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Process optimization for foam-mat drying and physicochemical properties of leafy vegetable powder

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Abstract

High quantities of vegetable waste are produced worldwide during primary production, so foam-mat drying was used to add value and create products from three leafy vegetables. Response surface methodology was applied to optimize the foaming parameters. The optimal condition was 3.44% egg albumen as a foaming agent, 5.78 g/mL vegetable: water ratio, and 17 min of whipping time, providing response values of 95.55% foam stability, 294.70% overrun, and a foam density of 0.21 g/mL. The major factor that significantly influenced these responses was egg albumen concentration (X_1), whereas the quadratic terms of egg albumen and vegetable-water ratio (X_1^2 and X_2^2) mainly affected the foam density and overrun ($P<0.05$). The interaction between egg albumen concentration and vegetable: water ratio (X_1X_2) was a critical factor that affected foam stability. Optimal drying of vegetable foam at 50°C for 1.5 h provided comparable retention to freeze-drying for vitamin C (40%) in the vegetables. The derived vegetable powder had a relatively low moisture content (1.89–6.03%) and water activity (0.26–0.34). Egg albumen and drying conditions negatively impacted on the water solubility index and water absorption index. The derived powder showed promising oil (2.55 g/g) and glucose (50–68%) absorption capacities.

Keywords: Foam-mat drying; Egg albumen; Leafy vegetable; Vegetable powder

1. Introduction

Over the past few years, the trend in consumer eating patterns toward fresh vegetables is to gain some beneficial health effects and balanced daily diet because many essential substances in vegetables, such as fibers, vitamins, and polyphenols, may reduce the risks of cardiovascular diseases, metabolic disorder, and certain cancers (Karam *et al.,* 2016). Leafy vegetables are particularly popular, providing convenient consumption without any primary preparation steps. However, the highly perishable nature of fresh leafy vegetables limits the shelf-life even under chilled storage conditions.

Commercially, partially perished and substandard vegetables are sorted out either as low-value products or waste. Food processing and preservation technologies are extensively applied to overcome perishability and prevent losses. Drying is the most common process used to improve the stability of vegetables, providing the desired quality and resulting in low amounts of waste. Although hot air drying is a simple and economical process, there are still several disadvantages, such as low product quality and losses of nutrients and color (Santos and Silva, 2008). Freeze drying can overcome these problems as it operates at a low temperature and provides high quality and raw material-like products. Despite these advantages, this energy-consuming equipment has a long operation time and thus incurs both, high operating and capital costs. Therefore, a suitable method for the practical production of dried leafy vegetables should be simple, cheap, and operated at mild temperatures with a short drying period in order to prevent losses of bioactive compounds and quality.

Foam-mat drying is an alternative method that, by applying a whipping process, followed by conventional oven drying, converts a liquid or semi-solid material into stable foam in the presence of a foaming agent. Due to the large surface area, it provides a rapid drying rate and a short drying time, even at low temperatures. The low water content of the derived product limits the potential for microorganism growth and chemical and enzymatic reactions. Some studies, where food have been converted into food powder by foam-mat drying, were performed on yacon (Franco *et al.,* 2016), sour cherry (Abbasi and Azizpour, 2016), beetroot (Ng and Sulaiman, 2018), lime (Dehghannya *et al.,* 2019), cocoa (Benković *et al.,* 2019), mango (Lobo *et al.,* 2017), or muskmelon (Sangamithra *et al.,* 2015). The major factors affecting foam-mat drying in these studies included temperature, velocity and relative humidity of the air, thickness and composition of the foam, the type and concentration of foaming agent and stabilizer, soluble solids content, and whipping time. To the best of our knowledge, foam-mat drying has not yet been applied to produce a leafy vegetable powder, also the optimization of the process parameters has not been considered in most studies. In addition, the possible influence of foaming and drying on the stability of bioactive substances, especially vitamin C, which is widely used as a quality index for vegetable and fruit products, has not been fully investigated.

Therefore, the objectives of this study were 1) to optimize the foam-mat process parameters for production of a leafy vegetable powder using egg albumen as a foaming agent and 2) to characterize the derived powder for its physicochemical properties (moisture content, water activity [aw], color, water solubility index [WSI], water absorption index [WAI], oil absorption capacity [OAC], and glucose absorption capacity [GAC]) and its chemical properties (total phenolic content, vitamin C, crude fiber, and protein content).

2. Materials and Methods

2.1 Materials

Substandard leafy vegetables, specifically green oak, cos lettuce, and baby green cos lettuce, were obtained from Doi Kham Food Products Co., Ltd (Chiang Mai, Thailand). Egg albumen (80.7% protein content) was purchased from Ovosur (Lima, Peru).

