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Chemical compositions, functional properties, and microstructure of defatted macadamia flours

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Abstract

The objective of this research was to study the chemical compositions, functional properties, and microstructure of partially defatted flours (PDF, 12–15% fat, dry basis (db)) and totally defatted flours (TDF, 1% db fat) from three macadamia cultivars, PY 741, DS 344, and DS 800, grown in Northern Thailand. The defatted flours were high in protein (30.40–36.45% db) and carbohydrate (49.29–57.09% db). For each macadamia cultivar, while emulsion activities and emulsion stabilities of the TDF tended not to be different from those of the PDF ($p > 0.05$), TDF had significantly greater water absorption capacities (WAC), oil absorption capacities and foaming capacities (FC), but had significantly lower foaming stability (FS) than the PDF ($p \leqslant 0.05$). The TDF from PY 741 cultivar possessed the highest WAC and FC but the lowest FS. The variation in the functional properties of the defatted flours could mainly arise from the difference in the quantity and characteristics of the proteins in the flours. Structure determination of macadamia flours showed that the proteins bodies and starch granules were embedded in kernel tissues. The starch granules were oval and approximately 10 μm in diameter.

Keywords: Macadamia; Flour; Chemical compositions; Functional properties; Microstructure

1. Introduction

Macadamia is a genus of flowering plants in the family Proteaceae. Only two of the species, *Macadamia integrifolia* and *Macadamia tetraphylla*, generate edible nuts and are of commercial importance. *M. integrifolia*, commonly known as the smooth-shell macadamia, provides kernels with higher quality, whereas *M. tetraphylla*, known as the rough-shell macadamia, is more adaptable and can grow more easily at low temperatures or over a wide range of temperatures. At present, the USA and Australia are the two major countries producing high quality macadamia nuts. (Aradhya, Yee, Zee, & Manshardt, 1998; Australian Macadamia Society, 2006). In Thailand, this plant is mainly cultivated in the northern region.

Not only does the macadamia nut have desirable taste and aroma, it is also nutritious, because the nut contains no cholesterol and is low in sodium and saturated fats. Over 70% of the total fatty acids in macadamia are monounsaturated fatty acids (USDA, 2006; Venkatachalam & Sathe 2006), which possibly help lower blood cholesterol, and reduce the risk of heart disease. Therefore, many groups of researchers have been interested in studying the composition and health benefits of macadamia oils (Ako, Okuda, & Gray, 1995; Garg, Blake, & Wills, 2003; Kaijser, Dutta, & Savage, 2000; Maguire, O'Sullivan, Galvin, O'Connor, & O'Brien, 2004). Other studies on the chemical composition of macadamia nuts have focused on the effect of reducing sugars on the browning reaction during drying or roasting (Albertson et al., 2005; Prichavudhi & Yamamoto, 1965; Stephenson & Gallagher, 1986; Wall & Gentry, 2007). However, only few studies on other chemical components exist. For instance, Bora and Ribeiro (2004) conducted an experiment on the influence of pH on the extraction yield and functional properties of macadamia protein isolates.

Macadamia nuts are mainly consumed as a raw or roasted kernel. The nuts have also been used as raw material for extracting macadamia oils, providing low-fat kernel

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residues as by-products. Macadamia flour, which can be derived from low-fat kernel residues, seems to be a promising product which can be further used as a food ingredient. However, studies on the physicochemical and functional properties of macadamia flours is scarce. The objective of the present research was to study the chemical compositions, functional properties, and microstructure of the defatted flours from different macadamia cultivars. This study could provide some basic information, which would help determine an application for defatted macadamia flours in food products.

2. Materials and methods

2.1. Materials

Three macadamia cultivars, PY 741, DS 344, and DS 800, grown in Chiang Mai province, Thailand, were used in this research. Details of their systematic nomenclature and growing area are shown in Table 1.

