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Drying of edamames by hot air and vacuum microwave combination

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Abstract

The characteristics of hot air and vacuum microwave drying were compared using edamame as the raw material, and an optimized combination drying process was then established thereof so as to achieve increased drying rate and enhanced product quality. Edamame was subjected to 70 °C hot air drying for 20 min, and then microwave dried at power intensity 9.33 W/g for 15 min under −95 kPa (gauge pressure). The optimized combination drying process exhibited significantly shortened drying time as compared with conventional hot air drying, and greatly decreased mass loads on the vacuum microwave dryer.

Keywords: Hot air drying; Vacuum microwave drying; Combination drying; Parameter optimization

1. Introduction

Edamame (*Glycine Max (L.)* Merrill.), also called vegetable soybean, is the soybean harvested at approximately 80% maturity. It is rich in protein, fat, phospholipids, calcium, iron, vitamins and diet fibre, and popularly consumed after blanching in Korea, Japan, China, and other Far East, countries. It also have potentials for cancer prevention and suppression due to its high content of genistein. In recent years, with the increase of the human being's awareness of health and knowledge about the health function of natural products, edamame produces have gradually attracted extensive attention worldwide. Edamame production and trading volume has kept on the rise over the years (Gai, Wang, & Chen, 2002; Song, An, & Kim, 2003).

Vacuum microwave drying (VMD) is one of the emerging food processing methods in recent years. It relies on the principle of the dielectric loss properties in microwave field. Water molecules, with the largest dielectric constant, absorb the microwave energy and generate evident heat effect. Because microwaves can penetrate directly into the material, the entire product is heated (from the inside out) in a fast and uniform manner, causing rapid evaporation of water and creating an outward flux of rapidly escaping vapor. In conventional drying methods, however, heat transfer from the surface into the interior of materials costs time because of the temperature gradient across the section. The directions of heat and mass transfer are opposite. The outer layer of the product becomes dry first, forms a poor heat conductor which hinders the dehydration process. In vacuum microwave drying process, heat and mass transfer are in the same direction, and the moisture transfer conditions can be greatly improved. Because the boiling point of water falls down under vacuum conditions, VMD can increase the moisture gradients and speed up the drying rate. Therefore, VMD can accomplish drying tasks in a shorter time at lower temperature (Xu, Min, & Mujumdar, 2004).

Comparing with conventional hot air drying, VMD has the following advantages: (i) the drying rate can be greatly quickened; (ii) the nutritional value, color and original flavor can be largely maintained; puffing, drying and sterili-

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zation are accomplished at the same time, which enhancs the product quality; (iii) heat loss is much lower because drying time is shortened and the difference of temperature between the inside and the outside of the equipment is small; (iv) energy absorption is proportional to the residual moisture content, and can be easily controlled by itself and (v) VMD can be performed at lower temperature and thus suitable for processing heat sensitive materials (Tang, 2002). Thanks to these unique properties, VMD justifies itself as an excellent method for processing health snack foods with nutritional values and pleasant flavor.

However, the progressing of VMD application at the industry level has been relatively slow due to its high initial capital investment and large operating cost compared with conventional drying methods. Larger VMD equipment size is required in the case of high moisture fruits and vegetables processing, because the equipment scale is proportional to the loads of drying (water contents to be removed). The vapor escaping from the materials, which cannot be expelled from the closed vacuum microwave dryer cavity in time, will recondense on the inner wall, and thus increase the loads of drying. Therefore, VMD alone is not an economical drying method. In order to save investment and the operating cost, the raw materials should be dried with hot air drying (AD) to remove a fraction of the moisture, and then dried in the vacuum microwave dryer to the final desired moisture content.

The objective of this study was to compare AD, VMD and combination AD-VMD methods for edamame processing in terms of drying rate, product color, nutrient preservation, and sensory quality, and to optimize a combination AD-VMD process for edamame processing.

2. Materials and methods

2.1. Materials

Deep-frozen edamames used in this study were obtained from Haitong Food Group Ltd. Co with an initial moisture content of 71% (w.b.). All edamames used for drying were from the same batch.