2.2 Methods

2.2.1 Sample Preparation

Green oak, cos lettuce, and baby green cos lettuce, as examples of commonly eaten leafy vegetables, were selected for vegetable powder production. These vegetables (3:1:1 w/w/w) were washed, drained, and cut into 3-cm long pieces before further used.

2.2.2 Optimization of Foaming Parameters

Experimental Design

The response surface methodology (RSM) and a three-level, three-factor Box–Behnken design were chosen to evaluate the effect of three independent variables, namely egg albumen content (X_1; 1–5 g/100g), vegetable:water ratio (X_2; 3–7 g/mL), and whipping time (X_3; 15–25 min). The complete design contained 17 combinations, including five replicates of the center point (Table 1). The foam expansion was carried out in a kitchen aid processor (5KSM7590WWH, KitchenAid®, USA) set at speed no.4. Afterward, the derived vegetable foams were analyzed for overrun, foam stability, and foam density.

The experimental data were fitted to a second-order polynomial model, and the regression coefficients were obtained. The following generalized second-order polynomial model was used in the response surface analysis (Equation 1):

$$Y = \beta_0 + \sum_{i=1}^{3} \beta_i X_i + \sum_{i=1}^{3} \beta_{ii} X_i^{\,2} + \sum_{i-1}^{2} \sum_{j=2}^{3} \beta_{ij} X_i X_j \qquad (1)$$

where β_0 is the constant, β_i is the linear coefficient, β_{ii} is the quadratic coefficient, and β_{ij} is the interaction coefficient. X_i and X_j were levels of the independent variables.

The analysis of variance (ANOVA) table was generated, and the effect and regression coefficients of individual linear, quadratic, and interaction terms were determined. The significances of all terms in the polynomial were evaluated statistically by computing the F-value at p = 0.05. The RSM was applied to optimize the conditions for foam preparation under the variables studied.

Determination of Response Values

Overrun

One hundred milliliters of each mixture solution from the 17-combination treatment was weighed. After whipping, the derived foam was transferred to a cylinder of known weight to obtain a final volume of 100 mL, and then the weight of foam was investigated. The percentage of overrun was calculated by the following equation:

$$\text{Overrun (\%)} = \frac{\text{(Weight of mixture solution – Weight of foam)}}{\text{(Weight of foam)}} \times 100 \quad (2)$$

Foam Stability

Whipped foam systems were transferred to 100-mL cylinders. The initial volume of foam and the final volume after 30 min were recorded. Foam stability was calculated as follows:

$$\text{Foam stability (\%)} = \frac{\text{Volume of foam after 30 min}}{\text{Initial volume of foam}} \times 100 \quad (3)$$

Foam Density

The foam was transferred to a cylinder of known weight. The foam weight was determined, and the foam density was calculated as grams per volume (mL) of foam.

2.2.3 Drying Condition of Leafy Vegetable Foam

Vegetable foams were prepared based on the optimized foaming parameters. Whipped foam systems were uniformly spread on stainless-steel trays of 3-mm thickness. Each foam was dried at various temperatures (50, 60, 70°C) and drying times (1.5, 3.0, 4.5 h) in a hot air oven (30-1060, Memmert GmbH + Co. KG, Germany). The air velocity was set at 1.8 m/s. Dry foams were scrapped from the tray, ground, packed in an aluminum foil zip-lock bag, and stored at -20°C for further determinations.

2.2.4 Physicochemical Properties

Moisture Content and Water Activity (a_w) Determinations

Moisture content was determined for each sample by drying the sample in a hot air oven at 105°C until constant weight. The remaining water content was calculated as the moisture content percentage. The aw of each sample was measured at 25°C, using an aw meter (S36092 Aqua Lab, Dragon Devices, Inc., USA).

Water Solubility Index (WSI) and Water Absorption Index (WAI)

WSI and WAI were assessed by the method of Dehghannya *et al.* (2018). Centrifuge tubes containing 25 mL of water and 2.5 g of sample were placed in a shaking water bath (WNB 14, Memmert, Germany) at 30°C for 30 min, then centrifuged at 3,000g for 10 min. The supernatant was transferred to a moisture can and dried in oven. WSI was calculated as the ratio of solids in the dried supernatant to the dry weight of the initial sample. In addition, the ratio of wet solids remaining to the dry weight of the initial sample was calculated as the WAI.

Oil Absorption Capacity (OAC)

Centrifuge tubes containing 10 mL of soybean oil and 1 g of powder sample were mixed using Vortex (Genie 2, Scientific Industries, USA) for 3 min and then centrifuged at 3000g for 10 min. The ratio of remaining wet solids to the dry weight of the initial sample was calculated as the OAC.

