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Characterisation of mechanically-pressed avocado oil from cultivars grown in Sabah, Malaysia☆

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Abstract – This study investigates the lipid characteristics of mechanically-pressed crude pulp oil derived from three avocado (*Persea americana*) cultivars – Bacon Green (BG), SNR, and QAV1–with a focus on their physicochemical profiles, including fatty acid and triacylglycerol (TAG) compositions, and thermal behaviours. Notably, the BG cultivar produced oil that remained solid at room temperature (25°C), while oils from the SNR and QAV1 cultivars were liquid under the same conditions. All three oils were rich in unsaturated fatty acids, particularly monounsaturated oleic acid, which accounted for 32.74–44.50% of the total fatty acids across cultivars. Despite these compositional similarities, the cultivars exhibited significant differences in TAG distribution. While POL -i.e. Palmitic, Oleic, Linoleic TAG- (20.68–22.41%), PLL (11.46–17.15%), and POO (11.15–15.49%) were consistently among the major TAGs in all cultivars, differences in the concentrations of the overall TAG components contributed to variations in melting behaviour. While cooling profiles were relatively similar, distinct melting transitions were observed, indicating cultivar-specific thermal responses. These findings highlight the diversity in lipid properties among local Malaysian avocado cultivars and suggest promising industrial potential, with the solid-state BG oil offering potential as a natural alternative to hydrogenated fats in food formulations, while the liquid oils from SNR and QAV1 may be suitable for cosmetic and nutraceutical uses. The study underscores the value of underexplored tropical avocado varieties as functional lipid sources with tailored applications.

Keywords: Malaysian avocado / avocado oil / characteristics / mechanical press / pulp oil

Résumé – Caractérisation de l'huile d'avocat obtenue par pressage mécanique de cultivars cultivés à Sabah, Malaisie. Cette étude examine les caractéristiques lipidiques de l'huile brute de pulpe obtenue par pressage mécanique à partir de trois cultivars d'avocat (*Persea americana*) – Bacon Green (BG), SNR et QAV1–en se concentrant sur leurs profils physico-chimiques, notamment leur composition en acides gras et en triacylglycérols (TAG), ainsi que leurs comportements thermiques. Il est à noter que l'huile du cultivar BG reste solide à température ambiante (25 °C), tandis que celles des cultivars SNR et QAV1 sont liquides dans les mêmes conditions. Les trois huiles sont riches en acides gras insaturés, en particulier en acide oléique mono-insaturé, qui représente 32,74 à 44,50% des acides gras totaux selon les cultivars. Bien

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qu'ayant une composition similaire, les cultivars se distinguent par des différences notables dans la distribution des TAG. Les TAG palmitique-oléique-linoléique (POL, 20, 68–22,41%), le PLL (11, 46–17, 15%) et le POO (11, 15–15, 49%) figurent systématiquement parmi les principaux TAG de tous les cultivars, et les variations de leurs concentrations modifient leurs points de fusions. Si les profils de refroidissement sont relativement similaires, des transitions de fusion spécifiques à chaque cultivar ont été observées, indiquant des réponses thermiques propres à chaque variété. Ces résultats soulignent la diversité des propriétés lipidiques parmi les cultivars d'avocat malaisiens locaux et suggèrent un potentiel industriel prometteur : l'huile solide de BG pourrait servir d'alternative naturelle aux graisses hydrogénées dans les formulations alimentaires, tandis que les huiles liquides de SNR et QAV1 pourraient convenir à des applications cosmétiques et nutraceutiques. L'étude met en lumière la valeur des variétés tropicales d'avocat peu exploitées comme sources lipidiques fonctionnelles aux applications ciblées.

Mots-clés : Avocat / Malaisie / huile d'avocat / caractéristiques / pressage mécanique / huile de pulpe

Highlights

- Three Malaysian avocado cultivars [Bacon Green (BG), SNR and QAV1], revealing distinct TAG profiles with oleic acid was the most predominant fatty acid and thermal behaviours. BG oil was solid at 25 °C, SNR and QAV1 oils were liquid, offering diverse applications and advancing understanding of cultivar-specific lipid functionality.

1 Introduction

Avocado (*Persea americana* Mill.) is a subtropical fruit tree from the Lauraceae family, native to regions spanning from Mexico to the Andes. It is widely cultivated in subtropical and tropical areas around the world due to its nutritional value and commercial potential. The fruit is rich in essential nutrients including lipids, dietary fibre, potassium, magnesium, vitamins C, E, and B-complex, as well as phytochemicals with antioxidant properties (Wang *et al.*, 2020). The flesh of avocado is an abundant source of oil, whereby its lipid content has been reported as the highest among all known fruit and vegetable varieties (Wang *et al.*, 2020). This makes the fruit a valuable source of oil, which contains significant amounts of monounsaturated fatty acids (MUFA), particularly oleic acid, along with bioactive compounds such as chlorophyll, tocopherols, phytosterols, carotenoids, and polyphenols (Cervantes-Paz and Yahia, 2021).