2.2. Preparation of macadamia flours

Macadamia nuts with shell on were dried in a tray dryer at 50 °C, until their moisture reached approximately 2%. Then, the kernels were manually separated from the shells. Oil was separated from the macadamia kernels using a hydraulic press, which could extract 75–79% of the total oil from the kernel (55–62 g oil/100 g dried kernel). The kernel residues were subsequently defatted by soaking in petroleum ether. To produce partially defatted flours (PDF), the kernels were soaked in petroleum ether for 17–19 h, in order to obtain a residual fat content of 10–15%. The production of totally defatted flours (TDF) required a longer soaking time, approximately 144–196 h, to obtain less than 1% of residual fat. The defatted samples were dried for two hours at ambient temperature in a fume hood, to remove the remaining solvent. The defatted kernels were then ground, and sifted through a 70-mesh sieve. The flours were packed in laminated aluminum (OPP/Al/PE) bags and stored at 4–7 °C until use.

2.3. Proximate composition

Flour samples from different macadamia cultivars were estimated for their moisture, ash, fat, fibre and protein ($N \times 5.30$) contents by the method of AOAC (1995).

2.4. Functional properties of macadamia flours

2.4.1. Water and oil absorption capacity

Water and oil absorption capacities of macadamia flours were determined by the modified method of Sosulski and McCurdy (1987). For the water absorption capacity test, 2 g (dry basis, db) of each flour sample were weighed into a pre-weighed centrifuge tube and 5 ml of distilled water were added. For the oil absorption capacity test, 5 ml of soybean oil were added, instead of distilled water. The dispersions were stirred occasionally and allowed to stand for 30 min before being centrifuged at 2000*g* for 25 min. The supernatant was decanted, and sample was reweighed. The water and oil absorption capacities were expressed as grams of water or oil bound per gram of sample on a dry basis. The experiment was done in triplicate.

2.4.2. Emulsion activity and stability

Emulsion activity and stability were measured according to the modified method given by Naczk, Diosady, and Rubin (1985). One gram (db) of each flour sample was dispersed in 50 ml of distilled water. The mixture was homogenised for 30 s; 25 ml of soybean oil were added, and the mixture was homogenised again for 30 s. Then, another 25 ml of soybean oil were added, and the mixture was homogenised for 90 s. Each emulsified sample was divided equally into two centrifuge tubes. The first centrifuge tube, directly centrifuged at 1100*g* for 5 min, was used to determine the emulsion activity. In order to determine the emulsion stability, the second centrifuge tube was heated in a water bath at 85 °C for 15 min, cooled down to room temperature, and centrifuged under the same conditions as the first tube. The experiment was conducted in triplicate. The emulsion activity (EA) and emulsion stability (ES) were calculated according to the following equations:

$$\mathrm{EA}\ (\%) = v_2 \times 100/v_1$$
$$\mathrm{ES}\ (\%) = v_3 \times 100/v_1$$

where v_1 is the volume of emulsion before centrifugation, v_2 is the volume of the emulsified layer, v_3 is the volume of the remaining emulsified layer after heating.

2.4.3. Foaming capacity and stability

The modified method of Coffman and Garcia (1977) was used for the determination of the foaming capacity and stability of macadamia flours. Two grams (db) of flour were mixed with 100 ml of distilled water and the suspension was whipped with a kitchen blender. The whipped suspension was transferred into a 250 ml graduated cylinder. Volumes of the whole mixture were recorded before and after whipping. The experiment was done in triplicate. The foaming capacity (FC) and foaming stability (FS) were calculated using the following equations:

$$\mathrm{FC}\ (\%) = (v'_2 - v'_1) \times 100/v'_1,$$
$$\mathrm{FS}\ (\%) = v'_3 \times 100/v'_2,$$

where v'_1 is the volume of initial mixture, v'_2 is the volume of the mixture after whipping, v'_3 is the volume of the mixture at 8 h after whipping.

Table 1
Details of macadamia cultivars used in this research

Name of cultivar used in this research	Growing area	HAES[a] No.	Cultivar[b]
PY 741	Pong Yang subdistrict, Mae Rim district, Chiang Mai	741	Mauka
DS 344	Doi Saket district, Chiang Mai	344	Kau
DS 800	Doi Saket district, Chiang Mai	800	Makai

[a] Hawaii Agricultural Experiment Station.

[b] Aradhya et al. (1998).

2.5. Microstructure of macadamia flours

Characterisation of the microstructure of macadamia flours was done under a light microscope (BX51TF, Olympus, Japan) with normal and polarised light source and scanning electron microscope (JSM-5400, Jeol, Japan).

2.6. Statistical analysis

Analysis of variance of the experimental data was performed and least significance difference test was used to evaluate the differences between means at the 95% confidence interval.

