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Dehydration of phenolic-rich extract from rambutan (Nephelium lappaceum L.) peel by foam mat drying

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ABSTRACT

Foam mat drying was used for the dehydration of a phenolic-rich rambutan peel extract. Foam products were evaluated for their physicochemical stability during storage. Experiments were carried out to determine the effect of foaming (10% of egg albumin/soy protein/pea protein) and stabilizing agents (0.5% of methylcellulose); storage conditions i.e. type of packages (polyethylene, glass), packaging techniques (modified atmosphere packaging, vacuum) under light or dark at 30 °C on phenolic compositions, antioxidant activity, water activity (a_w), and color of foam products during 5 months storage. Foam products produced from egg albumin showed the highest total phenolic content (TPC) (8.73 ± 0.17 mg GAE/g) and antioxidant activity (7.47–9.70 mg TE/g). During storage, TPC, antioxidant activity, and the amount of individual phenolic compounds (geraniin, corilagin, rutin, ellagic acid, and quercetin) mostly decreased independent of the presence of light. A_w in all samples increased from 0.25 to 0.38 - 0.45 (except for the samples in glass packaging); whereas the color of the samples was insignificantly changed for 5 months. Rambutan peel phenolic-rich extract encapsulated within egg albumin can be stored at least 5 months with minimal quality changes and might be used as a food preservative ingredient.

1. Introduction

Fruit and vegetable processing activities yearly generate large amounts of by-products, mainly composed of leaves, peels, pomace, skins, rinds, cores, pits, pulp, stems, seeds, twigs, and spoiled fruits and vegetables. In the US, these by-products were approximated at 7.8 and 18.9 million tons from fruits and vegetables respectively in 2009. They are potential sources for extracting valuable natural compounds and chemicals. The most products were produced such as bioactive compounds, enzymes, exopolysaccharides, bioplastics, biopolymers, and biofuels (Esparza et al., 2020).

Rambutan fruit (*Nephelium lappaceum* L.) is one of the tropical fruits with a high world annual production (estimated at approximately 1.4 million metric tonnes (MMT) in 2015–2017 (FAO, 2018)). It is consumed as fresh and processed fruit. During processing, rambutan peel (RP) and seeds are discarded in the environment. RP recently received much attention due to its phenolic profile, such as the presence of geraniin, ellagic acid, quercetin, rutin, and corilagin (Nguyen et al., 2019). Some studies indicated that RP extracts possess several potential properties namely antioxidant (Phuong, Le, Dang, et al., 2020a,b,c), antidiabetic (Ma et al., 2017), and antimicrobial activities (Phuong, Le, Dang, et al., 2020a,b,c).

However, the obtained extracts do not exist in a solid form; and thus, they are often unstable and cannot easily be applied. Dehydration is the most commonly used technique for transferring liquid products into dried ones or powdery forms, which increases the shelf-life of dried extracts and opens perspectives for the use of these products in different food formulations. Several processes are used for dehydration such as spray drying, foam mat drying, freeze drying, vacuum drying, infrared drying, microwave drying, radio frequency drying, electro-hydrodynamic drying, and hybrid drying (Shishir & Chen, 2017; Zhang et al., 2017). Freeze drying and vacuum drying are often considered to be too costly to be applied on a large scale for dehydrating liquid food ingredients. Spray drying is commonly used to produce powdery

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products. However, spray drying has some disadvantages of which one is its high drying temperature (can be more than 200 °C) and this might lead to the degradation of phenolic compounds (Shishir & Chen, 2017). In the meantime, foam mat drying is a process with several advantages compared to the other mentioned drying techniques such as it is a relatively simple and inexpensive process, and it has a rapid drying rate at a low temperature (de Cól et al., 2021). Foam mat drying is very well suited for the dehydration of heat-sensitive, sugar-rich, sticky, and viscous food products e.g. fruit juices that are difficult to dry using other drying methods (Hardy & Jideani, 2017). The produced powder from foam mat drying is capable of rehydrating in water and restoring its original product quality. In this process, a liquid product is converted into a stable foam by the addition of foaming agents (e.g. egg albumin, soy protein, ovalbumin, soy lecithin, gelatin, and whey protein) and/or stabilizing agents (e.g. methylcellulose, carboxymethyl cellulose, xanthan gum, and alginates). Among surface-active agents, methylcellulose has foaming, emulsifying and stabilizing properties and is commonly used as a stabilizer in the foam mat drying technique (Dehghannya et al., 2018). The percentage of methylcellulose that can be used is up to 2–3% (Qadri et al., 2020; Samyor et al., 2021). The foam is then oven-dried at relatively low temperatures (40–90 °C) in a short time (2–3 h) to form a thin porous honeycomb sheet or mat which can be disintegrated to yield a fine powder (Hardy & Jideani, 2017; Rajkumar et al., 2007). Therefore, foam mat drying is commonly applied for the preparation of fruit and vegetable powders of e.g. grape juice (Maria et al., 2019), lime juice (Dehghannya et al., 2018), beetroot (Ng & Sulaiman, 2018), jambolan juice (Iasnaia et al., 2017), mango (Lobo et al., 2017; Rajkumar et al., 2007), carrot juice (Janiszewska-Turak et al., 2017), date (Seerangurayar et al., 2017), sour cherry (Abbasi & Azizpour, 2016), muskmelon (Asokapandian et al., 2016), yacon juice (Franco et al., 2015), papaya (Kandasamy et al., 2012), tamarind (Phaechamud et al., 2012), mandarin (Kadam et al., 2011), tomato juice (Kadam & Balasubramanian, 2011), and banana (Thuwapanichayanan et al., 2008). Those studies focused on the efficiency of foam mat drying to preserve the chemical quality (i.e. total phenolic content, anthocyanin content, antioxidant activity of bioactive compounds) and physical properties (i.e. density, color, and solubility index) of the food matrix. However, the dried products by foam mat drying might not always remain of good quality in comparison with other drying techniques (e.g. spray drying). Indeed, oxidative reactions can be accelerated due to an enormous increase in the liquid-gas contact surface. This leads to the deterioration of product quality including flavor and vitamin loss (Qadri et al., 2020).