The world avocado production has consistently been led by Mexico, accounting for 28% of the world's avocado production (2.97 million tonnes) in the year 2023 alone (FAO, 2024). While avocado fruits are primarily consumed fresh, interest in avocado oil has increased in recent years due to its versatility in food and cosmetic applications, as well as its recognized health benefits (Cervantes-Paz and Yahia, 2021). To date, numerous studies on the health benefits of avocado oil consumption have been published. The main benefits reported in the literature of avocado oil are the management of chronic diseases such as hypercholesterolemia (Sari and Wasita, 2023; Tan *et al.*, 2018b), hypertension (Monge *et al.*, 2023; Márquez-Ramírez *et al.*, 2018), diabetes (Ortiz-Avila *et al.*, 2024; de Oliveira Marques *et al.*, 2022), and fatty liver (García-Berumen *et al.*, 2022).

In Malaysia, avocado cultivation is still developing but gaining traction, particularly in Sabah. According to the Department of Agriculture, Malaysia currently imports most of its avocado supply, but there is growing interest and ongoing efforts to expand local cultivation. In Sabah specifically, the state government has supported initiatives to assess the commercial viability of different cultivars. Among those receiving attention are Bacon Green (BG), SNR, and QAV1, selected for their high productivity, pulp quality, and resistance to pests. Although avocado fruits may appear similar externally, variations in cultivar can significantly influence the physicochemical properties of the oil (Nasri *et al.*, 2021), making cultivar-specific evaluations important for both agricultural practices and product development.

There is a growing interest in avocado oil, including the determination of its compositional characteristics. Although several researchers have studied the chemical composition of avocado oil, only a few has reported the characteristics of oil obtained from Malaysian avocado cultivars (Tan *et al.*, 2017; Yanty *et al.*, 2011). Moreover, these previous studies focused on oil extraction methods using supercritical fluid and Soxhlet, while mechanical extraction studies are still scarce. Nevertheless, no comparative study on the different cultivars of Sabahan avocados has been published yet. Additionally, no comparative study on the avocado cultivars from Sabah, Malaysia has been conducted, particularly with regard to their thermal properties and potential for unique oil behaviours. Thus, the present study aimed to evaluate and compare the characteristics of crude pulp oils obtained through mechanical extraction from three avocado cultivars grown in Sabah, Malaysia.

2 Materials and methods

2.1 Materials

Three local avocado cultivars (BG, SNR, and QAV1) were supplied by Koperasi Tataba Ranau Berhad, located in Ranau, Sabah, Malaysia, under the supervision of Sabah Agriculture Department. The fruits were harvested in 2023 and 2024 from May to July for BG, August to October for SNR, and in June to September for QAV1, when each cultivar had reached its peak maturity as indicated by the development of large fruit size. Post-harvest, the fruits were left to naturally ripen until the exocarp darkened and the mesocarp softened, following the indicators described by Tripathi *et al.* (2024). Images of the ripened cultivars are provided in Figures 1–3.

Once ripened, the pulp was collected and mashed into smooth paste, before dried in a cabinet tray dryer (TD-78T-SD,

Fig. 1. Bacon Green (BG) avocado cultivar.

Fig. 2. SNR avocado cultivar.

Thermoline, Australia) for 24 h at 40 °C. The dried paste was then reduced to fine powder using a Waring blender (Model HGBTWTS3, Dynamic Corporation of America, New Hartford, USA), before stored in airtight container until the extraction process. All chemicals used were of analytical grades, unless otherwise specified.

2.2 Oil extraction

The finely ground avocado pulp was subjected to mechanical extraction using a hydraulic press machine (Model ID33634, Knight Auto, Malaysia) to obtain the crude oil sample. The pulp powder was placed in a filter cloth and pressed at room temperature (25 °C) under a pressure of 150 bar. The extracted oil was filtered using a filter paper, and subsequently stored in a sealed amber bottle at −20 °C until further use.

2.3 Determination of physicochemical properties

The physical properties of the oils were analysed in terms of colour (L*, a*, b*), refractive index (RI), slip melting point (SMP), and cloud point (CP). The physical properties, along with the iodine value (IV), free fatty acid (FFA) content, peroxide value (PV), and p-anisidine value (p-AV) of the oils were determined according to the AOAC (2023) standard analytical methods.

Fig. 3. QAV1 avocado cultivar.

2.4 Determination of fatty acid composition

The fatty acid composition of the oils was determined by conversion of oil to fatty acid methyl esters (FAME), based on the method described by Fadzillah *et al.* (2019) with slight modifications. Briefly, the FAMEs were prepared by dissolving a solution of 50 mg of oil in 0.8 mL of hexane with 0.2 mL of 1 M sodium methoxide (PORIM, 1995). The FAMEs were then analysed using gas chromatography (GC) (7890A, Agilent Technologies, California, USA), equipped with a flame ionisation detector (FID) and an automated liquid sampler. The column used was a DB-23 polar capillary column (length= 30 m; internal diameter= 0.25 mm; film thickness= 0.25 μm, Agilent Technologies, California, USA). The oven temperature was programmed as follows: initial temperature of 50 °C for 1 min, increased to 175 °C at 25 °C/min and finally increased to 230°C at 4 °C/min. Both injector and detector temperatures were maintained at 280 °C throughout the analysis. Helium carrier gas was maintained at 1.0 mL/min constant flow rate with a split ratio of 10:1. Fatty acids in the oils were identified and qualitatively analysed by comparing their retention time with FAME standards (Sigma St. Louis, Missouri, USA). The relative percentage of individual fatty acids was reported as the relative proportion of the total fatty acids.

