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Research Article

Enhancing the Efficiency of Phytochemical Extraction from *Artocarpus odoratissimus* and *Baccaurea lanceolata* Using Glycerol-Water Systems

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ABSTRACT

Recently, the focus on utilizing food processing by-products, such as peels and seeds, has increased due to their significant phytochemical content, transforming them from waste to valuable resources. This study investigated the antioxidant properties of two local wild fruits, *Artocarpus odoratissimus* (peel and seed) and *Baccaurea lanceolata* (peel, seed and flesh), using a glycerol-water extraction system for "green" extraction. Samples underwent ultrasonic extraction at different temperatures (room temperature, 50°C, and 80°C) and glycerol percentages (20–80%). The total phenolic (TPC), flavonoid (TFC), and anthocyanin (TAC) contents were analyzed spectrophotometrically. Antioxidant properties were assessed using DPPH free radical scavenging and FRAP assays. The optimal extraction temperatures were 50°C for *A. odoratissimus* and 80°C for *B. lanceolata*. The extraction solvent systems were 60% glycerol for *A. odoratissimus* peel, *B. lanceolata* seed and flesh, and 80% glycerol for *A. odoratissimus* seed and *B. lanceolata* peel. The results show TPC, TFC and TAC of all fruit parts ranging from 6.30 to 175.20 mg GAE/g, 2.80 to 22.50 mg QUE/g, and 0.30 to 9.50 mg c-3-gE/100 g, respectively, across all extraction conditions. Meanwhile, the reducing ability and radical scavenging activities ranged from 20.15 to 891.70 mM TE/g and 1.15 to 319.40 mg TEAC/g, respectively. Overall, *A. odoratissimus* peel and *B. lanceolata* seed exhibited higher phytochemical contents and antioxidant activity, with *A. odoratissimus* peel showing the highest TPC (154.95 ± 1.42 mg GAE/g) and TFC (22.46 ± 0.31 mg QUE/g), and the highest antioxidant capacity by FRAP (850.20 ± 2.44 mM TE/g) and DPPH (319.43 ± 1.93 mg TEAC/g) assays.

Keywords: *Artocarpus odoratissimus*; *Baccaurea lanceolata*; phytochemicals; glycerol-water extraction.

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INTRODUCTION

Polyphenols, a diverse group of naturally occurring compounds in plants, can be categorized into phenolic acids, flavonoids, and tannins (Chiocchio et al., 2021). They serve as a defense mechanism against environmental stressors like ultraviolet radiation and pathogen attacks with diverse biological activities, including antihypertensive, anti-cancer, antibacterial, anti-inflammatory, and antidiarrheal effects (Chiocchio et al., 2021; Zagoskina et al., 2023). In recent years, there has been a growing focus on utilizing food processing by-products, such as peels and seeds, due to their significant phytochemical content (Barba et al., 2016; Pinto et al., 2021). These by-products, typically discarded, have become valuable resources for extracting polyphenols and other bioactive compounds.

For centuries, phytochemicals have played a crucial role in global healthcare, serving as medicinal compounds derived from plant materials to treat various diseases. The extraction of these compounds is fundamental to natural product research, with a continual pursuit of improved methods. Recent studies have identified ultrasonication as an advanced and environmentally friendly technique (Ranjha et al., 2021) that exhibits superiority (Jovanović et al., 2017; Saifullah et al., 2020).

Moreover, research has focused on employing green solvents while optimizing extraction techniques for improved time efficiency and cost reduction (Jovanović et al., 2017; Kowalska et al., 2021). Previous studies have demonstrated the effectiveness of glycerol-based solvents in enhancing the polyphenol yields. In red grape pomace, ultrasound-assisted extraction using a range of glycerol concentrations showed a dramatic increase in phenolic yield from 4.32 mg GAE/g to 11.85 mg GAE/g using 10 and 90% glycerol, respectively (Trasanidou et al., 2016). Similar results were reported for onion solid waste, where 90% glycerol as a solvent with solid-to-liquid ratio of 1:90 produced the highest phenolic yield (64.91 mg GAE/g), outperforming lower glycerol percentages (Katsampa et al., 2015). In apple peel waste, room-temperature extraction with 70% glycerol yielded higher phenolic content (15.08 mg GAE/g) than 50% ethanol (12.70 mg GAE/g) (Blidi et al., 2015). At higher temperatures, the yield improved significantly to 17.47 mg GAE/g and 19.32 mg GAE/g, indicating that temperature can significantly improve the yield. In potato peel, replacing water with 45% glycerol substantially increased the phenolic yield from 3.78 mg GAE/g to 6.82 mg GAE/g, indicating the strong enhancing effect of glycerol on phenolic recovery (Paleologou et al., 2016). Another study comparing methanol, ethanol, glycerol, and water showed that glycerol yielded the highest flavonoid content (6.02 mg RtE/g) from potato peel, followed by methanol (3.14 mg RtE/g), ethanol (2.68 mg RtE/g), and water (1.98 mg RtE/g) (Manousaki et al., 2016). Eggplant peel also followed this trend, with glycerol achieving 12.85 mg RtE/g, which clearly surpasses the other solvents (between 9.60 mg RtE/g and 10.13 mg RtE/g) (Manousaki et al., 2016). In the extraction of anthocyanin content of black chokeberry, 50% ethanol extracted the highest yield of 107.97 mg/L, but 50% glycerol produced a competitive yield of 81.49 mg/L, markedly higher than pure water (55.82 mg/L) (Kowalska et al., 2021).

There is a limited number of papers comparing the efficiency of glycerol as an extraction solvent against more complex green solvents. In grapefruit peel, both 20% glycerol and a deep-eutectic solvent (lactic acid:glucose) produced higher polyphenol yields than water, with glycerol outperforming the DES (El Kantar et al., 2019). In *Jasione montana*, a natural deep-eutectic solvent (NADES) containing proline and glycerol achieved higher phenolic content than an optimized 60% glycerol-water solvent, suggesting that tailored NADES can offer a more efficient extraction (Juszczak et al., 2023). Conversely, studies with olive leaf and red

grape pomace show that certain additives, for instance, cyclodextrins and tartaric acid, provide little to no improvement on the phenolic yield, highlighting the strong intrinsic solvation capacity of glycerol (Makris et al., 2016; Mourtzinos et al., 2016). Collectively, these findings demonstrate that glycerol solvent systems perform superior to or comparable to methanol, ethanol, water and certain DES/NADES solvent systems in extracting polyphenols from diverse plant matrices. This supports the rationale for selecting glycerol as a green, efficient and skin-friendly solvent for the present study.

Artocarpus odoratissimus Blanco ("tarap" in Sabah, and "marang" in the Philippines) is a popular tropical fruit indigenous to Southeast Asia and a member of the Artocarpus genus alongside jackfruit, "cempedak" and breadfruit (Abu Bakar & Abu Bakar, 2018). Rich in essential minerals and vitamins, it also exhibits diverse biological activities, including antibacterial, antiviral, antifungal, anti-inflammatory, tyrosinase inhibitory, cytotoxic and antiarthritic properties (Jagtap et al., 2010; Tang et al., 2013). Previous studies found that peel extracts have shown superior antidiabetic and antioxidant activities compared to extracts from the edibles (Abu Bakar et al., 2009; Jonatas et al., 2020; Ismail et al., 2023).

Baccaurea lanceolata (Miq.) Müll.Arg. ("liposu" in Sabah and "limpasu" in Kalimantan, Indonesia) is another indigenous fruit thriving in the diverse ecosystems of Borneo and nearby regions (Lim, 2012). It is commonly consumed fresh all year round and can be used in traditional medicine as an acne remedy, natural sunscreen, and to address various ailments, such as stomach aches, headaches, diarrhea and to alleviate drunkenness (Galappathie et al., 2014; Hadi et al., 2017; Radcliffe-Smith & Haegens, 2000; Kulip, 2003; Suwardi et al., 2020). It has significant minerals (Voon & Kueh, 1999) and showed antimicrobial activity against various bacterial strains, revealing medium to potent inhibition (Fitriansyah et al., 2018; Galappathie et al., 2014).

Although extensive research has focused on optimizing green extraction methods for widely commercialized fruits, such as grape pomace, apple peel waste and potato peel, studies on underutilized tropical species remain scarce, particularly for endemic Southeast Asian fruits that are rich in bioactive compounds. Phytochemical investigations of *A. odoratissimus* and *B. lanceolata* fruits remain limited to the use of organic solvents and conventional extraction techniques. This study integrates a green extraction technique with a skin-friendly solvent to provide benchmark data on two indigenous Southeast Asian fruits, demonstrating their potential as sustainable sources of natural antioxidants for dermal applications. In addition to contributing to our ongoing work on fruit-derived skin formulations, this research supports bioresource diversification, promotes circular economy practices to achieve zero waste, and advances the development of eco-friendly raw materials for food and cosmetic industries.

METHODOLOGY

Samples and sample preparation

The ripe *A. odoratissimus* fruits (Fig. 1A) were collected from Keningau, Sabah, Malaysia, and the unripe (green coloured) *B. lanceolata* fruits (Fig. 1B) were collected from Kota Belud, Sabah, Malaysia, between February and May 2023. The fruits' species identification was confirmed by Mr. Johnny Gisil, a botanist from the Institute for Tropical Biology and Conservation (ITBC), UMS. The fruits were cleaned gently under running tap water and separated into peel and seed for *odoratissimus,* and peel, seed and flesh for *B. lanceolata*. These were cut into small pieces and freeze-dried (Labconco FreeZone Console Freeze Dryer

710611050) at -80°C for five days. Subsequently, the samples were ground into fine powder using a commercial electric blender, sieved through a 125 µm sieve, and stored in zip-lock plastic bags at -50°C for future use.

