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Physicochemical Properties and Nutritional Compositions of Foamed Banana Powders (Pisang Awak, *Musa sapientum* L.) Dehydrated by Various Drying Methods

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Abstract

The objective of this research was to evaluate the physicochemical properties and nutritional compositions of foamed banana powders, as affected by various drying methods. The foaming process of banana puree was undertaken by using whey protein concentrate (5 %) as a foaming agent. After that, the banana foam was dehydrated by various drying methods, including hot air drying, vacuum drying, and freeze drying. Unfoamed banana puree dried by hot air drying was used as the control treatment. All the foamed banana powders exhibited higher L* and b* and lower a* values than that of the unfoamed one. Lower solubility and hygroscopicity were observed in the unfoamed banana powder, compared to all the foamed banana powders. All the foamed banana powders contained higher total phenolic contents (TPC), β-carotene, thiamine, and riboflavin, as well as ascorbic acid, compared with the unfoamed banana powder. Among the foamed banana powders, the freeze dried powder had the lowest bulk and compaction density, while the solubility and hygroscopicity were the highest. The highest nutrition components, mentioned above, and antioxidant activities were found in the foamed banana powders dehydrated by freeze drying, followed by vacuum drying and hot air drying, respectively. Therefore, the banana powder made by the foaming process and consequently subjected to freeze drying was of a higher quality, in terms of nutritional compositions as well as antioxidant capacities.

Keywords: Foam mat drying, banana, foam, freeze drying, hot air drying, vacuum drying

Introduction

Bananas (Musa ssp.) are important agricultural commodities of Thailand, and can be produced throughout the country. In particular, Kluai Hom (Gros Michel, *Musa sapientum* L. Fam) and Kluai Khai (Pisang Mas, *Musa acuminate* Colla.) have good potentiality for production and export. As for Kluai Nam Wa (Pisang Awak, *M. sapientum* L.), this fruit is usually consumed within the country and produced for desserts. The nutritional importance of banana is mainly due to its β-carotene, as well as its phenolic compounds, depending on the cultivars. Other important vitamins are ascorbic acid (vitamin C), thiamine (vitamin B1), and riboflavin (vitamin B2), and it is also rich in dietary fiber [1-3]. Thailand has large plantations that only aim at exportation of the fruit. Part of the production does not meet the minimal standard required for export and is lost after harvesting. Excess production is frequent, and there is excessive fruit loss after harvesting because bananas are perishable and cannot be stored for long periods. Thus, preservation techniques such as drying should be applied to produce banana powder [4]. Based on the nutritional components (ascorbic acid, thiamine and riboflavin) of banana, banana powder can be used as an ingredient in some new formula foods and, consequently, have a large market potential. For example, banana powder is currently applied in new product developments such as banana milk drink, banana cake, banana biscuit, infant banana powder, and banana powder juice drink.

Foam-mat drying is an alternative and relatively simple method which enables the removal of water from heat-sensitive, high-sugar content and viscous foods that are difficult to dry. The main advantages of foam-mat drying are that lower temperatures and shorter drying times are used when compared to non-foamed material. Over the years, foam-mat drying has been applied to many fruits and other food materials, including mango [5,6], star fruit [7], cowpea [8], tomato [9], and mandarin orange [10]. There are some reports related to the production of banana powder by foam-mat drying [3,4]. Thuwapanichayanan *et al*. [3] studied the effects of foam density and types of foaming agents (fresh egg albumen, soy protein isolate, and whey protein concentrate) on the moisture effective diffusivity and quality of banana foams. They found that egg albumin and whey protein concentrate (WPC) provided superior foam ability than soy protein isolate. In addition, WPC banana foam had the least shrinkage, highest void area fraction, and highest value of the effective moisture diffusivity. Sankat and Castagine [4] examined the drying characteristics of banana foam mats and identified the factors which influenced its drying characteristics. They reported that the drying behavior of the banana foam mat was strongly affected by the physical characteristics of the foam (the density and thickness). However, there have been no reports showing the effects of different drying methods on the properties and nutritional components of the foamed banana powder. The Pisang Awak (Kluai Nam Wa) is currently selected for use as raw material, since this banana is normally planted in Thailand; however, its shelf life and application in food products are still limited. This results in large losses of the crop and a lessening in value. Thus, the production of the banana powder could be used as an alternative way to apply Kluai Nam Wa for new product developments. According to our preliminary investigations, 2 categories of foaming agents, such as proteins (WPC, soy protein, gelatin, egg albumin) and polysaccharide (methyl cellulose) were tested for foaming agent selection. The results showed that the proper foaming agent was WPC for banana foam production, as considered from the foam density and the foam expansion. In addition, Thuwapanichayanan *et al*. [3] reported that the banana foam produced using WPC was the most stable during whipping, compared to the utilization of soy protein isolate and egg albumin as foaming agents as mentioned previously. Based on the preliminary experiment and the research of Thuwapanichayanan *et al.* [3], WPC was therefore applied as a foaming agent for production of the banana foams. Therefore, the objective of this study was to assess the physicochemical properties and nutritional compositions of the foamed powders, as affected by various drying methods.