Although foam mat drying has been used to produce different fruit powders, very few studies have reported the application of foam mat drying on plant extracts as well as on the extracts of fruit by-products to keep their bioactive compounds e.g. carotenoid extract from pequi fruit (Pinto et al., 2018). Indeed, lyophilisation is often used as a drying method of plant extracts for laboratory experiments. Especially, there are few studies evaluating the stability of extracts in powdery forms obtained by foam mat drying. For instance, proanthocyanidins in red sorghum extract were encapsulated using foam mat drying (Susanti et al., 2021). In this study, the authors showed the yield of encapsulation of 16.24–18.29% (wb). In another study, anthocyanins extracted from Indonesian black glutinous rice were encapsulated with 10% maltodextrin and 7.5% egg white, giving the highest anthocyanins content (0.45 ± 0.06 mg/g powder) (Pramitasari & Herlina, 2023). Therefore, the objectives of this study were to investigate (1) the effect of different foaming agents (egg albumin, soy, and pea proteins) and a stabilizing agent (methylcellulose); and (2) the effect of type of packaging materials (i.e. polyethylene and glass), packaging techniques (i.e. modified atmosphere packaging-MAP and vacuum), and storage conditions (i.e. light and dark) at 30 °C on the changes of physicochemical quality such as total phenolic content, antioxidant activity, phenolic composition, color, and water activity of foam rambutan peel extract powder.

2. Materials and methods

2.1. Materials

2.1.1. Chemicals

Folin-Ciocalteu (FC) reagent, 2,2′-azinobis-(3-ethylbenzothiazoline-6-sulfonic acid) radical cation ($ABTS^{\cdot+}$), 2,2-diphenyl-1-picrylhydrazyl (DPPH), 6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid (trolox), methylcellulose, egg albumin (62–88% protein), gallic acid, ellagic acid, and rutin were from Sigma-Aldrich (St. Louis, MO, USA). Sodium carbonate (Na_2CO_3), HPLC-grade methanol, and HPLC-grade water were purchased from VWR International (Leuven, Belgium). Geraniin and corilagin were purchased from Phytolab (Vestenbergsgreuth, Germany). Quercetin dihydrate was obtained from Extrasynthese (Lyon, France). Soy protein (68–69%) and pea protein (83–85%) were kindly provided by Vita blend (The Netherlands) and INGRIZO N.V (Belgium), respectively.

2.1.2. Rambutan peel extract preparation

Three batches of 5–10 kg of rambutan fruits (Java type, commercial ripeness with red color for whole fruit, °Brix 18–19) were purchased at local markets (Can Tho City, Vietnam). The fruits were transported to the laboratory at room temperature. The peel was carefully separated by hand and prepared as described by Nguyen et al. (2019). They were then oven-dried at 65 °C for 24 h. Dried rambutan peel (RP) was stored in polyethylene (PE) bags and covered with aluminum bags, and then stored at −20 °C. Before extraction, dried RP was ground into a powdery form (passed through a 1 mm sieve mesh) using a grinder (Moulinex-DPA141, France). Extraction of phenolic compounds from RP was done using methanol 80%, according to the method of Nguyen et al. (2019). Methanol from the extract was completely evaporated using a rotary evaporator (RV 10 Basic, IKA, Germany). The yield of RP extract was about 10–12%. The concentrated extract was stored at −20 °C for further use.

2.1.3. Foam production

Egg albumin, soy and pea proteins were used as foaming agents and methylcellulose (MC) as a stabilizing agent in the foam mat drying process, according to the methods of Lobo et al. (2017) and Rajkumar et al. (2007). Concentrated RP extract prepared in part 2.1.2 (10%, w/w) was well mixed with MC (0.5%, w/w), foaming agents (10%, w/w), and distilled water (79.5%). The mixture was whipped using an ultraturrax (IKA, Germany) at 10 000 rpm for 3–5 min. The foam was then oven-dried (Venti-line, VWR, Poland) at 60 °C on stainless steel trays with 1–2 mm thickness until the moisture content was constant (approximately 2–4 h, moisture content of 6–7%). After drying, the products were ground into fine powder for further experiments. Control samples (without RP extract) were also prepared. The experiment was carried out in two independent repetitions (duplicate for a treatment, n = 4). A total of 24 samples ((3 foaming agents + 3 control samples) x 2 replications x 2 independent repetitions) were produced.

2.2. Experimental designs

The foam products prepared in part 2.1.3 were packed in small portions (0.5 g) in PE bags with ziplock (40 × 60 mm, 50 μm of thickness) and glass vials with aluminum caps (1.5 mL, 11.6 × 32 mm) without flushing. The samples in PE bags were sealed with vacuum (Multivac, Kansas, US) (referred to as PE-V) and air (referred to as PE-A). All samples were stored at 30 °C in a storage room equipped with an air conditioner together with a controller (ambient temperature in Southeast Asia i.e. Vietnam) in dark and light conditions. For the light condition, samples were placed in a closed chamber equipped with two lamps (LED 9 W, 700 lumen per each). At different time points (0, 1, 2, 3, 4, and 5 months), the samples were taken for stability evaluation. The experiment was carried out in two independent repetitions (two batches,

duplicate for a batch, n = 4).

2.3. Analytical assays

2.3.1. Total phenolic content (TPC) and antioxidant activity assays

First, phenolic compounds from foam powder (0.1 g) were re-extracted in 6 mL of 20, 50, and 80 % methanol and water. Methanol 20% gave the highest yield (Table 1S-supplementary file) and was therefore used for re-extraction of the phenolic compounds of the foam powders. The extraction was done for all treatments, including control samples. These methanolic extracts that might include interference with unencapsulated compounds were assayed for TPC and antioxidant activity.

The TPC was determined using Folin-Ciocalteu (FC) reagent and was measured following the methods of Singleton et al. (1999) and Phuong, Le, Dang, et al. (2020)a,b,c. In a test tube, 1 mL extract was mixed with 0.5 mL of FC reagent (10 times dilution with distilled water) and left for 6 min, followed by the addition of 1.5 mL of sodium carbonate (20%, w/v). The mixtures were kept for 2 h in the dark at room temperature. The absorbance was measured at 760 nm (UV–1800, Shimadzu, Japan). TPC was expressed as mg of gallic acid equivalent (GAE) per g of foam powder.

Antioxidant activity (ABTS and DPPH assays) followed the method of Nguyen et al. (2019). For ABTS assay, 20 μl extract was reacted with 2 mL of the $ABTS^{\bullet+}$ solution for 5 min in the dark at room temperature. The absorbance was then measured at 734 nm. For DPPH assay, the extract (100 μL) was allowed to react with 2 mL of the DPPH solution for 30 min in the dark at room temperature. The absorbance was then measured at 517 nm. The results were expressed in mg trolox equivalent (TE) per g of foam powder.