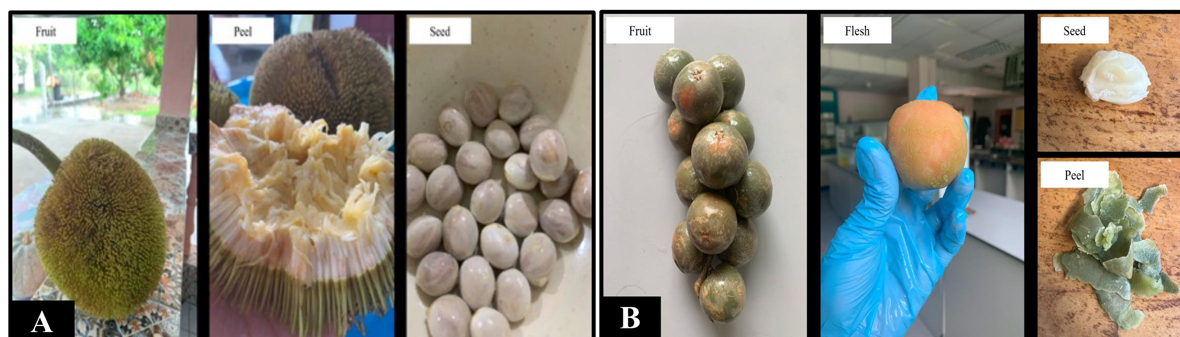

Figure 1: A. Ripe *A. odoratissimus.* **B.** Unripe (green coloured) *B. lanceolata.*

Sample extraction using glycerol-water solvents

The solvents were anhydrous glycerol (99.5% purity) purchased from SYSTEM Chemicals (Selangor, Malaysia) and purified water, which was produced in-house using a water purifier (ELGA, UK). The dried samples (0.5 g) of *A. odoratissimus* (seed and peel) and *B. lanceolata* (seed, peel and flesh) were weighed and placed in 50 mL centrifuge tubes. Then, a specified extraction solvent, prepared per Table 1, was added to the centrifuge tube. Following the parameters outlined in Table 1, the extraction process was carried out in a temperature-controlled ultrasonic bath (Elmasonic S 180 H, 37 kHz) for 20 minutes. Each parameter was applied to every component of both *A. odoratissimus* and *B. lanceolata*. The samples were filtered through filter papers, and then the filtrate was used for further assays. Every extract was prepared in triplicate.

Table 1: Extraction parameters include sample weight, solid-to-liquid ratio, temperature, and extraction systems. The designation code G refers to the percentage of glycerol in the given extraction system.

Sample Code	Sample Weight (g)	Solid-to-Liquid Ratio	Temperature (°C)*	The Extraction System (v/v, %)	
				Glycerol (G)	Water (W)
r30	0.5	1:30	RT	20	80
r50	0.5	1:50	RT	20	80
RT20G	0.5	1:70	RT	20	80
RT40G	0.5	1:70	RT	40	60
RT60G	0.5	1:70	RT	60	40
RT80G	0.5	1:70	RT	80	20
50T20G	0.5	1:70	50	20	80
50T40G	0.5	1:70	50	40	60
50T60G	0.5	1:70	50	60	40
50T80G	0.5	1:70	50	80	20
80T20G	0.5	1:70	80	20	80
80T40G	0.5	1:70	80	40	60
80T60G	0.5	1:70	80	60	40
80T80G	0.5	1:70	80	80	20

*RT = room temperature

Determination of total phenolic content (TPC)

Following a protocol (Ainsworth & Gillespie, 2007), an aliquot of 100 µL of the samples and 200 µl of 10% (v/v) Folin-Ciocalteu reagent were briefly mixed. After 5 mins, 800 µL of 700 mM Na_2CO_3 solution was added and mixed using a vortex mixer (Stuart SA8) at 1,600 rpm, and it was allowed to stand at room temperature for 2 hours in the dark room. The absorbance was measured at 765 nm using a spectrophotometer (Thermo Scientific Multiskan Go N10588). Similarly, the absorbance of gallic acid standard solutions (0-100 µg/mL) was measured, and the standard calibration curve was plotted. The TPC of the samples was expressed as milligram gallic acid equivalent (mg GAE/g) seaweed extract.

Determination of total flavonoid content (TFC)

Following a modified protocol (Chang et al., 2020), an aliquot of 120 µL of samples, 360 µL of methanol, 24 µL of 10% (v/v) aluminum chloride, 24 µL of 1.0 M potassium acetate, and 680 µL of distilled water were mixed using a vortex mixer (Stuart SA8) at 1,600 rpm. The mixture was allowed to stand at room temperature for 30 minutes. The absorbance was measured at 415 nm using a spectrophotometer (Thermo Scientific Multiskan Go N10588). Similarly, the absorbance of quercetin standard solutions (0-100 µg/mL) was measured, and the standard calibration curve was plotted. The TFC was expressed as mg quercetin equivalents in 1.0 g of sample (mg QUE/g).

Determination of total anthocyanin content (TAC)

Following a modified protocol (Shehat et al., 2020), an aliquot of 150 µL of samples and 1,050 µL of 0.025 M potassium chloride were mixed in a vial tube and adjusted to pH 1.0 using a pH meter (Mettler Toledo). In another vial tube, an aliquot of 150 µL of the samples and 1,050 µL of 0.025 M sodium acetate (pH 4.5) were mixed. The mixtures were mixed using a vortex mixer (Stuart SA8) at 1,600 rpm and allowed to stand at room temperature for 30 mins. The absorbance was measured at 515 nm and 700 nm (for the correction of haze) using a spectrophotometer (Thermo Scientific Multiskan Go N10588). The TAC was expressed in mg cyanidin-3-glucoside equivalents (c-3-gE) in 100 g of sample (mg c-3-gE/100 g), using the following equation (eq.1):

$$\text{TAC}\left(\frac{\text{mg}}{100}\text{ g of dried sample}\right) = (A \times MW \times DF \times 1000) / (\varepsilon \times \text{C}) \qquad \text{(eq.1)}$$

where *A* is the absorbance value = $(A_{515} - A_{700})_{pH1.0} - (A_{515} - A_{700})_{pH4.5}$; *MW* is the molecular weight of cyanidin-3-glucoside = 449.2 g/mol; *DF* is the dilution factor of the samples; ε is the molar absorptivity of cyanidin-3-glucoside = 26,900 L/mol cm; *C* is concentration of the buffer in mg/mL.

Evaluation of total antioxidant capacity based on ferric ion (III) reduction (FRAP)

Following a modified protocol (Russo et al., 2013), FRAP reagent was prepared by mixing 300 mM acetate buffer (pH 3.6) with 2,4,6-tri-2-pyridinyl-1,3,5-triazine (TPTZ) solution, and 20 mM ferric chloride solution in a ratio of 10:1:1. An aliquot of 20 µL of samples and 180 µL of FRAP reagent were mixed in a 96-well plate and incubated at 37°C in the dark for 40 mins. The absorbance was measured at 593 nm using a spectrophotometer (Thermo Scientific Multiskan Go N10588). Similarly, the absorbance of Trolox standard solutions (0 - 100 µg/mL) was measured, and the standard calibration curve was plotted. The antioxidant activity was expressed as mg ferric reducing ability in 1.0 g of sample (mg/g).

Evaluation of total antioxidant capacity based on free-radical scavenging activity (DPPH)
Following a protocol (Chan et al., 2012), 50 µL of the samples, with their respective concentrations, and 195 µL of 0.1 mM DPPH- methanolic solution were added into a 96-well plate. The mixtures were swirled gently for 1 minute and allowed to stand in the dark for 1 hour. The absorbance was measured at 540 nm using a spectrophotometer (Thermo Scientific Multiskan Go N10588). Similarly, the absorbance of Trolox standard solutions (0 - 100 µg/mL) was measured and the standard calibration curve was plotted. The DPPH radical scavenging activity was expressed as mg Trolox equivalent antioxidant capacity (mg TEAC) in 1.0 g of sample (mg TEAC/g).

Statistical analysis
All determinations were performed in triplicate, and the values were averaged. The data were analyzed by way of applying one-way analysis of variance (ANOVA), followed by least significant difference (LSD) tests ($p < 0.05$). The statistical analyses of data were carried out using the software IBM SPSS Statistics Version 27 (IBM Corp., Armonk, N.Y., U.S.A.).

RESULTS

In this study, three extraction factors (solid-to-liquid, % glycerol in the extraction system, and temperature) were explored based on their effects on the extraction of phytochemicals (polyphenol contents and antioxidant capacities) in different parts of the fruit samples. The first set of tests carried out was to find out the optimum solid-to-liquid ratio with a fixed 20% glycerol at room temperature. This was followed by varying the % glycerol at three different temperatures at a fixed (optimum) solid-to-liquid ratio. The quantitative results of TPC, TFC, TAC, FRAP and DPPH of *A. odoratissimus* and *B. lanceolata* under the different factors are shown in Tables 2–6. Meanwhile, Figs. 2–6 display comparative trends of the phytochemical contents and activities of the fruits against the different factors.

