 ± 0.25 ^a
M-BDSF	77.55 ± 1.60 ^b	94.54 ± 0.16 ^a
M-HDSF	53.17 ± 0.91 ^c	92.39 ± 0.17 ^a
MBF	0.85 ± 0.13 ^f	7.03 ± 3.18 ^e
ALF	0.53 ± 0.13 ^f	40.81 ± 1.79 ^d

Values are presented as the mean ± standard deviation of triplicate determinations. Different letters within the same column indicate significant differences ($p < 0.05$).

DPPH radical-scavenging activity (DPPH-RSA) followed a similar trend to TPC, ranging from 40.81% in ALF to 94.54% in M-BDSF (Table 2). The high RSA observed in all durian seed flours, particularly those from the M variety, indicates strong antioxidant potential. A significant positive correlation between TPC and RSA ($r = 0.731$, $p < 0.05$) further suggests that phenolic compounds are major contributors to the antioxidant capacity of durian seed flours. These antioxidant effects are primarily mediated through hydrogen atom donation and single-electron transfer, which neutralize free radicals and inhibit oxidative reactions [37].

Compared with commercial legume and nut flours, durian seed flours—especially those from the M variety—exhibited markedly higher antioxidant capacities than both MBF and ALF. This superior activity is consistent with their substantially higher phenolic contents, which enhance free-radical scavenging potential. Overall, these findings highlight durian seed flour as a promising plant-based source of natural antioxidants. Moreover, the pronounced bioactive properties support the valorization of durian seed waste into value-added functional food ingredients, offering a sustainable, natural alternative to synthetic antioxidants such as butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT).

3.4. Physical Properties

3.4.1. Color

Color is a key quality attribute that influences consumer perception and determines the suitability of flours for specific product applications. The Hunter color parameters (L^* , a^* , and b^*) of durian seed flours from the L and M varieties, along with commercial legume and nut flours (MBF and ALF), are presented in Table 3. Significant differences among flour types were observed for all color parameters ($p < 0.05$). Among the L flours, L-NDSF showed the highest L^* value, followed by L-HDSF and L-BDSF ($p < 0.05$); the M flours exhibited a similar trend across treatments. In contrast, M-BDSF had the lowest L^* value ($p < 0.05$), indicating pronounced darkening. The reduced lightness of M flours may be attributed to Maillard browning and caramelization during heating, which generate melanoidins that absorb visible light and decrease brightness, as well as to the oxidation

of phenolic compounds to quinones [34,38–40]. This observation is consistent with the higher protein and phenolic contents of M flours across treatments (Table 1). Among the commercial reference flours, MBF exhibited the highest L^* value ($p < 0.05$), reflecting the bright appearance typical of legume-based flours, whereas ALF showed intermediate lightness characteristic of nut-derived powders. These findings agree with Phetrit et al. [34] and Jiang et al. [38], who reported that heat treatment enhances nonenzymatic browning in high-sugar matrices.

Table 3. Color parameters (L^* , a^* , and b^*), whiteness index (WI), and the bulk density of durian seed flours from local Bang Nara (L) and Monthong (M) varieties prepared using different processing methods: native durian seed flour (NDSF; control), boiled durian seed flour (BDSF), and hydrated durian seed flour (HDSF), compared with commercial mung bean flour (MBF) and almond flour (ALF).

Samples	Color Parameters			Whiteness Index (WI)	Bulk Density (g/mL)
	L^*	a^*	b^*		
L-NDSF	86.24 ± 0.03 ^b	2.79 ± 0.00 ^f	8.81 ± 0.03 ^g	83.43 ± 0.02 ^b	0.93 ± 0.03 ^b
L-BDSF	75.01 ± 0.03 ^e	3.10 ± 0.03 ^e	13.40 ± 0.06 ^e	71.48 ± 0.01 ^d	1.01 ± 0.003 ^a
L-HDSF	82.43 ± 0.02 ^c	3.89 ± 0.01 ^d	9.78 ± 0.02 ^f	79.51 ± 0.01 ^c	0.91 ± 0.07 ^{bc}
M-NDSF	72.52 ± 0.24 ^f	6.76 ± 0.02 ^c	14.14 ± 0.02 ^d	68.36 ± 0.21 ^f	0.83 ± 0.005 ^d
M-BDSF	57.50 ± 0.06 ^h	7.66 ± 0.01 ^b	15.01 ± 0.02 ^c	54.28 ± 0.06 ^h	0.87 ± 0.002 ^{cd}
M-HDSF	64.77 ± 0.03 ^g	8.19 ± 0.05 ^a	15.43 ± 0.06 ^b	60.68 ± 0.02 ^g	0.83 ± 0.02 ^d
MBF	94.92 ± 0.02 ^a	−0.34 ± 0.02 ^h	2.22 ± 0.02 ^h	94.44 ± 0.02 ^a	0.53 ± 0.03 ^e
ALF	76.68 ± 0.05 ^d	0.15 ± 0.02 ^g	19.46 ± 0.13 ^a	69.63 ± 0.05 ^e	0.49 ± 0.01 ^e

Values are presented as the mean ± standard deviation of triplicate determinations. Different letters within the same column indicate significant differences ($p < 0.05$).

The a^* values (red–green axis) varied considerably among samples. M flours had significantly higher a^* values (6.76–8.19) than L flours (2.79–3.89), indicating a stronger reddish hue. This difference may be related to the higher protein and phenolic contents of the M variety (Tables 1 and 2), which can promote pigment formation via Maillard and other condensation reactions during thermal processing. In contrast, MBF showed a slightly negative a^* value (−0.34), indicating a faint greenish tone, whereas ALF (0.15) was nearly neutral. Overall, these results indicate that durian seed flours—particularly those from the M variety—undergo more pronounced color development than the commercial reference flours.

For b^* values (yellow–blue axis), all durian seed flours showed positive values, confirming a yellowish appearance. M samples (14.14–15.43) had significantly higher b^* values than L samples (8.81–13.40) ($p < 0.05$), indicating stronger yellowness. This may be attributed to higher pigment concentrations and the formation of Maillard reaction products, caramelized compounds, and oxidized phenolics during heating [34]. ALF exhibited the highest b^* value (19.46), consistent with its naturally yellow-cream tone associated with pigments such as carotenoids and phenolic compounds in almond kernels [41], whereas MBF had the lowest b^* value, in line with its pale green appearance and higher reflectance in the green region.