2.3.2. High-performance liquid chromatography (HPLC)

Quantification of the phenolic compounds in RP extract followed the method of Thitilertdecha et al. (2010) with some modifications. Phenolic compounds of foam RP powder were firstly re-extracted with methanol 20% as described in part 2.3.1. Analysis was then done with an Agilent 1100 series HPLC system equipped with on-line degasser (Model 590, Alltech elite degassing system, USA), quaternary pump (G 1311A), Alltima™ - column18 (5 mm, 4.6 mm × 150 mm; Grace, Deerfield, IL), photodiode array detector (DAD) (G 1315B, Agilent 1100 series). Mobile phase A and B consisted of HPLC-grade water and methanol of 95:5 and 5:95 (v/v), respectively. Both solvent A and B contained 0.4% (v/v) formic acid. The analysis was achieved as follows: 0 min, 100% A, 0–5 min, 5% B, 5–10 min, from 5 to 20% B, 10–11 min, 30% B, 11–16 min, 30% B, 16–20 min, 60% B, 20–22 min, 100% B, 22–30 min, 100% B. Identification was done by comparing retention times (RT) and spectra from the DAD detector with pure standards i.e. geraniin and corilagin (280 nm); rutin, ellagic acid, and quercetin (254 nm). Quantification was done by external calibration curves for each phenolic compound. Results are expressed as mg per g of foam powder. Some validation parameters of the method are given in Table 1.

2.3.3. Color measurement

Color of foam-dried products was measured using a colorimeter (ColorFlex EZ 0130–45/0, HunterLab, USA). The calibration was conducted with black and white ceramic plates. The L*, a*, and b* values define the three-dimensional color space in which L^* was expressed for the lightness from black (0) to white (100), a^* from green (−) to red (+), b^* from blue (−) to yellow (+), and total color change was expressed as:

$$\Delta E^* = \sqrt{\left[(L - L_o)^2 + (a - a_o)^2 + (b - b_o)^2\right]}$$

where L^*, a^*, and b^* color values of the samples, and L_o^*, a_o^*, and b_o^* color values of the control samples (month 0).

2.3.4. Water activity

Water activity (a_w) was measured using the chilled-mirror dewpoint technique at 25 ± 0.05 °C (Aqualab 4 TE, Biosystem, US).

2.4. Statistical analysis

All the experiments were performed in independent biological replicates and each replicate was analyzed twice. Results are presented as mean ± standard deviation. The normality of a distribution of the data set was checked before performing the one-way ANOVA and the two-way ANOVA. The Tukey test and paired-samples T Test were conducted using the IBM SPSS statistical software version 20 (New York, United States). Differences between the mean levels of the treatments in the different experiments were taken to be statistically significant at $p < 0.05$. For two-factor experiments, we presented the effects of two factors, and possible interaction effects of the two factors, on a response

Table 2
Effects of foaming agents on phenolic compositions and antioxidant activity of foam rambutan peel powder.

Chemical composition	Foaming agent			
	Egg albumin	Soy protein	Pea protein	*p value*
TPC (mg GAE/g)	8.73 ± 0.17^{c*}	3.34 ± 0.25^{b}	2.05 ± 0.08^{a}	*0.001*
DPPH (mg TE/g)	7.47 ± 0.20^{b}	5.81 ± 0.09^{a}	5.03 ± 0.26^{a}	*0.002*
ABTS (mg TE/g)	9.70 ± 1.49^{ns}	9.11 ± 0.99^{ns}	6.52 ± 0.35^{ns}	*0.106*
Phenolics (mg/g)				
Geraniin	3.86 ± 0.27^{b}	2.55 ± 0.26^{ab}	1.90 ± 0.06^{a}	*0.026*
Corilagin	0.26 ± 0.17^{ns}	0.32 ± 0.01^{ns}	0.15 ± 0.02^{ns}	*0.367*
Rutin	0.48 ± 0.06^{a}	0.70 ± 0.01^{b}	0.59 ± 0.05^{ab}	*0.037*
Ellagic acid	1.15 ± 0.23^{ns}	1.08 ± 0.01^{ns}	1.53 ± 0.11^{ns}	*0.108*
Quercetin	5.47 ± 0.08^{c}	1.23 ± 0.11^{b}	0.50 ± 0.01^{a}	*0.001*
Total	*11.22 ± 0.55*	*5.88 ± 0.40*	*4.67 ± 0.53*	

TPC, total phenolic content; GAE, gallic acid equivalent; TE, trolox equivalent. *, mean ± STDEV; means within a row with different lower case letters are significantly different ($p < 0.05$); ns: not significant.

Table 1
Calibration data of phenolic standards.

Phenolic compounds	Linearity range (mg/L)	Calibration equation[a]	Correlation factor (r^2)	LOD[b] (mg/L)	LOQ[c] (mg/L)	REC[d] (%)
Geraniin 1	12.5–200	Y = 1.82x + 17.83	0.9964	4.81	16.03	100.69
Geraniin 2	12.5–200	Y = 1.07x + 9.60	0.9936	6.44	21.46	99.41
Ellagic acid	6.25–100	Y = 10.72x + 243.60	0.9856	4.83	16.09	98.63
Rutin	6.25–100	Y = 24.27x + 9.61	0.9964	2.42	8.06	105.38
Quercetin	6.25–100	Y = 1.17x + 12.47	0.9967	2.30	7.65	98.41

[a] 5 data points.
[b] Limit of detection.
[c] Limit of quantification.
[d] Recovery.

variable (Tables 3–5). Deeply, to compare the effect of different storage time points, the data was presented for response variables by storage time. To compare the effect of different packagings, the data was presented for response variables by packaging.