Color

The color (L^*, a^*, b^*) of powder was measured using a colorimeter (CR-10, Konica Minolta Optics, Inc., Japan), where L^* represents lightness (0–100), a^* represents tones between green (-) and red (+), and b^* represents tones between blue (-) and yellow (+). The color difference (ΔE) of the vegetable powders was calculated by the following equation:

$$\Delta E = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]\text{^}½ \quad (4)$$

2.2.5 Chemical Analyses

Vitamin C

Vitamin C was measured by the 2,6-dichlorophenol indophenol titration method (Dinesh *et al.*, 2015). Ten milliliters of 4% oxalic acid were mixed with 5 mL of the ascorbic acid working standard (0.5 mg/5 mL). The mixture was titrated against the dye solution (84 mg NaHCO3 and 104 mg of 2,6-dichlorophenol indophenol in 400 mL of distilled water) until the solution turned pale pink (V1). Vegetable powder (5 g) and 10 mL of 4% oxalic acid were mixed, filtered, and the final volume adjusted to 25 mL. The test sample (5 mL) was titrated against the dye solution (V2). Ascorbic acid content was calculated using the following equation:

$$\text{Ascorbic acid (mg/100 g)} = \frac{0.5 \times V2 \times 25 \times 100}{V1 \times \text{Weight of vegetable powder} \times \text{Volume of test sample}} \quad (5)$$

Total Phenolic Content

The total phenolic content was assayed as described by Maseko *et al*. Vegetable powder and methanol were mixed (1:10 w/v) for 5 min. The filtrate (55 mL) was combined with 3 mL of distilled water, then 750 µl Na_2CO_3 and 250 µL of Folin–Ciocalteu reagent were added. The absorbance of the solution was read at 725 nm using a UV–Vis spectrophotometer (GENESYS™ 10S, Thermo Scientific, USA) after 40 min incubation. The total phenolic content was expressed as milligrams of gallic acid equivalents per gram of powder.

Crude Fiber and Protein Content

The crude fiber content of vegetable powders was analyzed by following the AOAC official method 978.10 (AOAC, 2000). Protein content was quantified by using an automatic Dumas combustion analyzer (Leco FP-528, 601500, Leco Corporation, USA). The conversion factor of 6.25 was used to calculate the protein content.

2.2.6 Glucose Absorption Capacity (GAC)

GAC was evaluated based on the method of Peerajit *et al.* (2012). The selected sample (1 g) was mixed with 50 mL of glucose solution (10–200 mM) and incubated at 37°C for 6 h. After centrifugation (Z206A, Hermle Labortechnik GmbH, Germany) at 4000g for 20 min, the glucose content in the supernatant was assayed by the dinitrosalicylic colorimetric method.

2.2.7 Statistical Analysis

The experimental results of the optimization were evaluated using Design Expert (version 6.0). All physicochemical and chemical properties were determined in triplicate, and all data were reported as mean ± standard deviation. Statistical significance was evaluated using ANOVA and Duncan's new multiple range test at $P<0.05$.

3. Results and Discussion

3.1 Optimization of Foaming Parameters

3.1.1 Model Fitting and Influence of Independent Variables on Response Values

The lowest overrun value (62.98%) corresponded to the condition with a low level of egg albumen and short whipping time. The highest overrun (657%) was reached by using 3% egg albumen and 3 g/mL vegetable:water ratio, even when a short whipping time was applied (Table 1). For foam density and stability, the values ranged between 0.12–0.51 g/mL and 81.33–96.67%, respectively. Each response was fitted to the quadratic polynomial model by using multiple regression analysis. ANOVA test was used to estimate the effects of the studied variables, their interactions, and the suitability of the derived equation models (Table 2). All equation models were significant for fitting the responses ($P<0.05$), indicating that these models could well explain the relationship between the independent variables and response values. Moreover, for all models, high multiple correlation coefficients (R^2) of 0.9989, 0.9707 and 0.8173 were achieved. In addition, the lack-of-fit value of each model (0.0666, 0.9259 and 0.4416) was also statistically insignificant ($P>0.05$), confirming that the developed model could adequately represent the real relationship among the parameters chosen. The linear, quadratic, and interaction terms were significant ($P<0.05$) for foam density, indicating that egg albumen (X_1), vegetable:water ratio (X_2), and whipping time (X_3) are the crucial factors. Especially, egg albumen had a major negative effect (regression coefficient = -0.110) on foam density. The reason is that the proteins in albumen are denatured at the interphase during the whipping process. Denaturation induces co-aggregation of the molecules, which incorporate the air, causing foam expansion and resulting in low foam density. Additionally, whipping time also showed a negative effect caused by foam structure collapse and mechanical deformation during an excessive whipping time. This result was similar to that obtained by foam-mat drying of muskmelon (Sangamithra *et al.*, 2015).

