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The Optimal Drying Process of Silkworm Pupae

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Silkworm pupae were subjected to 3 drying methods including freeze drying (FD), hot air drying (HAD) and microwave assisted hot air drying (MHAD). Using FD for 24 h, moisture content of the silkworm pupae was reduced to 1.01 g water/100 g dry solid. For HAD, increasing air temperature from 60 to 80 °C, drying time was reduced from 20 to 10 h. Using MHAD, drying time could be reduced to 14 min. Increasing temperature of HAD reduced the protein content from 53.33 to 50.27 g/100 g dry solid. In contrast, when the silkworm pupae were dried by MHAD, protein content increased to 54.67-58.09 g/100 g dry solid. Hardness of FD and HAD samples were significantly ($P<0.05$) lower than that of MHAD samples. L*-value of MHAD samples was the highest (50.97-53.49). From scanning electron microscope (SEM), microstructure of the dried silkworm pupae was damaged as affected by drying process.

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Introduction

The world population keeps increasing and will grow to 9.6 billion people in 2050, according to forecasting by the United Nations. That means the world requires the increased food and feed outputs. Edible insect may become the future prospect for global food security (Nowak et al., 2016). In the future, people should adapt to other sources of proteins because traditional sources of protein including beef, poultry or pork become unsustainable. Integration of edible insects in human food should be deserved more attention in the future (Caparros Megido et al., 2014). The consumption of insects has been documented in Japan, Korea, China, India, Thailand, Lao, Viet Nam, Myanmar, Africa, Brazil, Latin America, Australia, Netherland, Belgium, France, Mexico and other parts of the developing countries (Raksakantong et al., 2010; Longvah et al., 2011; Van Huis et al., 2013; Kouřimská and Adámková, 2016). Not only high nutrients, but consumption of insects also enriches the human diet in bioactive components, for example biologically active peptides obtained from food products, as a result of protein digestion (Zielińska et al., 2017). Silkworm pupae were one of the popular insects for consumption in Thailand (Usub et al., 2010).

Silkworm is a traditional product that is now distributed on a global scale. About 137,000 households raise silkworms in Thailand. In 2004, about USD 50.8 million was generated from production (Van Huis et al., 2013). Methods for insect preservation included drying, texturing, grounding and heating (e.g., cooking, boiling, frying, roasting, toasting, extrusion, and canning) (Van der Spiegel, 2016). Drying was demonstrated as the effective method in safeguarding shelf-life and safety by the control of Enterobacteria (Klunder et al., 2012). However, containing high water content in dead pupae was a drawback, because it caused rapid decomposition (Usub et al., 2008). Rate of heat transfer during drying is determined by the size of the individual pupae. Thus variation in size may cause over-processing or under-processing (Kanjanawanishkul et al., 2015).

Convective drying is possibly the most common technique for dehydration of particulate foods. However, the quality is often low, as the rehydration capacity and physical properties were often inferior (Funebo et al., 2002). Freeze drying performed at low temperature with vacuum assisted to remove water from foods. This method has been applied to dry foods with delicate flavours and textures, in order to ensure better quality required by consumers. The absence of liquid water and the low temperature required for freeze-drying can inhibit most of degradation and microbiological reactions, thereby promoting an excellent quality to the final product (Jorge et al., 2014). Microwave drying offers the short drying time and homogeneous energy distribution. High moisture materials undergoing the microwave drying have the advantage over the conventional drying techniques. This process results in drying without overheating phenomena on the surface (Krishna Murhty et al., 2012). Dried silkworm pupae are often used as an ingredient in snack food (Usub et al., 2008), and bakery (Zielińska et al., 2017).

The objective of this study was to investigate quality of silkworm pupae which was dried by various conditions including freeze drying, hot air drying and microwave assisted hot air drying. Composition, water activity, colour, texture and microstructure of the dried silkworm pupae were determined.

Materials and Methods

Material

The frozen silkworm pupae was purchased from the Chul Thai Silk Co.,Ltd, Thailand. It was composed of 13.11 g protein/100 g dry solid, 35.85g fat/100 g dry solid, 4.50 g fiber/100 g dry solid and 0.96 g ash/100 g dry solid.