2.2. Drying equipment

A vacuum microwave dryer (WZD4S-1, Nanjing, China for schematic diagram see Fig. 1), with a maximum nominal power of 4.2 kW and an operation frequency of 2450 MHz, was used in this research. The operation power is adjustable between 700 W and 4200 W at 700 W increments. The dimensions of the microwave cavity were $1050 \times 1080 \times 800$ mm. The maximum vacuum degree is −95 kPa. Six plates in the cavity move round at 1 rpm during operation. A temperature-adjustable hot air dryer (SHT series, Shangyu, China) with steam flow tray was used to dry the samples.

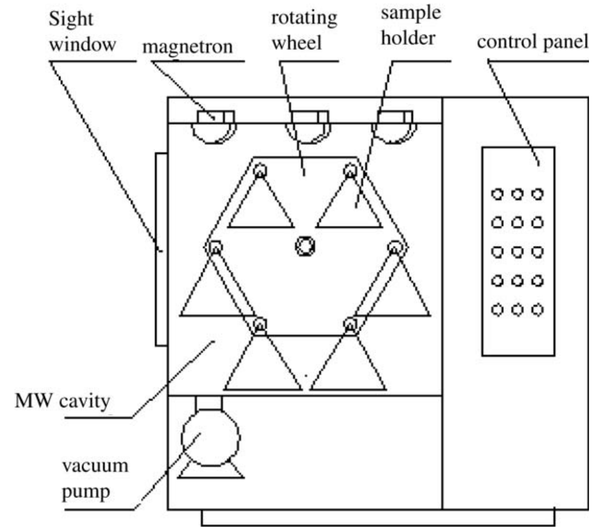

Fig. 1. Schematic diagram of the vacuum microwave dryer.

2.3. Drying procedures

Preparation of materials: Deep-frozen edamames were unfrozen at room temperature, immersed in 3% salt solution for 1 h, and then drained.

Hot air drying: The pretreated materials were spread uniformly as a single layer on the bed (mesh) of tray dryer. Hot air was flowed perpendicularly through the bed at 1.5 m/s velocity and 20% relative humidity. The temperature of the hot air were controlled at 60, 70, 80 °C, respectively. The samples were dehydrated until they reached the final moisture content.

Microwave drying: The samples were spread into thin layers in the plates of the microwave cavity. Different microwave power densities (2.1, 2.8, 3.5 kW) were investigated under constant vacuum degrees. Drying was performed according to a pre-set power and time schedule.

Optimization of combination AD-VMD drying procedures: Drying was carried out by a combination of AD-VMD techniques. The samples were dried by hot air initially for 20–40 min until the water content dropped to 40–60% of initial moisture content, and then vacuum microwave dried to the final water content. An orthogonal design was used to gain the optimal parameters.

All the experiments above were repeated twice and the average of three results of moisture content for each treatment was used for drawing the drying curves. The dehydrated samples were packed immediately after drying into polyethylene bags for further analyses.

2.4. Water content determination

Water content was determined by the oven method (Lin, 1997). At regular time intervals during the drying processes samples were taken out and dried in the oven (Binder FED, Germany) for 7–8 h at 105 °C until constant weight. Weighing was performed on a digital balance (HANGPING

FA1104, China). Finally, the water content (w.b.) was calculated.

2.5. Vitamin C and chlorophyll contents

Vitamin C was determined using 2,6-dichlone indophenol titration (Lin, 1997). Chlorophyll determination was adopted from Arnon (Li, 2000), using a spectrophotometer (Lingguang 752, China). Data were calculated on a dry basis and expressed as micrograms per 100 g solids.

2.6. Color

The color of dried samples was evaluated by a Model WSC-S spectrocolorimeter (Shenguang, China). The results were expressed as Hunter L^*, a^*, b^*, respectively, where L^* is the degree of lightness, a^* the degree of redness (+) and greenness (−), and b^* the degree of yellowness (+) and blueness (−). The Hunter L^*, a^*, b^* values of each treatment was measured for three times.

2.7. Sensory evaluation

The sensory evaluation of dried samples was carried out by a tasting panel of nine untrained judges. The panelists were asked to indicate their preference for each sample, based on the quality attributes of color, appearance, texture, aroma/flavor, and overall acceptability. A balanced 10-point hedonic rating was employed for all the attributes evaluated where 9–10 denoted "like very much" (7–8 "like", 5–6 "Neutral", 3–4 "dislike") and 1–2 indicated "dislike very much". The judges were asked to give their remarks about each of the samples.