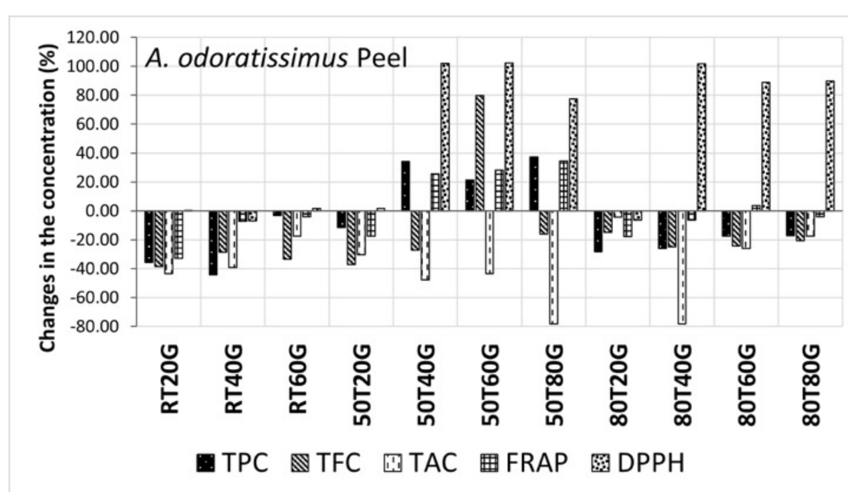

Figure 2: Changes in TPC, TFC and TAC and antioxidant capacities of *A. odoratissimus* peel compared with 80% glycerol-water extracts at RT. Sample code-designations as in Table 1.

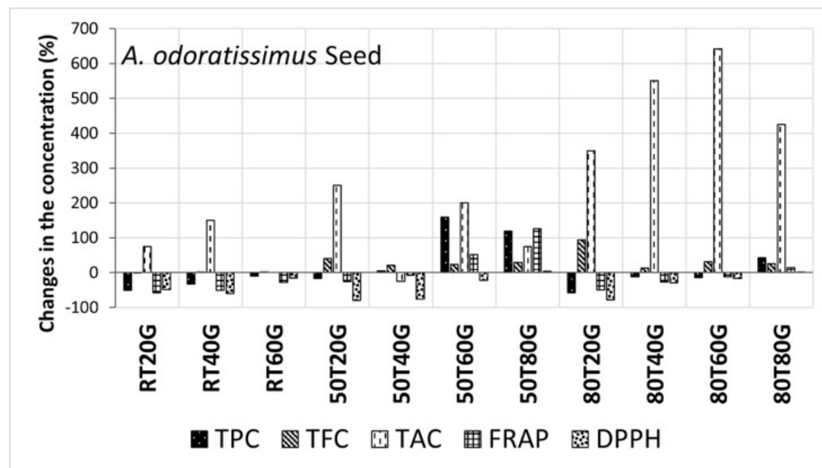

Figure 3: Changes in TPC, TFC, and TAC and antioxidant capacities of *A. odoratissimus* seed compared with 80% glycerol-water extracts at RT. Sample code-designations as in Table 1.

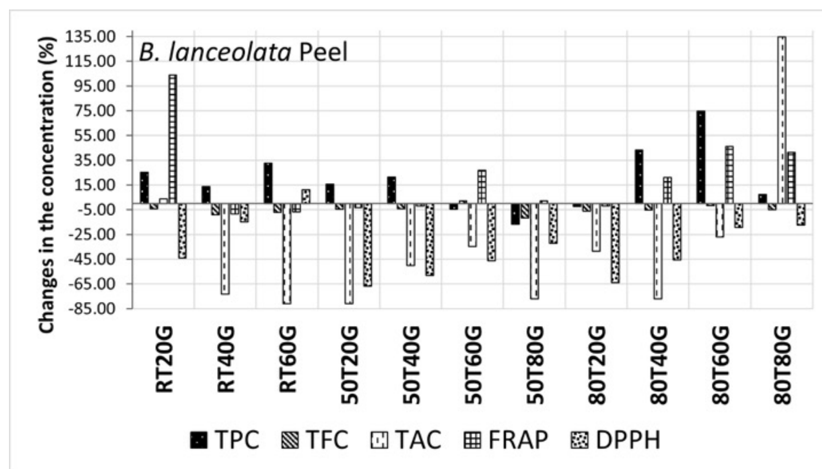

Figure 4: Changes in TPC, TFC, and TAC and antioxidant capacities of *B. lanceolata* peel compared with 80% glycerol-water extracts at RT. Sample code-designations as in Table 1.

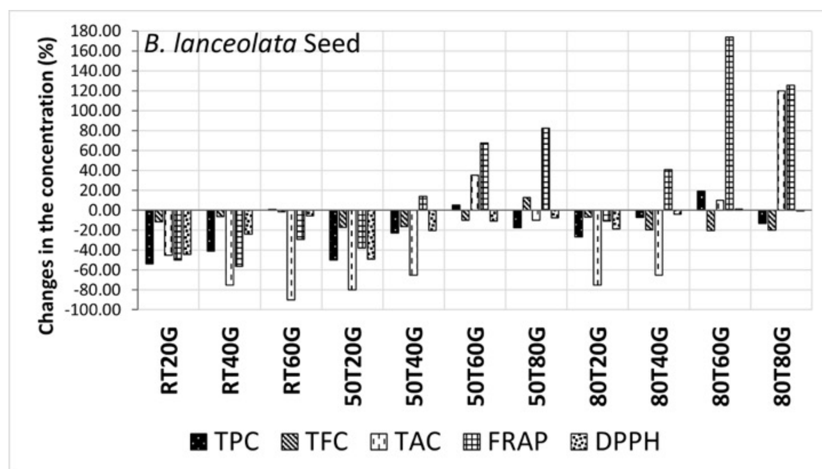

Figure 5: Changes in TPC, TFC, and TAC and antioxidant capacities of *B. lanceolata* seed compared with 80% glycerol-water extracts at RT. Sample code-designations as in Table 1.

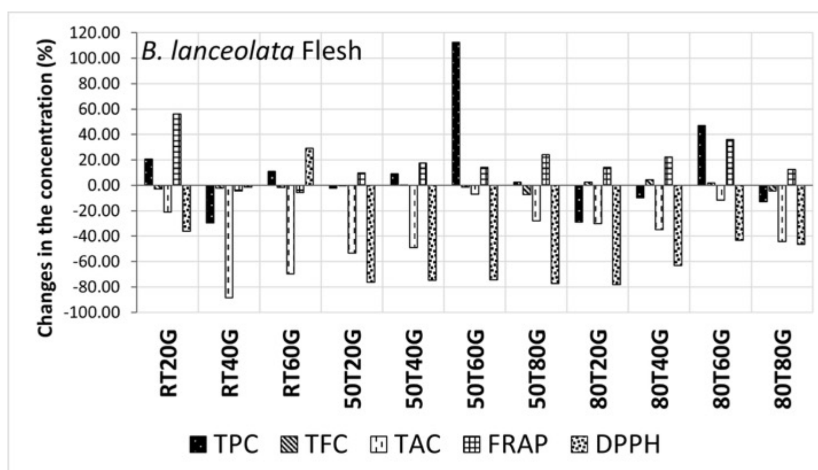

Figure 6: Changes in TPC, TFC, and TAC and antioxidant capacities of *B. lanceolata* flesh compared with 80% glycerol-water extracts at RT. Sample code-designations as in Table 1.

Effects of solid-to-liquid ratio

Based on Table 2, it is apparent that the highest values of TPC (9.47 mg GAE/g to 82.11 mg GAE/g), TFC (2.91 mg QUE/g to 7.68 mg QUE/g), and FRAP (27.04 mM TE/g to 445.66 mM TE/g) are consistently observed across all fruit parts at the 1:70 solid-to-liquid ratio. All these phytochemical contents are significantly higher at this ratio except for *B. lanceolata* peels, whose values at 1:70 and 1:50 ratios are not significantly different. TAC has no significant difference at 1:70 and 1:50 for all the fruit parts. For the *A. odoratissimus* seed, the TAC values are not significantly different for all the solid-to-liquid ratios.

Table 2: Phytochemical contents of *A. odoratissimus* and *B. lanceolata* extracts using a 20G extraction system at room temperature at different solid-to-liquid ratios.