Materials and methods

Banana puree preparation

Banana (Pisang Awak, *M. sapientum* Linn.) was obtained from Talad Thai fresh market (Pathum Thani province) at the mature stage of 5, which contained total soluble solids of approximately 20° Brix. To prevent discoloration by enzymatic browning, the sliced bananas (2×1 cm) were pretreated by immersing them in 0.5 % (w/w) citric acid solution for 5 min and then rinsed with distilled water until the sour taste was not detected by sensory evaluation. The pretreated banana slices were chopped into small pieces and then blended in a blender for 1 min to obtain banana puree. The puree was packaged, taking care to exclude as much air as possible, in plastic polyethylene pouches (10×5 cm) with 15 g of puree, and was vacuum sealed. Pouches of puree were stored under refrigerated temperatures (4 - 10 °C) until being used within 2 days.

Foaming experiment

Whey protein concentrate (WPC, 82 % protein, 5 % lactose, 4 % moisture, pH 6.0 - 6.8, 6 % fat, 5 % ash, Hilmar ingredients, USA) was selected as a foaming agent, based on our preliminary experiments and the work of Thuwapanichayanan *et al.* [3]. The foaming agent was incorporated into banana puree (approximately 200 g) at different concentrations, such as 0.0, 2.5, 5.0, 7.5, and 10.0 % (on a wet puree basis). Because of the high sugar content in ripe banana, maltodextrin (dextrose equivalent = 10) was added in the formulation as a drying aid agent. The maltodextrin (5.0 %, on a wet puree basis) was added in each treatment. The mixtures of banana puree, maltodextrin, and foaming agent were whipped in a Kenwood mixer (KitchenAid USA.) at a maximum speed for different times, such as 0, 5, 10, 15, 20, and 25 min. The properties of the banana foam, such as foam density and foam expansion, were measured for each experimental condition.

Determination of foam density

Foam density was determined by measuring the mass (*M*) of a fixed volume (*V*) of the foam and expressed as g/cm^3 [2]. The foam (100 ml) was transferred into a 250 ml measuring cylinder and weighed. The foam transferring was carefully done to avoid destroying the foam structure or trapping the air voids filling the cylinder.

$$\text{Foam density} = M/V \tag{1}$$

Determination of foam expansion

Foam expansion was determined by comparing the volume of puree and the volume of corresponding foamed puree, according to the method described by Kandasamy *et al.* [11]. Foam expansion was calculated using the following relationship;

$$\text{Foam expansion} = [(V_1 - V_0)/V_0] / 100 \tag{2}$$

where V_0 is the initial volume of puree and V_1 is the volume of foam, cm^3.

Drying of foamed banana

The foamed banana puree was dehydrated by various methods, such as freeze drying, vacuum drying, and hot air drying. The foamed banana puree was produced by using suitable concentrations of foaming agent and whipping time, as decided from the foam density and foam expansion. After the foaming process used for the banana puree, each foamed sample was dried according to the different methods as described below, and its moisture content monitored at 30 min intervals until the moisture content was below 10 %. Then, all dried banana samples were ground and sieved (100 mesh) to obtain fine powder. Each foamed banana powder was packed into aluminum foil bags and stored at a temperature of under 4 °C for further analysis.

Freeze drying: The foamed banana puree was first frozen (–20 °C) for 24 h and dried in a pilot scale lyophiliser (Vertis Company Inc., Gardiner, NY, USA). The drying time was approximately 8 h.

Vacuum drying: The foamed banana puree was dried under a vacuum cabinet dryer set at 60 °C and vacuum of 0.06 MPa. The drying time was around 3 h.

Hot air drying - The foamed banana puree was also dried in a cabinet convective air dryer operated at 60 °C. The drying time used was about 6 h.

The unfoamed banana puree was used as a control in the treatment and dried in a cabinet convective air dryer operated at 60 °C. The drying time used was about 8 h.

Quality evaluations of the foamed banana powder

Physical quality measurements

The color of the banana powder was determined by using a Hunter Lab Colorflex EZ colorimeter (Hunter Associates Laboratory, Inc., USA). The results were expressed as Hunter color values of L* (lightness), a* (redness and greenness), and b* (yellowness and blueness). The bulk density of the powder was calculated from its mass and volume. First, a 10 ml graduated cylinder was placed on the electronic balance, and a funnel was fixed in the stand above the cylinder. The powders were slowly poured into the funnel until the weight of the powders was 2 g in the cylinder. Then, the volume of the powders was read and the bulk density was calculated [12]. The compaction density was determined according to the method of Peleg [13]. The cylinder with the powders was vibrated with a shaker. After that, the volume of the powders was read. The compaction density was calculated from its mass and volume. The hygroscopicity of the powders was determined according to Caparino *et al.* [12] with some modifications. Samples (about 1 g) of each powder were placed in an aluminum can, weighed, and equilibrated over a saturated salt solution NaCl (relative humidity of 75.3 %) in desiccators at an ambient temperature. After one week, the samples were weighed and the hygroscopicity expressed as g moisture/100 solids. The solubility of the powder was determined using the method described by Cano-Chauca *et al.* [14]. The banana powder (2.0 g) and distilled water (25 ml) were vigorously mixed in a 100 mL centrifuge tube, incubated in a 37 °C water bath for 30 min, and then centrifuged for 20 min at 10,000 rpm. The supernatant was carefully collected in a pre-weighed aluminum can and oven dried at 105±2 °C. The solubility (%) was calculated as the percentage of dried supernatant with respect to the amount of the original powder.