3. Results and discussion

3.1. Proximate composition

The results in Tables 2 and 3 showed the chemical compositions, calculated as wet basis (wb) and dry basis (db), respectively, of both PDF and TDF from three macadamia cultivars. The fat, protein, ash, crude fibre, and carbohydrate contents of flours from different cultivars were significantly different ($p \leqslant 0.05$). The variation in chemical compositions among cultivars could result from the genetic variation and different growing areas. For each cultivar, TDF had higher protein, ash, crude fibre, and carbohydrate contents than PDF, and these differences were greater when the calculation was done on a dry basis (Table 3). In this research, the determination of functional properties was performed by using the weight of flours on a dry basis, in order to eliminate the effect of the difference in moisture content. Therefore, the results in Table 3 were used in the discussion regarding the effect of chemical compositions on functional properties of flours.

To avoid erroneous measurement of protein and carbohydrate due to browning reactions, the raw macadamia nuts with shell on, with an approximate initial moisture content of 17% (wb), were dried in a tray dryer at 50 °C for 46 h until their moisture reached approximately 2%. At this final moisture content, the colour of the kernels was still light yellow without any browning on the exterior or centre of the kernels. Our observation was consistent with the previous study of Prichavudhi and Yamamoto (1965), which reported that macadamia nuts with shell dried at ambient temperature, 125 °F, and 140 °F for 4 days provided light-coloured kernels, which were indistinguishable among treatments. Thus, the temperature of 50 °C (122 °F) employed in the current study was not likely to induce a great degree of browning. The effect of browning reaction on the measured protein and carbohydrate contents of the macadamia flours could therefore be ignored.

One of the major differences between PDF and TDF was their fat content. The type of residual fat in PDF was proposed by considering the composition of the extracted macadamia oil. The following unpublished data were obtained from Subhimaros's research group in our department. According to the study of macadamia oils extracted from the same lot and cultivars as used in the current study, macadamia oils contained mostly monounsaturated fatty acids (MUFAs) (81.7–82.4 g/100 g lipid), having oleic acid (62.5–65.4 g/100 g lipid) as the predominant MUFA. Regardless of the macadamia cultivar, the ratio of saturated fatty acids to MUFAs to polyunsaturated fatty acids found in macadamia oils was approximately 1:5:0.1, which was comparable to previous published data (Venkatachalam & Sathe, 2006). Therefore, we hypothesised that the residual fat in PDF would be rich in MUFAs, which could be another nutritional benefit of the PDF flours.

Considering the protein contents of macadamia flours on a wet basis (Table 2), it was found that the TDF from three macadamia cultivars contained lower protein contents compared to those found in defatted soy flours which had 47.01% wb protein (USDA, 2006). However, totally defatted macadamia flours had higher or similar protein content in comparison with flours from other nuts and cereals, such as chickpea flours (0.53–1.21% wb fat and 20.6–26.7% wb protein; Kaur & Singh, 2005), bambara groundnut flours (7.3–8.5% wb fat and 17.5–21.1% wb protein; Onimawo, Momoh, & Usman, 1998), jack bean flours (3.4–4.7% wb fat and 28.9–35.0% wb protein; Vadivel & Janardhanan, 2001), wholewheat flours (1.87% wb fat and 13.7% wb protein; USDA, 2006), and sorghum flours (3.30% wb fat and 11.3% wb protein; USDA, 2006).

3.2. Functional properties of macadamia flours

3.2.1. Water and oil absorption capacity

Water absorption capacity (WAC) represents the ability of a substance to associate with water under a limited water condition (Singh, 2001). The major chemical compositions that enhance the WAC of flours are proteins and carbohydrates, since these constituents contain hydrophilic parts, such as polar or charged side chains (Hodge & Osman, 1976; Pomeranz, 1985). According to Table 4, the WAC of TDF from each cultivar tended to be higher than those of PDF. Due to smaller lipid content (db) in TDF, the

Table 2
Proximate composition (calculated as wet basis) of PDF and TDF from different macadamia cultivars[ab]