Fruit & Parts	Ratio	TPC[1]	TFC[2]	TAC[3]	FRAP[4]	DPPH[5]
***A. odoratissimus* Peel**	1:30	60.17 ± 1.32[a]	4.20 ± 0.08[a]	0.78 ± 0.58[a]	304.92 ± 4.63[a]	**161.51 ± 0.33**[b]
	1:50	64.27 ± 0.95[b]	6.29 ± 0.09[b]	**2.18 ± 0.22**[a]	333.36 ± 3.91[b]	161.13 ± 0.57[b]
	1:70	**82.11 ± 0.98**[c]	**7.68 ± 0.06**[c]	2.03 ± 0.96[a]	**445.66 ± 4.33**[c]	158.05 ± 1.52[a]
***A. odoratissimus* Seed**	1:30	7.11 ± 0.09[d]	2.57 ± 0.15[d]	2.03 ± 0.79[b]	17.97 ± 1.59[d]	4.46 ± 0.09[c]
	1:50	9.54 ± 0.19[e]	4.08 ± 0.07[e]	**2.65 ± 0.79**[b]	17.00 ± 0.40[d]	5.27 ± 0.58[c]
	1:70	**12.27 ± 1.44**[f]	**5.18 ± 0.24**[f]	1.09 ± 0.22[b]	**27.04 ± 0.45**[e]	**8.37 ± 0.13**[d]
***B. lanceolata* Peel**	1:30	7.89 ± 0.37[g]	2.43 ± 0.10[h]	0.31 ± 0.44[c]	19.00 ± 0.06[f]	1.28 ± 0.60[e]
	1:50	9.43 ± 0.83[h]	2.17 ± 0.03[g]	0.47 ± 0.00[c]	29.50 ± 0.39[g]	**2.29 ± 0.74**[e]
	1:70	**9.47 ± 0.48**[h]	**3.04 ± 0.11**[i]	**4.21 ± 1.01**[d]	**44.81 ± 0.70**[h]	1.94 ± 0.53[e]
***B. lanceolata* Seed**	1:30	6.84 ± 0.99[i]	1.60 ± 0.09[j]	1.09 ± 0.22[ef]	28.62 ± 0.62[i]	5.29 ± 0.14[f]
	1:50	7.82 ± 0.39[i]	2.24 ± 0.08[k]	0.78 ± 0.58[e]	41.73 ± 0.35[j]	**6.26 ± 0.99**[f]
	1:70	**12.01 ± 1.32**[j]	**3.58 ± 0.15**[l]	**1.71 ± 0.22**[f]	**53.15 ± 0.83**[k]	5.16 ± 0.46[f]
***B. lanceolata* Flesh**	1:30	5.71 ± 0.49[k]	1.23 ± 0.06[m]	3.58 ± 0.58[g]	20.82 ± 0.27[l]	2.16 ± 0.38[g]
	1:50	6.43 ± 1.13[k]	2.13 ± 0.08[n]	5.14 ± 0.00[h]	30.73 ± 0.15[m]	3.14 ± 0.24[h]
	1:70	**12.25 ± 1.10**[l]	**2.91 ± 0.08**[o]	**5.30 ± 0.79**[h]	**41.05 ± 0.66**[n]	**3.68 ± 0.21**[h]

Results were expressed as mean values ± SD (*n*=3); [a–o]—different lowercase letters (within column) indicate significant difference ($p < 0.05$); [1]TPC was expressed as mg gallic acid equivalent (mg GAE) in 1.0 g of dry sample; [2]TFC was expressed as mg quercetin equivalent (mg QUE) in 1 g of dry sample; [3]TAC was expressed as mg cyanidin-3-glucoside equivalent (mg c-3-gE) in 100 g of dry sample; [4]FRAP expressed as mM Trolox equivalent (mM TE) in 1.0 g of dry sample; [5]DPPH was expressed as mg Trolox equivalent antioxidant capacity (mg TEAC) in 1 g of dry sample.

Effects of temperature and glycerol amount

Total phenolic content (TPC)

At a 1:70 solid-to-liquid ratio, the phytochemical contents and antioxidant activities of the fruit samples extracted with varying portions of glycerol at increasing temperatures showed mixed trends. For the *A. odoratissimus* extracts, there is a general trend of increasing TPC with higher glycerol content (Table 3). However, fluctuations are observed across the extraction systems specifically at 50°C. Conversely, in *B. lanceolata* extracts, the TPC predominantly reaches its peak at the 60G extraction system across the entire temperature range. The TPC of the extracts was in the order of *A. odoratissimus* peel > *A. odoratissimus* seed > *B. lanceolata* seed > *B. lanceolata* flesh > *B. lanceolata* peel.

Table 3: The TPC of *A. odoratissimus* and *B. lanceolata* extracts at different temperatures and glycerol amounts.

Temperature (°C)	Extraction System	*A. odoratissimus*		*B. lanceolata*		
		Peel	**Seed**	**Peel**	**Seed**	**Flesh**
RT	**20G**	82.11 ± 0.98^{b}	12.27 ± 1.44^{a}	9.47 ± 0.48^{b}	12.01 ± 1.32^{a}	12.25 ± 1.10^{b}
	40G	71.24 ± 0.98^{a}	16.84 ± 0.93^{b}	8.59 ± 0.27^{ab}	15.37 ± 0.46^{b}	7.16 ± 0.71^{a}
	60G	123.57 ± 0.73^{c}	22.51 ± 1.47^{c}	10.03 ± 0.89^{b}	26.30 ± 0.55^{c}	11.28 ± 1.09^{b}
	80G	127.77 ± 1.49^{d}	24.89 ± 1.35^{c}	7.56 ± 1.06^{a}	26.04 ± 1.12^{c}	10.16 ± 1.17^{b}
50°C	**20G**	113.00 ± 1.44^{e}	20.90 ± 1.29^{d}	8.75 ± 0.46^{d}	13.09 ± 0.76^{d}	9.93 ± 1.10^{c}
	40G	171.26 ± 1.00^{g}	26.03 ± 1.20^{e}	9.16 ± 0.27^{d}	20.09 ± 1.23^{e}	11.09 ± 0.30^{c}
	60G	154.95 ± 1.42^{f}	**64.46 ± 0.21**^{g}	7.22 ± 0.72^{c}	27.44 ± 1.43^{f}	**21.59 ± 0.40**^{d}
	80G	**175.25 ± 1.08**^{h}	54.46 ± 1.10^{f}	6.30 ± 0.69^{c}	21.48 ± 0.58^{e}	10.40 ± 0.63^{c}
80°C	**20G**	91.52 ± 0.89^{i}	10.58 ± 0.16^{h}	7.37 ± 0.41^{e}	19.12 ± 0.77^{g}	7.23 ± 0.50^{e}
	40G	94.38 ± 0.78^{j}	21.88 ± 0.35^{i}	10.84 ± 0.69^{f}	24.14 ± 0.19^{h}	9.16 ± 1.29^{e}
	60G	105.31 ± 1.26^{k}	21.40 ± 0.42^{i}	**13.20 ± 0.42**^{g}	**31.03 ± 1.46**^{i}	14.94 ± 1.00^{f}
	80G	105.63 ± 1.21^{k}	35.46 ± 1.12^{j}	8.11 ± 0.59^{e}	22.57 ± 0.71^{h}	8.83 ± 0.83^{e}

Results were expressed as mean values ± SD (n = 3); $^{a–k}$—different lowercase letters (within column of the respective temperature) indicate significant difference ($p < 0.05$); TPC was expressed as mg gallic acid equivalent (mg GAE) in 1.0 g of dry sample.

For *A. odoratissimus* peel and seed, and *B. lanceolata* flesh, the highest TPC was observed when the extraction was carried out at 50°C. At this temperature, the most optimal extraction system for both *A. odoratissimus* seed and *B. lanceolata* flesh is at 60G, whereas for *A. odoratissimus* peel, it is at 80G, yielding TPC in the range of 21.59 mg GAE/g to 175.25 mg GAE/g. In the *A. odoratissimus* peel, there are significant differences ($p < 0.05$) between the extraction at 50°C and the extraction at room temperature or 80°C. Conversely, when extracted at 80°C using a 60G extraction system, *B. lanceolata* peel (13.20 mg GAE/g) and seed (31.03 mg GAE/g) demonstrate improved values. Furthermore, for *B. lanceolata* flesh, the highest phenolic yield was produced using a 60G extraction system at 50°C, with a notably greater value compared to the other extraction conditions ($p < 0.05$).

Total flavonoid content (TFC)

According to the data in Table 4, the TFC across the various components *A. odoratissimus* and *B. lanceolata* extracts are lower than their corresponding TPC, and with significantly reduced deviations. The TFC of the extracts was in the order of *A. odoratissimus* peel > *A. odoratissimus* seed > *B. lanceolata* seed > *B. lanceolata* peel > *B. lanceolata* flesh.

Table 4. The TFC of *A. odoratissimus* and *B. lanceolata* extracts at different temperatures and glycerol amounts.