2.8. Drying rate

Drying rates (Y_1) are the average values of moisture changes in the total drying times (including AD and VMD), which are calculated using Eq. (1) and expressed as g water/g dry solids min.

$$Y_1 = \frac{X_d - X_0}{T_{AD} + T_{VMD}} \quad (1)$$

where X_d and X_0 are the water contents of the dehydrated sample and the fresh sample on dry basis. T_{AD} and T_{VMD} are the drying times of air drying process and vacuum microwave drying process, respectively.

2.9. Synthetic evaluation index

A Synthetic evaluation index (S) was adopted to reflect the contributions of drying rate and dried product quality. It composed of drying rate, sensory valuation, vitamin C content and chlorophyll content. According to their degree of significances (drying rate > sensory valuation > vitamin C content > chlorophyll content) to the drying process, they were assigned weight coefficients λ_1, λ_2, λ_3, λ_4 at 0.4, 0.3, 0.2, and 0.1, respectively. Then a synthetic evaluation index was calculated using the following equation (Liu, 1998).

$$S_j = \sum_{i=1}^{4} \lambda_i \frac{Y_{ij} - Y_{i\min}}{Y_{i\max} - Y_{i\min}} \quad (j = 1,2,3,4,5,6,7,8,9) \quad (2)$$

2.10. Statistical analysis

Statistical analysis was conducted by analysis of variance (ANOVA) using the general linear model (SPSS 10.0). The data were analyzed using the ANOVA module and Duncan's multiple-range test to detect the differences among treatments (Liu, 1998). Comparisons between the indices relative to different treatments were conducted using ANOVA, and significance of difference was defined at $p \leqslant 0.05$ in color evaluation and Vitamin C and chlorophyll content evaluation.

3. Result and analysis

3.1. Hot air drying characteristics

In the AD process, drying rate decreased along with decreasing of edamame moisture contents and drying air temperatures, which might be attributed to slower moisture migration rate from interior to surface and evaporation rate from surface to air caused by decreased sample moistures. At the same air velocity, the drying times required at 60, 70, 80 °C were 600, 540, 360 min, respectively (Fig. 2). But higher temperature and longer drying time will cause deterioration of edamame color and nutrients. Case-hardening is another drawback encountered in hot-air dried products. Therefore, extremely high air temperatures should be avoided to minimize damages to the finished product quality. The AD process is divided into two phases. The early stage of drying characterized by higher drying rate could be explained by the ease of the free water

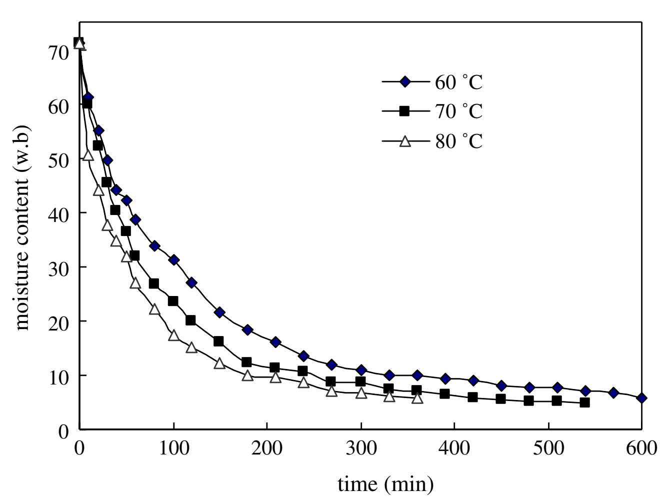

Fig. 2. Effect of hot air temperature on drying time.

at or near the surface to be removed. The least efficient portion of a conventional drying system is near the end, where the drying rate is controlled by water diffusion from interior to the surface, and sample shrinkage restricts the diffusion rate causing decreases in the drying rate. Generally, around two thirds of the drying time may be spent removing the last one third of the moisture contents to be reduced (Ana, Cristina, & Pedro, 2004), which makes hot air drying a time-consuming task.