Chemical quality measurements

The proximate compositions (moisture, lipid, protein, crude fiber, and ash) of the banana powder were determined according to AOAC [15]. The moisture content was gravimetrically measured using a vacuum oven at 70 °C for 48 h. The ash content was determined using a muffle furnace at 550 °C for 24 h. The protein and fat content were determined by the Kjeldahl and Soxhlet extraction methods. Crude fiber was analyzed using Fibertec systems (Foss Tecator, Sweden). The ascorbic acid content was analyzed by high performance liquid chromatography (HPLC) according to AOAC [15]. The β-carotene content was also determined by HPLC, as suggested by Schuep and Schierle [16]. The thiamine and riboflavin were analyzed by HPLC, according to the standard methods as described in the European standard EN 14122: 2003 and EN 14152: 2003, respectively [17,18]. The total phenolic content (TPC), expressed as gallic acid equivalent, was extracted with 95 % ethanol and determined by the method of Balange and Benjakul [19]. DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging activity was assayed using the method described by Binson *et al.* [20]. The ABTS (3-ethylbenzothiazoline-6-sulfonic acid) antioxidant activity of the banana powder was carried out using the $ABTS^+$ radical cation decolorization assay [21]. FRAP (ferric reducing antioxidant powder) was measured following the protocol by Benzie and Strain [22]. The standard curves for DPPH, ABTS and FRAP assays were prepared using trolox.

Statistical analysis

The experiment was made in 2 replications, and the measurement was taken in triplicates per each replication. The mean ± SD values were reported based on six measurements obtained from two replications (three measurements from each replication). Differences in means were analyzed by one-way analysis of variance (ANOVA). Duncan's multiple range test was applied to assess significant differences ($p < 0.05$) between samples.

Results and discussion

Foam density

The effects of the concentration of WPC on the foam density of the banana foams are illustrated in **Figure 1**. It was found that the concentration of WPC affected the foam density of the banana puree. An increase in concentration of WPC caused a reduction in the foam density. Apparently, at higher concentrations of WPC, the air bubbles were stable, because the critical thickness required for interfacial film could be formed. This led to the reduction in the foam density. The use of low concentration of WPC caused a high foam density. This was due to the fact that the movement of the foaming agent from the aqueous phase towards the air–aqueous interface was limited. This was insufficient for the reduction in surface tension which enhanced the foam formation [1]. In addition, a decrease in the foam density was found during whipping for the banana foams produced by 2.5 - 7.5 % WPC until the whipping time reached 15 (for 2.5 and 5.0 % WPC) and 20 (7.5 % WPC) minutes. From then, an increase in foam density was observed until the end of whipping time. This indicated that prolonged whipping could cause foam to collapse. However, the foam density of the foams treated with 10.0 % WPC continuously decreased during 15 min of whipping time. From that time, no change in foam density was detected until the end of whipping time (25 min). The reduction in foam density as found in the foams created by 2.5 - 7.5 % WPC could be explained by too high degree of aeration. The thinning of the liquid film between the foam bubbles and mechanical deformation can lead to rupture of the bubble wall structure. This suggests that the increase in the foam density was due to more liquid film thinning, more mechanical deformation, and more bubble wall rupture during extended whipping [11]. A high concentration of WPC (10 %) could prevent the deformation or collapse of foam during long whipping time. Foams with higher concentrations were denser, because of an increase in the thickness of the interfacial films [3].

Foam expansion

Figure 2 shows the change in the foam expansion of the banana foams whipped with different concentrations of WPC. As the concentration of WPC in the puree increased, the foam expansion also increased. Higher foam expansion indicated that more air was trapped in the foam, and this gave rise to higher foam expansion. The WPC at a concentration of 2.5 - 7.5 % stabilized foams which exhibited their maximum up to 15 (for 2.5 and 5.0 % WPC) and 20 (for 7.5 % WPC) min of whipping. Thereafter, the decline in the foam expansion occurred while no appreciable increase in the foam expansion was found in the foam prepared by 10 % WPC after 15 min of whipping time. This result of the foam expansion correlated well with the foam density. The expansion of the banana foams increased with whipping time up to the maximum; it decreased thereafter, probably because excessive whipping (over-beating) could cause the foam to collapse [23]. However, small differences in the maximum foam density and foam expansion were found between the foams produced by WPC in the range of 2.5 - 7.5 %. Therefore, the concentration of WPC and whipping time selected to prepare the banana foam was 5.0 % and 15 min, respectively.

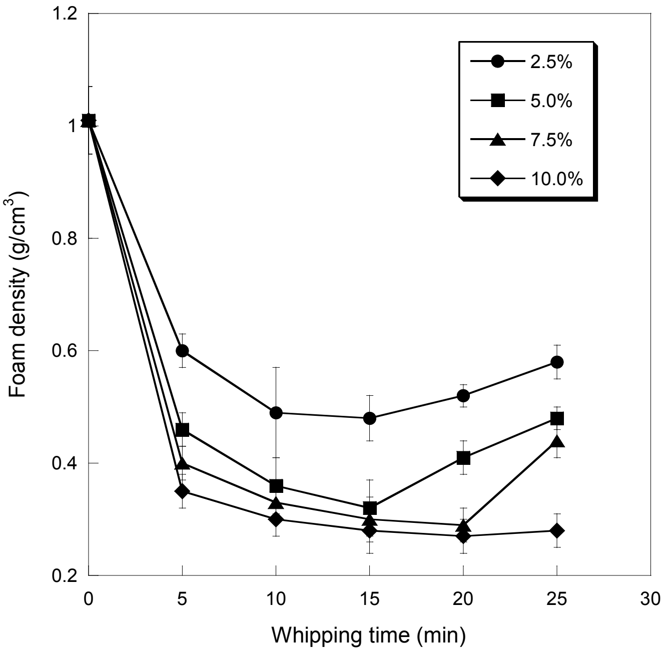

Figure 1 Effect of WPC concentrations on the foam density of the banana foams.