Drying of silkworm pupae

Frozen silkworm pupae (500g) were bought from The Queen Sirikit Department of Sericulture. It was blanched in hot water at 95-100oC for 10 min. Then the samples were dried by 3 conditions as follows:
Hot air drying (HAD): The 100 g of silkworm pupae (0.94 x 2.9 x 0.81 cm) was dried by a hot air oven (BWS model Frecon, Bangkok, Thailand) at 60oC, 70 oC and 80oC for 20 h, 16 h and 10h, respectively.
Freeze drying (FD): The 100 g of silkworm pupae (0.94 x 2.9 x 0.81 cm) was dried at -54 °C, 2.73 Pa for 24 h, by a freeze dryer (Lyolab 3000, Thermo Fisher Scientific Heto, Denmark).
Microwave assisted hot air drying (MHAD): The 100 g of silkworm pupae (0.94 x 2.9 x 0.81 cm) was dried using microwave at 600 W together with hot air drying at 100°C, 120°C, 140°C and 160°C for 14 min.

Determination of quality of dried silkworm

The dried silkworm pupae were ground by a blender. Moisture content of dried silkworm pupae was an analysed using an oven method (AOAC, 2000). Water activity of dried silkworm was determined by AquaLab (Series 3 TE, Decagon Devices, Inc., USA).
Texture of the dried silkworm was investigated using a texture analyser (TA-XT Plus, Stable Micro System, UK). A cylinder probe (36 mm diameter) was used to compress the samples at 2 mm/s. The samples were compressed to 85 % of their original thickness. Then hardness was determined from the maximum compression force with 10 measurements.
Microstructure of the dried silkworm pupae was cut into thin cross-section and coated with a thin conductive gold layer. Then it was analysed using a scanning electron microscope (Quanta 450, FEI, Japan) at an accelerating voltage from 10KV. Magnification was adjusted to 250x.
Colour of the dried silkworm pupae was determined by a spectrophotometer (Minolta CM-3500d; Konica Minolta Holdings Inc., Tokyo, Japan). Three parameters: L*(brightness), a* (green-red axis) and b* (blue-yellow axis) were obtained using a D65 illuminant at 10° observation. For proximate composition determination of the dried silkworm, protein content, fat content, fiber content and ash content was analysed by the method of Association of Analytical Chemists (AOAC, 2000). For the protein analysis, nitrogen was determined using the Kjeldahl method. Protein content was calculated as 6.25 x N (Rumpold and Schlüter, 2013).

Statistical analysis

All tests were analysed using the statistical package SPSS® version 12.0 (SPSS (Thailand) Co., Ltd., Bangkok, Thailand). Analysis of variance (ANOVA) comparison between means was done to determine the significance of the main effects. Significant difference between ($P \leq 0.05$) means was identified using Duncan's multiple range tests.

Results and Discussion

Moisture content and water activity of dried silkworm pupae

Using FD for 24 h, moisture content of the silkworm pupae was reduced to 1.01 g water/100 g dry solid and water activity is 0.116. For HAD at 60, 70 and 80 °C, moisture content was 2.23, 1.76 and 1.13 g water/100 g dry solid respectively. This was coincided with the reduced water activity to 0.167, 0.152 and 0.108, respectively. By using MHAD, drying time could be reduced to 14 min. With the assistance of hot air temperature at 100, 120, 140 and 160^{o}C, moisture content was reduced to 5.42, 4.28, 2.73 and 2.38 water/100 g dry solid, respectively. Water activity was also reduced to 0.344, 0.296, 0.246 and 0.229, respectively. Low moisture content and water activity indicated shelf life stability.