3.2. Vacuum microwave drying characteristics

3.2.1. Effect of microwave power

The total drying times under −95 kPa vacuum pressure required to reach the final moisture content were 35, 25 and 22 min, respectively at 2.1, 2.8 and 3.5 kW power density levels (Fig. 3). Evidently the drying of edamames by VMD is much faster than by AD. The microwave drying time for edamames is reduced to 0.5 h equivalent to 5–15% of air drying time. Drying rate increased as the microwave power density is increased. The microwave output power had a crucial effect on the drying rate, which can be attributed to the acceleration of interior moisture migration and resultant increased surface water evaporation by higher microwave power.

However, too high microwave power drying has also been associated with physical damages to the products, e.g. scorching, over-heating or charring, and uneven temperature distribution. Such physical damages are the result of continuous local temperature rising even though the loss factor of material being dried decreases with reduction in moisture contents. This also indicates a possible non-uniform distribution of microwaves inside the cavity. Hence it is difficult to control the quality of the dried products when higher power densities are used.

3.2.2. Effect of mass load

The drying time was prolonged with the increase of the mass loads (Fig. 4), which is attributable to higher mass loads and in turn higher water content to be removed. All this decreases the microwave power density efficiency versus sample weights.

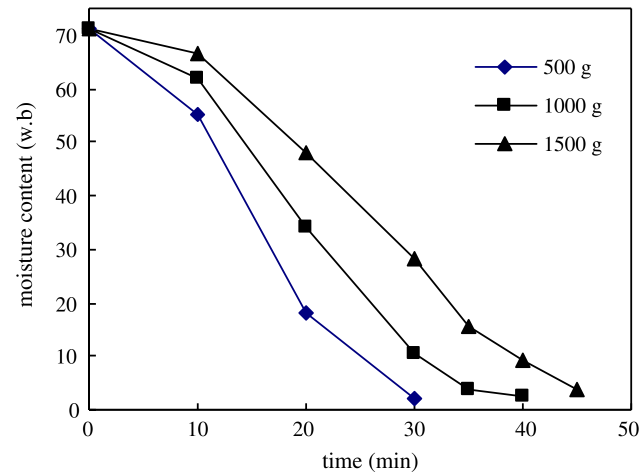

Fig. 4. Effect of the mass load on drying time ($P = -95$ kPa, 2.8 kW).

3.2.3. Effect of vacuum pressure

The moisture content versus time curves for drying of edamames as influenced by different vacuum pressure (0, −50, −80 and −95 kPa) are shown in Fig. 5, under the same conditions 2.8 kW and 500 g. Vacuum degree has important effects on drying time. For example, the drying time under the maximum vacuum degree (−95 kPa) was 25 min, which was only 42% that under 0 kPa (atmospheric pressure). The greater the environment vacuum degree, the lower the boiling point of water in the edamame. Higher vacuum degree increases the driving force for mass transfer and facilitates the evaporation and volatilization of water from the materials, and thus greatly shortens the drying time. But higher vacuum degrees normally would give rise to glow discharges or electrical arcing in the cavity, and cause local overheating and irreversible damages to the product. Therefore, relatively higher vacuum degrees

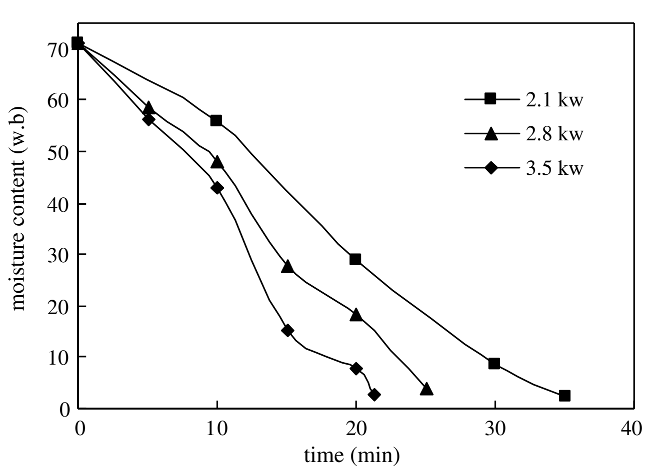

Fig. 3. Effect of microwave power on drying time ($P = -95$ kPa, 500 g).