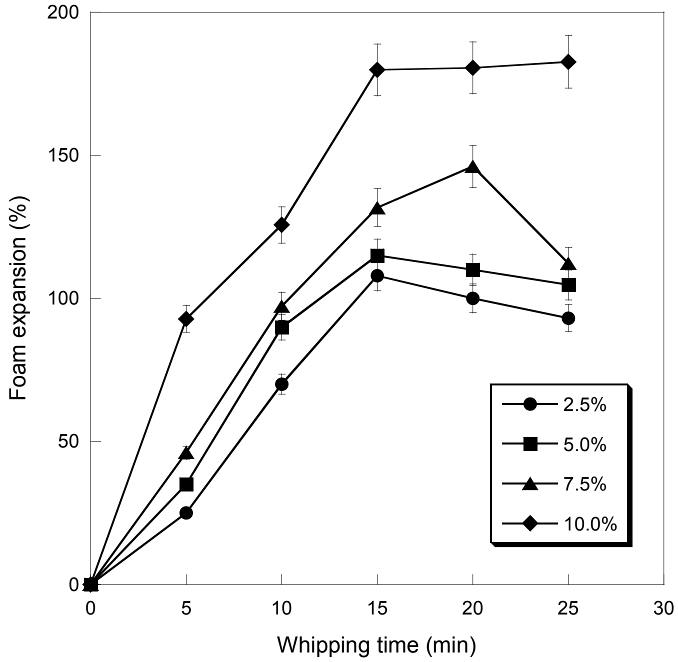

Figure 2 Effect of WPC concentrations on the foam expansion of the banana foams.

Physical properties of banana powders

Color

Color is one of the most important quality parameters for dried materials. Thermal processes generally change the original color of products, especially for foods like fruits and vegetables that consist of a high content of water, carbohydrates, proteins, and fractions of lipids. These compounds are easily modified in high temperature drying conditions and result in degradation of food quality. The effect of various drying methods on the color of the foamed banana powders is given in **Figure 3**. It was found that the drying method affected the color of the banana powder. A mix of cream, yellow and brown colors made up the major color of the banana powder, due to the presence of carotenoids from the banana and thermal reactions, such as Maillard reaction [4,12]. According to the results, higher L* and b* and lower a* values were found in all the banana powders prepared by a foaming process prior to drying, compared to the control treatment. This indicated that the color of the control treatment was browner and redder. This result suggested that the foaming process could reduce formation of brown color during drying. The rate of moisture removal in the foamed banana pulp was very high as compared to the non-foamed pulp. This was due to the fact that the water present in the foamed pulp was in the form of thin films, making for easier vaporization. Because a very high surface area of foam is exposed to the drying air, the rate of water removal during drying is accelerated, and drying time is shortened. This leads to a reduction in Maillard reaction and degradation of carotenoids during drying. Normally, the discolorations of dried products caused by nonenzymatic browning and pigment degradation are highly dependent on the processing temperature and time [12,24-26]. Thus, the combination of long drying time and high drying temperature used in the unfoamed banana powder could promote brown color formation. Among the banana powders produced by the foaming process, the freeze-dried treated sample had the highest L* and lowest a* values. The lowest L* and the highest a* values were observed in the foamed banana powder dried under hot air drying. The brown color in the foamed banana powder dried under hot air drying can be mainly the result of browning reaction or Maillard reaction. These are caused by the chemical reaction between sugars and amino acids, as mentioned previously. Higher L* and lower a* values were found in the foamed banana powder dehydrated by vacuum drying, compared to that of the foamed banana powders dehydrated by hot air drying. Vacuum drying is a drying method in which drying is performed using low pressure. It makes use of the fact that the boiling point of water is reduced as the pressure is reduced. Thus, shorter drying time could minimize the color degradation of products caused by thermal processes. The minimal color change of the product produced by freeze drying suggests the appropriateness of this process to produce high quality products. It has been reported in the literature that freeze drying develops dried products with a higher degree of brightness when compared to the materials dried by conventional hot air methods [27].

Bulk density

The bulk densities of the foamed banana powders produced by different drying methods are shown in **Table 1**. A higher bulk density was observed in the unfoamed banana powders, compared to those of all the foamed banana powders. Generally, the foam mat dried products show low bulk density because of their honeycomb structures, created by foaming process [28]. Among the foamed banana powders, the highest bulk density was found in the banana powders dehydrated by hot air drying, followed by vacuum drying and freeze drying, respectively. High bulk density, as found in the foamed banana powder dehydrated by hot air drying, was due to the difference in the pore size of the powders formed during the drying process. The porosities of the hot air dried banana powders become smaller due to surface hardening and shrinkage [26]. Therdthai *et al.* [29] reported that the structure of the hot air dried materials is normally packed and dense, because of a slow drying process that creates hard surfaces and shrinkage. By contrast, lower bulk density in the foamed banana powder dehydrated by vacuum drying was found when compared to that of the foamed powder one prepared by hot air drying, suggesting that the structure of the foamed banana powder dehydrated under vacuum conditions was likely to be porous. This was because of the shorter drying time and decrease in pressure. However, the lowest bulk density was observed in the foamed banana powder dehydrated by freeze drying, indicating that the particle shape of freeze-dried powders maintained the original form by the sublimation of ice distributed uniformly within the particles by rapid freezing. It is well recognized that, in the freeze drying of foods in the form of either puree or as a whole, the material is first frozen. This allows it to maintain its structure following the sublimation of ice under high vacuum. The liquid phase in the material is not present during this process. Therefore, there is no transfer of liquid water to the surface but, instead, the ice changes to vapor below the collapse temperature, without passing the liquid state. Thus, the effect of the collapse and shrinkage of the product is prevented, thereby resulting in a porous dried material [12].