Temperature (°C)	Extraction System	*A. odoratissimus*		*B. lanceolata*		
		Peel	Seed	Peel	Seed	Flesh
RT	**20G**	7.68 ± 0.06^{a}	5.18 ± 0.24^{a}	3.04 ± 0.11^{ab}	3.58 ± 0.15^{a}	2.91 ± 0.08^{a}
	40G	8.93 ± 0.10^{c}	5.26 ± 0.18^{a}	2.88 ± 0.03^{a}	3.80 ± 0.17^{ab}	2.93 ± 0.04^{a}
	60G	8.31 ± 0.43^{b}	5.30 ± 0.13^{a}	2.94 ± 0.09^{a}	3.98 ± 0.11^{b}	2.95 ± 0.04^{a}
	80G	12.49 ± 0.23^{d}	5.23 ± 0.19^{a}	3.17 ± 0.06^{b}	4.06 ± 0.10^{b}	3.00 ± 0.13^{a}
50°C	**20G**	7.84 ± 0.26^{e}	7.35 ± 0.19^{c}	3.03 ± 0.06^{cd}	3.35 ± 0.14^{c}	2.99 ± 0.11^{c}
	40G	9.09 ± 0.16^{f}	6.35 ± 0.24^{b}	3.04 ± 0.16^{cd}	3.39 ± 0.15^{c}	3.01 ± 0.04^{c}
	60G	**22.46 ± 0.31**^{h}	6.46 ± 0.15^{b}	**3.24 ± 0.13**^{d}	3.66 ± 0.14^{c}	2.96 ± 0.09^{bc}
	80G	10.49 ± 0.99^{g}	6.74 ± 0.15^{b}	2.80 ± 0.09^{c}	**4.58 ± 0.23**^{d}	2.78 ± 0.06^{b}
80°C	**20G**	10.65 ± 0.37^{j}	**10.16 ± 0.17**^{f}	2.97 ± 0.15^{e}	3.79 ± 0.05^{f}	3.08 ± 0.15^{de}
	40G	9.39 ± 0.25^{i}	5.93 ± 0.41^{d}	3.01 ± 0.01^{e}	3.27 ± 0.05^{e}	**3.13 ± 0.04**^{e}
	60G	9.44 ± 0.25^{i}	6.84 ± 0.58^{e}	3.12 ± 0.11^{e}	3.23 ± 0.05^{e}	3.06 ± 0.12^{de}
	80G	9.93 ± 0.65^{ij}	6.57 ± 0.10^{de}	3.02 ± 0.08^{e}	3.25 ± 0.01^{e}	2.87 ± 0.07^{d}

Results were expressed as mean values ± SD (n = 3); $^{a–j}$—different lowercase letters (within column of the respective temperature) indicate significant difference ($p < 0.05$); TFC was expressed as mg quercetin equivalent (mg QUE) in 1.0 g of dry sample.

Across the *A. odoratissimus* peel, there is a notable increase in the flavonoid content at 50°C compared to that at room temperature and 80°C, particularly evident in the 60G extraction system (22.46 mg QUE/g). Conversely, *A. odoratissimus* seed exhibits a less consistent trend, displaying minor fluctuations across different temperatures and extraction systems, especially at room temperature and 50°C. The TFC in *A. odoratissimus* seed reached its peak at 80°C using the 20G extraction system (10.16 mg QUE/g).

Similar trends are observed in *B. lanceolata* components, albeit with varying degrees of fluctuation. *B. lanceolata* peel and flesh demonstrate relatively stable flavonoid content across temperatures and extraction systems, showing marginal deviations. Both the peel and flesh exhibit comparable maximum total flavonoid content, recording values of 3.24 mg QUE/g and 3.13 mg QUE/g, respectively. *B. lanceolata* seed, on the other hand, demonstrates a somewhat more apparent response, exhibiting a maximum TFC of 4.58 mg QUE/g, extracted at 50°C in the 80G extraction system.

Total anthocyanin content (TAC)

The data presented in Table 5 are the TAC of the extracts, ranging from 0.31 mg c-3-gE/100 g to 9.51 mg c-3-gE/100g, in the order of *B. lanceolata* peel > *B. lanceolata* seed > *B. lanceolata* flesh > *A. odoratissimus* seed > *A. odoratissimus* peel. The anthocyanin content in *B. lanceolata* is generally higher than that in *A. odoratissimus*. The highest TAC for *A. odoratissimus* peel is 3.58 mg c-3-gE/100 g when extracted using an 80G extraction system at room temperature.

Interestingly, a similar value of 3.43 mg c-3-gE/100 g was obtained with the 20G extraction system, but at a higher temperature of 80°C. Similar trends can be observed in *B. lanceolata* flesh, peaking at 6.70 mg c-3-gE/100 g at the same extraction system and temperature.

Table 5: The TAC of *A. odoratissimus* and *B. lanceolata* extracts at different temperatures and glycerol amounts.

Temperature (°C)	Extraction System	*A. odoratissimus*		*B. lanceolata*		
		Peel	Seed	Peel	Seed	Flesh
RT	20G	2.03 ± 0.96[a]	1.09 ± 0.22[a]	4.21 ± 1.01[b]	1.71 ± 0.22[b]	5.30 ± 0.79[b]
	40G	2.18 ± 0.44[a]	1.56 ± 0.44[a]	1.09 ± 0.79[a]	0.78 ± 0.58[a]	0.78 ± 0.58[a]
	60G	2.96 ± 0.58[a]	0.62 ± 0.58[a]	0.78 ± 0.22[a]	0.31 ± 0.22[a]	2.03 ± 0.58[a]
	80G	**3.58 ± 0.79**[a]	0.62 ± 0.44[a]	4.05 ± 0.44[b]	3.12 ± 0.22[c]	**6.70 ± 0.79**[b]
50°C	20G	2.49 ± 0.96[c]	2.18 ± 0.22[d]	0.78 ± 0.44[c]	0.62 ± 0.22[d]	3.12 ± 0.44[c]
	40G	1.87 ± 0.00[bc]	0.47 ± 0.00[b]	2.03 ± 0.22[d]	1.09 ± 0.22[d]	3.43 ± 0.79[cd]
	60G	2.03 ± 0.96[bc]	1.87 ± 0.38[cd]	2.65 ± 0.58[d]	4.21 ± 0.00[e]	6.23 ± 0.44[e]
	80G	0.78 ± 0.22[b]	1.09 ± 0.79[bc]	0.94 ± 0.38[c]	2.81 ± 0.76[f]	4.83 ± 0.79[de]
80°C	20G	3.43 ± 0.96[e]	2.81 ± 0.38[e]	2.49 ± 0.22[ef]	0.78 ± 0.44[g]	4.68 ± 0.38[fg]
	40G	0.78 ± 0.79[d]	4.05 ± 0.22[fg]	0.94 ± 0.76[e]	1.09 ± 0.96[g]	4.36 ± 1.34[fg]
	60G	2.65 ± 0.79[e]	**4.63 ± 0.25**[g]	2.96 ± 0.96[f]	3.43 ± 0.58[h]	5.92 ± 0.58[g]
	80G	2.96 ± 0.22[e]	3.27 ± 0.66[ef]	**9.51 ± 0.88**[g]	**6.86 ± 0.79**[i]	3.74 ± 0.38[f]

Results were expressed as mean values ± SD (*n* = 3); [a–i]—different lowercase letters (within column of the respective temperature) indicate significant difference ($p < 0.05$); TAC was expressed as mg cyanidin-3-glucoside equivalent (mg c-3-gE) in 100 g of dry sample.

Ferric reducing antioxidant power (FRAP) assay

Based on the tabulated data (Table 6), the ferric reducing ability of the extracts was in the order of *A. odoratissimus* peel > *B. lanceolata* seed > *A. odoratissimus* seed > *B. lanceolata* peel > *B. lanceolata* flesh. Across different extraction systems and temperatures, the reducing ability of *A. odoratissimus* extracts is consistent, reaching its highest at 891.70 mM TE/g (peel) and 142.30 mM TE/g (seed). Conversely, *B. lanceolata* peel and flesh attained their highest values at room temperature with the lowest glycerol content, measured at 44.80 mM TE/g and 41.05 mM TE/g, respectively. *B. lanceolata* seed displays a significantly higher reducing ability of 289.80 mM TE/g, employing the 80G extraction system at 80°C.

Table 6: The FRAP assay of *A. odoratissimus* and *B. lanceolata* extracts at different temperatures and glycerol amounts.

Temperature (°C)	Extraction System	*A. odoratissimus*		*B. lanceolata*		
		Peel	Seed	Peel	Seed	Flesh
RT	20G	445.67 ± 4.33[a]	27.04 ± 0.45[a]	**44.81 ± 0.70**[c]	53.15 ± 0.83[b]	**41.05 ± 0.66**[c]
	40G	615.24 ± 3.48[b]	31.08 ± 1.21[b]	20.15 ± 1.12[a]	46.16 ± 1.17[a]	25.12 ± 0.55[a]
	60G	637.05 ± 5.86[c]	45.26 ± 0.39[c]	20.46 ± 0.31[ab]	75.05 ± 0.61[c]	24.76 ± 0.19[a]
	80G	663.39 ± 1.99[d]	63.00 ± 1.18[d]	21.96 ± 0.13[b]	105.80 ± 1.25[d]	26.28 ± 0.37[b]
50°C	20G	547.62 ± 7.77[e]	46.74 ± 2.16[e]	21.26 ± 0.09[d]	65.53 ± 3.41[e]	28.82 ± 1.17[d]
	40G	832.57 ± 6.78[f]	58.00 ± 0.19[f]	21.55 ± 0.39[d]	120.65 ± 3.04[f]	30.85 ± 0.29[de]
	60G	850.20 ± 2.44[g]	95.94 ± 1.88[g]	27.89 ± 0.56[f]	177.32 ± 3.69[g]	30.02 ± 2.19[de]

	80G	**891.70 ± 5.57**^{h}	**142.28 ± 2.47**^{h}	22.47 ± 0.18^{e}	193.03 ± 3.01^{h}	32.66 ± 1.03^{e}
80°C	**20G**	545.04 ± 3.36^{i}	31.43 ± 1.22^{i}	21.52 ± 0.26^{g}	94.48 ± 2.78^{i}	29.97 ± 1.07^{f}
	40G	620.72 ± 6.76^{j}	46.38 ± 1.04^{j}	26.59 ± 1.33^{h}	148.97 ± 2.04^{j}	32.14 ± 0.82^{g}
	60G	688.04 ± 4.87^{l}	55.71 ± 1.51^{k}	32.07 ± 1.06^{i}	**289.79 ± 3.56**^{l}	35.74 ± 0.40^{h}
	80G	636.81 ± 8.69^{k}	72.20 ± 0.42^{l}	31.02 ± 0.69^{i}	238.32 ± 3.64^{k}	29.59 ± 0.91^{f}

Results were expressed as mean values ± SD (n = 3); $^{a–l}$—different lowercase letters (within column of the respective temperature) indicate significant difference ($p < 0.05$); FRAP expressed as mM Trolox equivalent (mM TE) in 1.0 g of dry sample.