For overrun, all terms were significant (P<0.05), except for the quadratic term (X_3^2) and the interaction X_1X_2 (P>0.05). Egg albumen and whipping time had a positive effect (regression coefficient = 152.76 and 24.06), but the vegetable:water ratio negatively impacted (regression coefficient = -87.48) on foam expansion, as explained by the fact that a high-viscosity liquid prevents the trapping of air during whipping (Karim and Wai, 1999). This result was consistent with the study by Affandi *et al.* (2017), who reported that increasing the egg albumen concentration caused an increase in foam expansion during the production of Nigella sativa beverage powder under foam-mat drying. A greater amount of a foaming agent allows the incorporation of a larger amount of air into the foam structure (Benković *et al.*, 2019).

Table 1 Experimental and Predicted Values of 17-Treatment Combinations

Factors			Experimental values			Predicted values			Residuals		
EB[1]	R[2]	T[3]	Overrun (%)	Density (g/mL)	Stability (%)	Overrun (%)	Density (g/mL)	Stability (%)	Overrun (%)	Density (g/mL)	Stability (%)
3	5		262.89	0.23	88.40	261.81	0.23	90.91	1.08	0.00	-2.51
1	5		62.98	0.51	88.93	60.78	0.50	88.39	2.20	0.01	0.54
1	7	20	91.38	0.45	90.93	90.44	0.45	88.41	0.94	0.00	2.52
3	3	15	657.00	0.12	91.33	652.79	0.11	89.23	4.21	0.01	2.10
3	5	20	256.90	0.24	90.67	261.81	0.23	90.91	-4.91	0.01	-0.24
5	3	20	569.98	0.12	96.67	570.92	0.12	93.41	-0.94	0.00	3.26
3	7	25	521.74	0.15	95.07	525.94	0.15	92.59	-4.20	0.00	2.48
5	5	15	430.00	0.16	94.00	433.26	0.17	93.43	-3.26	-0.01	0.57
3	5	20	262.14	0.23	86.67	261.81	0.23	90.91	0.33	0.00	-4.24
1	3	20	206.63	0.32	81.33	213.04	0.33	86.76	-6.41	-0.01	-5.43
3	7	15	231.77	0.32	90.13	234.91	0.33	90.93	-3.14	-0.01	-0.80
3	3	25	461.13	0.14	93.33	457.99	0.13	95.09	3.14	0.01	-1.76
5	7	20	350.00	0.22	93.33	343.59	0.21	95.11	6.41	0.01	-1.78
3	5	20	261.34	0.20	92.00	261.81	0.23	90.91	-0.47	-0.03	1.09
5	5	25	412.21	0.18	93.33	414.41	0.19	90.89	-2.20	-0.01	2.44
1	5	25	179.11	0.31	89.33	175.85	0.31	88.39	3.26	0.00	-0.94
3	5	20	265.76	0.26	90.00	261.81	0.23	90.91	3.95	0.03	-0.91

[1]EB: egg albumen concentration (g/100g), [2]R: vegetable:water ratio (g/mL), [3]T: whipping time (min)

Furthermore, only the linear term of egg albumen (X_1) had a significant and positive influence on foam stability (P<0.05). This finding may be supported by the reduction of surface tension when a highly efficient foaming agent is applied. The increase in foaming agent concentration increases the film thickness, which helps to coat and stabilize the bubbles (Ng and Sulaiman, 2018). However, the interaction term X_1X_2 was significant (P<0.05), and negatively affected foam stability, probably because of foam structure interruption by the high solid content.

3.1.2 Optimization and Validation

The maximum value of foam stability was established as a critical foaming parameter because this attribute is essential for efficient foam-mat drying. The foam should be able to retain its open structure throughout the drying process in order to increase the total surface area, accelerating water removal during drying (Karim and Wai, 1999). Numeric optimization was chosen to find the optimal condition for foam preparation. In this study, the optimized condition was 3.44% egg albumen, 5.78 g/mL vegetable:water ratio, and a whipping time of 17.03 min, providing the predicted response values of 96.50% foam stability, 255.02% overrun, and a foam density of 0.28 g/mL. This condition was validated by triplicate experiments. The experimental values were 95.55% foam stability, 294.70% overrun, and a foam density of 0.21 g/mL. The experimental condition generated comparable response values to the predicted condition with 93.59-100% accuracy, especially foam stability (P>0.05). Therefore, this optimal condition was used to prepare vegetable foam for further investigation of the drying effect on vegetable powder properties.