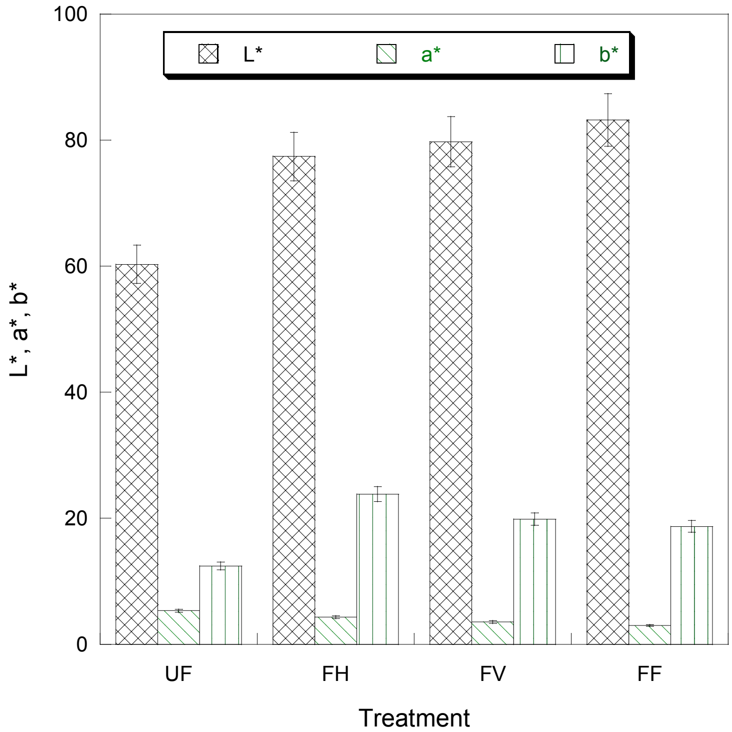

Figure 3 Color of the foamed banana powders dehydrated by various drying methods. UF = unfoamed; FH = hot air drying; FV = vacuum drying; FF = freeze drying.

Table 1 Bulk density, compaction density, hygroscopicity and water solubility index of the banana powders.

Properties/Treatment	**UF**	**FH**	**FV**	**FF**
Bulk density (g/ml)	0.63 ± 0.01^{a}	0.58 ± 0.01^{b}	0.50 ± 0.02^{c}	0.43 ± 0.01^{d}
Compaction density (g/ml)	0.73 ± 0.02^{a}	0.68 ± 0.01^{b}	0.60 ± 0.03^{c}	0.51 ± 0.02^{d}
Hygroscopicity (%)	0.25 ± 0.03^{d}	0.31 ± 0.03^{bc}	0.35 ± 0.02^{b}	0.47 ± 0.01^{a}
Water solubility index (%)	59.41 ± 0.32^{c}	63.71 ± 0.54^{c}	66.35 ± 0.48^{b}	69.42 ± 0.62^{a}

Note: Means within the same row with different letters are significantly different ($p \leq 0.05$). UF = unfoamed; FH = hot air drying; FV = vacuum drying; FF = freeze drying.

Compaction density

Table 1 also shows the compaction densities of the banana powders when using different drying methods. Compaction densities showed similar tendencies to the bulk densities. A higher compaction density was observed in the unfoamed banana powder, compared to all the foamed banana samples. Among the foamed banana powders, the compaction density of the banana powder dehydrated by freeze drying was the lowest, followed by the foamed banana powders dehydrated by vacuum drying and hot air drying, respectively. This result indicated that the structure of the freeze-dried particles did not collapse easily during tapping, because the powders treated by freeze drying maintained the original form. On the other hand, the hot air-dried particles might easily collapse during tapping [26].

Solubility

Solubility is an important criterion to indicate the behavior of powder in aqueous solutions. This state is attained after the powder undergoes the dissolution steps of sinkability, dispersability and wettability. It was found that the foaming process could improve the solubility of the banana powders, as shown by the higher solubility that was observed in all the foamed banana powders compared to that of the unfoamed one (**Table 1**). The solubility of the foamed banana powder dehydrated by vacuum drying was greater than that of the foamed banana powder dehydrated by hot air drying. However, it was lower than that of the foamed banana powder dehydrated by freeze drying. Bulk density and compaction density can be correlated with solubility. The results indicated that lower density products had greater solubility. The use of vacuum drying may lead to a reduction in shrinkage and an increase in cell expansion. In addition, the highest solubility was observed in the foamed banana powder dehydrated by freeze drying, as noted earlier. Similar findings were also found in mango peel and kernel powders dried by various methods, such as freeze drying, vacuum drying, and hot air drying. Our results also showed that the highest solubility was also found in the freeze-dried powder. The development of a porous structure with minimized shrinkage can lead to an improved reconstitution of the water potential [21].