3. Results and discussion

3.1. Effects of foaming agents on total phenolic composition and antioxidant activity of foam rambutan peel powder

Foam mat drying with different foaming agents i.e. egg albumin, soy and pea proteins; and stabilizing agent i.e. methylcellulose (MC) was used for dehydrating RP extract into a powdery form. The RP foam characteristics in terms of phenolic content and antioxidant activity are presented in Table 2. The treatment of egg albumin recorded the highest TPC with a value of 8.73 ± 0.17 mg GAE/g of foam ($p = 0.001$), followed by the treatments of soy protein (3.34 ± 0.25 mg GAE/g) and pea protein (2.05 ± 0.08 mg GAE/g). The results on TPC were correlated with antioxidant activity assayed by DPPH method. Indeed, the highest value was also found for the treatment with egg albumin with 7.47 ± 0.20 mg TE/g of foam ($p = 0.002$). Although TPC of the treatment with soy protein was lower than those in the treatment with egg albumin, antioxidant activity assayed by ABTS method was the same (9.11 - 9.70 mg TE/g) ($p = 0.106$). Main phenolic compounds namely geraniin, corilagin, rutin, ellagic acid, and quercetin were quantified in foam RP powder (Table 2). Not only TPC but also the phenolic compositions in the different treatments were not the same. Clearly, quercetin contributed to 49% of the phenolic compounds in the egg albumin treatment while it was only 11% in pea protein treatment. Conversely, rutin (4.28%) and ellagic acid (10.25%) were only present in a small proportion in egg albumin treatment, but they contributed to a high extent in the total phenolic compounds in pea protein treatment i.e. 13% (rutin) and 33% (ellagic acid). Geraniin (34.4–43.37%) and corilagin (2.30–5.44%) were almost present in the same proportions in all treatments. In comparison with the proportion of the phenolic compounds in the original extract, the proportion of phenolic compounds in the foam powders was changed depending on the type of foaming agents used during drying. Indeed, geraniin was in the original extract present in the highest proportion (51%), followed by ellagic acid (23%) and quercetin (22%). Rutin and corilagin had only a limited contribution as their proportions were 4.67 and 2.0%, respectively. It can be hypothesised that the effect of foaming agents on the ability of phenolic encapsulation and the differences observed among the different phenolic compounds can be explained by the differences in the structure and polarity of phenolic compounds, as well as in the difference in amino acid compositions of the proteins and their hydrophobic/hydrophilic properties. Another explanation could be due to the partial unfolding (surface denaturation) of proteins during foam production. The ability of egg albumen to rapidly adsorb on the air-liquid interface during the whipping process forms a cohesive viscoelastic film that acts as a foaming agent (Lomakina & Mikova, 2006). Lechevalier et al. (2005) indicated that the configuration (tertiary and secondary structures) of ovalbumin, ovotransferrin, and lysozyme present in egg albumin could unfold irreversibly during foaming production, in which amino acids (i.e. amino acids with sulfhydryl groups) could be exposed and react with phenolic compounds. This denaturation could occur to a different extent depending on proteins, thus the ability for encapsulation of egg albumim, soy, and pea proteins towards phenolic compounds was different.

Some studies showed that the possible reaction of phenolic compounds was at the reactive side chains of proteins (i.e. lysine) or at the heterocyclic *N*-atom of tryptophan through covalent binding. Phenolic compounds like quercetin and myricetin with hydroxy substituents on the ring B and C (positions 3, 3′, 4′, 5’) of flavonoids have strong reactions with lysine side chains of proteins to form covalent bonds (Kroll et al., 2003). However, this hypothesis was incomplete since other studies showed amino acid residues like proline, methionine, histidine, and tyrosine also had the potential to react with phenolic compounds (Kroll et al., 2003; Kroll & Rawel, 2001). The reaction of phenolic compounds and proteins can change the hydrophilic and hydrophobic characteristics of protein derivates which might affect their proteolytic digestion.

The foaming characteristics are very important for the design and preparation of foam products. The foam structure stability is one of the important factors in drying foamed materials and this stability enables a high speed of drying due to a huge surface area exposed to the drying air, ensuring a fast moisture removal. Therefore, foam mat-dried materials can keep the quality of the products and protect potentially heat-sensitive components during oven drying (Ayetigbo et al., 2021; Hardy & Jideani, 2017). In this study, using the same amount of foaming and stabilizing agents, the foam from the treatment with egg albumin had more expansion and stability than other treatments (soy and pea proteins) (Fig. 1). Thus, drying time of the treatment with egg albumin (2 - 2 h 30) was faster and preserved a higher total phenolic content and antioxidant activity of RP extract than other proteins (drying time of 3–4 h) as also demonstrated in previous studies (Garau et al., 2007; Vega-Gálvez et al., 2009). This is because the structure and compositions

Table 3
The change of total phenolic content and antioxidant activity of foam rambutan peel powder using different foaming agents during storage in different packages under light condition at 30 °C.

	Egg albumin			Soy protein			Pea protein		
	TPC	DPPH	ABTS	TPC	DPPH	ABTS	TPC	DPPH	ABTS
Storage time (month)									
0	$8.73 \pm 0.13^{c*}$	7.47 ± 0.16^{a}	9.70 ± 1.49^{abc}	3.34 ± 0.19^{d}	5.81 ± 0.07^{bc}	9.11 ± 0.76^{c}	2.05 ± 0.06^{c}	5.03 ± 0.20^{d}	6.52 ± 0.27^{d}
1	8.28 ± 0.16^{b}	9.40 ± 2.02^{b}	9.70 ± 1.49^{abc}	2.55 ± 0.30^{bc}	4.66 ± 0.59^{a}	6.81 ± 0.90^{b}	1.11 ± 0.09^{a}	4.25 ± 0.59^{c}	3.88 ± 0.48^{ab}
2	8.28 ± 0.19^{b}	16.97 ± 0.75^{e}	9.70 ± 1.49^{abc}	2.36 ± 0.13^{ab}	5.42 ± 0.37^{b}	6.88 ± 0.94^{b}	1.45 ± 0.10^{b}	3.93 ± 0.38^{bc}	5.50 ± 0.44^{cd}
3	8.25 ± 0.15^{b}	13.70 ± 0.36^{c}	9.82 ± 0.61^{abc}	2.13 ± 0.19^{a}	4.40 ± 0.34^{a}	6.68 ± 0.59^{b}	1.13 ± 0.08^{a}	2.91 ± 0.45^{a}	4.25 ± 0.36^{ab}
4	8.29 ± 0.17^{b}	15.86 ± 0.46^{d}	8.04 ± 0.81^{ab}	2.76 ± 0.32^{c}	6.11 ± 0.66^{c}	7.16 ± 0.71^{b}	1.42 ± 0.19^{b}	3.64 ± 0.42^{bc}	4.72 ± 0.58^{bc}
5	7.81 ± 0.13^{a}	17.88 ± 0.76^{f}	7.68 ± 0.16^{a}	2.03 ± 0.27^{a}	5.63 ± 0.42^{bc}	5.57 ± 0.71^{a}	1.28 ± 0.11^{ab}	3.26 ± 0.66^{ab}	3.56 ± 0.83^{a}
p value	*0.001*	*0.001*	*0.001*	*0.001*	*0.001*	*0.001*	*0.001*	*0.001*	*0.001*
Packaging									
PE-V	8.30 ± 0.35^{ns}	13.65 ± 3.61^{ns}	10.80 ± 1.09^{ns}	2.56 ± 0.43^{ab}	5.19 ± 0.58^{a}	7.21 ± 1.09^{ab}	1.36 ± 0.37^{ns}	3.81 ± 1.06^{ns}	4.60 ± 1.22^{ns}
PE-A	8.29 ± 0.29^{ns}	13.68 ± 3.90^{ns}	10.79 ± 1.80^{ns}	2.40 ± 0.60^{a}	5.23 ± 0.93^{a}	6.62 ± 1.42^{a}	1.44 ± 0.34^{ns}	3.73 ± 0.79^{ns}	4.78 ± 1.24^{ns}
Glass	8.23 ± 0.29^{ns}	13.30 ± 4.82^{ns}	10.72 ± 2.31^{ns}	2.61 ± 0.47^{b}	5.60 ± 0.69^{b}	7.26 ± 1.35^{b}	1.42 ± 0.32^{ns}	3.97 ± 0.61^{ns}	4.84 ± 1.01^{ns}
p value	*0.352*	*0.046*	*0.968*	*0.031*	*0.007*	*0.027*	*0.155*	*0.298*	*0.577*

*, mean ± STDEV; means within a column with different lower case letters are significantly different ($p < 0.05$) using two-way ANOVA and presented for a factor; ns: not significant; PE-V, PE-A, and Glass referred to samples stored in vacuum, air polyethylene bags, and glass bottles, respectively; mg gallic acid equivalent/g for TPC; mg trolox equivalent/g for DPPH and ABTS.