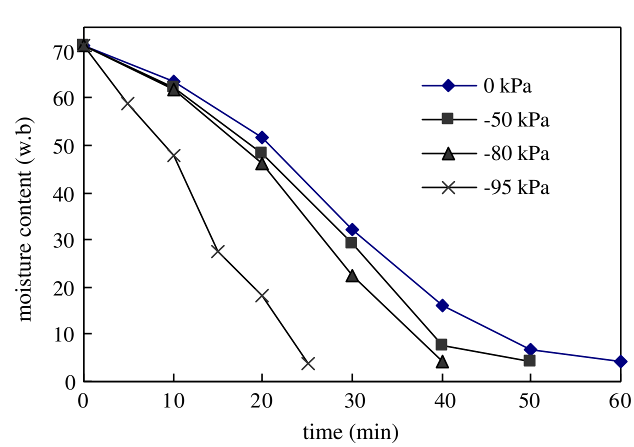

Fig. 5. Effect of vacuum pressure on drying time (2.8 kW, 500 g).

should be used to save drying time on preconditions that product quality is not significantly damaged.

3.3. Comparison between the effects of AD and VMD on product quality

Drying time and temperature are the most important operating parameters affecting dried food quality, which is usually evaluated based on their effects on nutrient retention and sensory characteristics. Thermal damage incurred by a product during drying is directly proportional to the temperature and time involved. Too high temperature and too long drying time often cause heat damage and poor texture, color, flavor and nutritional value of foods. VMD was not only a much faster drying process than AD, but also worked at lower temperature than AD. Moreover, the absence of air during drying may avoid oxidative reactions, and therefore, effectively preserve food color and nutrients (Lin & Durance, 1998). In this study, for example, the maximum retention rate of vitamin C and chlorophyll exceed 84.1%, 32.6% for VMD samples, and 35.6%, 25.2% for AD sample, respectively. AD resulted in a darker (lower L^* value), less green (higher a^* value), and more yellow color (higher b^* value) than VMD. The AD-VMD sample color was close to that of VMD. The greenness of sample decreased with the increase of temperature in AD ($p \leqslant 0.05$), but the change in green color values was not dependent on the microwave power intensity ($p > 0.05$) (Table 1).

3.4. Experiments and analysis of combination AD-VMD

From experimental results above, the drying rate of AD was very high in early period of process, but very slow in the late stage, while VMD remained at higher drying rate in the whole process. It has been suggested, essentially for economic reasons, that microwave energy should be applied to lower moisture content foods to finish drying. Combination of AD and VMD can greatly shorten the drying time, reduce the mass loads of the microwave equipment, and ensure good product quality (Ana et al., 2004; Medeni, 2001).

An orthogonal design of three factors at three levels was used to optimize a combination AD-VMD drying process

Table 2
The design of L_9 (3^3) orthogonal test

Factors	MV power intensity (W/g)	Temperature (°C)	Time (min)
Levels	7.00(1)	60(1)	20(1)
	9.33(2)	70(2)	30(2)
	11.67(3)	80(3)	40(3)

for edamame processing. The factors include air temperature, AD drying times in the first stage, and VMD power intensity in the final stage (Table 2). After the AD step, 300 g samples were subjected to VMD to the final moisture content.

The synthetic evaluation index related with treatment no. 8 reached 0.9087, which is evidently higher than any of other treatments. Treatment no. 8 only took 12 min in the VMD step and 32 min in the whole combination drying process, the total drying time being close to that of straight VMD and 6% that of AD (70 °C, 540 min). This combination AD-VMD process not only shortens the drying time than straight AD, but also maintains food color and nutrient (Table 1). Similar results were gained by Sharma with regard to dried garlic cloves by microwave-hot air combination (Sharma & Prasad, 2001).

The significance of three factors studied is in the order: AD time > air temperature > microwave power from polar difference analyses (Table 3). In the treatments tested, air drying for 20 min (treatment nos. 1, 6, and 8) exhibited the highest synthetic evaluation index, which can be attributed to increase in the drying rate and reduction in quality damage of edamame; and brought down the moisture content to less than 50% (w.b.), which greatly decreased the mass loads of microwave dryer. Since microwave power was the least significant factor affecting the synthetic evaluation index, it was determined to assume a lower level of 9.33 W/g rather than 11.67 W/g in the best treatment (treatment no. 8) so as to control energy consumption and overheating of edamames. The drying time was correspondingly prolonged to 15 min, a minor and tolerable increase from 12 min in the best treatment (treatment no. 8). The optimal combination AD-VMD drying process was thus obtained: 70 °C hot air was used to heat the edamames for 20 min in the prophase, and then vacuum micro-