Hygroscopicity

Hygroscopy is the ability of a substance to attract and hold water molecules from the surrounding environment [12]. The results indicate higher hygroscopicity in all the foamed banana powders, as compared to the unfoamed banana powder (**Table 1**). The hygroscopicity was low in the unfoamed sample, possibly because of the presence of a rigid and shrunken structure caused by the combination of high drying temperature and long drying time. This can be ascribed to the fact that the hot air drying caused considerable shrinkage and collapse of the cell walls, as mentioned above. Among the foamed banana samples, the freeze dried powder one exhibited the highest hygroscopicity, indicating its strong capacity to attract water molecules when in contact with the surrounding air. However, there was a small difference in the hygroscopicity between the foamed banana powder dehydrated by vacuum drying and by hot air drying.

Nutritional compositions

Proximate compositions

The proximate compositions of the banana powders obtained from various drying methods are presented in **Table 2**. All the banana powders prepared by the foaming process contained higher protein, lipid, and ash content than that of the unfoamed banana powder. This result may be because the inherent content of the foaming agent (WPC) used contributed to the protein, fat, and ash contents in the samples. However, the drying methods showed no significant effects ($P > 0.05$) on the moisture, protein, lipid, crude fiber, and ash content of all the banana powders treated by the foaming process. Similar results were found in yam flour that was dried by different drying methods [30].

Sugar content

Sugar is a major component in banana powders. The total sugar and reducing sugar content of the unfoamed banana powder was approximately 60.55 and 53.81 %, respectively. Lower total sugar and reducing sugar contents were detected in all the foamed banana powders, compared to the unfoamed one (**Table 2**). This result could be explained by the reduction in banana pulp by substitution with the foaming agent. However, there was no significant difference in total sugar content among all the foamed banana powders. With regards to the reducing sugar content, the highest reducing sugar content was observed in the unfoamed banana powder. This was followed by the foamed banana powder dehydrated by hot air drying, vacuum drying, and freeze drying, respectively. The difference in the reducing sugar content is responsible for the inversion reaction during drying. This suggests that the highest inversion reaction took place in the unfoamed banana powder. During the drying, sucrose was hydrolyzed to glucose and fructose. This reaction was accelerated by the thermal process. The combination of long drying time and high drying temperature used for the unfoamed banana powder may be responsible for its highest inversion reaction. However, a similar drying temperature was applied for the banana foam dehydrated by vacuum drying, hot air drying, and the unfoamed banana. Thus, the reduction of drying time caused by the foaming process can minimize sucrose inversion, therefore lowering the formation of reducing sugar content, compared with the process used for unfoamed powder. As expected, the combination of the foaming process and freeze drying could effectively reduce the inversion reaction, resulting in the low formation of the reducing sugar. The reducing sugar content is an important parameter that affects the properties of banana powder during storage, since it can act as a substrate for a Maillard reaction and decrease its glass transition temperature.

Table 2 Proximate compositions and chemical constituents of the banana powders.

Properties/Treatment	UF	FH	FV	FF
Protein (g/100g)	4.12±0.37^{b}	10.13±0.56^{a}	10.45±0.43^{a}	10.76±0.58^{a}
Lipid (g/100g)	0.09±0.03^{b}	0.21±0.03^{a}	0.23±0.04^{a}	0.25±0.03^{a}
Ash (g/100g)	1.84±0.11^{b}	2.13±0.12^{a}	2.04±0.15^{a}	2.11±0.13^{a}
Moisture (g/100g)	4.24±0.24^{a}	4.67±0.27^{a}	4.32±0.30^{a}	4.39±0.26^{a}
Crude fiber (g/100g)	2.15±0.21^{a}	1.43±0.19^{b}	1.54±0.22^{b}	1.48±0.14^{b}
Total carbohydrate (g/100g)	87.55±0.55^{a}	82.96±0.65^{b}	83.15±0.41^{b}	82.64±0.52^{b}
Total sugar (g/100g)	60.55±0.58^{a}	40.35±0.42^{b}	40.24±0.51^{b}	40.73±0.49^{b}
Reducing sugar (g/100g)	53.81±0.32^{a}	40.31±0.63^{b}	36.53±0.44^{c}	30.26±0.57^{d}
Total phenolic content (mg/100g)	63.63±0.75^{d}	70.43±0.39^{c}	80.53±0.61^{b}	92.46±0.66^{a}
β-carotene (μg/100g)	166.32±1.56^{d}	534.55±1.42^{c}	735.21±1.86^{b}	985.54±1.53^{a}
Vitamin C (mg/100g)	1.15±0.21^{d}	3.21±0.19^{c}	6.45±0.22^{b}	9.32±0.14^{a}
Thiamine (μg/100g)	30.45±1.61^{d}	38.64±1.52^{c}	50.61±1.79^{b}	61.43±1.44^{a}
Riboflavin (μg/100g)	66.45±1.81^{c}	110.64±2.15^{b}	145.26±1.87^{a}	144.33±2.02^{a}

Note: Means within the same row with different letters are significantly different ($p \leq 0.05$). UF = unfoamed; FH = hot air drying; FV = vacuum drying; FF = freeze drying. All results were expressed as dry basis.