Table 4
The stability of phenolic compositions of foam rambutan peel powder in different packages under light condition at 30 °C.

	Geraniin	Corilagin	Rutin	Ellagic acid	Quercetin
	(mg/g)				
	Egg albumin				
Storage time (month)					
0	$3.86 \pm 0.01^{b*}$	0.26 ± 0.13^{a}	0.48 ± 0.05^{b}	1.15 ± 0.18^{ab}	5.47 ± 0.07^{b}
3	4.26 ± 1.03^{b}	1.09 ± 0.29^{c}	0.43 ± 0.16^{b}	1.35 ± 0.60^{b}	2.41 ± 0.56^{a}
5	1.46 ± 0.32^{a}	0.70 ± 0.26^{b}	0.27 ± 0.05^{a}	0.83 ± 0.23^{a}	1.84 ± 0.40^{a}
p value	*0.001*	*0.001*	*0.002*	*0.020*	*0.001*
Packaging					
PE-V	3.30 ± 0.59^{ns}	0.73 ± 0.44^{ns}	0.37 ± 0.12^{ns}	1.08 ± 0.33^{b}	3.16 ± 0.89^{ns}
PE-A	3.18 ± 0.48^{ns}	0.79 ± 0.45^{ns}	0.46 ± 0.15^{ns}	1.39 ± 0.48^{b}	3.35 ± 0.68^{ns}
Glass	3.19 ± 0.40^{ns}	0.54 ± 0.38^{ns}	0.35 ± 0.11^{ns}	0.87 ± 0.32^{a}	3.24 ± 0.08^{ns}
p value	*0.880*	*0.205*	*0.050*	*0.021*	*0.660*
	Soy protein				
Storage time (month)					
0	3.86 ± 0.01^{c}	0.26 ± 0.13^{a}	0.48 ± 0.05^{b}	1.15 ± 0.18^{c}	5.47 ± 0.07^{b}
3	1.45 ± 0.58^{b}	0.53 ± 0.10^{b}	0.61 ± 0.05^{c}	0.67 ± 0.16^{b}	0.25 ± 0.24^{a}
5	0.27 ± 0.09^{a}	0.16 ± 0.07^{a}	0.29 ± 0.03^{a}	0.38 ± 0.09^{a}	ND
p value	*0.001*	*0.001*	*0.001*	*0.001*	*0.001*
Packaging					
PE-V	2.07 ± 0.64^{b}	0.34 ± 0.24^{ns}	0.48 ± 0.14^{ns}	0.74 ± 0.34^{ns}	1.97 ± 0.72^{ns}
PE-A	1.81 ± 0.65^{ab}	0.35 ± 0.18^{ns}	0.46 ± 0.17^{ns}	0.74 ± 0.40^{ns}	1.93 ± 0.75^{ns}
Glass	1.70 ± 0.70^{a}	0.27 ± 0.14^{ns}	0.44 ± 0.14^{ns}	0.70 ± 0.38^{ns}	1.82 ± 0.82^{ns}
p value	*0.012*	*0.422*	*0.539*	*0.786*	*0.125*
	Pea protein				
Storage time (month)					
0	1.90 ± 0.28^{c}	0.15 ± 0.02^{a}	0.60 ± 0.04^{b}	1.53 ± 0.08^{b}	0.5 ± 0.01
3	1.23 ± 0.42^{b}	0.29 ± 0.08^{b}	0.59 ± 0.06^{b}	1.24 ± 0.33^{b}	ND
5	0.21 ± 0.08^{a}	0.10 ± 0.05^{a}	0.26 ± 0.05^{a}	0.53 ± 0.19^{a}	ND
p value	*0.001*	*0.001*	*0.001*	*0.001*	
Packaging					
PE-V	1.23 ± 0.84^{ns}	0.19 ± 0.11^{ns}	0.46 ± 0.19^{ns}	1.01 ± 0.60^{ns}	0.5 ± 0.01
PE-A	1.16 ± 0.79^{ns}	0.16 ± 0.04^{ns}	0.48 ± 0.20^{ns}	1.11 ± 0.54^{ns}	ND
Glass	0.96 ± 0.09^{ns}	0.20 ± 0.13^{ns}	0.50 ± 0.14^{ns}	1.18 ± 0.36^{ns}	ND
p value	*0.223*	*0.485*	*0.460*	*0.517*	

*, mean ± STDEV; means within a column for a foaming agent with different lower case letters are significantly different ($p < 0.05$) using two-way ANOVA and presented for a factor; ns: not significant; PE-V, PE-A, and Glass referred to samples stored in vacuum, air polyethylene bags, and glass bottles, respectively; ND, not detected.

of proteins determine the properties of foaming. Egg albumin mainly consists of ovalbumin (45 kDa) which represents about 54% of the total protein content, next to other proteins present (i.e. ovotransferrin, ovomucoid, ovomucin, and lysozyme). It is responsible for most of its functional properties such as foaming, emulsification and heat-setting (Pereira et al., 2016). On the other hand, soy and pea proteins have mainly a larger molecular weight distribution. Indeed, soy protein mainly consists of globulins (80%) i.e. glycinin (360 kDa) and β-conglycinin (150–180 kDa) (Nishinari et al., 2014), pea protein consists of globulins (65–80%) (i.e. legumin with 320–380 kDa) and albumin (66.5 kDa) (10–20%) (Barac et al., 2010; Burger & Zhang, 2019). Ovalbumin forms a single layer at the air-water interface which is a good characteristic to act as a surfactant; it usually provides the best foaming properties (Hardy & Jideani, 2017). Besides, the functional characteristics of soy protein isolates are gelation, emulsification, viscosity, water binding, dispersability and foaming properties. However, if the concentration of soy protein used in the formulation is too high (more than 10%), this leads to the reduction of the foaming density, and the instability of soy protein foams (Sangamithra et al., 2015). This may be due to the compact tertiary structure of the soy protein which provides poor foaming properties such as foam formation. The results were similar to the ones of Rajkumar et al. (2007) who reported that egg albumin and MC retained the highest nutritional quality characteristics of mango pulp compared to the use of soy protein as a foaming agent.