Texture and microstructure of silkworm pupae dried

Hardness defined as the maximum force required to achieve a given deformation. Hardness of FD sample and HAD samples were significantly ($P<0.05$) lower than that of MHAD samples. By increasing HAD temperature to 60, 70 and 80^{o}C, hardness of the dried silkworm pupae was 3.34, 3.32 and 2.75 kg, respectively (Table 1). The hardness of silkworm dried from FD was 2.73 kg which was not different from HAD samples at 80^{o}C. On the other hand, increasing air temperature in MHAD did not affect hardness ($P \geq 0.05$). The higher drying temperature during HAD at 80^{o}C may damage microstructure, resulting in low hardness. The previous research also reported that the maximum compression force of silkworm pupae dried at 80^{o}C were only 1.77-2.57 kg (Srikaew and Songsermpong, 2012).
According to SEM (Fig. 1), microstructure of the dried silkworm pupae was damaged as influenced by drying condition. The drying method induced structural changes and protein denaturation. Fig. 1A and 1B shows the structure of the dried silkworm pupae from freeze drying and hot air drying at low temperature (60^{o}C) for 20 h had a rough surface and a compact structure. The dried silkworm pupae from the hot air drying at 70^{o}C for 16 h

and at 80°C for 10 h had rough and loose surface with compact structure (Fig. 1C and 1D).

Table 1. Moisture content, water activity and hardness of the dried silkworm pupae

Drying operation	Condition	Moisture content (g water /100 g dry solid)	Water activity	Hardness (kg)
FD	-54 °C, 2.73Pa(24h)	1.01[g]± 0.11	0.116[g]± 0.010	2.73[b]± 0.76
HAD	60°C (20h)	2.23[e]± 0.09	0.167[e]± 0.010	3.34[b]± 1.12
	70°C (16h)	1.76[f]± 0.13	0.152[f]± 0.006	3.32[b]± 0.61
	80°C (10h)	1.13[g]± 0.11	0.108[g]± 0.009	2.75[b]± 0.87
MHAD	600W,100°C (14min)	5.42[a]± 0.11	0.344[a]± 0.006	11.99[a]± 2.89
	600W,120°C (14min)	4.28[b]± 0.06	0.296[b]± 0.007	12.17[a]± 3.74
	600W,140°C (14min)	2.73[c]± 0.07	0.246[c]± 0.012	12.35[a]± 3.46
	600W,160°C (14min)	2.38[d]± 0.07	0.229[d]± 0.003	12.50[a]± 2.37

[a-g] means within the same column with different letters are significantly different ($P \leq 0.05$)

Table 2. Colour of the dried silkworm pupae

Drying operation	Condition	L*	a*	b*
FD	-54 °C, 2.73Pa(24h)	46.03[d] ± 0.50	6.69[a] ± 0.14	24.25[f] ± 0.37
HAD	60°C (20h)	48.69[c] ± 0.14	4.89[b] ± 0.10	27.67[d] ± 0.26
	70°C (16h)	44.90[e] ± 0.50	4.97[b] ± 0.14	25.57[e] ± 0.55
	80°C (10h)	43.58[f] ± 0.47	4.65[c] ± 0.05	24.34[f] ± 0.25
MHAD	600W,100°C (14min)	53.07[a] ± 0.31	4.55[c] ± 0.09	30.17[b] ± 0.17
	600W,120°C (14min)	52.96[a] ± 0.46	4.30[d] ± 0.12	30.72[a] ± 0.36
	600W,140°C (14min)	52.85[a] ± 0.16	4.28[de]±0.06	30.62[a] ± 0.17
	600W,160°C (14min)	50.97[b] ± 0.20	4.19[e] ± 0.20	29.25[c] ± 0.16

[a-f] means within the same column with different letters are significantly different ($P \leq 0.05$)

During microwave drying, water molecules could directly absorb the microwave energy and generate heat dramatically within a short time (Deng et al., 2015). The dried silkworm pupae from MHAD at 100°C had intact and smooth surface (Fig. 1E). By increasing hot air temperature to 120°C, the dried silkworm pupae had loose surface (Fig..1F). When temperature was increased to 140°C, only partial complex system exhibited a damaged surface with an exposed internal structure (Fig..1G). Uniformity was decreased at the high hot air temperature operations, especially MHAD at 160°C. The morphology of sample was obviously broken down. The dried silkworm pupae were coated with a thin layer of fat resulting in hiding the internal porous network. Hu et al., (2017) reported that the microwave technique efficiently promoted the release of oil by breaking down the cell structure of the silkworm pupae and localized and rapid heating. As a result, the microwave led to the obvious cell rupture. In current study, SEM showed the considerable difference in the cellular structure depending on drying methods.