Table 2 Response Models and Statistical Parameters Obtained from ANOVA Analysis

Variables	Foam density		Overrun		Foam stability	
	Regression coefficient	***p*-value**	**Regression coefficient**	***p*-value**	**Regression coefficient**	***p*-value**
Intercept	0.230	-	261.81	-	89.54	-
X_1	-0.110	<0.0001*	152.76	<0.0001*	3.35	0.0023*
X_2	0.055	<0.0001*	-87.48	<0.0001*	0.85	0.2965
X_3	-0.042	<0.0001*	24.06	0.0004*	0.83	0.3054
X_1^2	0.078	<0.0001*	-77.07	<0.0001*	-0.023	0.9840
X_2^2	-0.032	<0.0001*	119.76	0.0111*	1.04	0.3490
X_3^2	-0.018	<0.0001*	76.43	0.0909	1.88	0.1112
X_1X_2	-0.005	<0.0001*	-26.18	0.6132	-3.23	0.0170*
X_1X_3	0.053	<0.0001*	-33.48	0.0008*	-0.27	0.8106
X_2X_3	-0.048	<0.0001*	121.46	0.0014*	0.73	0.5149
Model	<0.0001*		<0.001*		0.0244*	
Lack of fit	0.0666		0.9259		0.4416	
Adjust R^2	0.9989		0.9707		0.8173	

*P values lower than 0.05 were considered as statistically significant

3.2 Effect of Drying on Physicochemical Properties

3.2.1 Moisture Content and Water Activity (a_w)

Moisture content and a_w of vegetable powders (Table 3) revealed that these properties were directly affected by the drying temperature and time. Moisture content was lower for the foam-mated powder than the freeze-dried sample ($P<0.05$) by about 1.5-4.9-fold. Lower moisture content was observed at higher drying temperatures because of the higher rate of water removal with increasing temperature. The moisture content of the powder ranged from 1.89 to 6.03%, and aw was in the range of 0.26–0.34. These values complied with the requirement for dry food powders that moisture content and aw shall be less than 15% and 0.5, respectively. Thus, the vegetable powder obtained by foam-mat drying is safe for consumption because the chemical reaction and microbial growth are restricted at this very low availability of water.

3.2.2 Water Solubility Index (WSI) and Water Absorption Index (WAI)

The WSI of foamed vegetable powder (Table 3) showed that the solubility index of freeze-dried powder (19.91 g/g powder) without egg albumen was much higher ($P<0.05$) relative to the foam-mated samples (3.1–11.2 g/g powder). The better dissolution in water may be explained by its high soluble solid content. WSI was restricted in the foam-mated powder containing egg albumen, especially when drying temperature and drying time were increased. During drying, egg albumen may become denatured and coagulated, decreasing the solubility of powders (Affandi *et al.,* 2017).

For WAI, foamed vegetable powder presented a significantly higher WAI when compared with the freeze-dried sample ($P<0.05$) as shown in Table 3, indicating the major role of egg albumen, which has several free hydroxyls that are able to bind water molecules (Franco *et al.,* 2016). However, excessive addition of protein may decrease the WAI. As Dehghannya *et al.* (2018) reported, increasing the ovalbumin content from 2% to 4% dramatically reduced the WAI of foam-mated lime juice. Among the foam-mat samples, the WAI (5.60–6.67%) tended to be lower at higher drying temperatures or longer drying time. A marked lowering of the WAI was also observed in foamed shrimp powder when the temperature was increased from 45 to 90°C (Azizpour *et al.,* 2016). This trend is mainly attributed to the unfolding of proteins, resulting in hydrophobic groups migrating to the surface of the protein, decreasing the hydrogen bonding. These actions can cause the aggregation and coagulation of protein molecules, and the water absorption as well as water solubility decrease because of the reduced protein surface in contact with water (Fennema, 1996).