DPPH free radical scavenging assay

The data in Table 7 presented the radical scavenging activity of *A. odoratissimus* and *B. lanceolata* extracts, reflecting a substantial range from 3.85 mg TEAC/g to 319.40 mg TEAC/g. The radical scavenging activity of the extracts was in the order of *A. odoratissimus* peel > *A. odoratissimus* seed > *B. lanceolata* seed > *B. lanceolata* flesh > *B. lanceolata* peel. The radical scavenging activity in *A. odoratissimus* peel varies notably across different extraction systems and temperatures, reaching the peak at the 60G extraction system at 50°C. Conversely, *A. odoratissimus* seed exhibited fluctuations in radical scavenging activity, notably lower than that of *A. odoratissimus* peel. As for *B. lanceolata* components, a similar trend emerges, albeit with different magnitude shifts in radical scavenging activity across extraction conditions. *B. lanceolata* seed consistently demonstrates notably higher radical scavenging activity compared to other *B. lanceolata* components.

Table 7: The DPPH Free Radical Scavenging assay of *A. odoratissimus* and *B. lanceolata* extracts at different temperatures and glycerol amounts.

Temperature (°C)	Extraction System	*A. odoratissimus*		*B. lanceolata*		
		Peel	Seed	Peel	Seed	Flesh
RT	**20G**	158.05 ± 1.52^{b}	8.37 ± 0.13^{b}	1.94 ± 0.53^{a}	5.16 ± 0.46^{a}	3.68 ± 0.21^{a}
	40G	146.83 ± 3.43^{a}	6.49 ± 0.48^{a}	2.95 ± 0.49^{ab}	7.03 ± 0.03^{b}	5.69 ± 0.22^{b}
	60G	160.31 ± 0.58^{b}	13.87 ± 0.38^{c}	**3.85 ± 0.60**^{b}	8.72 ± 0.23^{c}	**7.46 ± 0.14**^{c}
	80G	157.83 ± 3.79^{b}	16.31 ± 0.43^{d}	3.47 ± 0.79^{b}	9.24 ± 0.04^{c}	5.77 ± 0.14^{b}
50°C	**20G**	160.32 ± 3.57^{c}	3.34 ± 0.02^{e}	1.15 ± 0.39^{c}	4.68 ± 0.17^{d}	1.37 ± 0.36^{d}
	40G	319.00 ± 1.24^{e}	4.00 ± 0.18^{e}	1.45 ± 0.11^{cd}	7.36 ± 0.12^{e}	1.45 ± 0.30^{d}
	60G	**319.43 ± 1.93**^{e}	12.59 ± 0.63^{f}	1.86 ± 0.27^{de}	8.23 ± 0.13^{f}	1.49 ± 0.44^{d}
	80G	280.32 ± 9.01^{d}	**17.02 ± 0.03**^{g}	2.35 ± 0.26^{e}	8.55 ± 0.12^{g}	1.32 ± 0.15^{d}
80°C	**20G**	148.00 ± 0.18^{f}	3.53 ± 0.05^{h}	1.25 ± 0.24^{f}	7.52 ± 0.28^{h}	1.27 ± 0.37^{e}
	40G	318.56 ± 1.63^{h}	11.63 ± 0.53^{i}	1.89 ± 0.27^{g}	8.89 ± 0.15^{i}	2.13 ± 0.03^{f}
	60G	298.35 ± 5.63^{g}	13.64 ± 0.42^{j}	2.79 ± 0.21^{h}	**9.34 ± 0.05**^{j}	3.27 ± 0.20^{g}

80G	299.32 ± 6.31^{g}	16.42 ± 0.23^{k}	2.87 ± 0.22^{h}	9.15 ± 0.06^{ij}	3.08 ± 0.41^{g}

Results were expressed as mean values ± SD (*n* = 3); $^{a–l}$—different lowercase letters (within column of the respective temperature) indicate significant difference ($p < 0.05$); DPPH was expressed as mg Trolox equivalent antioxidant capacity (mg TEAC) in 1.0 g of dry sample.

Determination of optimum conditions for extraction

Graphs in Figs. 2–6 illustrate the percentage changes in the phytochemical contents and antioxidant capacity when compared to 80% glycerol-water extracts from *A. odoratissimus* and *B. lanceolata* at room temperature. Notably, increased concentrations are evident in extracts primarily obtained at a temperature of 50°C for *A. odoratissimus* and room temperature and 80°C for *B. lanceolata*. Thus, the optimal extraction condition for *A. odoratissimus* peel appears to be at 50°C using the 60G extraction system (Fig. 2). Meanwhile, for the *A. odoratissimus* seed, extraction at 50°C using an 80G extraction system stands out as the most optimal condition (Fig. 3).

For *B. lanceolata* peel, the most optimal condition appears to be at 80°C using an 80G extraction system (Fig. 4). In the *B. lanceolata* seed, the optimal condition is at 80°C employing a 60G extraction system (Fig. 5), which also proves to be optimal for the *B. lanceolata* flesh (Fig. 6). A summary of all optimal extraction conditions for both *A. odoratissimus* and *B. lanceolata* fruit components has been tabulated (Table 8).

Table 8: Summary of all optimal extraction conditions for both *A. odoratissimus* (peel and seed) and *B. lanceolata* (peel, seed, and flesh).

Parameters	*A. odoratissimus*		*B. lanceolata*		
	Peel	Seed	Peel	Seed	Flesh
Temp. (°C)	50	50	80	80	80
Extraction System	60G	80G	80G	60G	60G

DISCUSSION

Effects of solid-to-liquid ratio

In solid-liquid extraction, the compounds of interest are transferred from the solid matrix into the liquid solvent. This process depends on diffusion rates, which can be influenced by different factors that impact the yield of phytochemical contents, such as the solvent, the solvent-to-liquid ratio, the type of extraction method and temperature (Philippi et al., 2016).

This result shows that the higher solid-to-liquid ratio (1:70) enhanced the solubility and accessibility of phytochemical compounds in aqueous glycerol. This facilitates more effective extraction and leads to increased yields of phenolic and antioxidant compounds. A study on the extraction of anthocyanin from black chokeberry and elderberry fruits (Kowalska et al., 2021) revealed that aqueous alcohol is more effective than aqueous glycerol due to the high viscosity of glycerol ($\eta = 11.10$ mPa), which reduces the diffusion rate. However, increasing the solid-to-liquid ratio of the more viscous solvent, such as glycerol, can enhance the diffusion rate, potentially resulting in a comparable extraction yield (Philippi et al., 2016). This aligns with Fick's law of diffusion, which states that molecules move from regions of higher concentration to regions of lower concentration. Hence, all the experiments for the effects of temperature and % glycerol were set at a 1:70 ratio.

Effects of temperature and glycerol amount

Total phenolic content (TPC)

The study indicates that a higher glycerol content resulted in a better yield of phenolic content, consistent with findings in other studies. For instance, in apple peel extraction, the phenolic content increased with the rise in glycerol content from 10% to 70% (Blidi et al., 2015). Similar trends were observed in red grape pomace extraction, with phenolic content yield increasing up to 50% glycerol (Eyiz et al., 2020), and in the eggplant peel extraction, where the yield increased up to 90% glycerol content (Philippi et al., 2016). This phenomenon is attributed to the decreased polarity of the solvent in aqueous glycerol. Consistent with another study, aqueous solutions containing glycerol or alcohol tend to reduce the polarity of the extraction solvent due to the relatively lower dielectric constant of glycerol ($\varepsilon = 42.5$) and alcohols ($\varepsilon = 32.7$ for methanol, 24.3 for ethanol) (Eyiz et al., 2020; Kowalska et al., 2021). Hence, aqueous mixtures are considered more efficient solvents, considering the limited solubility of polyphenols in water (Bitwell et al., 2023). Moreover, the intermolecular forces, in particular hydrogen bonds, between solute and solvents, along with steric effects, significantly influence the types of compounds that dissolve in the selected solvent (Galanakis et al., 2013).

The TPC in methanol extracts from *A. odoratissimus* peel and seed, as investigated by Abu Bakar et al. (2015), measured at 42.38 mg GAE/g and 13.72 mg GAE/g, respectively, represents the highest TPC among other Artocarpus species. Other Artocarpus species, such as *A. integer* and *A. kemando*, extracted using methanol, have been reported to contain phenolic content ranging from 4.40-21.29 mg GAE/g (flesh < seed < peel) and 6.57-11.67 mg GAE/g (flesh < peel < seed), respectively (Abu Bakar et al., 2014; Abu Bakar et al., 2015). In comparison, durian (*Durio* spp.) flesh, widely known as the “king of fruits”, has been reported to exhibit phenolic content of 74.77 mg GAE/g when extracted with methanol at 80°C for 60 minutes (Sujang et al., 2024). The exceptionally high phenolic content in the peel compared to other counterparts is attributed to its role in self-protection against pathogens, microorganisms and predators (Abu Bakar et al., 2015). These concentrations significantly differ from the glycerol extracts in the present study, even at room temperature.