Total phenolic content (TPC)

In addition to its physical properties, the benefit for health is an important attribute which enhances the quality of banana powder. Normally, bananas can be claimed to be a good source of phenolic compounds. Therefore, it is important to consider the effect of the drying methods on the TPC of the banana powders. With regards to the effects of the drying process, the TPC of the banana powders showed a wide range, depending on the drying methods. The results showed that the foamed banana powder dehydrated by freeze drying retained the highest TPC, followed by the foamed powders dehydrated by vacuum drying, hot air drying, and the unfoamed banana powder, respectively (**Table 2**). The results of the present study are in accord with the findings found in mango peel and kernel powder [21], persimmon fruit powder [24], strawberry [27,31], and jujubes [32]. Among the drying methods applied, freeze drying resulted in less damage to the final product because of limited thermal and chemical degradation, as it was performed at low temperature. In addition, the freeze drying method is known to be effective in obtaining the highest TPC yield [32,33]. This is because the ice crystals formed within the plant matrix can rupture the cell structure, which leads to the promotion of extraction. In addition, the freeze drying could reduce the degradation of phenolic compounds. The findings of the present and the above-mentioned studies show that freeze drying has more advantages than the other drying methods, in terms of the quality of the end product. However, freeze drying is a relatively expensive process, requiring a long processing time and high energy consumption. In addition, higher TPC was observed in the foamed banana powder obtained by vacuum drying, compared to that of the foamed banana powders dehydrated by hot air drying and the unfoamed banana powder, as noted earlier. Vacuum drying is a technique employed for the drying of various food products for better retention of their nutritional contents. A vacuum enhances mass transfer, due to an increased pressure gradient inside and outside the sample. The key benefits of vacuum drying include lower drying usages (drying temperature or time) and, hence, greater energy efficiency and an improved drying rate, leading to the minimization of TPC loss. Comparing the unfoamed banana powder and the foamed banana powder dehydrated by hot air drying, the unfoamed banana powder contained lower TPC than the foamed banana powder. The lower amounts of TPC in unfoamed banana powder may be attributed to the oxidative and thermal degradation of the phenolic compounds with the increased heat intensity and length of heat treatment. There are some contrary reports relating to the effect of heat treatment on TPC content. The Chaga mushroom powder [27], shiitake mushroom powder [34], and sage powder [35] dehydrated by hot air drying exhibited higher TPC than those of the samples dehydrated by freeze drying. It was explained that the hot-air drying apparently promoted the disruption of the cell wall polymers. Consequently, cell wall phenolics or bound phenolics can be released, thus causing more phenolics to be extracted. However, the effect of the drying methods on phenolic compounds from different materials may not be the same.

Ascorbic acid (vitamin C)

The retention of ascorbic acid can be used as a quality index for dried products. This is because, if the ascorbic acid content is well retained, the other nutrients are also generally preserved [27]. Fruits, like banana, are normally seen as an important source of ascorbic acid. However, ascorbic acid is a heat labile vitamin, and is easily destroyed by thermal processes such as drying. The highest ascorbic acid content was observed in the foamed banana powder obtained by freeze drying (**Table 2**). Lower ascorbic acid values were found in the foamed banana powders prepared by vacuum drying and hot air drying, while the unfoamed banana powder showed the lowest ascorbic acid content. Ascorbic acid is known to be a labile vitamin that loses activity because of a number of factors, including pH, moisture content, oxygen, temperature, and metal ion catalysis [27,31,33]. These results suggested that ascorbic acid might be degraded by thermal processes, and oxidised during air drying. Thus, the oxidation of ascorbic acid in the presence of hot air drying is a possible explanation for the loss. Freeze drying and vacuum drying could minimize the loss of ascorbic acid. This suggests that these techniques, performed under low temperature and vacuum conditions, result in the reduction in ascorbic oxidation and degradation. Using the combination of a high temperature and a long time, as in hot air drying, could promote the destruction of ascorbic acid.

β-carotene

Banana pulp generally contains intermediate amounts of carotenoids such as β-carotene. The drying methods that utilized heat had significant effects on carotenoid degradation. The results showed that the highest level of β-carotene content was detected in the foamed banana powders prepared by freeze drying, followed by vacuum drying, hot air drying, and the unfoamed banana powder, respectively (**Table 2**). Similarly, with ascorbic acid, the two main factors affecting the retention of β-carotene are processing temperature and oxygen. In addition, drying times under high temperatures also influenced the stability of β-carotene [36]. There were two possible reasons for the lower β-carotene degradation in the foamed banana powders dehydrated by freeze drying and vacuum drying. The low temperature and low oxygen conditions were responsible for the promotion of β-carotene stability. However, a higher β-carotene content was found in the foamed banana powder obtained by hot air drying, compared to that of the unfoamed banana powder. This suggested that the foaming process could minimize the loss of β-carotene by reduction of the drying time.

Thiamine and riboflavin contents

Since fruits such as banana are among the most important sources of B vitamins, and comprise an important part of any diet, the retention of micronutrients like B group vitamins during processing is of considerable interest. Thiamine (vitamin B1) and riboflavin (vitamin B2) are two of the major water-soluble vitamins found in banana. However, thiamine and riboflavin can be lost during thermal processing. It was noted that all the banana powders produced by the foaming process improved the retention of thiamine and riboflavin contents. The lowest thiamine and riboflavin contents were detected in the unfoamed banana powder (**Table 2**). In addition, lower thiamine and riboflavin contents were observed in the foamed banana powder prepared by hot air drying, compared to the foamed banana powders obtained by vacuum and freeze drying. The highest retention of thiamine was found in the foamed banana powder dehydrated by freeze drying. However, there were no significant differences in riboflavin content between the foamed powders prepared by vacuum drying and freeze drying. Moreover, the highest riboflavin content was found in the foamed banana powder dehydrated by freeze drying. Thiamine is highly susceptible to losses during thermal processing in an acid food medium, and riboflavin is more stable when heated during processing than thiamine [37]. According to the results, thiamine was found to be more sensitive to drying than riboflavin.