Another consideration is the interactions/incompatibilities between proteins and MC in the solution. The protein-MC interactions are very important for the formation, structure, and physical properties of mixed gel systems (Benichou et al., 2002; Turgeon et al., 2003). Proteins form a visco-elastic adsorbed layer, creating a mechanical barrier against coalescence, whereas MC forms a fluid layer that allows it rapidly to spread in response to surface tension gradients. As a result of these interactions in solution, the adsorption of hydrocolloids at the interface and functional properties of the system may well be affected. The impact may be positive in terms of synergistic interactions giving an increase in surface elasticity, or they may be negative as a result of hindered adsorption and higher interfacial tensions (Arboleya & Wilde, 2005). Therefore, foam properties totally depend on the structures and compositions of proteins and types of surfactants. These hypotheses partially explain the current results in which the foaming stability was different for egg albumin, soy, and pea proteins used.

3.2. The stability of physicochemical properties of foam rambutan peel powder during storage at different conditions

The quality and stability of foam RP powder need to be recorded for some time because the structures of some foaming agents can be

Table 5
The color stability of foam rambutan peel powder using egg albumin as foaming agent in different packages under light conditions at 30 °C.

Storage time (month)	L^*	a^*	b^*	ΔE
0	76.98 ± 0.11^{b**}	2.79 ± 0.10^{a}	26.66 ± 0.20^{c}	–
1	75.75 ± 0.22^{ab}	3.13 ± 0.22^{b}	24.49 ± 3.07^{a}	3.19 ± 2.31^{a}
2	76.19 ± 0.69^{ab}	3.17 ± 0.30^{b}	24.39 ± 2.27^{a}	2.75 ± 1.93^{a}
3	74.93 ± 0.61^{a}	3.25 ± 0.20^{b}	25.28 ± 2.60^{ab}	3.17 ± 1.64^{a}
4	75.70 ± 0.94^{ab}	3.32 ± 0.10^{b}	25.42 ± 3.10^{ab}	3.00 ± 2.02^{a}
5	76.22 ± 0.76^{ab}	3.31 ± 0.14^{b}	25.83 ± 3.04^{bc}	2.69 ± 1.80^{a}
p value	*0.004*	*0.001*	*0.001*	*0.686*
Packaging				
PE-V	75.91 ± 0.90^{ns}	3.21 ± 0.22^{b}	22.45 ± 2.08^{a}	5.31 ± 0.77^{b}
PE-A	75.94 ± 1.08^{ns}	3.28 ± 0.24^{b}	26.60 ± 0.38^{b}	1.60 ± 0.81^{a}
Glass	76.03 ± 0.60^{ns}	2.99 ± 0.22^{a}	26.98 ± 1.42^{b}	1.96 ± 0.49^{a}
p value	*0.911*	*0.001*	*0.001*	*0.001*

**, mean ± STDEV; means within a column with different lower case letters are significantly different ($p < 0.05$ using two-way ANOVA and presented for a factor; ns: not significant; PE-V, PE-A, and Glass referred to samples stored in vacuum, air polyethylene bags, and glass bottles, respectively.

changed or degraded during storage under accelerated conditions i.e. light, oxygen as well as packaging materials, affecting the encapsulation ability of foaming agents towards phenolic compounds. Therefore, the physicochemical stability of foam RP powder was evaluated for 5 months of storage at 30 °C under dark and light conditions with different packages.

3.2.1. Chemical compositions

Foam powder produced from RP extract with egg albumin, soy, and pea proteins and MC was packed in glass bottles without flushing and LDPE package by vacuum and air. During 5 months of storage, the TPC of foam powder in the treatments with egg albumin, soy and pea proteins significantly decreased with time of storage ($p = 0.001$), while the packaging had only a significant impact on foam powder with soy protein (Table 3) ($p = 0.031$). In light conditions, TPC loss started at the first month in all treatments; and after 5 months a TPC loss in egg albumin, soy, and pea protein treatments of 10.54, 39.22, and 37.56% was observed independent of the type of packaging ($p = 0.001$) (Table 3). The same trends were found for all treatments under dark conditions (Table 2S – supplementary file). The results were according to the findings of Ramakrishnan et al. (2018) who reported that the anthocyanin and carotenoid content of tamarillo powders were degraded (6–10%) in the presence of light at 25 °C after 28 days.

Regarding the antioxidant activity, the results of all treatments under light conditions are presented in Table 3. Similarly, storage time had a significant influence on the antioxidant activity (DPPH and ABTS values) of RP phenolics encapsulated with all proteins ($p = 0.001$); whereas packaging only showed the effect on the antioxidant activity of soy protein treatment during 5 months of storage ($p = 0.007–0.027$). Particularly, antioxidant activity in the treatments with soy and pea proteins had a downward trend after 5 months of storage in which the ABTS values varied from 9.11 ± 0.76 to 5.57 ± 0.71 mg TE/g and from 6.52 ± 0.27 to 3.56 ± 0.83 mg TE/g, respectively. Although ABTS values of egg albumin treatment were unchanged, DPPH values increased from 7.47 ± 0.16 to 17.88 ± 0.76 mg TE/g after 5 months ($p = 0.001$). Antioxidant activity in all the treatments almost decreased as the decrease of TPC was observed. However, the increased antioxidant activity observed in the egg albumin treatment can probably be because lysozyme (3.5%, 14.4 kDa) is present in egg albumin. Lysozyme may be a good substrate for the production of bioactive peptides with antioxidant activity (Carrillo et al., 2016), which was also confirmed by You et al. (2010). However, this should be demonstrated if there was any remaining lysozyme activity in the egg albumin used in this study. Also, proteins might be hydrolyzed into free amino acids with antioxidant properties (i.e. cysteine, methionine, tyrosine, and histidine) during storage that have an effect on the antioxidant activity measurement (Atmaca, 2004; You et al., 2010). Therefore, the antioxidant activity of foam RP powder in egg albumin treatment probably partly increased due to these peptides/free amino acids. Additionally, this hypothesis can be confirmed by the results of the total amount of individual phenolic compounds presented in Table 4. During storage, the amount of the phenolic compounds decreased, while antioxidant activity increased; which means other antioxidative compounds were probably formed during storage.