Table 3. Composition of the dried silkworm pupae

Drying operation	Condition	Protein content (g/100 g dry solid)	Fat content(g/100 g dry solid)	Ash content(g/100 g dry solid)	Fiber content (g/100 g dry solid)
FD	-54 °C, 2.73Pa (24h)	54.30[cde] ± 2.72	24.01[e]± 0.52	2.48[b] ± 0.062	4.95[e]± 0.14
HAD	60°C (20h)	53.33[de]± 2.13	39.79[b]± 0.52	2.46[b] ± 0.123	6.51[b]± 0.27
	70°C (16h)	52.54[e]± 0.40	40.62[b]± 0.21	2.50[b] ± 0.141	6.88[a]± 0.25
	80°C (10h)	50.27[f]± 1.68	42.29[a]± 0.47	2.51[b] ± 0.231	7.04[a]± 0.31
MHAD	600W,100°C (14min)	54.67[cd]± 0.89	35.96[d]± 0.25	2.73[a] ± 0.050	5.47[d]± 0.34
	600W,120°C (14min)	55.72[bc]± 0.80	36.54[cd]± 0.33	2.71[a] ± 0.058	5.77[cd]± 0.17
	600W,140°C (14min)	57.13[ab]± 0.92	37.30[c]± 0.20	2.56[ab] ± 0.138	5.97[c]± 0.16
	600W,160°C (14min)	58.09[a]± 2.06	37.32[c]± 2.00	2.50[b] ± 0.132	5.99[c]± 0.18

[a-f] means within the same column with different letters are significantly different ($P \leq 0.05$)

Colour of the dried silkworm pupae

L*-values of the dried silkworm pupae from HAD at 60, 70 and 80°C were at 48.69, 44.90 and 43.58 respectively (Table 2). This was in good agreement of the previous work (Srikaew and Songsermpong, 2012) that reported the decrease in L*-value of the dried silkworm pupae as the temperature increased. By increasing air temperature to 100, 120, 140 and 160°C during MHAD, L*-values were changed to 53.07, 52.96, 52.85 and 50.97 respectively. Then colour of MHAD samples was lighter than the one from HA. The dried silkworm by FD showed the L*-value of 46.03. Redness (positive a*-value) of the dried silkworm pupae from FD was the highest ($P<0.05$). For the yellowness (positive b*-value), the dried silkworm pupae from MHAD had more b-value than those from HAD and FD. Actually the freeze drying could maintain the original colour of the silkworm pupae. Mishra et al., (2003) reported that the colour of Eri, Muga and Mulberry pupae was amber brown, cherry brown and golden brown, respectively. During blanching, the insect colour was usually changed from the original shades of grey, blue or green to red. Improperly dried insects may be black. Properly dried insects are golden or brown (Kouřimská and Adámková, 2016).