The whiteness index (WI) further supported these differences (Table 3). MBF (94.44) had the highest WI, followed by L-NDSF (83.43), whereas M-BDSF (54.28) showed the lowest value ($p < 0.05$). These results confirm that L flours were generally whiter than M flours. The lower WI in M samples may reflect more intense Maillard reactions and/or greater accumulation of brown pigments during prolonged heat exposure. From a technological perspective, lighter flours—particularly L-NDSF—may be preferable for bakery or dairy applications requiring a neutral color base, whereas darker flours such as BDSF may be advantageous for cocoa-based products or whole-grain analog formulations. The appearance of durian seed flours and the reference flours (MBF and ALF) are shown in Figure 4.



Figure 4. Visual appearance of durian seed flours from local Bang Nara (L) and Monthong (M) varieties prepared using different processing methods: native durian seed flour (NDSF; control), boiled durian seed flour (BDSF), and hydrated durian seed flour (HDSF). Commercial mung bean flour (MBF) and almond flour (ALF) were included for comparison.

3.4.2. Bulk Density

Bulk density, a key physical property influencing flour handling, packaging, and rehydration behavior, reflects the compactness of the powder and is affected by particle size, morphology, and the spatial arrangement of granules within the matrix [42]. Durian seed flours exhibited higher bulk densities (0.60–0.69 g/mL) than MBF (0.53 g/mL) and ALF (0.49 g/mL), suggesting more compact particle structures (Table 3). Among the durian flours, BDSF from both M and L varieties exhibited the highest bulk density values ($p < 0.05$), likely due to heat-induced gelatinization and particle shrinkage, which reduced internal porosity and void space, resulting in denser granules. Particle morphology plays a crucial role in this behavior: smaller or irregularly shaped particles can fill interstitial spaces more efficiently, thus increasing packing efficiency [43]. This explanation aligns with SEM observations (Section 3.6), which revealed collapsed and compacted granule structures for BDSF. Higher bulk density may enhance flowability and mixing uniformity in dry formulations [44], making these flours advantageous in applications such as bakery premixes or high-viscosity systems. Conversely, for applications requiring low-density powders, such as instant beverages or aerated foods, NDSF or HDSF, which retain partial porosity, may be more suitable.

Overall, these findings reveal that varietal differences and processing conditions markedly influence the color and physical characteristics of durian seed flours. L flours

are characterized by lighter color, higher WI, and greater bulk density, while M flours exhibit darker, more reddish-yellow tones. When compared with commercial flours, durian seed flours display lower whiteness but higher density, suggesting their potential as functional ingredients in formulations where compactness, viscosity, and textural stability are desirable.

3.5. Structural Characterization

3.5.1. Thermal Properties

The thermal behavior of durian seed flours from the L and M varieties, together with commercial MBF and ALF, was evaluated by DSC (Table 4). For the NDSF and HDSF samples from both varieties, the onset temperature (T_o) values were closely grouped (74.07–75.01 °C), which is comparable to the T_o reported for native durian seed starch (71.6 °C) [7]. In contrast, both boiled samples (L-BDSF and M-BDSF) showed significantly lower T_o values (58.62–59.08 °C; $p < 0.05$), along with markedly reduced peak temperature (T_p ; 65.43–65.94 °C) and conclusion temperature (T_c ; 72.24–72.75 °C). These shifts strongly suggest the partial disruption of starch granules and loss of crystalline order during boiling, which increases water accessibility and promotes earlier gelatinization upon reheating.

Table 4. Thermal transition parameters—onset (T_o), peak (T_p), and conclusion (T_c) temperatures—and transition enthalpy (ΔH) of durian seed flours from local Bang Nara (L) and Monthong (M) varieties prepared using different processing methods: native durian seed flour (NDSF; control), boiled durian seed flour (BDSF), and hydrated durian seed flour (HDSF). Commercial mung bean flour (MBF) and almond flour (ALF) were included for comparison.

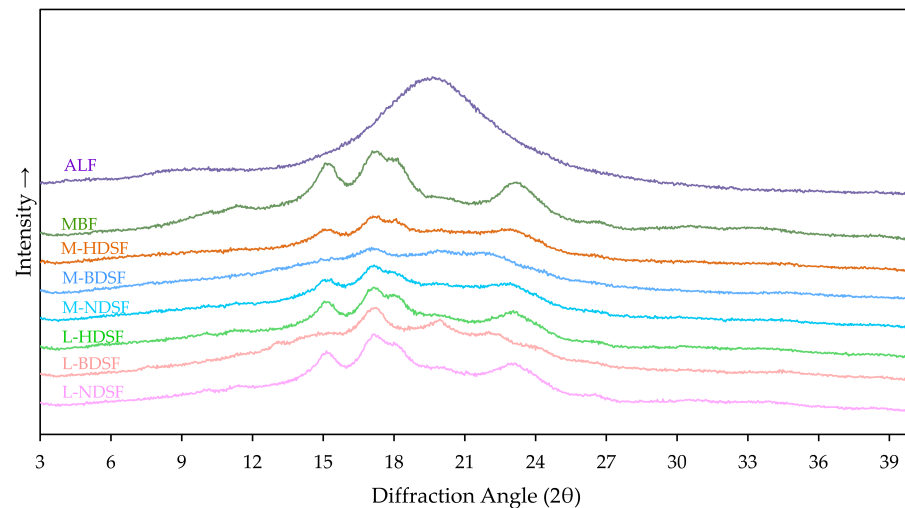
Samples	Gelatinization Temperature (°C)			ΔH (J/g)
	T_o	T_p	T_c	
L-NDSF	75.01 ± 1.22 ^b	80.29 ± 0.78 ^b	85.92 ± 0.83 ^b	5.44 ± 4.06 ^{ab}
L-BDSF	58.62 ± 0.19 ^c	65.43 ± 0.34 ^d	72.24 ± 0.71 ^d	2.56 ± 0.23 ^{cd}
L-HDSF	74.94 ± 0.33 ^b	80.03 ± 0.26 ^b	85.05 ± 0.28 ^{bc}	7.86 ± 1.18 ^a
M-NDSF	74.73 ± 0.46 ^b	79.92 ± 0.48 ^b	85.49 ± 1.13 ^{bc}	5.56 ± 0.49 ^{ab}
M-BDSF	59.08 ± 0.85 ^c	65.94 ± 0.18 ^d	72.75 ± 0.40 ^d	1.48 ± 0.32 ^d
M-HDSF	74.07 ± 0.18 ^b	79.99 ± 0.35 ^b	85.36 ± 0.51 ^{bc}	4.81 ± 0.57 ^{bc}
MBF	64.71 ± 10.11 ^c	72.25 ± 2.82 ^c	77.91 ± 0.37 ^{cd}	6.21 ± 0.00 ^{ab}
ALF	88.81 ± 4.49 ^a	93.38 ± 4.20 ^a	93.60 ± 9.46 ^a	0.78 ± 0.35 ^d