Table 1
The effect of drying method on color values, retention of vitamin C and chlorophyll

Drying mode	L^*	a^*	b^*	Vc (mg/100 g)	Chlorophyll (mg/100 g)
AD (60 °C)	74.47 ± 0.17^b	-8.50 ± 2.26^b	30.32 ± 1.29^b	16.00 ± 0.29^c	11.35 ± 0.27^c
AD (70 °C)	73.08 ± 2.73^b	-7.28 ± 1.16^b	34.54 ± 5.04^a	22.55 ± 0.22^c	14.10 ± 0.34^c
AD (80 °C)	73.78 ± 0.02^b	-5.31 ± 1.89^a	32.90 ± 1.44^a	18.44 ± 0.16^c	$24.47 \pm 0.29^{b,c}$
VMD (2.1 kW)	79.92 ± 0.06^a	-10.20 ± 0.19^c	28.59 ± 0.81^c	43.49 ± 0.72^b	29.01 ± 0.32^b
VMD (2.8 kW)	79.62 ± 0.24^a	-9.95 ± 0.59^c	26.67 ± 1.27^c	44.39 ± 0.55^b	29.85 ± 1.28^b
VMD (3.5 kW)	79.67 ± 0.37^a	-11.00 ± 0.18^c	27.81 ± 0.03^c	53.28 ± 0.35^{ab}	31.66 ± 0.03^b
AD + VMD[e]	$76.80 \pm 0.12^{a,b}$	-10.48 ± 0.76^c	30.49 ± 0.16^b	42.08 ± 1.74^b	28.64 ± 0.45^b
Fresh sample	67.86 ± 2.91^c	-18.08 ± 1.46^d	33.69 ± 0.48^a	63.35 ± 0.87^a	97.11 ± 0.31^a

[a,b,c,d] Different letters in the same column indicate a significant difference ($p \leqslant 0.05$).
[e] AD + VMD is treatment no. 8 in the orthogonal test.

Table 3
The testing values and the synthetic evaluation index at the design of L_9 (3^3) orthogonal test

No.	MW power (W/g)	T (°C)	Time (min)	Y_1 (g/g min)	Y_2	Y_3 (mg/100 g)	Y_4 (mg/100 g)	S
1	1	1	1	5.394	9	38.55	21.78	0.5970
2	1	2	2	4.852	8	42.62	17.78	0.5201
3	1	3	3	4.174	4	43.32	21.74	0.3059
4	2	1	2	5.151	7	43.89	31.67	0.6314
5	2	2	3	4.746	6	30.25	26.84	0.3053
6	2	3	1	7.478	5	33.30	26.51	0.6332
7	3	1	3	4.727	7	41.71	24.68	0.4983
8	3	2	1	7.506	8	42.08	28.64	0.9087
9	3	3	2	6.282	2	36.39	26.09	0.4030
A1[a]	0.474	0.576	0.713					
A2[a]	0.523	0.578	0.518					
A3[a]	0.603	0.447	0.370					
R[b]	0.129	0.131	0.343					

[a] A1, A2, A3 are the average values of total evaluation related with the same factor at three levels, respectively.
[b] $R = A_{i\max} - A_{i\min}$, $i = 1,2,3$.

wave at power intensity 9.33 W/g, vacuum pressure −95 kPa was used to continue drying for 15 min.

4. Conclusions

1. In the conventional hot air drying process, the drying rate was fast in the beginning stage, but decreased sharply in the last stage. Raising of the hot air temperature could not enhance the drying rate in the last stage, but caused damages to the food quality.
2. In the microwave drying process, the drying rate increased with increase of microwave power and vacuum degree, and decrease of mass loads. The drying time can be greatly shortened compared with conventional drying.
3. Combination AD-VMD are close to straight VMD in terms of product quality and drying time, but superior in terms of mass load, power consumption, and equipment investment. Combination AD-VMD is superior to straight AD with respect to all these indices except equipment investment.
4. A combination AD-VMD drying process was obtained: 70 °C hot air was used to heat the edamames for 20 min in the prophase, and then vacuum microwave at power intensity 9.33 W/g, vacuum pressure −95 kPa was used to continue drying for 15 min.

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