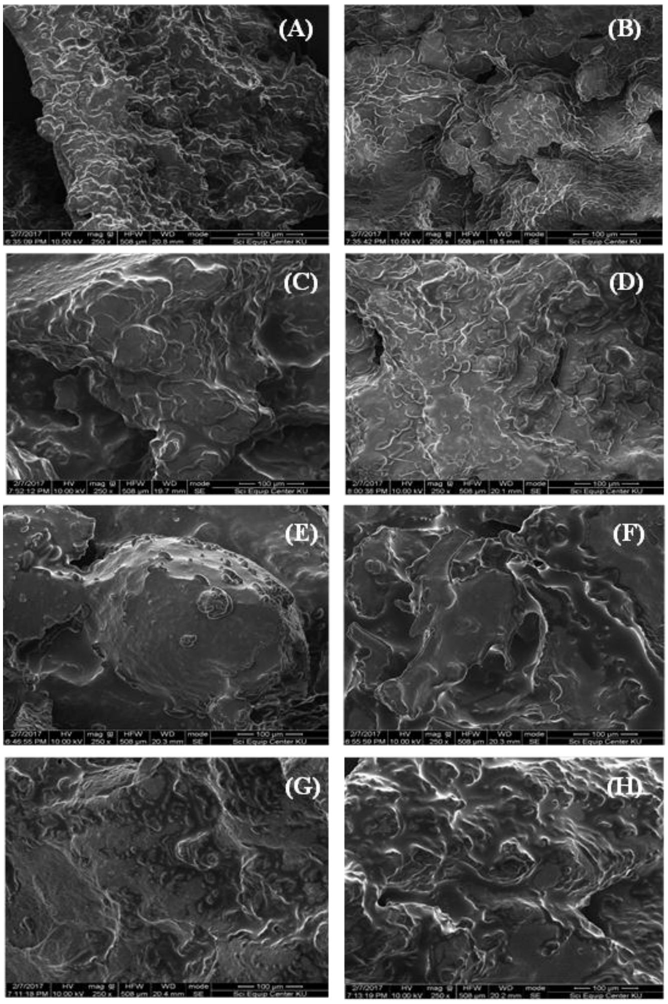

Fig. **1.** Scanning electron micrographs of the inner layer of silkworm pupae dried at (A) FD ; (B) HAD at 60°C ; (C) HAD at 70°C; (D) HAD at 80°C; (E) MHAD at 100°C; (F) MHAD at 120°C; (G) MHAD at 140°C and (H) MHAD at 160°C

Composition of the dried silkworm pupae

Protein content of the insects were found to be much higher than those reported for beef and pork, the two most accepted animal meat around the world (Ghosh et al., 2017). The dried silkworm pupae contained 50.27-58.09 g protein/100 g dry solid, depending on drying condition. Increasing HAD temperature to 60, 70 and 80 °C reduced protein content to 53.33, 52.54 and 50.27 g/100 g dry solid, respectively. In contrast, when the silkworm pupae was dried by MHAD, increasing temperature to 100, 120, 140 and 160 °C, protein content was increased to 54.67, 55.72, 57.13 and 58.09 g/100 g dry solid, respectively.

Fat content of the dried silkworm was 24.01-42.9 g/100 g dry solid. The lowest fat content was found in the samples from FD. This reduction of fat content suggests that, during drying, fat may have exuded along with moisture evaporation (Akonor et al., 2016). Ash content of the dried silkworm from HAD was in the range of 2.46- 2.51 g/100 g dry solid. Using the FD, ash content was around 2.48 g/100 g dry solid. However, the ash content of the dried silkworm from MHAD at 100-120°C was significantly higher than others ($P<0.05$). Fiber content of FD samples was the lowest ($P<0.05$). The highest fiber content could be obtained from HAD at 70-80°C (6.88-7.04 g/100 g dry solid) The previous research (Longvah et al., 2011) reported more than 48.7% protein and more than 25% fat in the silkworm pupae. Similarly, Kumar et al., (2003) suggested that silkworm pupae contained 55.60% protein and 32.2% lipid content. In addition, the nutrient composition of silkworm such as saturated fat content was around 2.23-2.33g in 100 g sample (Payne et al., 2016).

Conclusions

To preserve the silkworm pupae (Bombyx mori) from silk spinning for longer time, drying could be used. Nevertheless drying condition affected quality of the dried silkworm pupae including moisture content, water activity, fat content, protein content, microstructure and hardness. Increasing drying temperature in HAD significantly ($P<0.05$) increased ash and protein content. However, increasing hot air temperature of MHAD decreased ash content, but increased protein content and hardness. FD decreased the fat content, fiber content, moisture content and hardness. However, the protein content of FD samples was similar to samples from MHAD at 100°C. The optimal process of the dried silkworm pupae was MHAD at 600W together with hot air drying at 160 °C for 14 min, because of short time drying and high protein content (58.09 g/100 g dry solid) to ensure alternative source of food protein.

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Conflict of Interest

All the authors declare that they have no conflict of interest.

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