Values are presented as the mean ± standard deviation of triplicate determinations. Different letters within the same column indicate significant differences ($p < 0.05$).

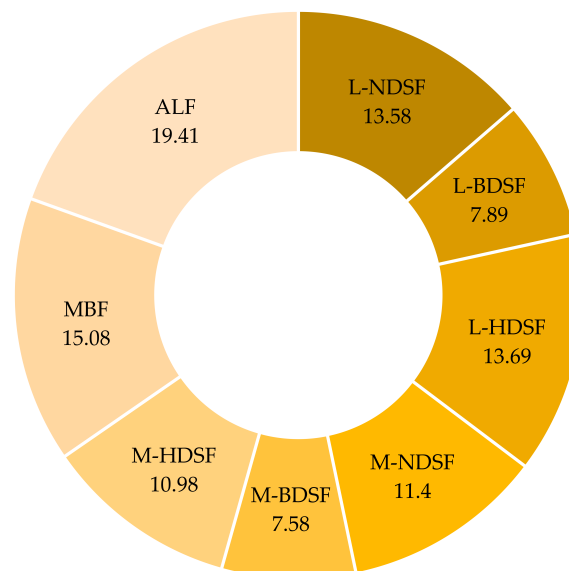
Consistent with this pattern, the T_p of non-boiled durian seed flours (NDSF and HDSF) remained around ~80 °C (79.92–80.29 °C), slightly higher than the value reported for native durian starch (76 °C) [7]. This increase may reflect varietal differences in starch structure (e.g., amylose/amylopectin organization) and matrix effects from non-starch components. Proteins and lipids can restrict water diffusion into granules, thereby shifting gelatinization to higher temperatures [45], while differences in amylopectin features may also alter the energy required for transition [46]. Among the commercial flours, MBF exhibited intermediate gelatinization temperatures (T_o 64.71 °C; T_p 72.25 °C; T_c 77.91 °C), whereas ALF showed the highest transition temperatures (T_o 88.81 °C; T_p 93.38 °C; T_c 93.60 °C).

Gelatinization enthalpy (ΔH) of durian seed flours ranged from 1.48 to 7.86 J/g. The boiled flours had the lowest ΔH values (1.48–2.56 J/g), consistent with their lower crystallinity (7.58–7.89%; see Figure 5b) and a more amorphous structure requiring less energy to disrupt [45]. In contrast, the native and hydrated samples showed higher ΔH values (4.81–7.86 J/g), indicating more ordered structures and/or a greater fraction of ungelatinized starch remaining after processing. Notably, MBF had the highest ΔH (6.21 J/g) and was significantly different from the other samples ($p < 0.05$), suggesting a higher contribution of starch gelatinization enthalpy in this flour matrix. ALF presented an important special case: despite the highest crystallinity (19.41%; Figure 5b), it showed

the lowest ΔH (0.78 J/g). This is plausible because ALF contains relatively low starch and high lipids [16,32]; thus, the DSC endotherm and crystallinity may largely reflect ordered lipid phases and amylose–lipid complexes rather than starch crystallites alone [47]. In lipid-rich systems, high crystallinity does not necessarily correspond to high ΔH , because lipid melting transitions can involve relatively low enthalpy compared with disrupting carbohydrate-dominated crystalline domains [48].



(a)



(b)

Figure 5. X-ray diffraction (XRD) patterns (a) and crystallinity index (%) (b) of durian seed flours from local Bang Nara (L) and Monthong (M) varieties prepared using different processing methods: native durian seed flour (NDSF; control), boiled durian seed flour (BDSF), and hydrated durian seed flour (HDSF). Commercial mung bean flour (MBF) and almond flour (ALF) were included for comparison.

Overall, the DSC results indicate that boiling most strongly reduces molecular order (lower crystallinity) and shifts gelatinization to lower temperatures with reduced enthalpy, whereas native and hydrated treatments retain higher transition temperatures near ~ 80 °C. Differences among flours are therefore best explained by their starch organization and flour

matrix composition (protein/lipid interactions), together with processing history (heat intensity and drying conditions) [49,50].

3.5.2. Crystalline Properties

The X-ray diffraction (XRD) patterns of all durian seed flours revealed typical A-type crystalline structures (Figure 5a), characterized by reflections in the range of $15\text{--}23^\circ$ (2θ), similar to patterns observed in cereal and tuber starches [51]. The NDSF showed four major peaks: 15.15° , 17.20° , 18.10° , and 23.01° for the L variety; 15.16° , 17.14° , 17.93° , and 22.80° for the M variety. These reflections correspond to the orthorhombic packing of double helices within amylopectin clusters, confirming the presence of short-range molecular order [51].

In contrast, both BDSF samples displayed only three major peaks (17.17° , 19.85° , and 22.06° for L variety; 17.09° , 19.97° , and 21.71° for M variety), indicating a partial loss of crystalline order. The disappearance of the 15° reflection peak suggests disruption of the crystalline lamellae during heating [52], consistent with the lower ΔH values obtained from DSC (Table 4). Heating and gelatinization cause the amylopectin double helices to unwind, thereby reducing long-range order and crystallinity [53].

All durian seed flour samples exhibited XRD patterns closely resembling that of MBF but differing markedly from ALF. The MBF and durian flours displayed well-defined starch crystalline peaks, whereas ALF showed a broad amorphous hump typical of materials rich in protein, lipid, and fiber rather than starch [54].