Macadamia flours	Moisture (%)	Fat (%)	Protein[c] (%)	Ash (%)	Crude fibre (%)	Carbohydrate (%)
PDF PY 741	8.04 ± 0.05c	11.18 ± 0.20c	28.47 ± 0.10d	4.52 ± 0.08bc	2.47 ± 0.10c	45.33 ± 0.32c
PDF DS 344	5.51 ± 0.12e	12.10 ± 0.28b	28.73 ± 0.16d	3.54 ± 0.34d	2.94 ± 0.15b	47.19 ± 0.79b
PDF DS 800	7.72 ± 0.17c	13.75 ± 0.31a	29.45 ± 0.11c	3.73 ± 0.36d	2.44 ± 0.12c	42.91 ± 0.69d
TDF PY 741	12.59 ± 0.07a	0.90 ± 0.01d	31.86 ± 0.26b	5.53 ± 0.12a	3.46 ± 0.08a	45.66 ± 0.16c
TDF DS 344	6.99 ± 0.16d	0.54 ± 0.01e	32.85 ± 0.73a	4.38 ± 0.02c	3.39 ± 0.11a	51.84 ± 0.77a
TDF DS 800	9.43 ± 0.93b	0.55 ± 0.01e	30.00 ± 0.15c	4.89 ± 0.09b	3.42 ± 0.11a	51.71 ± 0.69a

[a] Means followed by same letter within a column do not differ significantly ($p \leqslant 0.05$).
[b] Means ± SD of triplicate analyses.
[c] Total nitrogen × 5.30.

Table 3
Proximate composition (calculated as dry basis) of PDF and TDF from different macadamia cultivars[ab]

Macadamia flours	Fat (%)	Protein[c] (%)	Ash (%)	Crude fibre (%)	Carbohydrate (%)
PDF PY 741	12.15 ± 0.22c	30.96 ± 0.12e	4.91 ± 0.08c	2.69 ± 0.11d	49.29 ± 0.33d
PDF DS 344	12.80 ± 0.29b	30.40 ± 0.21e	3.74 ± 0.36d	3.11 ± 0.16c	49.94 ± 0.79d
PDF DS 800	14.90 ± 0.33a	31.92 ± 0.17d	4.04 ± 0.40d	2.65 ± 0.13d	46.49 ± 0.68e
TDF PY 741	1.03 ± 0.01d	36.45 ± 0.29a	6.33 ± 0.13a	3.96 ± 0.09a	52.23 ± 0.21c
TDF DS 344	0.58 ± 0.01e	35.32 ± 0.78b	4.71 ± 0.03c	3.65 ± 0.13b	55.74 ± 0.80b
TDF DS 800	0.61 ± 0.01e	33.12 ± 0.22c	5.40 ± 0.04b	3.77 ± 0.11ab	57.09 ± 0.18a

[a] Means followed by same letter within a column do not differ significantly ($p \leqslant 0.05$).
[b] Means ± SD of triplicate analyses.
[c] Total nitrogen × 5.30.

effect of lipid on hindering the absorption of water by hydrophilic constituents could be less. Moreover, the TDF contained a greater amount of chemical constituents having hydrophilic parts, such as proteins and carbohydrates (Table 3). Thus, the WAC could be enhanced.

Oil absorption capacity (OAC) is another important functional property of flours, since it plays an important role in enhancing the mouthfeel and retaining the flavour (Kinsella, 1976). The major chemical component affecting OAC is protein, which is composed of both hydrophilic and hydrophobic parts. Non-polar amino acid side chains can form hydrophobic interactions with hydrocarbon chains of lipid. The OAC of the TDF from each cultivar was greater than those of the PDF (Table 4). This could result from higher protein content (db) of the TDF, leading to a greater extent of hydrophobic interactions between protein and fat in the flours.

Table 4
Water and oil absorption capacities of PDF and TDF from different macadamia cultivars[ab]

Macadamia flours	Water absorption capactiy (g water/g flour, db)	Oil absorption capactiy (g oil/g flour, db)
PDF PY 741	5.59 ± 0.35b	3.39 ± 0.04b
PDF DS 344	5.40 ± 0.07b	3.16 ± 0.06b
PDF DS 800	3.68 ± 0.16d	3.05 ± 0.09b
TDF PY 741	6.72 ± 0.14a	4.40 ± 0.79a
TDF DS 344	4.71 ± 0.17c	4.93 ± 0.06a
TDF DS 800	4.48 ± 0.09c	4.65 ± 0.17a

[a] Means followed by same letter within a column do not differ significantly ($p \leqslant 0.05$).
[b] Means ± SD of triplicate analyses.