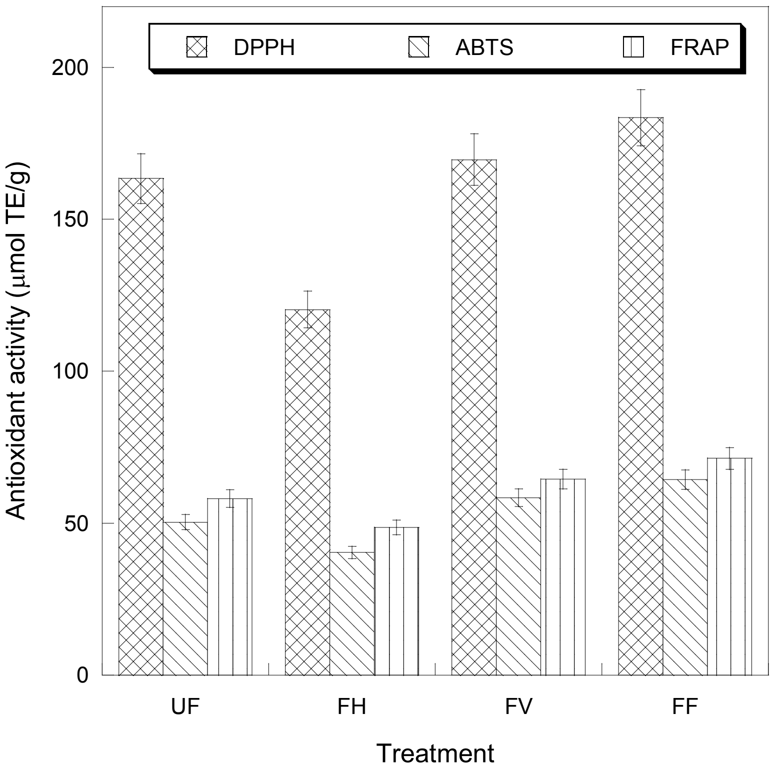

Figure 4 Antioxidant activities of the foamed banana powders dehydrated by various drying methods. Note: UF = unfoamed; FH = hot air drying; FV = vacuum drying; FF = freeze drying. The unit of antioxidant activities is μmol Trolox/gram sample. All results were expressed as dry basis.

Antioxidant activity

In this study, the methods used to evaluate the antioxidant activity included DPPH radical scavenging, ABTS antioxidant activity, and FRAP assay. These methods, which have been established and widely used to measure the antioxidant activity of fruit and vegetable extracts, are simple assays that give fast, reproducible results [38]. The antioxidant activities are shown in **Figure 4**. The processing methods are known to have variable effects on the antioxidant activity of fruit samples. Some processing methods may result in the reduction or the enhancement of the antioxidant properties. Food processing can improve the properties of naturally occurring antioxidants, or induce the formation of new compounds with antioxidant properties, so that the overall antioxidant activity increases or remains unchanged. Similar trends were observed in all antioxidant methods (**Table 2**). It was found that the highest antioxidant activities were found in the foamed banana powder dehydrated by freeze drying, followed by vacuum drying, the unfoamed powder, and the foamed powder dehydrated by hot air drying, respectively. High antioxidant activity in the freeze-dried samples correlates well with high TPC, ascorbic acid, thiamine, riboflavin, and β-carotene contents. Phenolic compounds, ascorbic acid, thiamine, riboflavin and β-carotene have been reported to be responsible for the antioxidant activities of plants [32,37]. Many studies have reported losses in the TPC and antioxidant activity of plant samples following drying treatments [21,24]. Losses in antioxidant properties of heat-treated samples have been attributed to the thermal degradation of all nutritional compounds, as mentioned above. There is little thermal degradation in freeze drying, and the process does not allow for degradative enzymes to function. Furthermore, freeze drying is known to have high extraction efficiency, because the ice crystals formed within the plant matrix can rupture the cell structure, as noted earlier. This allows for the loss of cellular components and their access to solvents and, consequently, to better extraction. Freeze-dried marionberry, strawberry, and corn also yielded higher antioxidant activities than air-dried samples [27,33]. The results in the present study indicate that the combination of long drying time and high drying temperature might affect the antioxidant compounds, as noted above. However, higher antioxidant activity was found in the unfoamed banana powder, compared to the foamed banana powder prepared by hot air drying. This result might be due to higher Maillard reaction products formed in the unfoamed sample, compared to that of the foamed banana powder prepared by hot air drying. These were responsible for its antioxidant activity, which have antioxidant power, often brought about by a chain breaking type mechanism. Therefore, this result can infer that the increased antioxidant activity for the unfoamed powder can be attributed to Maillard reaction products. This hypothesis appears to be confirmed by the color results obtained [39-42].

Conclusions

There are different drying applications used in the food industry. Drying methods that include heat treatment are undesirable for some raw materials, particularly fruits like banana, which have high sugar content. In addition, high drying temperatures and long drying times normally have a negative effect on the appearance and nutritional compositions of fruit powder. The results of this current study suggest that the application of foaming processes prior to drying could reduce the drying time and, consequently, lower the formation of a brown color. In addition, the foaming process could minimize the loss of nutritional components, such as TPC, ascorbic acid, thiamine, and riboflavin, as well as β-carotene. Among the drying methods used to dry the foamed banana puree, freeze drying is superior to other drying methods for preserving the color, TPC, ascorbic acid, thiamine, riboflavin, and β-carotene. It also enhances the solubility of the banana powders. This study provides an opportunity for the powder processing industry to select a better drying technique that could be utilized for the manufacture of high quality banana powder.

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