2.5 Determination of triacylglycerol composition

The triacylglycerol (TAG) composition of the oils was determined by non-aqueous reverse-phase high-performance liquid chromatography (HPLC), according to the method of Manaf *et al.* (2018). The HPLC used was Agilent G1213B (Agilent Technologies, California, USA), equipped with C-18 column (250 mm × 4.6 mm, Kromasil 100-5-C18). Detection

Table 1. Physicochemical properties of avocado oils.

Analysis	Avocado oil		
	BG	SNR	QAV1
SMP (°C)	28.67 ± 0.58^{b}	18.00 ± 0.00^{a}	17.33 ± 0.58^{a}
CP (°C)	27.00 ± 1.00^{b}	3.67 ± 0.58^{a}	3.33 ± 0.58^{a}
RI	1.4690 ± 0.00^{a}	1.4720 ± 0.00^{a}	1.4740 ± 0.00^{a}
IV (g I_2/100 g)	86.90 ± 0.19^{b}	83.46 ± 0.10^{a}	96.17 ± 0.12^{c}
FFA (as % oleic acid)	1.41 ± 0.18^{a}	1.81 ± 0.15^{b}	1.24 ± 0.11^{a}
PV (meq O_2/kg)	3.03 ± 0.08^{c}	2.07 ± 0.14^{b}	1.33 ± 0.15^{a}
p-AV	6.54 ± 0.15^{a}	12.54 ± 0.03^{c}	11.01 ± 0.02^{b}
L*	28.37 ± 0.01^{a}	29.08 ± 0.01^{c}	28.88 ± 0.01^{b}
a*	0.65 ± 0.03^{a}	2.26 ± 0.02^{c}	2.11 ± 0.01^{b}
b*	-0.45 ± 0.01^{a}	0.93 ± 0.01^{c}	0.68 ± 0.02^{b}

Each value in the table represents the mean ± standard deviation of three replicates. Values within each row bearing different superscript letters are significantly ($p < 0.05$) different.
SMP= slip melting point; CP= cloud point; RI= refractive index; IV= iodine value; FFA= free fatty acid; PV= peroxide value; p-AV= p-anisidine value.

of TAG was performed using a refractive index detector (Model RID-6A). Mobile phase used was a 63.5:36.5 acetone:acetonitrile (v/v) mixture, with a flow rate of 1 mL/min. The column temperature was isothermal at 30 °C, and the total run time was 40 min. Auto-injection was set at 10 μL of 5% (w/w) oil in chloroform. Chromatographic peaks were identified using a set of TAG standards, and quantified based on relative percentages using the peak areas produced.

2.6 Determination of thermal profile

The melting and cooling profiles of the oils were evaluated using differential scanning calorimeter (DSC) equipped with a refrigerated cooling system, referring to the method of Manaf *et al.* (2018). The DSC (Diamond DSC, Perkin Elmer) system was purged using nitrogen gas at a rate of 20 mL/min. Approximately 3-5 mg of oil sample was hermetically sealed in a standard DSC aluminium pan. An empty pan was used as a reference during the measurements. The time temperature program was as follows: held isothermally at 60 °C for 2 min, then cooled to −60 °C and held for 1 min, before finally heated from −60 to 60 °C and held at 2 min, all process at the rate of 5 °C/min. The Pyris software version 13.4.0.0064 was used to evaluate the melting and cooling profiles.

2.7 Statistical analysis

The triplicate data of the oil samples were analysed to determine the mean and standard deviation values using the Statistical Package for Social Sciences (SPSS) software version 29.0.0.0. Analysis of variance (ANOVA) accompanied with Tukey's test was performed to determine the significant differences at a 0.05 probability level ($p \leq 0.05$).

3 Results and discussion

3.1 Physicochemical properties

The quality of avocado oils extracted from the three local avocado cultivars was assessed through physicochemical parameters, including SMP, CP, RI, IV, FFA, PV, p-AV, and colour. The results are presented in Table 1.

The oil extracted from the BG cultivar was solid at room temperature (25 °C), whereas oils from the SNR and QAV1 cultivars remained liquid. In contrast, Yanty *et al.* (2011) reported semisolid oils at similar temperature for local avocado cultivars grown in Malaysia. A similar observation was also noted by Tan *et al.* (2018a), where solvent-extracted avocado oil appeared semisolid at room temperature. However, these earlier studies did not specify the locations or cultivars of the avocado. The differences in oil form could be attributed to variations in extraction methods as well as the fatty acid and triacylglycerol (TAG) compositions (Indriyani *et al.*, 2016).