In a separate study conducted by the same group on methanol extracts of *B. lanceolata*, the TPC across all three counterparts ranges from 3.29 mg GAE/g to 4.81 mg GAE/g (Abu Bakar et al., 2014), which is relatively lower compared to the glycerol extracts at room temperature in this study (7.56 mg GAE/g to 26.04 mg GAE/g). The high phenolic content in the seed may be attributed to the maturity state of the fruit, where phenolics act as antioxidants in the process of seed germination, preventing internal damage from oxidation (Abu Bakar et al., 2015; Dueñas et al., 2009). The ripe pulp of *B. motleyana* exhibited the highest phenolic content at 149.49 mg GAE/g compared to the peel and seed, which contained 53.10 mg GAE/g and 47.60 mg GAE/g, respectively (Prodhan & Mridu, 2021).

Total flavonoid content (TFC)

The TFC of the glycerol extracts is either similar or comparatively lower than that of the corresponding methanol extracts (Abu Bakar et al., 2014; Abu Bakar et al., 2015), even at higher temperatures. The TFC in *A. odoratissimus* seed reached its peak at 80°C using the 20G extraction system (10.16 mg QUE/g), surpassing the other *A. odoratissimus* seed extracts under different conditions. This can be attributed to the increased solubility of flavonoids in water at higher temperatures. According to Arrhenius principles, the activation energy for solute diffusion decreases at higher temperatures, thereby improving extraction efficiency. Additionally, the increased temperatures are likely to stimulate the formation of cavitation

bubbles, enhancing the diffusion rate from the solid to the solvent by maximizing the contact area (Chaves et al., 2020).

At higher glycerol content, a notable decrease in flavonoid content is observed, possibly stemming from reduced cavitation resulting from the viscosity of glycerol or thermal degradation of specific flavonoids (Rodriguez De Luna et al., 2020). The structure of certain flavonoids, which mainly exist as C-glycoside dimers or oligomers, is sensitive to high temperature and prolonged heating (Sharma et al., 2015; ElGamal et al., 2023). Under these conditions, hydrolysis into monomeric forms can occur, resulting in lower measurable flavonoid content (Manach et al., 2004). Similarly, in the study of peppermint and nettle, a significant decrease in flavonoid content was observed as the glycerol content increased from 30% to 50%, reaching its lowest point at 80% glycerol content at 20°C (Kowalska et al., 2021). In methanol-based extractions, *B. macrocarpa* exhibits the highest flavonoid content in the pericarp (44.68 mg cE/g) compared to its flesh and seed, whereas under the same conditions, *B. lanceolata* exhibits the highest flavonoid content in the flesh (4.73 mg cE/g) (Abu Bakar et al., 2014). These findings highlight the influence of solvent choice on flavonoid distribution across different parts of the plant.

Total anthocyanin content (TAC)

Anthocyanins, natural water-soluble flavonoid pigments, infuse fruits and vegetables such as blueberries, plums (Shehat et al., 2020), black chokeberries (Kowalska et al., 2021) and eggplant peels (Philippi et al., 2016) with vibrant blue, red, or purple hues. Despite their susceptibility to degradation during processing and storage, anthocyanins offer benefits for vision and lipid profiles (Kowalska et al., 2021). Industrially, they serve as natural colours in various products, including foods, cosmetics, and drugs, playing a prominent role in pastries, candies, drinks and jellies (Kowalska et al., 2021). Due to their antioxidant properties, anthocyanins contribute to immune system health, potentially aiding in disease prevention and overall well-being. The disparities in anthocyanin levels between these two fruits can be attributed to the influence of the plant material matrix on anthocyanin extraction (Silva et al., 2017). Additionally, *B. lanceolata* fruits transition from purple to green and eventually to brown as they reach full maturity.

Heat enhances the extraction of anthocyanins by increasing the diffusion rate, softening plant tissue, and improving solvent penetration, which collectively enhances the solubility of chemical compounds (Philippi et al., 2016). In the present study, raising the temperature to 80°C notably improves the response in *A. odoratissimus* seed at 4.63 mg c-3-gE/100 g using the 60G extraction system. This aligns with findings in another study on *A. odoratissimus* seed, where the recorded total anthocyanin content was 3.80 mg c-3-gE/100 g (Abu Bakar et al., 2009). Similarly, both *B. lanceolata* peel and seed recorded 9.51 mg c-3-gE/100 g and 6.86 mg c-3-gE/100 g, respectively, employing the 80G extraction system at the highest temperature, showing significant differences compared to the other extraction systems. This may be due to several factors, including the presence of heat-stable acylated anthocyanins that are more resilient at higher temperatures, along with the use of glycerol, which can stabilize and protect anthocyanins against thermal degradation (Zhao et al., 2021).

However, in *A. odoratissimus* peel, the response decreases from 3.58 mg c-3-gE/100 g at room temperature to 2.96 mg c-3-gE/100 g at 80°C using the highest glycerol concentration. This may be attributed to the presence of more monoacylated compounds that are prone to degradation into small colourless compounds (Xue et al., 2024). A similar trend was observed in *B. lanceolata* flesh.

The methanolic extraction of *Mangifera pajang* demonstrated significantly higher anthocyanin content in the peel (28.29 mg c3g/100 g) than in the flesh (1.47 mg c3g/100 g) (Abu Bakar et al., 2009). In contrast, another *Baccaurea* species, *B. angulata* exhibited higher anthocyanin levels in the berries than in the skin (1.20 mg c3g/100 g vs 0.96 mg c3g/100 g) (Abu Bakar et al., 2014). Additionally, *Canarium odontophyllum*, a fruit native of Borneo, has been reported to contain anthocyanin content of 2.49 mg c3g/100 g (Chew et al., 2011). Notably, the rind of seasonal purple *Garcinia mangostana* demonstrated exceptionally high total monomeric anthocyanin content (17,652.54 mg/L) when extracted using an acidified solvent system via microwave-assisted extraction, highlighting its strong potential as a safe natural food colourant (Netravati et al., 2024).

Ferric reducing antioxidant power (FRAP) assay

The FRAP assay measures a substance's antioxidant capacity by evaluating its ability to reduce ferric ions (Fe^{3+}) to ferrous ions (Fe^{2+}), resulting in noticeable changes in colour. The colour shift correlates directly with the antioxidant concentration or the reducing power of the sample. Essentially, the FRAP assay offers a way to evaluate a substance's capacity as an electron donor, effectively reducing oxidized species. It serves as a valuable tool to gauge the potential antioxidant capabilities of a substance.

Notably, the highest values were obtained at 50°C using the 80G extraction system for *A. odoratissimus* extracts. The values across the extraction systems at each temperature showed significant differences ($p < 0.05$), indicating an effect of the glycerol percentage on the reducing ability. This effect can be attributed to the strong hydrogen-bonding capacity of glycerol, which contains three hydroxyl groups (Chen et al., 2022). The solvent can form extensive hydrogen bonds with phenolics, particularly those with high electron-donating potential, thereby enhancing their mass transfer and solubilization. As these polyphenols are responsible for reducing Fe^{3+} to Fe^{2+}, higher glycerol content leads to an increase in the ferric reducing ability of the extract.

Conversely, *B. lanceolata* peel and flesh attained their highest values at room temperature with the lowest glycerol content, measured at 44.80 mM TE/g and 41.05 mM TE/g, respectively. These components exhibited comparatively lower reducing ability compared to the seed, indicating a similar capacity of ferric ion reduction for both peel and flesh. Evidently, *B. lanceolata* seed displays a significantly higher reducing ability of 289.80 mM TE/g, employing the 80G extraction system at 80°C, implying a potentially heightened antioxidant activity compared to its counterparts. These findings suggest distinct chemical compositions or antioxidant profiles in *B. lanceolata* seed compared to the other components.

Similar to *A. odoratissimus* peel, *A. integer* peel exhibited significantly higher reducing ability of 218.91 µM/g than its seed and flesh (Abu Bakar et al., 2015). In contrast, *A. kemando* seed demonstrated higher reducing ability (61.45 µM/g) compared to its other counterparts (Abu Bakar et al., 2015). In addition, methanolic extraction of its bark has been reported to yield remarkably high reducing ability of 3,382 µmol/g, highlighting the strong reducing potential of non-edible tissues (Mohd Yazid et al., 2021).

DPPH free radical scavenging assay

The DPPH assay evaluates a substance's antioxidant capacity by gauging its ability to neutralize DPPH free radicals. When the stable deep, purple-coloured free radical reacts with antioxidants in the samples, electron transfers occur, resulting in a reduction or discolouration of the purple hue. Typically, the outcomes from the DPPH assay are expressed as Trolox

Equivalent Antioxidant Capacity (TEAC), offering a standardized measure that benchmarks the sample's antioxidant capacity against Trolox, a well-known synthetic antioxidant.