Table 3 Moisture Content, Water Activity, WAI, WSI, and OAC of Vegetable Powders

Treatments		Moisture content (%)	Water activity (a_w)	WAI (g/g)	WSI (g/g)	OAC (g/g)
Temperature	Time					
50	1.5	6.03 ± 0.25^{b}	0.30 ± 0.01^{ab}	6.67 ± 0.13^{b}	9.10 ± 2.69^{bc}	2.55 ± 0.18^{c}
	3.0	5.90 ± 0.00^{b}	0.32 ± 0.01^{a}	6.59 ± 0.25^{b}	5.60 ± 1.13^{c}	2.69 ± 0.06^{c}
	4.5	5.04 ± 0.00^{d}	0.29 ±0.01^{ab}	6.29 ± 0.88^{bc}	5.50 ± 0.78^{c}	2.80 ± 0.17^{bc}
60	1.5	5.51 ± 0.00^{c}	0.33 ± 0.01^{a}	6.28 ± 0.05^{c}	8.60 ± 0.84^{b}	2.83 ± 0.12^{b}
	3.0	5.30 ± 0.42^{cd}	0.31 ± 0.01^{a}	6.27 ± 0.22^{c}	4.90 ± 1.83^{cd}	3.10 ± 0.13^{ab}
	4.5	2.92 ± 0.03^{e}	0.28 ± 0.01^{b}	6.30 ± 0.29^{bc}	3.10 ± 1.14^{d}	3.31 ± 0.09^{a}
70	1.5	2.26 ± 0.00^{f}	0.34 ± 0.02^{a}	5.98 ± 0.24^{c}	11.2 ± 3.96^{b}	3.36 ± 0.16^{a}
	3.0	1.94 ± 0.00^{fg}	0.26 ± 0.01^{b}	5.72 ± 0.04^{cd}	4.70 ± 0.99^{cd}	3.41 ± 0.07^{a}
	4.5	1.84 ± 0.00^{h}	0.28 ± 0.01^{b}	5.60 ± 0.06^{d}	3.60 ± 1.69^{cd}	3.44 ± 0.08^{a}
Freeze-dried vegetable powder		9.02 ± 0.00^{a}	0.30 ± 0.03^{ab}	9.95 ± 0.32^{a}	19.91 ± 0.03^{a}	2.23 ± 0.07^{d}

Different letters in each row represent significant different mean values (P<0.05).
Number of replicates: n=3.

3.2.3 Oil Absorption Capacity (OAC)

According to OAC reported in Table 3, it was evident that egg albumen and the foam-mat drying process positively affected the OAC. The OAC was significantly lower for the freeze-dried vegetable powders than foam-mat powders (P<0.05). The highest OAC (3.44 g oil/g powder) was derived from drying at 70°C for 4.5 h. The main cause might be a physical entrapment of vegetable powder. However, a lower OAC was observed when lower temperatures and shorter drying time were applied, as interactions between hydrophobic groups of unfolded protein are created during thermal denaturation and when surrounded by an oil phase. The more denatured the structure, the greater the exposed hydrophobicity, resulting in higher OAC, as exemplified by a previous study in which heat treatments noticeably improved the OAC of rice bran protein by approximately 8.9–9.7% (Lv *et al.*, 2017).

3.2.4 Color

Fresh vegetables displayed the highest brightness (L^*) of approximately 60.0, which was significantly different from the processed vegetable powders (P<0.05) (Table 4). It can be seen that the color of foam-mat powder darkened as a function of temperature, whereas freeze-drying, operated at a relatively lower temperature, provided a brighter color. The darkening is likely caused by the heat-induced non-enzymatic browning reaction (Maillard reaction) between free amino acids in the powder containing egg albumen and the reducing sugars in vegetables, resulting in brown pigments. The effect of drying on color values a^* and b^* was similar to that on L^*. A large color difference (ΔE) between these values and reference samples was found when the temperature was increased or the drying time was prolonged. Our results were consistent with the reports of foamed muskmelon powder (Sangamithra *et al.*, 2015), grape concentrate powder (Gupta and Alam, 2014) and Nigella sativa (herbaceous plant) powder (Affandi *et al.*, 2017).

Table 4 Color Parameters of Vegetable Powders

Treatments		L^*	a^*	b^*	ΔE_{FV}	ΔE_{FD}
Temperature	Time					
50	1.5	53.67 ± 0.36^{c}	-7.76 ± 0.22^{ef}	16.47 ± 0.13^{c}	3.32	2.99
	3.0	52.09 ± 0.27^{d}	-7.85 ± 0.11^{f}	17.41 ± 0.29^{bc}	3.53	3.20
	4.5	51.29 ± 0.37^{e}	-7.54 ± 0.15^{e}	16.61 ± 0.28^{c}	4.49	4.16
60	1.5	51.33 ± 0.25^{e}	-6.58 ± 0.05^{d}	12.78 ± 0.25^{fg}	5.75	5.42
	3.0	50.70 ± 0.07^{fg}	-6.73 ± 0.05^{d}	14.32 ± 0.08^{d}	5.37	5.04
	4.5	50.29 ± 0.42^{g}	-5.14 ± 0.11^{a}	13.46 ± 0.27^{e}	5.21	4.88
70	1.5	50.45 ± 0.21^{fg}	-6.09 ± 0.03^{c}	12.26 ± 0.10^{h}	6.20	5.87
	3.0	50.44 ± 0.02^{fg}	-6.15 ± 0.08^{c}	13.05 ± 0.37^{f}	5.68	5.35
	4.5	50.94 ± 0.32^{ef}	-5.82 ± 0.18^{b}	12.49 ± 0.06^{g}	5.87	5.54
Freeze-dried vegetable powder (FD)		58.92 ± 0.36^{b}	-8.14 ± 0.20^{g}	17.58 ± 0.16^{b}	0.33	-
Fresh vegetable (FV)		60.60 ±0.10^{a}	-12.22 ± 0.09^{h}	20.64 ± 0.14^{a}	-	-

Different letters in each row represent significant different mean values (P<0.05).
Number of replicates: n=3.