The SMP value of BG oil (28.67 °C) was significantly higher ($p < 0.05$) than those of SNR and QAV1 oils, which were comparable to values reported by Yanty *et al.* (2011). Meanwhile, the SMP values of SNR and QAV1 oils aligned with findings by Amin *et al.* (2024). The CP values were 27 °C, 3.67 °C, and 3.33 °C for BG, SNR, and QAV1, respectively. The RI values of the oils (1.4690–1.4740) showed no significant differences ($p > 0.05$) and were in line with the previously reported values (Flores *et al.*, 2024; Krumreich *et al.*, 2024; Shrestha, 2022). The slight variations in RI may be attributed to differences in the degree of unsaturation and structural characteristics of the oil components.

The IV, which reflects the degree of unsaturation, was lowest in SNR oil (83.46 g I_2/100 g), followed by BG (86.90 g I_2/100 g) and QAV1 (96.17 g I_2/100 g). Interestingly, although BG oil had a moderate IV, it was observed to be solid at room temperature, whereas both SNR and QAV1 remained in liquid form. This highlights that while IV is a common indicator of

Table 2. The fatty acid compositions of avocado oils.

Fatty acid	Avocado oil		
	BG	SNR	QAV1
C14:0	0.14 ± 0.02^{a}	0.14 ± 0.07^{a}	0.09 ± 0.03^{a}
C16:0	29.48 ± 1.83^{b}	26.07 ± 0.48^{a}	25.02 ± 0.09^{a}
C16:1	10.17 ± 0.09^{a}	12.17 ± 0.45^{b}	11.43 ± 1.01^{a}
C17:0	0.19 ± 0.02^{b}	ND	0.06 ± 0.02^{a}
C17:1	0.61 ± 0.10^{b}	0.31 ± 0.10^{a}	ND
C18:0	1.00 ± 0.06^{a}	1.20 ± 0.03^{b}	1.33 ± 0.08^{b}
C18:1	32.74 ± 1.39^{a}	44.50 ± 0.25^{b}	33.49 ± 0.59^{a}
C18:2	21.40 ± 0.49^{b}	13.20 ± 1.68^{a}	23.22 ± 0.66^{b}
C18:3	3.70 ± 0.37^{b}	1.79 ± 0.25^{a}	4.43 ± 0.30^{b}
C20:0	ND	ND	0.41 ± 0.04^{a}
C22:0	0.28 ± 0.11^{a}	0.24 ± 0.18^{a}	0.16 ± 0.04^{a}
C24:0	0.29 ± 0.06^{a}	0.38 ± 0.41^{a}	0.36 ± 0.03^{a}
MUFA	43.52	56.98	44.92
PUFA	25.10	14.99	27.65
UFA	68.62	71.97	72.57
SFA	31.38	28.03	27.43

Each value in the table represents the mean ± standard deviation of three replicates. Values within each row bearing different superscript letters are significantly ($p < 0.05$) different.

C14:0, myristic acid; C16:0, palmitic acid; C16:1, palmitoleic acid; C17:0, margaric acid; C17:1, heptadecenoic acid; C18:0, stearic acid; C18:1, oleic acid; C18:2, linoleic acid; C18:3, linolenic acid; C20:0, arachidic acid; C20:22, behenic acid; C24:0, lignoceric acid; MUFA, monounsaturated fatty acid; PUFA, polyunsaturated fatty acid; UFA, unsaturated fatty acid; SFA, saturated fatty acid, not detected; ND.

unsaturation and oil fluidity, it does not solely determine the physical state. Factors such as the specific types of fatty acids, particularly the proportion of saturated fatty acids and their distribution within TAG molecules also play significant roles in determining the physical behaviour of the oils. All IVs reported in this study fall within the typical range for avocado oils (63–95 g I_2/100 g), as established by Guthmann *et al.* (1992), and supported by more recent findings (Amin *et al.*, 2024; Manaf *et al.*, 2018; Indriyani *et al.*, 2016).

FFA content, PV, and p-AV are widely used to assess the quality and freshness of edible oils, with lower values generally indicating higher quality. As shown in Table 1, QAV1 oil had the lowest FFA content (1.24%), while SNR oil had the highest (1.81%). All FFA values were below the 2% maximum limit for crude avocado oils, as defined by CODEX (2019). The PV and p-AV, which assess primary and secondary oxidation respectively, also provide insight into oil quality. The PVs were 3.03 meq O_2/kg (BG), 2.07 meq O2/kg (SNR), and 1.33 meq O_2/kg (QAV1), all below the CODEX limit of 10 meq O_2/kg. These values were lower than those reported for Indonesian cultivars (5.22–5.44 meq O_2/kg) by Manaf *et al.* (2018). The p-AV values ranged from 6.54 to 12.54, slightly higher than those reported by Widowati *et al.* (2023), but within the range reported by Indriyani *et al.* (2016). Tan *et al.* (2017) observed similar PVs (2.73–2.82 meq O_2/kg) but lower p-AVs (2.82–3.03) in Malaysian cultivars. Overall, all PV and p-AV values in this study comply with CODEX standards, indicating acceptable oil quality.