The calculated crystallinity indices ranged between 7.58% and 13.69% for durian seed flours (Figure 5b). The lowest values were observed in the cooked samples (L-BDSF and M-BDSF), reflecting substantial structural degradation during heating. In contrast, the other groups retained moderate crystallinity (11.40–13.69%), indicating partial preservation of native starch structures. The M-HDSF showed slightly lower crystallinity (10.98%), indicating that processing had partially disrupted crystalline order while maintaining some structural stability. The correlation between higher crystallinity and greater ΔH reinforces the link between ordered starch structure and thermal stability.

Interestingly, ALF exhibited the highest apparent crystallinity (19.41%), although it lacked starch-based diffraction patterns. This pseudo-crystallinity likely arises from ordered protein–lipid aggregates within the almond matrix rather than amylopectin crystallites [55]. The low ΔH of ALF (0.78 J/g) supports this interpretation, as the endothermic event observed likely corresponds to protein denaturation or lipid melting rather than starch gelatinization.

3.5.3. Molecular Properties

FTIR spectroscopy was employed to further elucidate the molecular structures and functional group characteristics of durian seed flours relative to commercial legume/nut flours (Figure 6). All durian seed samples displayed similar spectral features, confirming comparable functional groups across varieties and treatments.

A broad absorption band between 3276.75 and 3332.18 cm^{-1} was attributed to hydroxyl (O–H) stretching vibrations, corresponding to hydrogen-bonded –OH groups and water molecules associated with starch granules [56]. This strong band indicates extensive hydrogen bonding, which contributes to the hydrophilicity and swelling behavior of starch. The peaks within $2886.67\text{--}2931.70\text{ cm}^{-1}$ were assigned to C–H stretching vibrations of methylene (–CH₂–) groups in the glucose units, confirming the carbohydrate nature of the flour matrix. The bands observed between 1608.36 and 1730.88 cm^{-1} correspond to carbonyl (C=O) stretching vibrations associated with amide I groups from residual proteins, indicating minor protein–starch interactions that may influence hydration and gelatinization behavior. Significant starch-related bands were detected between 996.88 and 1051.84 cm^{-1} , corresponding to C–O–C stretching in glycosidic linkages of starch polymers.

These bands are attributed to crystalline (amylopectin) and amorphous (amylose) regions within starch granules. The relative intensity ratio of bands near 1047 cm^{-1} (crystalline) and 1022 cm^{-1} (amorphous) provides insight into short-range molecular order [57,58]. A higher 1047/1022 ratio implies greater structural order, which aligns with the higher crystallinity values observed in pre-dried and untreated flours.

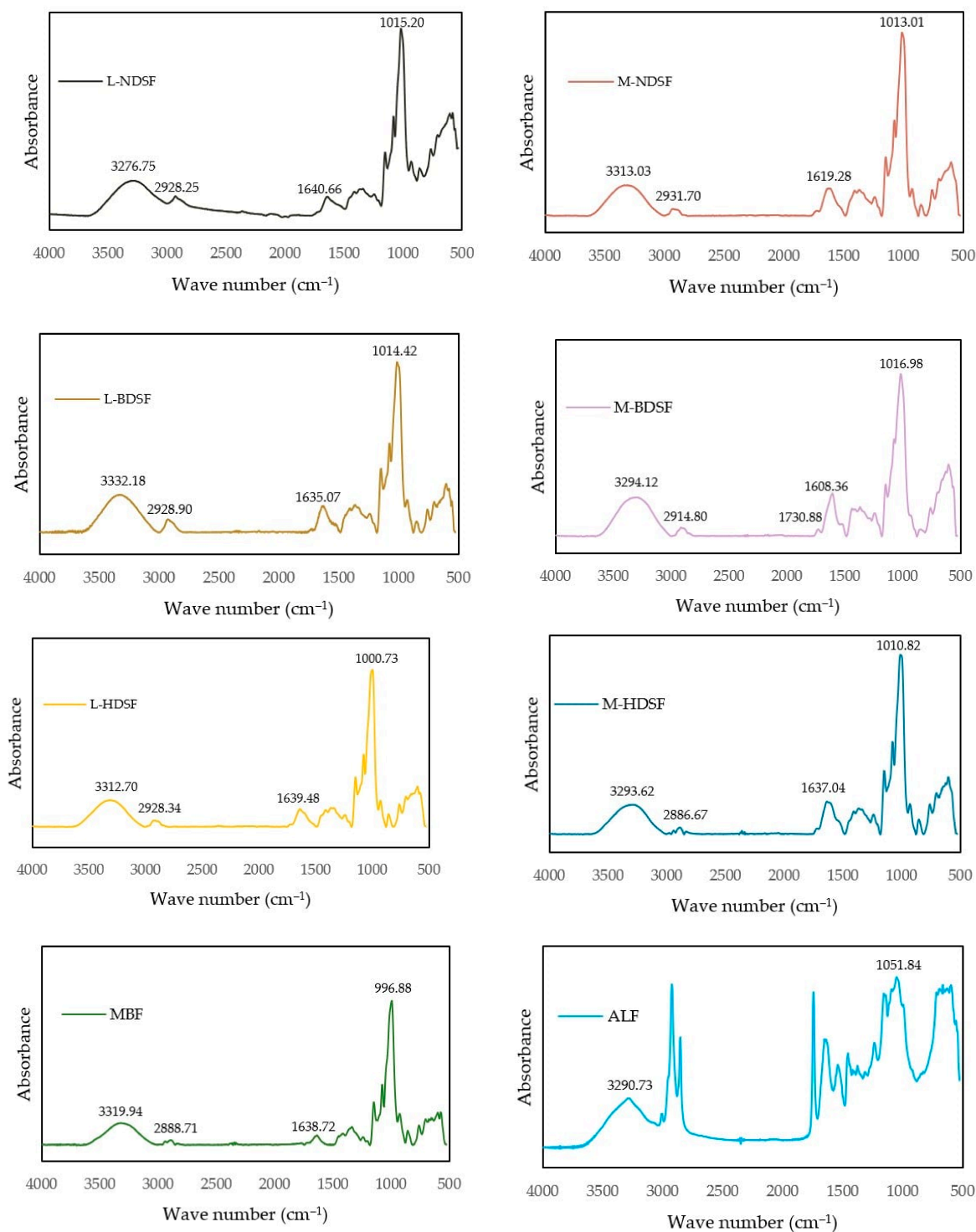


Figure 6. Fourier transform infrared (FTIR) spectra of durian seed flours from local Bang Nara (L) and Monthong (M) varieties prepared using different processing methods: native durian seed flour (NDSF; control), boiled durian seed flour (BDSF), and hydrated durian seed flour (HDSF). Commercial mung bean flour (MBF) and almond flour (ALF) were included for comparison.