The content of the individual phenolic compounds, as measured by HPLC, showed a downward trend in all the samples during storage. The changes in phenolic composition were almost the same under light and dark conditions (Fig. 2). The results showed that foaming agents clearly influenced the total individual phenolic content of foam RP powders. The highest value was found for egg albumin (11.22 mg/g), followed by soy (5.88 mg/g) and pea protein (4.67 mg/g) treatments ($p = 0.001$). During storage, the results showed that storage time affected the amount of individual phenolic compounds ($p = 0.001–0.02$); whereas the type of packaging did not show any effect on the phenolic compositions ($p = 0.05–0.88$), except for ellagic acid in egg albumin ($p = 0.021$) and geraniin in soy protein treatments ($p = 0.012$) (Table 4).

Particularly, amongst the main phenolic compounds corilagin was the most stable after 5 months except for egg albumin treatment in which corilagin slightly increased from 0.26 ± 0.13 to 0.70 ± 0.26 mg/g ($p = 0.001$). The other compounds i.e. geraniin, rutin, ellagic acid, and quercetin significantly decreased in all treatments after 5 months of storage. For instance, the amount of geraniin decreased from 3.86 ± 0.01 to 1.46 ± 0.32 mg/g (egg albumin), from 3.86 ± 0.01 to 0.27 ± 0.09 mg/g (soy protein), from 1.90 ± 0.28 to 0.21 ± 0.08 mg/g (pea protein) ($p = 0.001$). In particular, quercetin was not detected in soy and pea protein treatments after 3 or 5 months. This could be due to the fact that its initial level was quite low in soy and pea protein treatments, thus it might be degraded to a level that was lower than the detection limit.

Fig. 1. Foam production with different foaming agents.

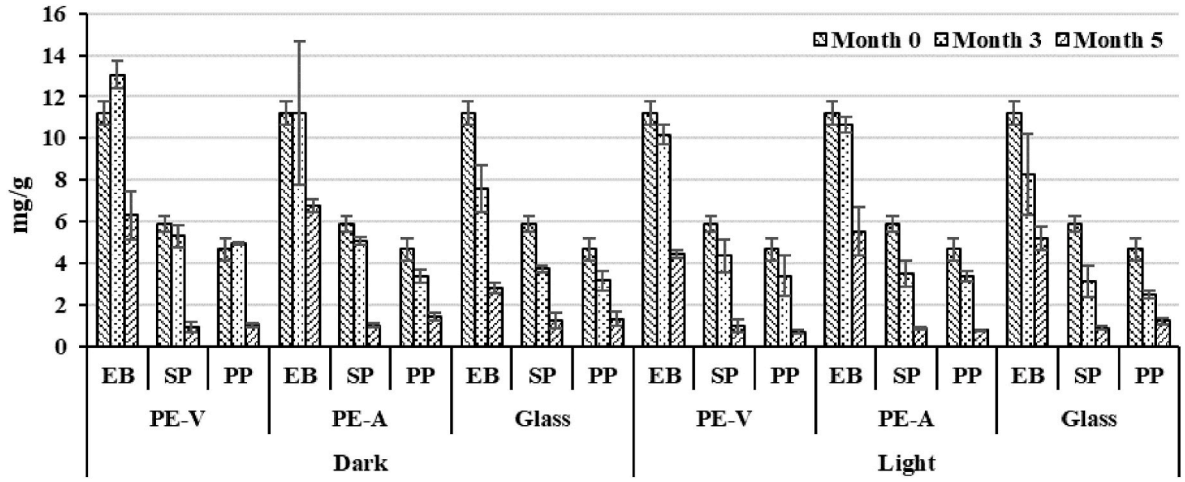

Fig. 2. The change of total phenolic compositions of foam rambutan peel powders during storage under dark and light conditions at 30 °C
The results expressed as mean ± STDEV; EB, SP, and PP referred as foam rambutan peel powder using egg albumin, soy, and pea proteins as foaming agents, respectively; PE-V, PE-A, and Glass referred to samples stored in vacuum, air polyethylene bags, and glass bottles, respectively.

Phenolic compounds have different structures and polarities and they can interact/link to proteins in different ways namely hydrogen-bond, pi-pi stacking, and hydrophobic interactions which were extensively reviewed in previous studies (Tao et al., 2020). This encapsulation also depended on the composition and hydrophobic/hydrophilic properties of proteins. Therefore, it can be concluded that the stability of phenolic compounds during storage depends on their characteristics and type of foaming agent used for their encapsulation.

3.2.2. *Physical properties*

Water activity (a_w) is the most important parameter of water in terms of the chemical and physical stability of food as well as microbial safety. A product is most stable at an a_w value of about 0.1–0.3 (Sablani et al., 2007). Foam RP powder had a low a_w, with values of 0.25 ± 0.004 for egg albumin, 0.27 ± 0.009 for soy protein, and 0.26 ± 0.001 for pea protein treatments. During 5 months of storage, both storage time and type of packaging influenced the a_w values of RP foam powder ($p = 0.001$). The a_w values of foam powder in all the treatments stored under light conditions were almost lower than those in dark conditions except for foam powder stored in glass bottles after 5 months (Fig. 3). For example, the a_w values of RP foam packed in PE-V and PE-A for egg albumin treatment increased to 0.38 in light and 0.43–0.44 in dark conditions after 5 months ($p = 0.008$–0.04); with an a_w value of those samples packed in glass bottles were almost stable with the values of 0.26 in both dark and light conditions after 5 months of storage ($p = 0.775$) (Fig. 3). Similar patterns were recorded for soy and pea protein treatments (Figs. 1S and 2S - supplementary file).

The a_w values of the treatments stored in dark conditions (excluding glass package) increased, but they were low (below 0.45) which means that the powders were microbiological safe. Other chemical reactions i.e. enzyme activity and browning might occur at a low rate due to a_w belonging to the adsorbed water zone (0.3–0.7) (Rahman, 2009). These results were in accordance with the result of Wilson et al. (2014) who indicated that there was an increase in moisture content of foam mango powder during storage. The a_w changes might come from the environmental fluctuations that could have altered relative humidity outside the packaging material (Taoukis et al., 1988; Wilson et al., 2014).