All oils displayed a dark green colour, indicating the presence of pigments such as chlorophyll and carotenoids. Visually, BG oil appeared darker than the SNR and QAV1 oils, which exhibited more green-yellowish hue. These visual observations were supported by colorimeter readings presented in Table 1, which showed significant differences ($p < 0.05$) in L*, a*, and b* values among the cultivars. BG recorded the lowest L* value, indicating it was the darkest. SNR and QAV1 oils exhibited higher a* and b* values, reflecting greater red and yellow pigmentation, which suggests a higher content of carotenoids.

3.2 Fatty acid composition

The fatty acid composition of the avocado oils analysed in this study is presented in Table 2. A total of twelve fatty acids were identified, comprising both major and minor components. The results indicated that the major fatty acid distribution was similar among the three cultivars, with oleic acid (32.74–44.50%) being the predominant component, followed by palmitic (25.02–29.48%), linoleic (13.20–23.22%), and palmitoleic acids (10.17–12.17%). This pattern is consistent with previous findings on the fatty acid profiles of avocado oils (Amin *et al.*, 2024; Li *et al.*, 2019; Manaf *et al.*, 2018; Chimsook and Assawarachan, 2017; Indriyani *et al.*, 2016). Despite the similarity in distribution, the concentrations of individual fatty acids differed from those reported in earlier studies. These discrepancies may be attributed to differences in cultivar or variety, ripening stage, geographical origin, and processing method (Maulida et al., 2024).

The fatty acid composition of the avocado oils analysed in this study (Tab. 2) shows both conformity and deviations when compared with the Codex Alimentarius Standard (2024). For instance, the palmitic acid (C16:0) in BG oil was slightly higher than the Codex upper limit (26.0%). Heptadecenoic acid (C17:1) and lignoceric acid (C24:0), though present in

Table 3. The TAG compositions of avocado oils.

TAG	Avocado oil		
	BG	SNR	QAV1
LLLn	2.56 ± 0.15^{b}	1.31 ± 0.06^{a}	3.10 ± 0.12^{c}
LLL	4.75 ± 0.20^{b}	2.86 ± 0.07^{a}	5.95 ± 0.34^{c}
OLL	6.21 ± 0.32^{a}	6.52 ± 0.25^{a}	7.34 ± 0.29^{b}
PLL	16.73 ± 0.11^{b}	11.46 ± 0.40^{a}	17.15 ± 0.15^{c}
OOL	6.37 ± 0.17^{a}	9.65 ± 0.17^{c}	7.99 ± 0.32^{b}
POL	20.71 ± 0.24^{a}	22.41 ± 0.34^{b}	20.68 ± 0.80^{a}
PPL	11.02 ± 0.21^{c}	8.18 ± 0.12^{a}	9.25 ± 0.44^{b}
OOO	4.30 ± 0.19^{a}	9.09 ± 0.04^{c}	5.85 ± 0.09^{b}
POO	12.65 ± 0.07^{b}	15.49 ± 0.15^{c}	11.15 ± 0.56^{a}
PPO	9.19 ± 0.04^{b}	10.32 ± 0.22^{c}	8.40 ± 0.67^{a}
PPP	2.93 ± 0.04^{b}	1.02 ± 0.09^{a}	1.11 ± 0.22^{a}
OOS	1.23 ± 0.09^{a}	1.11 ± 0.06^{a}	1.24 ± 0.23^{a}
SPO	0.79 ± 0.04^{b}	0.34 ± 0.10^{a}	$0.58 \pm 0.09^{a,b}$
PPS	0.57 ± 0.07^{b}	0.25 ± 0.08^{a}	0.21 ± 0.05^{a}
UUU	24.18	29.43	30.23
UUSt	51.32	50.46	50.22
UStSt	21.00	18.84	18.23
StStSt	3.50	1.27	1.32

Each value in the table represents the mean ± standard deviation of three replicates. Values within each row bearing different superscript letters are significantly ($p < 0.05$) different.
O, oleic; P, palmitic; L, linoleic; Ln, linolenic; S, stearic; U, unsaturated; St, saturated.

small amounts (0.31–0.61% and 0.29–0.38%, respectively), were also above the Codex ranges (ND–0.1% and ND–0.2%, respectively). Meanwhile, oleic acid (C18:0) in BG and QAV1 oils fell below the Codex minimum of 42.0%, while linoleic (C18:2) and linolenic (C18:3) acids in both oils [C18:2, 21.4% (BG) and 23.22% (QAV1); C18:3, 3.7% (BG) and 4.43% (QAV1)] exceeded the Codex maxima of 19.0% and 2.1%, respectively. These verified data highlight natural variations among local cultivars and could serve as a basis for refining and amending the Codex standards for avocado oil.