The fingerprint region ($400\text{--}1050\text{ cm}^{-1}$) exhibited absorption associated with C–O–C and C–O–H stretching of pyranose rings, typical of starch polysaccharides. These spectral patterns closely resembled those reported for avocado seed starches [59], confirming similar molecular arrangements among tropical seed starches. All durian seed flours showed FTIR spectra more similar to MBF than to ALF, particularly in the starch-associated region ($1000\text{--}1050\text{ cm}^{-1}$). The AP spectrum displayed weaker peaks and broader bands, consistent with its composition dominated by protein, lipid, and fiber [54].

3.5.4. Structural Implications

Integrating the DSC, XRD, and FTIR results reveals a coherent pattern of structure–property relationships in durian seed flours. The NDSF and HDSF samples retained partial crystalline order and moderate gelatinization enthalpy, indicating the presence of semi-crystalline starch domains. In contrast, the BDSF samples exhibited pronounced loss of crystallinity and reduced ΔH , reflecting structural breakdown and molecular disorder induced by heating. FTIR analysis confirmed the persistence of fundamental starch linkages even after thermal treatment, demonstrating that while the degree of order decreases, the primary molecular framework remains intact.

Collectively, these findings confirm that thermal processing significantly influences the molecular order, crystallinity, and hydrogen-bonding network of durian seed starches, yet sufficient structural integrity is retained to preserve functional properties. The overall structural profile of durian seed flour resembles that of MBF, underscoring its potential application as a starch-based functional ingredient in food formulations. The preservation of crystalline–amorphous balance is particularly advantageous for developing thermally processed or retrogradation-resistant starch systems in functional food and nutraceutical applications.

3.6. Microstructure

The microstructural characteristics of durian seed flours from both L and M varieties, together with commercial legume/nut flours, were examined using an SEM at $5000\times$ magnification (Figure 7a–h). The SEM micrographs reveal distinct differences in granule morphology and surface features among the samples, reflecting the combined effects of varietal origin and processing conditions on starch structure.

The SEM images of all durian seed flours, except for the cooked samples (L-BDSF and M-BDSF), exhibited rough, irregularly shaped granules with visible aggregates and some attached fibrous or mucilaginous material. These surface residues are likely associated with gums or mucilage components naturally present in durian seeds, as reported by Leemud et al. [8]. The presence of these materials may contribute to the cohesive and adhesive characteristics of durian seed flour, influencing its hydration and swelling properties during processing.

In contrast, the L-BDSF and M-BDSF samples displayed no clearly defined starch granules, indicating extensive gelatinization and degradation of starch granule integrity due to heat treatment during the cooking process. The resulting micrographs show amorphous, compacted, and fused structures with irregular particle morphology. Similar observations have been reported for gelatinized starches from other tropical seeds and roots, where high temperatures disrupt the crystalline lamellae and cause molecular disorganization [60]. This morphological collapse corresponds to the reduced crystallinity and ΔH values found in XRD and DSC analyses, confirming the structural breakdown induced by cooking.

The L-NDSF, L-HDSF, M-NDSF, and M-HDSF samples retained partially intact granules, appearing as spherical to oval aggregates with moderately rough surfaces. These granules exhibited some degree of surface cracking and fragmentation, likely caused by

partial gelatinization or drying stress during processing. The appearance of these fissures may facilitate water absorption and enzymatic hydrolysis during rehydration, which could be advantageous for certain food applications requiring rapid solubilization.