The lower a_w is desirable for food powders to prevent agglomeration

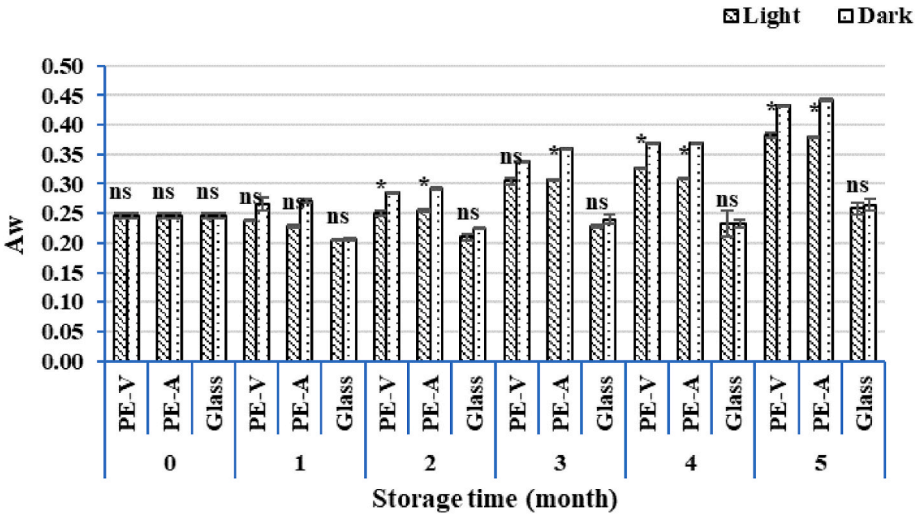

Fig. 3. The change of water activity of foam rambutan peel powder using egg albumin as foaming agent during storage in different packages under dark and light conditions at 30 °C
The results expressed as mean ± STDEV; ns, not significant difference ($p > 0.05$) between light and dark conditions for a packaging in a storage month; *, significant difference ($p < 0.05$) between light and dark conditions for a packaging in a storage month; PE-V, PE-A, and Glass referred to samples stored in vacuum, air polyethylene bags, and glass bottles, respectively.

and caking, which can result in wet powders, degradation of bioactive compounds, and hindrance of the flowability and dispersion, to extend the shelf life of the powders (Ramakrishnan et al., 2018). Packaging materials i.e. glass, plastic have different physical properties e.g. moisture absorption (water vapour permeability) and gas barrier. Glass material might prevent moisture absorption better than PE material. Although PE bags have a low water vapour permeability, they allow moisture absorption from dried products during storage. Moreover, we used LED to produce light which LED is not 100 % efficient at converting input power into light. Some of the energy is converted into heat and must be transferred to the ambient (Andonova et al., 2016). Therefore, powder sealed in glass bottles, which have a better heat transfer than PE package, prevents moisture absorption from the environment. Thus, the a_w values of foam prepared with different foaming agents stored in glass bottles were stable during storage.

Color is a major quality attribute in powdery products. The pigment compounds responsible for the color of RP peel are anthocyanins which can be extracted together with phenolic compounds. Therefore, the color of foam products came from the anthocyanins and the color of proteins. The results of L^*, a^*, and b^* of foam powder of egg albumin treatment in all packages in light conditions were recorded in Table 5. Visually no change in the color of the samples in all treatments under light and dark conditions was observed during storage. Storage time affected L^*, a^*, and b^* values ($p = 0.001$–0.004); while packaging only influenced a^* and b^* values ($p = 0.001$). Particularly, the initial L^*, a^*, and b^* values were 76.98 ± 0.11, 2.79 ± 0.10, and 26.66 ± 0.20, respectively. After 3 months, the L^* value decreased to 74.93 ± 0.61 and kept stable for 5 months (76.22 ± 0.76); whereas the a^* values changed after one month and remained unchanged until 5 months of storage (3.13 ± 0.22–3.31 ± 0.14). The b^* value decreased from the first month (24.49 ± 3.07) and kept the same value at the end of storage (25.83 ± 3.04). The same trends were found for other treatments (Tables 3S and 4S – supplementary file).

The total color difference (ΔE) of egg albumin treatment was not affected by storage time ($p = 0.686$), but it was affected by the type of packaging ($p = 0.001$). Certainly, the ΔE value was unchanged for 5 months of storage with the value around 3.19 ± 2.31–2.69 ± 1.80. However, the ΔE values of RP foam packed in PE-V (5.31 ± 0.77) were significantly different in comparison with those samples packed in PE-A (1.60 ± 0.81) and glass bottles (1.96 ± 0.49) ($p = 0.001$). The same patterns were found for soy and pea protein treatments (data not shown). The color of all samples stored under dark conditions did not change in terms of L^*, a^*, b^* and, ΔE values (Tables 3S and 4S – supplementary file). The color change of some powdery products i.e. tomato powder (Liu et al., 2010), mango powder (Jaya & Das, 2005), and carrot powder (Tang & Chen, 2000) during storage was reported to decrease in L^* value during storage (3–5 months) at 25–45 °C with or without the presence of light. These results were contrary to our study in which the L^* values were stable. It can be clear that the changes in physical properties of foam rambutan peel powder were not pronounced. The stability of foam products can be obtained due to foaming agents i.e. egg albumin and MC during foam production, foam stabilization during oven drying, and storage conditions.

4. Conclusions

The study demonstrated that foam mat drying is sufficient to obtain RP powder products with high retention of phenolic compounds, including geraniin, corilagin, rutin, ellagic acid, quercetin, and antioxidant activity. Egg albumin (10%) used as a foaming agent together with methylcellulose (0.5%) produced foam RP powder which maximally retained phenolic content and antioxidant activity. With the presence or absence of light, total phenolic content, individual phenolic compounds, and antioxidant activity in foam RP powder were influenced by storage time at 30 °C. However, the effect of packaging materials (glass and PE), as well as packaging techniques (vacuum and air) on phenolic compositions and antioxidant activity, was not pronounced. Glass material prevented moisture absorption and kept low a_w (about 0.3) of foam RP powder. Besides, the color of foam RP powder was stable during storage. Using foam mat drying for encapsulation of RP phenolics within protein matrices i.e. egg albumin, RP powder products could be preserved and used as natural ingredients/preservatives in the preparation of food products and pharmaceutical industries.

However, some points should be taken into consideration for a successful foam mat drying resulting in a high-quality powder. For instance, a common foam mat drying technique cannot be performed for oxygen-sensitive products because of the presence of air during whipping. Therefore, nitrogen or nitrous oxide gases can be incorporated for producing foam. Proper understanding of foaming characteristics such as foam density, foam expansion, and foam stability is needed for process optimization. Further studies on optimum conditions for the foaming process such as concentrations of egg albumin, MC agents, pH of foam, dried foam layer, and drying temperature need to be elaborated to improve foaming properties and maximize encapsulation efficiency.

CRediT authorship contribution statement

Nguyen Nhat Minh Phuong: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Thien Trung Le:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **John Van Camp:** Writing – review & editing, Supervision. **Katleen Raes:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.lwt.2024.115973.

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