All avocado oils analysed in this study exhibited a high total content of unsaturated fatty acids (UFAs). The highest proportion was observed in QAV1 oil (72.57%), followed by SNR (71.97%) and BG (68.62%) oils. This high degree of unsaturation was mainly attributed by monounsaturated (MUFA: 43.52–56.98%) and polyunsaturated fatty acids (PUFA: 14.99–27.65%). SNR oil had the highest MUFA content, driven by its high oleic acid level (44.50%), while QAV1 showed the highest PUFA content, attributed to its greater linoleic and linolenic acid concentrations. These variations in UFA composition were reflected in the IVs, where QAV1, with the highest PUFA content, recorded the highest IV (96.17 g I□/100 g), followed by BG (86.90 g I□/100 g) and SNR (83.46 g I□/100 g). The results support the well-established influence of PUFA on increasing iodine value due to their higher number of double bonds. Meanwhile, the higher SFA content in BG oil (31.38%) may contribute to its solid state at room temperature by promoting crystallisation.

Among the MUFAs, oleic acid consistently emerged as the dominant component, especially in SNR oil (44.50%), aligning with the values reported by Yanty *et al.* (2011) for Malaysian avocado oils (43-51%). Oleic acid has been associated with the reduction and management of cardiovascular diseases (Krumreich *et al.*, 2018), making its presence in all three oil nutritionally significant. In addition to oleic acid, the oils also contained notable levels of linoleic and linolenic acids, which are essential fatty acids that cannot be synthesized by human body and need to be supplemented through the diet. The relatively high levels of palmitoleic acid observed in all samples, compared to most seed oils, may represent a valuable attribute of avocado oil for both nutritional and cosmetic applications. These findings suggest that the avocado oils studied are valuable dietary sources of essential and health-promoting fatty acids, supporting their potential inclusion in a balanced diet.

3.3 Triacylglycerol (TAG) composition

Table 3 shows the TAG compositions of avocado oils from the three cultivars. Fourteen TAG components were identified in all three oil samples, with significant differences ($p < 0.05$) in their distribution.

All avocado oils in this study were predominantly composed of unsaturated-rich TAGs, with di-unsaturated types (50.22–51.32%) being the most abundant, followed by tri-unsaturated types (24.18–30.23%). This distribution is in accordance with the previous studies on avocado oil TAG profiles (Manaf *et al.*, 2018; Tan *et al.*, 2017; Yanty *et al.*, 2011). Among individual TAG species, POL was consistently the most abundant across all samples (20.68–22.41%) although the relative proportions of other TAGs varied, suggesting cultivar-specific differences. The major TAG component was followed by PLL, POO, and PPL in BG and QAV1, while for SNR is POO, PLL, and PPO. Notably, the

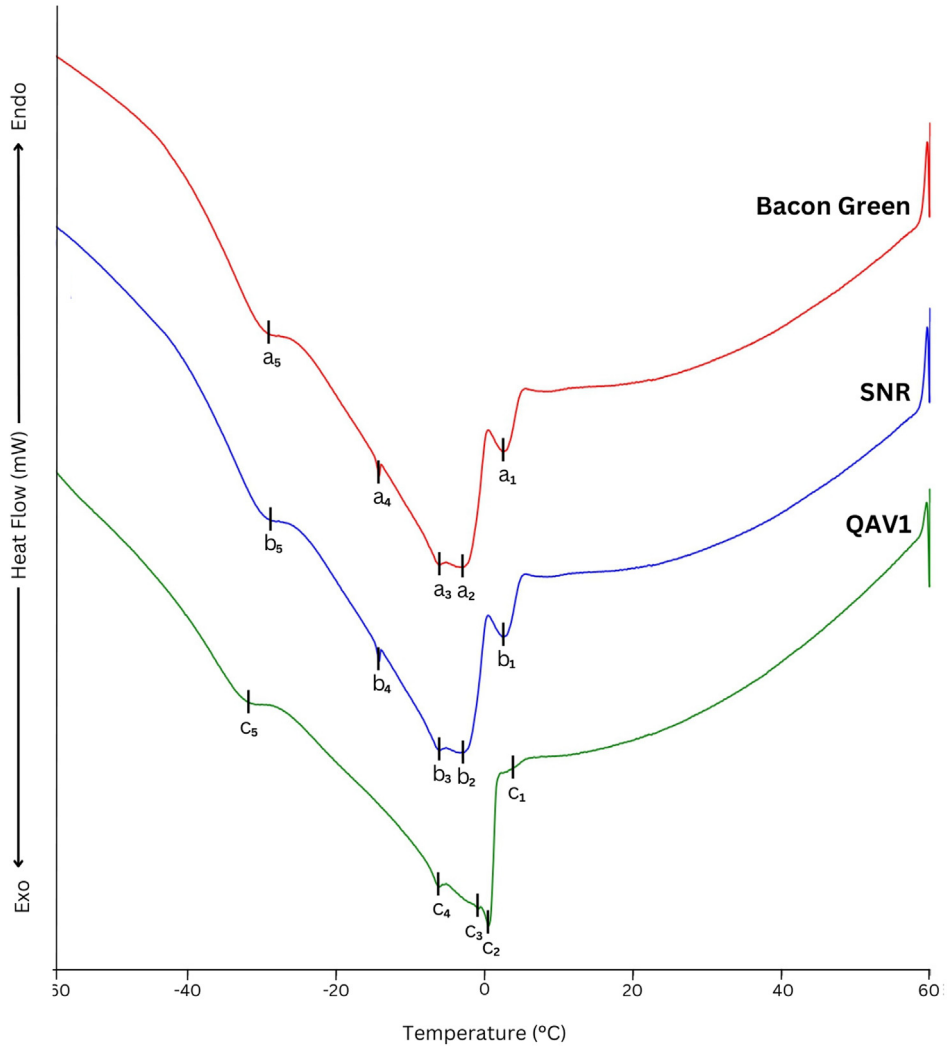

Fig. 4. Cooling thermogram of oils obtained from the pulp of three avocado cultivars.