According to the similar experimental conditions used in the determination of functional properties, the results from chickpea flours (Kaur & Singh, 2005) and sorghum flours (Elkhalifa, Schiffler, & Bernhardt, 2005) were chosen, to compare with those of the macadamia flours. It was found that the TDF from three macadamia cultivars showed higher WAC (4.71–6.72 g water/g flour) and OAC (4.40–4.93 g oil/g flour) than those of the chickpea flours, which possessed 1.33–1.47 g water/g flour WAC and 1.05–1.24 g oil/g flour OAC (Kaur & Singh, 2005). Also, WAC and OAC of TDF from three macadamia cultivars were higher than those of sorghum flour (WAC of 2.19–2.35 g water/g flour and OAC of 1.72–1.85 g oil/g flour; Elkhalifa et al., 2005). The difference between WAC and OAC among these flours could be because of the variation in chemical compositions, especially protein content.

3.2.2. *Emulsion activity and stability*

The emulsification properties of protein-containing products like legume flours may result from both soluble and insoluble protein, as well as other components, such as polysaccharides (McWatters & Cherry, 1977). Protein can emulsify and stabilise the emulsion by decreasing surface tension of the oil droplet and providing electrostatic repulsion on the surface of the oil droplet (Sikorski, 2002; Wong, 1989), while some types of polysaccharides can help stabilise the emulsion by increasing the viscosity of the system (Dickinson, 1994).

As reported in Table 5, for each macadamia cultivar, the emulsion activity (EA) and emulsion stability (ES) of the TDF tended not to be different from those of PDF ($p > 0.05$). This implied that fat contents in flours might be irrelevant to emulsion properties. Because of experimental procedures, such as homogenisation, residual lipids in flours might be sheared off and leached into the mixture. Those migrating lipids were not likely to impede the functional properties of proteins and polysaccharides. Thus, the emulsion properties might rely more heavily on other chemical compositions such as proteins and polysaccharides in terms of both characteristics and quantity. However, regardless of the statistical analysis, the results in Table 5 showed that, for each cultivar, the EA of the TDF tended to be smaller than that of the PDF, whereas the ES of the TDF tended to be greater than that of the PDF. The latter result could be due to the greater protein (Table 3) and polysaccharide content in the TDF. In order to determine ES, the flour suspension was heated, so that protein unfolding could occur. The hydrophobic residues that locate inside the protein structure were then exposed, causing the protein molecules to be better adsorbed on the oil–water interface. In addition, viscosity increase due to enhanced hydration and swelling of starch and non-starch polysaccharides in the heated sample could occur, which could be responsible for retarding the coalescence. These phenomena could enhance the ES of the mixture, and could occur to a greater extent in the flour with higher protein and polysaccharide contents. Moreover, the EA of the TDF from each cultivar was lower than their ES, which could be due to the thermal denaturation of proteins and the viscosity increase, as stated above. In contrast, this trend could not be clearly identified in the PDF. This could be because of the smaller protein and polysaccharide contents in the PDF (Table 3).

Considering the data from Table 5, it was found that the TDF from three macadamia cultivars had lower EA (49.1–50.8%) than that of chickpea flours (58.2–68.8%; Kaur & Singh, 2005), but had similar EA to those of sorghum flours (49.4–52.8%; Elkhalifa et al., 2005). Similarly, the TDF from three macadamia cultivars had lower ES (53.5–54.3%), compared to ES of chickpea flours (76.6–82.1%; Kaur & Singh, 2005), but had similar ES to those of sorghum flours (47.28–52.11%; Elkhalifa et al., 2005). Although both the chickpea and sorghum flours had a lower protein content than the totally defatted macadamia flours, the EA and ES of the chickpea and sorghum flours were higher or similar to those of the TDF. This could imply that not only did the properties of EA and ES depend on the quantity of protein, but these two properties also relied upon protein characteristics, such as its hydrophilic–hydrophobic portion.