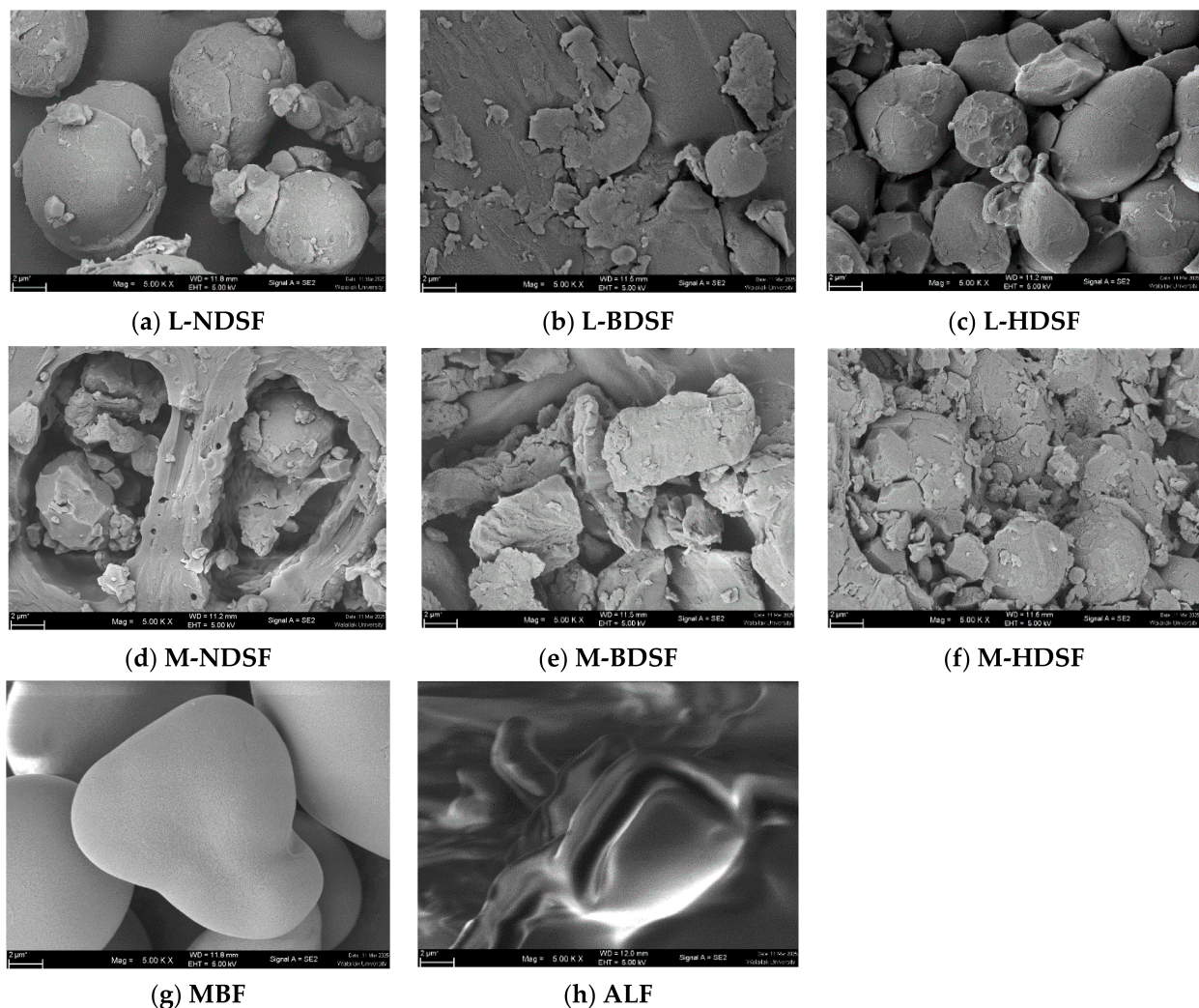


Figure 7. Scanning electron microscopy (SEM) micrographs (5.00 k $\times$ magnification; accelerating voltage, 5 kV) of durian seed flours from local Bang Nara (L) and Monthong (M) varieties prepared using different processing methods: (a) L-NDSF, (b) L-BDSF, (c) L-HDSF, (d) M-NDSF, (e) M-BDSF, (f) M-HDSF, (g) MBF, and (h) ALF. NDSF = native durian seed flour; BDSF = boiled durian seed flour; HDSF = hydrated durian seed flour; MBF = commercial mung bean flour; ALF = commercial almond flour.

In comparison, the commercial legume/nut flours displayed distinct and well-defined morphologies. The MBF showed typical heart-shaped and kidney-shaped granules with smooth, continuous surfaces and no fissures (Figure 7g), characteristic of native mung bean starch granules [61]. This intact granule morphology corresponds to the higher ΔH values (Table 4) and crystallinity (Figure 5b) recorded for MBF, indicating a structurally ordered starch matrix. In contrast, the ALF exhibited an amorphous, wave-like glossy surface with dimpled impressions (Figure 7h). These features are consistent with the high-lipid and protein content of almonds, as the oil-rich oleosomes contribute to a smooth, folded appearance and the absence of starch granules [62].

Overall, the SEM results confirm that processing methods profoundly affect the microstructure of durian seed flours, particularly the integrity of starch granules. The loss of distinct granule morphology in the cooked samples reflects extensive gelatinization, cor-

roborating the DSC and XRD findings of reduced crystallinity and lower ΔH . Conversely, the NDSF and HDSF samples retained partial granular structure, suggesting incomplete gelatinization and the preservation of semi-crystalline domains. These morphological features, together with the thermal and molecular analyses, indicate that durian seed flour retains a degree of structural resilience and functionality suitable for starch-based food and biopolymer applications.

3.7. Functional Properties

3.7.1. Water Absorption Capacity (WAC) and Oil Absorption Capacity (OAC)

WAC reflects the ability of flour to associate with water under limited availability, which contributes to product consistency and texture [26,63]. As shown in Table 5, the WAC of the M flours (M-NDSF and M-BDSF) was considerably higher (4.28 and 4.10 g/g, respectively) than that of other flour samples. This enhancement could be attributed to differences in protein content and structural modifications occurring during processing, which increase the exposure of hydrophilic groups capable of binding water [41]. The higher WAC observed in these M flours may also correlate with their greater swelling power, supporting the relationship between water uptake and starch granule expansion. In comparison to commercial ALF and MBF, which exhibited WAC values of 1.31 and 0.94 g/g, respectively, all durian seed flours demonstrated superior hydration capacity ($p < 0.05$). This highlights the strong water-binding potential of durian seed polysaccharides and proteins, likely enhanced by the natural mucilage associated with the seed endosperm. Such mucilage acts as a hydrocolloid, promoting hydration and water retention [7]. The difference between durian seed flours and legume-based MBF may also be related to their distinct protein conformations and starch compositions, as legume flours typically possess compact protein matrices that restrict water penetration [41]. Furthermore, compared with previously reported WAC values for durian seed flour (0.82–1.10 g/g) [7,41], the present study reveals that the applied preparation methods markedly enhance the flour's hydration capacity, rendering the resulting durian seed flours functionally comparable to, or even superior to, several plant-based commercial flours.

Table 5. Water absorption capacity (WAC), oil absorption capacity (OAC), emulsion activity (EA), and emulsion stability (ES) on a wet basis of durian seed flours from local Bang Nara (L) and Monthong (M) varieties prepared using different processing methods: native durian seed flour (NDSF; control), boiled durian seed flour (BDSF), and hydrated durian seed flour (HDSF). Commercial mung bean flour (MBF) and almond flour (ALF) were included for comparison.