major TAG composition in SNR oil resembled that of the Malaysian avocado cultivar reported by Amin *et al.* (2024), suggesting potential geographical or varietal similarities.

The TAG composition aligned closely with the fatty acid profiles of the oils. SNR oil, which showed the highest oleic acid (44.50%) and MUFA content (56.98%), also exhibited high levels of OOO and POO, which are TAGs rich in oleic acid. This was consistent with its relatively high IV (88.47 g I_2/100 g) and supports the impact of MUFA on unsaturation levels. Meanwhile, QAV1 oil, with the highest PUFA content (27.65%), showed greater levels of LLL, LLLn, and PLL, which are TAGs incorporating linoleic and linolenic acids, correlating with its highest IV (96.17 g I_2/100 g). These findings demonstrate a strong relationship between TAG structure, fatty acid composition, and the degree of unsaturation. In contrast, BG oil's solid state at room temperature may be attributed to its higher SFA content (31.38%) and greater proportion of saturated-rich TAGs such as PPP (2.93%) and PPL (11.02%), along with fully saturated TAG species (StStSt: 3.50%). These TAGs, particularly those containing palmitic acid, are prone to crystallisation and likely contribute to the oil's solid physical nature.

The distinct TAG profiles among the three oils not only reflect differences in fatty acid composition but also influence key physicochemical characteristics such as IV and physical state. As noted by Tan *et al.* (2017), the distribution of unsaturated components in avocado oils can vary significantly based on geographical origin and cultivar. These findings highlight the relevance of TAG profiling in evaluating the quality, functionality, and potential applications of avocado oils.

3.4 Thermal profile

Melting and cooling are two physical events commonly used to characterise the thermal characteristics of oils (Tan *et al.*, 2017). The cooling and melting profiles of the extracted oils are shown in Figures 4 and 5, respectively.