3.2.3. Foaming capacity and stability

Foam is a colloid of many gas bubbles trapped in a liquid or solid. Small air bubbles are surrounded by thin liquid films. Foam can be produced by whipping air into liquid as much and fast as possible (Sikorski, 2002; Wong, 1989). The reason why flours are capable of producing foams is that proteins in flours are surface active. Soluble proteins can reduce surface tension at the interface between air bubbles and surrounding liquid. Thus, the coalescence of the bubbles is obstructed. In addition, protein molecules can unfold and interact with one another to form multi-layer protein films with an increased flexibility at the air–liquid interface. As a result, it is more difficult for air bubbles to break, and the foams are more stabilised (Adebowale & Lawal, 2003).

For each macadamia cultivar, the foaming capacity (FC) of TDF was significantly higher than that of PDF ($p \leqslant 0.05$) (Table 6). This could be because of the increase in protein solubility after removing lipids. Greater concentration of soluble proteins in an aqueous phase could enhance the foam formation. According to the experiment, TDF PY 741 possessed a significantly highest FC ($p \leqslant 0.05$), which could arise from its highest protein content (Table 3). However, this flour had the lowest foaming stability (FS). Fig. 1 showed the inverse relationship between FC and FS. Flours with high foaming ability could form large air bubbles surrounded by thinner and less flexible protein films. These air bubbles might be easier to collapse and consequently lowered the foaming stability. On the other hand, flours with low FC could bring about the formation of smaller air bubbles surrounded by thicker

Table 5
Emulsion activity and stability of PDF and TDF from different macadamia cultivars[ab]

Macadamia flours	Emulsion activity (%, db)	Emulsion stability (%, db)
PDF PY 741	56.21 ± 1.08a	51.68 ± 1.10bc
PDF DS 344	51.94 ± 0.60b	53.22 ± 0.59ab
PDF DS 800	50.99 ± 1.53bc	50.44 ± 2.44c
TDF PY 741	50.81 ± 0.71bc	54.20 ± 2.03ab
TDF DS 344	50.47 ± 0.23bc	53.52 ± 0.32ab
TDF DS 800	49.05 ± 2.79c	54.26 ± 0.73a

[a] Means followed by same letter within a column do not differ significantly ($p \leqslant 0.05$).
[b] Means ± SD of triplicate analyses.

Table 6
Foaming capacity and stability of PDF and TDF from different macadamia cultivars[ab]

Macadamia flours	Foaming capacity (%, db)	Foaming stability (%, db)
PDF PY 741	22.67 ± 0.58d	91.85 ± 0.78a
PDF DS 344	31.00 ± 1.00c	86.52 ± 1.11b
PDF DS 800	33.67 ± 2.52c	84.07 ± 2.76b
TDF PY 741	126.00 ± 3.46a	56.27 ± 2.00d
TDF DS 344	62.33 ± 3.06b	73.53 ± 1.77c
TDF DS 800	65.67 ± 3.21b	75.07 ± 1.28c

[a] Means followed by same letter within a column do not differ significantly ($p \leqslant 0.05$).
[b] Means ± SD of triplicate analyses.

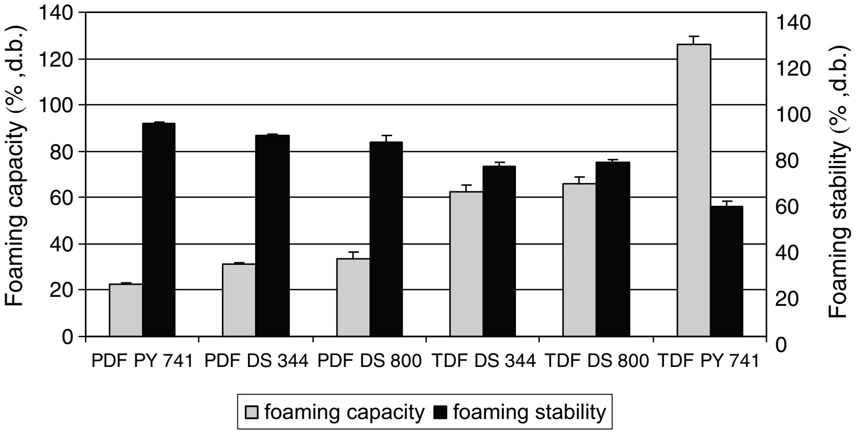

Fig. 1. Foaming capacity and stability of PDF and TDF from different macadamia cultivars.

and more flexible protein films, which discouraged the coalescence of air bubbles and consequently increased the foaming stability.