3.2.5 Chemical Composition

In Table 5, fresh vegetables had the highest vitamin C content (2638.98 mg/100g; P<0.05), whereas vitamin C was decreased by 60–84% in foamed vegetable powders. The vitamin C content decreased with increasing drying temperature and drying time, mainly as a result of thermal degradation. However, foam-mat drying is believed to retain vitamin C more efficiently than the conventional drying method. Rajkumar *et al.*, 2007 described the lower reduction in vitamin C of foam-mat dried mango flakes than non-foam dried flakes was because of a higher drying rate with shorter drying time in foam mat drying. Interestingly, drying at 50°C and 1.5 h significantly preserved the highest vitamin C content (1055.59 mg/100 g) among the foam-mat treatments (P<0.05), achieving a level comparable (P>0.05) to the vitamin C in the freeze-dried sample (1161.15 mg/g). These conditions can retain 40% of the initial vitamin C. The comparatively higher moisture content of the freeze-dried powders could explain the lower vitamin C retention. At high moisture content, the aqueous phase becomes less viscous, enhancing diffusion in the media, which facilitates the oxidation reaction and, consequently, the degradation of the oxidation-susceptible components in the sample (Santos and Silva, 2008). This result demonstrated that foam-mat drying is a practical and economical process to produce a vegetable powder with the same vitamin C retention as the freeze-dried one.

Among the foam-mated vegetable powders, the phenolic content was found to be influenced by the temperature and drying time (Table 5). Drying at 50°C for 1.5 h seemed to be the best condition for drying of vegetable foam, retaining a phenolic content of about 43% relative to 24.59 mg/g (wet basis) for the fresh vegetable. The content of total phenolic compounds was comparable among the vegetable foams even when dried at temperatures above 50°C (9.35–10.59 mg/g, P>0.05). However, exposing vegetable foams to 70°C for more than 4.5 h reduced the phenolic content significantly (P<0.05), as this condition would have promoted the thermal and oxidative degradation of phenolic compounds. (Dorta *et al.*, 2012) found that the phenolics in mango peel decreased 2.8-fold after oven-drying at 70°C, causing the antioxidant activity to decrease. As the reference method, freeze-drying preserved the

phenolic compounds most (P<0.05) because it is a gentle dehydration technique capable of maintaining product quality, owing to both its low processing temperature and the virtual absence of air oxygen during processing, which minimize degradation reactions (Karam *et al.*, 2016). It can be concluded that the phenolic compounds in green oak, cos lettuce, and baby green cos lettuce are probably heat-sensitive.

The fiber content in the mixed fresh vegetables was quite low, at about 1.26% (wet basis) (Table 5). Fiber content was highest (12.46%) in the freeze-dried vegetable powder because the water was almost completely removed. The incorporation of 3.44% egg albumen lowered the fiber content of the vegetable powder derived from foam-mat drying. However, the drying process did not affect the fiber content (P>0.05), which ranged from 7.56–8.88 g/100 g powder. According to the recommendation of American Heart Association (Krauss, 2000), twenty-five grams of fiber is recommended for a daily consumption, equivalent to about 2 kg of fresh vegetable. In contrast, only 200–300 g of vegetable powder derived from this study is needed. Moreover, the indirect benefit of consuming foam-mat vegetable powder is the digestible protein that is mainly derived from egg albumen (21–23 g/100 g powder), and this contributes to about 80% of the daily value for protein consumption recommended by the Food and Drug Administration (FDA). However, the studied drying conditions had no effect on protein content (P>0.05).