Samples	WAC (g/g)	OAC (g/g)	EA (%)	ES (%)
L-NDSF	3.15 ± 0.10 ^c	0.61 ± 0.02 ^b	35.14 ± 2.56 ^c	35.67 ± 1.83 ^b
L-BDSF	2.58 ± 0.01 ^d	0.58 ± 0.11 ^b	44.57 ± 1.54 ^a	44.43 ± 2.11 ^a
L-HDSF	1.22 ± 0.05 ^f	0.88 ± 0.06 ^b	10.00 ± 0.00 ^d	25.58 ± 1.54 ^c
M-NDSF	4.28 ± 0.09 ^a	0.75 ± 0.07 ^b	46.51 ± 3.55 ^a	35.31 ± 6.64 ^b
M-BDSF	4.10 ± 0.15 ^b	0.71 ± 0.03 ^b	40.20 ± 1.39 ^b	42.71 ± 0.21 ^a
M-HDSF	2.38 ± 0.09 ^e	0.88 ± 0.07 ^b	nd	nd
MBF	0.94 ± 0.03 ^g	0.64 ± 0.04 ^b	nd	nd
ALF	1.31 ± 0.00 ^f	1.41 ± 0.63 ^a	6.00 ± 0.00 ^e	4.07 ± 1.89 ^d

Values are presented as the mean ± standard deviation of triplicate determinations. Different letters within the same column indicate significant differences ($p < 0.05$). nd = not detected. All functional properties were determined using the prepared flour samples in their original form, without additional drying prior to analysis.

The OAC of durian seed flours ranged from 0.58 to 0.88 g/g, showing no significant difference among the various forms, and was comparable to that of MBF (0.64 g/g). In contrast, ALF exhibited the highest OAC (1.41 g/g; $p < 0.05$). The relatively moderate OAC of durian seed flours may be attributed to the limited presence of nonpolar or hydrophobic

amino acid side chains capable of binding lipids [64]. Although ALF demonstrated higher OAC, likely due to its rich lipid and protein content characteristic of nuts, the OAC of durian seed flours aligns closely with the range (0.62–0.70 g/g) reported by Siti Faridah et al. [41] and is much lower than the exceptionally high value (4.1 g/g) reported by Baraheng and Karrila [7]. From a functional standpoint, moderate OAC is advantageous for food applications that require controlled oil retention, contributing to improved mouthfeel and flavor stability without producing excessive greasiness. Thus, while ALF exhibits superior oil-holding capacity, durian seed flours demonstrate a more balanced hydrophilic–hydrophobic profile, making them suitable for diverse food formulations requiring both water retention and oil-binding functionality.

3.7.2. Emulsion Activity (EA) and Emulsion Stability (ES)

The hydration and oil-binding characteristics of flours, as described by WAC and OAC, play a crucial role in determining their performance as emulsifying agents. High WAC reflects the presence of hydrophilic groups that facilitate water–protein interactions and swelling, while OAC represents the degree of hydrophobic interaction with oil. The balance between these two properties directly affects how proteins and polysaccharides behave at the oil–water interface. Flours with optimal WAC and moderate OAC, such as M-BDSF and L-BDSF, tend to possess better emulsifying properties, since adequate hydration improves protein flexibility and solubility, while sufficient hydrophobic regions promote adsorption to oil droplets. Consequently, understanding the interplay between water and oil interaction capacities provides valuable insight into the emulsification behavior of durian seed flours.

An emulsion is a biphasic system composed of two immiscible liquids, in which one liquid is dispersed in the other as fine droplets ranging from 0.1 to 100 μm . In most food systems, the oil phase is dispersed within an aqueous phase [7,65].

The EA reflects the ability of a sample to form an initial emulsion, while ES represents its ability to maintain the integrity of that emulsion over time and under processing conditions. As shown in Table 5, significant variations were observed among the different durian seed flour samples. The EA values of the flours ranged from 6.00% to 46.51%, with M-NDSF (46.51%) and L-BDSF (44.57%) showing the highest emulsion-forming capacity ($p < 0.05$). This suggests that protein and polysaccharide components in these samples effectively enhanced interfacial film formation, facilitating droplet stabilization. The superior EA of these samples is consistent with their relatively high WAC, as higher WAC indicates increased hydration and swelling, which can improve protein solubility and flexibility—factors that favor interfacial adsorption and emulsion formation [41].

In comparison, the commercial flours displayed noticeably lower emulsion activity. ALF (6%) exhibited the lowest EA among all tested samples ($p < 0.05$), and MBF (18.63%) showed only moderate activity, indicating limited emulsifying potential relative to durian seed flours. The poor emulsifying ability of ALF may be attributed to the high lipid content and reduced protein solubility in ALF, which limit its interfacial adsorption capacity. Similarly, the moderate EA of MBF is typical of legume-based flours whose compact globular protein structures hinder unfolding at the oil–water interface [66,67]. These differences emphasize the superior emulsifying potential of durian seed flours, particularly after modification, as their structural and compositional properties favor surface activity. Conversely, both L-HDSF (10%) and M-HDSF (no detectable EA) showed the weakest emulsion-forming ability among the durian seed flours ($p < 0.05$). This reduction is likely due to protein denaturation and aggregation during heat treatments, which increase hydrophilicity but reduce surface hydrophobicity needed for adsorption at the oil–water interface [65]. This

observation also aligns with the lower WAC of these samples, suggesting that proteins with altered structure are less capable of binding water and forming emulsions.

In terms of ES, most samples displayed ES values ranging from 25.58% to 44.43%, with L-BDSF (44.43%) and M-BDSF (42.71%) showing the highest stability ($p < 0.05$). The ability of these samples to maintain emulsions over time could be attributed to the presence of cohesive protein–polysaccharide matrices forming viscoelastic interfacial films that resist droplet coalescence [68,69]. Interestingly, M-NDSF, despite exhibiting the highest EA, showed moderate ES (35.31%), indicating that while this flour could form emulsions efficiently, the resulting films were less mechanically stable. This is consistent with the report by Zhang et al. [70], who emphasized that ES is governed by the rigidity and cohesiveness of protein films rather than their initial EA. When compared to ALF (14.29%) and MBF (29.63%), all durian seed flours displayed superior ES values, confirming their potential as natural stabilizers. The relatively low ES of ALF reflects its limited hydrophilic network-forming ability, while the moderate ES of MBF is consistent with legume protein emulsions that rely mainly on soluble protein fractions for stability [71]. The strong ES values of durian seed flours, particularly M-BDSF and L-BDSF, likely result from synergistic effects between protein and mucilage components that form a stable viscoelastic layer around oil droplets, providing enhanced mechanical resistance and preventing coalescence.