Comparing the FC and FS of the TDF from three macadamia cultivars with the data of flours from other sources having similar experimental conditions, it was found that the TDF had higher FC (62–126%) than those of chickpea flours (10–13%; Kaur & Singh, 2005), bambara groundnut flours (57%), and jack bean flours (52%) (Adebowale & Lawal, 2004). On the other hand, the TDF had lower FS (56–75%) than those of chickpea flours (91–97%; Kaur & Singh, 2005), but had similar FS to those of bambara groundnut flours (70%), and jack bean flours (67%; Adebowale & Lawal, 2004). The difference in FC and FS of macadamia flours from other flours could result from the variations in protein content and protein solubility.

3.3. Microstructure of macadamia flours

The observations from both light microscope and scanning electron microscope (SEM) (Figs. 2a, 3a–c) revealed that the defatted macadamia flours mainly composed of globular structures embedded in flaky kernel tissues. Although the majority of the transparent globular structures found in the light microscope image of mature macadamia embryos were reported as lipid bodies (Walton & Wallace, 2005), the globular structures found in the defatted macadamia flours were likely to be protein bodies and starch granules rather than lipid bodies, because the flours were already defatted. Also, the occurrence of starch granules located together with spherical protein bodies could be found in starchy endosperm of some cereals (Chiang & Yeh, 2002; Irving & Jideani, 1997), as well as in cotyledon of some legumes and nuts (Hsieh, Swanson, & Lumpkin, 1999; Young, Pattee, Schadel, & Sanders, 2004). Switching the microscope's light source from normal light to polarised light under the same slide (Fig. 2a and b) helped differentiate the starch granules from the protein bodies. The position of the starch granules could be identified under polarised light by noticing the bright particle with birefringence. The starch granules were distributed throughout the tissue but were found at low levels. In general, the size of starch granules is larger than that of protein bodies (Chiang & Yeh, 2002; Hsieh et al., 1999; Irving & Jideani, 1997; Young et al., 2004), thus, the larger globular structures found in the SEM images (Fig. 3a and c) could

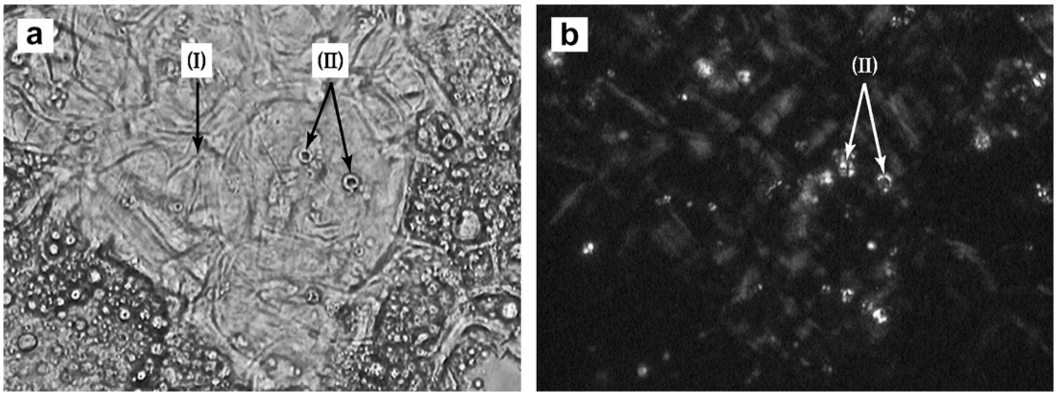

Fig. 2. Characterisation of the microstructure of PDF DS 344 at the same position under magnification of ×400 from a light microscope with (a) normal light and (b) polarised light. Each arrow indicates an example of (I) kernel tissues and (II) starch granules.