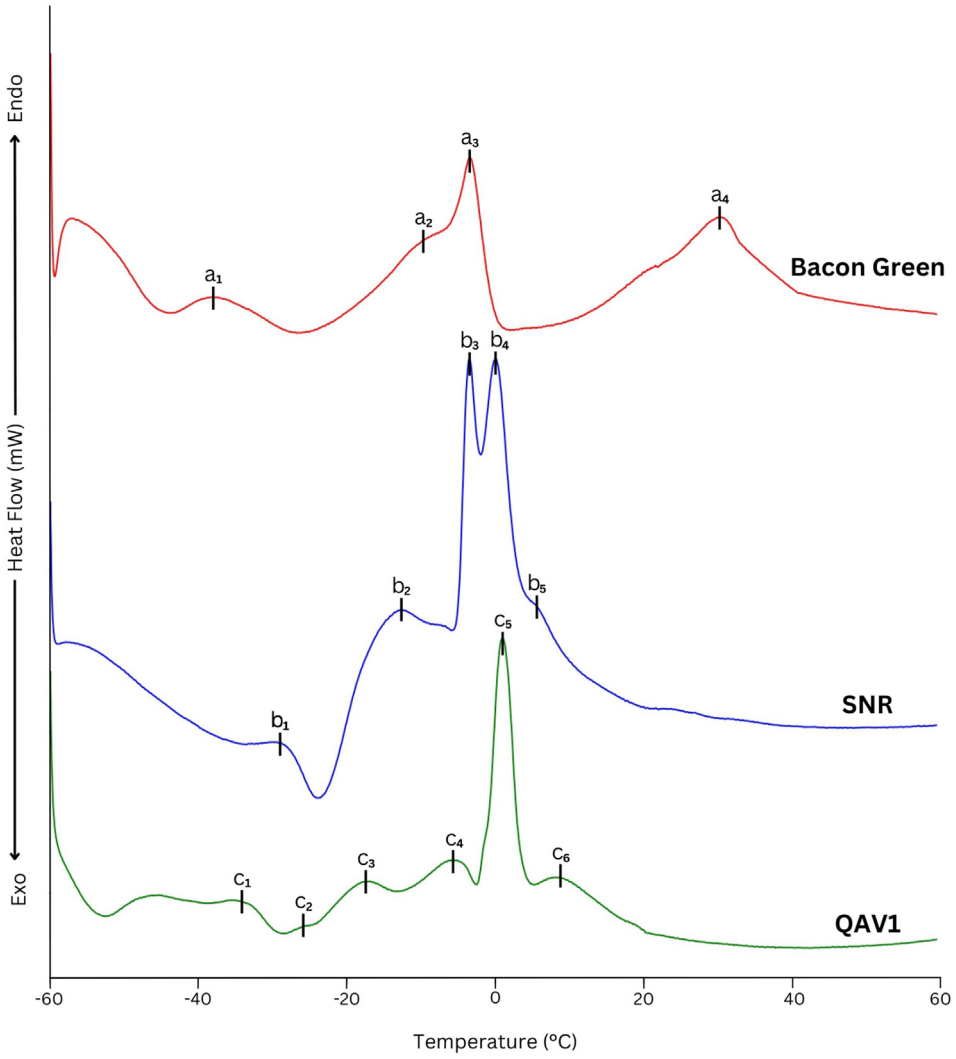

Fig. 5. Melting thermogram of oils obtained from the pulp of three avocado cultivars.

In Figure 4, it can be observed that the cooling profiles of the oils were quite comparable, although they differed in terms of exothermic temperatures. All oils had five exothermic peaks: three separate peaks at the initial (a_1, b_1, c_1) and towards the end of crystallisation process (a_4, b_4, c_4, and a_5, b_5, c_5), as well as a pair of split peaks (a_2, b_2, c_2, and a_3, b_3, c_3) in the middle of the process. The initial crystallisation points for the BG, SNR and QAV1 oils were at 27.5 °C, 4.9 °C, and 1.7 °C, respectively. During the cooling process, high-melting TAGs were crystallized first, followed by the low-melting TAGs (Tan *et al.*, 2017). Based on Table 3, the total percentages of di-unsaturated and tri-unsaturated TAGs in each of the three oils were comparable, which justifies the close crystallisation endpoints across all oils.

In contrast to the cooling profiles, the melting thermograms (Fig. 5) for the three avocado oils were more distinguishable. The BG, SNR, and QAV1 oils exhibited four, five, and six exothermic peaks, with final melting points of 34.6 °C, 20.8 °C, and 20.4 °C, respectively. Notably, the BG oil showed a thermal transition above 30 °C, while the SNR and QAV1 oils had completely melted below 10 °C. This explains the solid consistency of BG oil at room temperature, in contrast to the liquid state of SNR and QAV1. The melting thermogram of BG oil displayed an unusual endothermic peak around 35 °C, which was absent during the cooling cycle. This may reflect a small fraction of high-melting TAGs that did not fully crystallise during cooling due to kinetic limitations or undercooling, which are behaviours commonly observed in oils with complex TAG mixtures (Narine and Marangoni, 1999).

The observed differences in the thermal behaviour of the avocado oils can be further linked to variations in TAG composition. Fats and oils are complex mixtures of different TAGs, each with distinct crystallization and melting behaviours (Sato, 2001). As a result, oils do not exhibit specific crystallization or melting points but rather a range of temperatures. Low-melting TAGs, which contain a higher degree of unsaturation (*e.g.*, tri-unsaturated and di-unsaturated TAGs), begin melting at lower temperatures. Conversely, high-melting TAGs, which are more saturated (*e.g.*, tri-saturated and mono-unsaturated TAGs), melt at higher temperatures.

Understanding the crystallisation and melting behaviour of these avocado oils is crucial for designing products with desired textures, stability, and performance, as the oil's ability to remain liquid or solid at ambient temperature can significantly influence its applications in food and industrial products.

4 Conclusion

The growing interest in avocado oil applications has driven this study to evaluate the physicochemical properties of oils extracted from local avocado cultivars in Sabah, Malaysia. The results demonstrated that all three cultivars produced good-quality oils, meeting CODEX Alimentarius standards of <5% for FFA, <10 for PV, and <20 for p-AV. Oils were rich in monounsaturated fatty acids, particularly oleic acid with different major TAG molecules and distinct thermal behaviours. These findings suggest strong potential for local avocado oil as a source of oleic supplementation and for use in various high-value applications. In addition, different avocado cultivars exhibited varying physical states at room temperature, a characteristic that could be strategically utilised in product development to tailor texture, mouthfeel, and application-specific functionality. A key strength of this study is its novel investigation of underutilised local avocado cultivars for oil production, providing essential baseline data on their physicochemical and compositional characteristics to support future commercial development and value-added applications. However, this study is limited using seasonal avocado fruits obtained as variations in climate, flowering time, and fruit maturity across different seasons can influence the composition and quality of the extracted oils.

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Conflicts of interest

The authors have declared that no financial, professional, or personal conflicts of interest could have inappropriately influenced this work.

Author contribution statement

A.A. Amin: Formal analysis, Investigation, Methodology, Writing – original draft preparation. R.R. Yanis: Formal analysis, Investigation. M.N.M. Rosdi: Supervision. H.Y. Fan: Resources. J-S. Lee: Resources. S. Arshad: Resources. M.H. Wasoh: Resources. B.P. Nusantoro: Conceptualization, Supervision. Y.N.A. Manaf: Conceptualization, Supervision, Writing – review & editing.

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