Taken together, these results demonstrate that the balance between hydrophilic (WAC) and hydrophobic (OAC) interactions strongly influences the emulsion-forming and stabilizing properties of durian seed flours. Compared with commercial ALF and MBF, the durian seed flours exhibit significantly superior functional performance in both hydration and emulsification. Processing-induced modifications, particularly in protein conformation and mucilage composition, appear to enhance the physicochemical versatility of these flours, underscoring their potential as multifunctional, plant-based ingredients for food formulation.

3.7.3. Least Gelation Concentration (LGC)

Gelation is an important functional property that reflects the ability of starch or protein molecules to form a cohesive, three-dimensional network upon heating and cooling [72]. The LGC represents the minimum concentration at which a suspension forms a self-supporting gel when inverted. As shown in Table 6, the LGC of durian seed flours ranged from 10% to 12%, indicating good gel-forming capacity relative to the commercial legume and nut flours tested. Among the durian seed flours, L-BDSF, L-HDSF, M-NDSF, M-BDSF, and M-HDSF all formed gels at 10%, whereas L-NDSF required a slightly higher concentration (12%) to form a firm gel. This difference may result from the compositional and structural variations induced by the different processing methods. A lower LGC value generally signifies a stronger gelling capability, as less sample is required to achieve a stable gel network [73]. Therefore, most of the durian seed flours demonstrated superior gelation ability, suggesting favorable protein–starch interactions and efficient network formation.

When compared with commercial MBF and ALF, all durian seed flours exhibited markedly lower LGC values than ALF but higher than MBF. MBF formed a firm gel at a concentration of only 6%, whereas almond flour showed no gelation even at 20%. The much lower LGC of MBF corresponds to its high protein and starch content, both known to enhance gel formation via protein–starch crosslinking and hydrogen bonding [74]. In contrast, the inability of ALF to form a gel likely reflects its high fat content and low starch fraction, which interfere with network formation by competing with water and reducing hydrogen bond formation during gelation [75]. Despite MBF's slightly better gelation concentration numerically, the firmness and consistency of gels formed by the durian seed flours at higher concentrations (10–12%) were comparable or superior in strength,

particularly in the HDSF and BDSF, which exhibited very firm gels at 14–20%. This suggests that the polysaccharide–protein matrix of durian seed flour provides robust gel structure once sufficient concentration is reached.

Table 6. Least gelation concentration (LGC) of durian seed flours from local Bang Nara (L) and Monthong (M) varieties prepared using different processing methods: native durian seed flour (NDSF; control), boiled durian seed flour (BDSF), and hydrated durian seed flour (HDSF). Commercial mung bean flour (MBF) and almond flour (ALF) were included for comparison.

Suspension Concentrations (% <i>w/v</i>)	L-NDSF	L-BDSF	L-HDSF	Samples M-NDSF	M-BDSF	M-HDSF	MBF	ALF
2	—	—	—	—	—	—	—	—
4	—	—	—	—	—	—	—	—
6	—	—	—	—	—	—	+	—
8	—	—	—	—	—	—	++	—
10	—	+	+	+	+	+	+++	—
12	+	++	++	+	+	+	+++	—
14	+	++	+++	+	++	++	+++	—
16	+	++	+++	+	++	++	+++	—
18	+	+++	+++	+	++	++	+++	—
20	++	+++	+++	++	++	+++	+++	—

Symbols indicate gelation strength: (—) no gelation, (+) gel, (++) firm gel, and (+++) very firm gel.

The differences in gelation behavior among durian seed flours can be attributed to variations in protein content, starch composition, and degree of structural modification. During heating, protein molecules unfold, exposing reactive sulfhydryl groups that can form disulfide bonds and hydrophobic interactions with other residues, resulting in the development of a stable, three-dimensional gel matrix [76]. The presence of mucilage in durian seed flour may also promote water entrapment and reinforce gel strength. In particular, the BDSF and HDSF samples exhibited stronger gel consistency—ranging from “firm gel” to “very firm gel”—across the concentration gradients, suggesting that controlled preparation conditions facilitate proper protein denaturation and reinforce the gel network structure.

Overall, the LGC results confirm that durian seed flours possess desirable gelation properties, comparable to or exceeding those of commonly used plant-based flours. The ability to form firm gels at moderate concentrations (10–12%) highlights their potential as functional ingredients in food products requiring thickening, emulsifying, or gelling properties—such as sausages, sauces, soups, and dessert formulations [74,75]. The structural characteristics that favor high water absorption and swelling (as observed in WAC) also appear to contribute to effective gel network formation, suggesting a strong interrelationship among hydration, emulsifying, and gelling functions in durian seed flour systems.

4. Conclusions

This study characterized the physicochemical, structural, and functional properties of durian seed flours produced by three processing methods—native (NDSF; control), boiled (BDSF), and hydrated (HDSF)—from two varieties (local Bang Nara and Monthong). Variety and processing significantly affected flour attributes, with NDSF and BDSF generally outperforming HDSF in yield, hydration-related functionality, and structural integrity.

Durian seed flours were low in fat and rich in carbohydrates, protein, and dietary fiber. FTIR and XRD patterns suggested a starch-based molecular organization comparable to mung bean flour (MBF), while thermal and microstructural analyses confirmed that processing modified granule morphology and crystallinity, which in turn influenced functional behavior. Among the processing methods, NDSF exhibited the most balanced functional performance, particularly in water absorption, emulsion activity, and gelation-related behavior, supporting its application in sauces, dressings, soups, and bakery products. BDSF

also demonstrated favorable functional properties, especially in emulsion-related performance, suggesting its potential use in emulsified foods and products requiring texture improvement or partial fat replacement. In contrast, HDSF showed lower functional performance, which may limit its application in products requiring strong hydration or structural functionality. Monthong flour showed higher total phenolic content and antioxidant capacity than local Bang Nara flour, indicating greater potential for functional foods with added antioxidant value, while both varieties remain promising as starch-rich flour ingredients for different food applications.

Overall, durian seed flour shows strong promise as a sustainable functional ingredient that can partially replace or complement conventional flours such as MBF and almond flour (ALF), while adding value to durian-processing by-products in line with circular-economy and zero-waste goals. Future work should optimize processing to improve yield and functionality, isolate and characterize mucilage fractions and their rheological mechanisms, and validate performance in targeted food systems (e.g., baked products, emulsified sauces, and dairy alternatives), supported by pilot-scale trials and sensory evaluation.

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