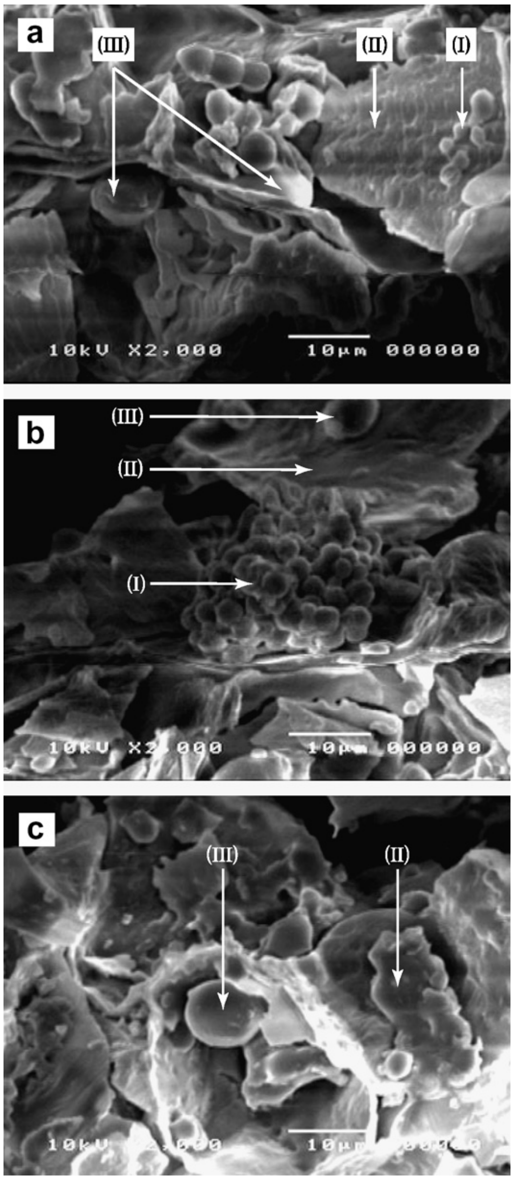

Fig. 3. Characterisation of the microstructure of TDF DS 800 ((a) and (b)) and TDF PY 741 (c) by SEM under magnification of ×2000. Each arrow indicates an example of (I) protein clusters; (II) kernel tissues and (III) starch granules.

possibly be starch granules, which were oval in shape and approximately 10 μm in diameter. Comparing the size of the starch granules from macadamia flours with others, it was found that the starch granules of macadamia were smaller than that of cassava (5–35 μm) and corn (5–25 μm), but larger than rice starch granules (3–8 μm) (Wurzburg, 1986).

The amino acid (AA) composition of protein (I in Fig. 3) in macadamia nut has been previously reported (Venkatachalam & Sathe, 2006). According to the study, the AA composition of macadamia nut was dominated by hydrophobic (37.2 g/100 g protein) AA, followed by acidic (32.3 g/100 g protein), basic (19.1 g/100 g protein), and hydrophilic (11.4 g/100 g protein) AA, respectively. The exact ratio of amylose to amylopectin in macadamia starch (II in Fig. 2 and III in Fig. 3) has not been determined, and is beyond the scope of this current research. As for the chemical compositions of the kernel tissues (I in Fig. 2 and II in Fig. 3), we proposed that the tissue could be mainly composed of dietary fibre and non-starch carbohydrate, such as sucrose and reducing sugars (Wall & Gentry, 2007). However, trace amounts of lipid and protein could be found in kernel tissues.

4. Conclusion

The chemical compositions of both PDF and TDF from different macadamia cultivars were significantly different ($p \leqslant 0.05$), which could stem from genetic variation and the different level of lipid extraction in the flour preparation process. The TDF from three macadamia cultivars differed significantly in their functional properties of WAC, OAC, FC, and FS. For each macadamia cultivar, the WAC, OAC, and FC of the TDF were significantly greater than those of the PDF ($p \leqslant 0.05$). The TDF from PY 741 cultivar showed highest WAC and FC, but lowest FS. These different functional properties could be due to variation in chemical compositions, especially protein content, in terms of its quantity and characteristics. Nevertheless, for each macadamia cultivar, the EA and ES of the TDF tended not to be different from those of PDF. The EA of the TDF from each cultivar was lower than their ES. Structure determination of macadamia flours revealed that the protein bodies and starch granules were embedded in flaky kernel tissues. The starch granules of the macadamia flours were oval in shape and approximately 10 μm in diameter, which was 2–3 times bigger than their protein bodies. Possible applications of the defatted macadamia flours can be determined from their chemical compositions and functional properties. Due to the high amount of protein content and the MUFA-rich residual fat, the PDF can be mainly used to improve nutritional value in food products such as bakery products. The TDF can enhance both nutritional and eating qualities of food products, since it provides high protein content and good functional properties, including WAC, OAC, FC, and FS.

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