Table 5 Chemical Compositions of Vegetable Powders

Treatments		Vitamin C	TPC	Crude fiber	Protein
Temperature	Time	(mg/100g)	(mg/g)	(g/100g)	(g/100g)
50	1.5	1055.59 ± 0.00^{b}	10.59 ± 1.19^{c}	8.31 ± 0.13^{b}	22.76 ± 0.12^{a}
	3.0	738.91 ± 149.28^{c}	8.78 ± 0.92^{cd}	8.50 ± 0.31^{b}	23.01 ± 0.08^{a}
	4.5	633.35 ± 0.00^{d}	8.21 ± 0.60^{d}	8.13 ± 0.07^{b}	21.88 ± 0.25^{a}
60	1.5	844.47 ± 0.00^{c}	9.83 ± 1.78^{c}	7.79 ± 0.24^{b}	22.32 ± 0.16^{a}
	3.0	633.35 ± 0.00^{d}	8.59 ± 1.62^{de}	8.66 ± 0.08^{b}	23.11 ± 0.24^{a}
	4.5	527.80 ± 149.28^{de}	8.02 ± 0.60^{de}	8.44 ± 0.06^{b}	21.65 ± 0.45^{a}
70	1.5	738.91 ± 149.28^{c}	9.35 ± 1.35^{c}	7.56 ± 0.00^{b}	22.56 ± 0.84^{a}
	3.0	527.80 ± 149.28^{de}	6.02 ± 1.57^{de}	7.84 ± 0.40^{b}	22.81 ± 0.52^{a}
	4.5	422.24 ± 0.00^{e}	4.50 ± 0.35^{e}	8.17 ± 0.10^{b}	23.16 ± 0.23^{a}
Fresh vegetable		2638.98 ± 74.64^{a}	24.59 ± 1.47^{b}	1.26 ± 0.17^{c}	-
Freeze-dried vegetable powder		1161.15 ± 149.28^{b}	31.92 ± 2.70^{a}	12.46 ± 5.18^{a}	-

Different letters in each row represent significant different mean values (P<0.05).
Number of replicates: n=3

3.3 Glucose Absorption Capacity (GAC)

The vegetable powder obtained from drying at 50°C for 1.5 h, having highest retentions of vitamin C and phenolics, was evaluated in vitro for GAC in glucose solutions (Fig 1). It was apparent that the amount of adsorbed glucose was concentration-dependent. Foamed vegetable powder was very effective at adsorbing glucose in the solution (50–68%). At the lowest level of glucose concentration (10 mM), the vegetable powder was still able to adsorb glucose (0.058 mmoL/g). This ability to maintain a relatively low level of glucose concentration might be transferrable to the environment in the small intestine, which would contribute to resisting hyperglycemia. The GAC of foam vegetable powder (0.058-1.155 mmoL/g) was higher than dietary fiber from bamboo shoot shells (Zheng *et al.*, 2019), but lower than those from lime (Peerajit *et al.*, 2012) and bamboo shoots (Phyllostachys praecox) (Wang *et al.*, 2017)

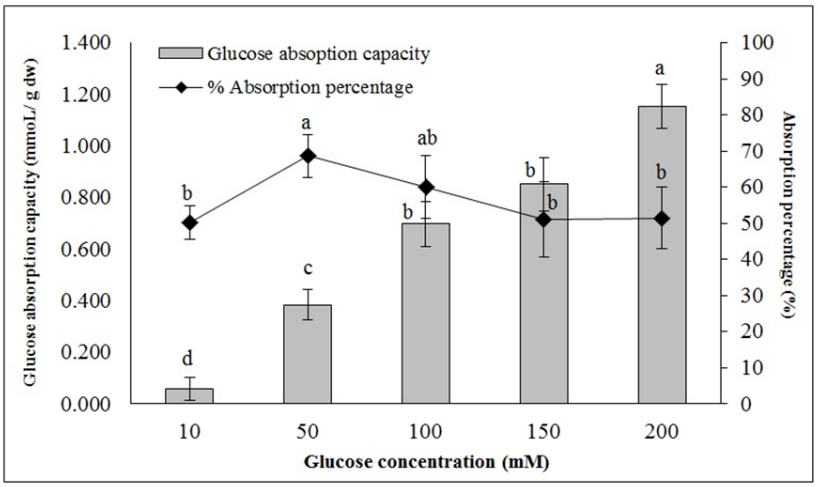

Fig 1 Glucose absorption capacity of selected vegetable powder. Different letters refer to significant different mean values and error bars represent standard errors of the mean.

4. Conclusion

The condition including 3.44% egg albumen, 5.78 g/mL vegetable:water ratio, 17.03 min whipping time, and drying temperature at 50°C for 1.5 h is applicable to produce a foam-mat vegetable powder from substandard vegetables with high retentions of vitamin C (40%) and total phenolic content (43%). According to its properties, the vegetable foam could be suggested for either application in food products that lack fiber and protein, or for further development as a functional ingredient that exhibits hyperglycemia resistance. The process obtained from this study provides a guideline for value-adding and extending the shelf-life of substandard vegetables.

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