The radical scavenging activity in *A. odoratissimus* peel varies notably across different extraction systems and temperatures. Comparable values ($p > 0.05$) were observed between the extraction systems at different temperatures; however, the increased temperature had an impact on the values. This effect can be attributed to the softening of the *A. odoratissimus* peel tissues, which facilitates the release of antioxidant compounds into glycerol as well as improved diffusion that leads to penetration of solvent into the cell wall (Gil-Martín et al., 2022). Additionally, increased thermal energy accelerates reaction kinetics, leading to more effective collisions between antioxidants and free radicals, thereby enhancing scavenging efficiency (Toydemir et al., 2022).

While temperature showed no impact ($p = 0.538$), glycerol content played a pivotal role in enhancing the values of *A. odoratissimus* seed ($p < 0.05$). This can be attributed to the moderate polarity of glycerol, which, when combined with water, creates a solvent system that can efficiently extract antioxidant compounds across a broad range of polarities (Lim et al., 2024).

As for *B. lanceolata* components, a similar trend emerges, albeit with different magnitude shifts in radical scavenging activity across extraction conditions. Interestingly, while *B. lanceolata* seed reaches its peak DPPH scavenging activity at 80°C, measured at 9.34 mg TEAC/g, the radical scavenging activity of *B. lanceolata* peel and flesh extracts peaks at room temperature (3.85 mg TEAC/g for peel and 7.46 mg TEAC/g for flesh). These values indicate that different parts of *B. lanceolata* are affected differently by temperature and extraction systems, resulting in varied radical scavenging activities.

Apart from the two fruits investigated in this study, many Bornean tropical fruits possess high antioxidant potential, particularly in their peels and seeds, such as mangosteen fruit peel (John et al., 2025), highlighting their value as sustainable sources of natural antioxidants for food, cosmetic, and pharmaceutical applications (John et al., 2025). The utilization of the non-edible parts reduces agricultural waste, which aligns with green chemistry principles. Strategic cultivation is essential to ensure sustainable and continuous raw phytochemical supply, promote agricultural diversification, and increase farmers' income through the development of value-added products.

Determination of optimum conditions for extraction

In the previous studies by Abu Bakar et al. (2014; 2015), *A. odoratissimus* and *B. lanceolata* were extracted using the conventional method with 80% methanol at room temperature. When compared with the results in this present study, the 80% glycerol-water extracts (at room temperature) exhibited significantly higher values of the phytochemical contents and antioxidant capacity. The enhanced efficiency of UAE, in terms of both extraction yield and time, is considered one of the contributing factors. Ultrasonic power generates cavitation bubbles within the liquid medium, which grow and release a significant amount of energy. This energy disrupts the integrity of the solid matrix, facilitating the dissolution of solutes into the liquid phase (Bitwell et al., 2023).

Analyzing the *A. odoratissimus* peel graph reveals a decrease across all the phytochemical contents at 20% glycerol content at all temperatures. At 50°C, the TPC, FRAP and DPPH percentages rise significantly at higher glycerol contents. Specifically, at 60% glycerol content, almost all phytochemical contents and antioxidant capacities surpass those observed under

other conditions. Thus, the optimal extraction condition for *A. odoratissimus* peel appears to be at 50°C using the 60G extraction system. Meanwhile, for *A. odoratissimus* seed, extraction at 50°C using 80G extraction system stands out as the most optimal condition, showcasing moderate increases in all the responses. At lower glycerol percentages, DPPH percentages tend to decrease across all temperatures. A remarkable anthocyanin content increase is observed at 80°C, yet the increase in other phytochemical contents is minimal or even demonstrates a decrease in percentage. Consequently, these incremental changes are negligible, rendering them insignificant.

For *B. lanceolata* peel, DPPH percentage predominantly decreased across varying temperatures and glycerol content compared to the extracts obtained at room temperature using 80G extraction system. However, considerable increases were observed in FRAP and polyphenols percentages at 80°C. At its highest glycerol content, there was a significant surge in the percentage of anthocyanin content. Hence, the most optimal condition for *B. lanceolata* peel appears to be at 80°C using an 80G extraction system. In the *B. lanceolata* seed, noticeable increments are evident at 60G and 80G extraction systems, especially at a temperature of 80°C. Despite two notably increased responses to the latter extraction system, the superiority lies with the 60G extraction system due to a greater number of responses showing substantial increments. This establishes that the extraction at 80°C employing a 60G extraction system is the most optimal condition for *B. lanceolata* seed. Correspondingly, this extraction condition also proves to be optimal for *B. lanceolata* flesh. The graph illustrates that at this specific parameter, there are noticeable percentage increases in total phenolic and flavonoid contents as well as ferric reducing ability. In addition, the decreases in other responses are comparatively less significant when compared to alternative parameters.

Potential industrial applications

The glycerol extracts derived from *A. odoratissimus* and *B. lanceolata* fruit wastes exhibit notable bioactivity, including remarkable antioxidant capacity (319.43 mg TEAC/g in *A. odoratissimus* peel) and substantial anthocyanin content (6.70 mg c-3-gE/100 g to 9.51 mg c-3-gE/100 g in *B. lanceolata*). These findings suggest broad potential for value-added applications in the cosmetic, nutraceutical and pharmaceutical industries. Glycerol has low toxicity when ingested, inhaled, or applied to the skin (Wernke, 2024), making these extracts generally safe for product development. However, further safety assessments remain necessary to confirm its suitability for intended applications.

The pronounced antioxidant activity, particularly in *A. odoratissimus* peel extracts, supports their incorporation as active ingredients in cosmetic formulations aimed at skin protection and rejuvenation. Their antioxidant properties may help to improve skin texture and enhance hydration. Additionally, these extracts can be explored for topical formulations related to wound healing or other oxidative stress-related skin conditions. In nutraceutical applications, the high anthocyanin content suggests a potential as natural colourants, although further purification and stability assessments are required. Apart from that, the phenolic-rich extracts can be incorporated into functional foods, beverages, or dietary supplements to combat oxidative stress and overall health (Nirmal et al., 2023). Further studies on safety, stability, bioavailability, and biological activities, including anti-inflammatory, antimicrobial, and cytotoxicity profiles, are vital to substantiate and refine their potential applications.

Future work

The primary aim of this study was to optimize the glycerol-based extraction parameters and evaluate the phytochemical content of the selected fruit components. Therefore, additional

investigations, such as solvent comparison, method validation, biological activity, toxicological assessments, and cosmetic formulations, were beyond the scope of the current work and are therefore proposed as future research. Also, a UAE using methanol under the same optimized parameters to enable a direct comparison with the glycerol-based system will be studied. This will allow a clearer evaluation of which solvent offers substantial efficiency in extracting phenolic compounds from *A. odoratissimus* and *B. lanceolata* fruits. Furthermore, recovery validation experiments, such as extraction efficiency tests or spiking recovery tests, shall be conducted to further assess the accuracy and reproducibility of the extraction method. To support their potential industrial applications, further work will also involve conducting biological evaluations, such as cytotoxicity, anti-inflammatory activity and antimicrobial activity of the extracts. The formal toxicological assessments will also be necessary to confirm their safety for potential dermal or oral applications. Once the safety and functional performance have been established, the extracts may be incorporated into cosmetic formulations. This will require a substantial amount of additional work, as multiple formulation parameters, such as texture, viscosity, pH, stability, and antioxidant activity, must be optimized and systematically evaluated. Further studies will also be necessary to determine how the formulated products interact with the skin, as well as to assess the preservation of antioxidant activity after incorporation. These steps are vital to develop high-quality cosmetic products, particularly for anti-aging applications.

CONCLUSIONS

This study highlights glycerol-water as an effective solvent for extracting phytochemicals from *A. odoratissimus* and *B. lanceolata*, demonstrating comparable to or higher polyphenolic yield than those reported for methanol extracts in previous studies. Results revealed diverse total phenolic, flavonoid, and anthocyanin content across fruit parts at different temperatures and solvent systems, influenced by the solid matrix and chemical composition. The optimal extraction temperatures were determined to be 50°C for *A. odoratissimus* and 80°C for *B. lanceolata*. The most effective extraction solvent systems were those with 60% glycerol content for *A. odoratissimus* peel, *B. lanceolata* seed, and *B. lanceolata* flesh, whereas *A. odoratissimus* seed and *B. lanceolata* peel demonstrated optimal results with 80% glycerol content. The inedible parts of *A. odoratissimus* and *B. lanceolata* consistently outperformed *B. lanceolata* flesh in phytochemicals content and antioxidant activities, aligning with existing studies that attribute these compounds to the inherent defense mechanism of the fruits against pathogens and parasites, as well as acting as antioxidants to mitigate internal damage. Notably, *A. odoratissimus* peel exhibited exceptionally high antioxidant activities, aligning with its abundant total phenolic content. This suggests that fruit waste, particularly *odoratissimus* peel, has potential as a potent antioxidant agent. Incorporating the extract into cosmetic, nutraceutical, or food products valorizes local fruit wastes and promotes environmental sustainability. It also creates economic opportunities for farmers and supports the development of eco-friendly products, utilizing their phytochemical richness to deliver functional benefits.

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DECLARATIONS

Research permit(s). Not applicable.
Ethical approval/statement. Not applicable.
Generative AI use. The authors declare that generative AI has been used in compliance with the JTBC policies, and that we have reviewed and edited the content after using this tool/service and we take full responsibility for the content of the publication.

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