Article

Microwave Drying for Production of Rehydrated Foods: A Case Study of Stink Bean (*Parkia speciosa*) Seed

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Featured Application: Microwave drying is implemented in the production of rehydrated food, as demonstrated in the case of stink beans.

Abstract: The potential of microwave drying in the production of rehydrated foods is demonstrated with stink beans (*Parkia speciosa*), smelly legumes of Africa and Asia. Compared to stink beans dehydrated by convective drying and freeze drying, the microwave products exhibit higher moisture contents, but the distribution of microscopic pores leads to good rehydration characteristics. Dehydration by microwave drying is also achieved within a much shorter period than that commonly used in freeze drying. The dehydration time can be further reduced to 6 h comparable to convective drying, and the moisture content is dropped to 11% by decreasing the pressure during microwave drying. However, the rehydration time remains around 65 min for products from both ambient and low-pressure (400 Pa) microwave drying. In rehydration, the period is successfully reduced to 30 min by increasing the water temperature to 70 °C. The results indicate that microwave drying does not affect the value of crude protein and rehydrated products are comparable to fresh stink beans. From these findings, the microwave drying technique is an applicable technology for both manufacturers and consumers, with acceptable drying time and rehydration characteristics.

Keywords: microwave drying; freeze drying; convective drying; rehydrated food; stink bean

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1. Introduction

Nowadays, rehydrated foods are very much in consumer demand because of their long shelf life without refrigeration, low contamination, volume decrease as well as ease of consumption and worldwide distribution. Rehydration is a complicated process utilized in food and is directed to bring back its original properties. The dried products are usually immersed in water during their use in food preparation. Rehydration characteristics and the retention of sensory qualities depend on structural changes after drying. Short drying time, high energy efficiency and maintaining the quality after drying are desirable. Product quality, physical appearance and rehydration time for dried products have therefore been improved to fulfill the needs of consumers. Examples of products from rehydration research are lyophilized rice [1] and vegetable and fruit powder beverages [2].

Drying technology can preserve foods by virtue of the evaporation of water and, hence, reducing the moisture content. There are several review drying techniques offered to fruits and vegetables [3] and the food processing industry [4]. Nowadays, drying is a way to add value to modern food products, not only a way to preserve foodstuffs. There are various drying techniques applied to agricultural products such as okara [5], beans [6], honeydew

honey powders [7], red beetroot [8], and medical plants [9]. Each drying technique has unique advantages, making them candidates in the production of rehydrated foods.

Convective drying produces dehydrated products with an extended shelf life. Heat is transferred from the surface into the food via hot air from a steam coil or fuel oils. With the circulation speed in the range of 0.5–5 m/s, the hot air will flow through the food usually prepared in the thickness of 2–6 cm and placed on a tray. If the temperature is higher than 70 °C, the dehydration rate may be too high. This technique is widely used for producing dehydrated vegetables and fruits because of the relatively low price and reasonable maintenance cost. However, the heating is unlikely to be uniform in various positions in the oven because of the uneven air flows. The drying characteristics of the sample are investigated, such as kiwifruits [10] and Mexican serviceberry fruit [11]. In addition to the dehydration, rehydration characteristics of green pea [12], pumpkin [13], and carrot [14] were reported.

Freeze drying is a dehydration process by the sublimation of a frozen product. The operations at low temperatures reduce microbial growth or impede a spoilage reaction to preserve the final product [15]. This method is suitable for foods that are sensitive to heat loss and nutritional value, giving rise to high quality products with good recovery properties. The drying characteristics of cherry [16], stink bean powder [17], stink bean [18] and acorn [19] were investigated. In addition to dehydration, the rehydration of strawberry [20] and mussel [21] were also characterized. Freeze drying is widely used to produce commercial rehydrated foods but has a high cost compared to conventional drying [22,23].

Microwave drying is based on dielectric heating by electromagnetic waves. In addition to a high drying rate within a short time, microwave drying tends to preserve the nutritional values of foods. It is a technology that is suitable for drying raw materials with low humidity. Microwave drying has already been applied to various products, i.e., fish [24], durian [25], instant noodles [26], *Gastrodia elata* Blume [27], potato cubes [28], amaranth leaves [29], bitter melon [30], and sweet potato chips [31]. The major drawback of microwave drying is its nonuniform heating, particularly the overheating at the sample edges [32]. To overcome these shortcomings, microwave drying has been combined with other drying methods.

Microwave vacuum drying has received much attention because of its high energy efficiency, a significant reduction in the drying time, and a superior quality of dehydrated products [33]. By utilizing microwave waves to rotate the water molecules and generate heat under a low-pressure condition, the obtained food products have high nutritional and sensory qualities, without severe shrinkage [34]. Microwave vacuum drying has already been applied to various products, i.e., blueberries [35], pumpkin [36], herbs [37], potato cubes [38], carrot [39], and apple [40]. The microwave vacuum drying and rehydration characteristics of rice [1], turnip seed [33], green bell pepper [41], squid shreds [42], shiitake mushroom [43], bird nest [44], pumpkin [45], and button mushroom [46] were investigated. Microwave vacuum drying is an innovative technology, but it has not been fully utilized in the commercial production of rehydrated foods.

One of the challenging cases of rehydrated food is stink bean (*Parkia speciosa*) or bitter bean, a perennial plant in the pea or bean family (Fabaceae) found naturally in Southeast Asia, South Asia and Africa [47]. The beans come in bright green seedpods 30–45 cm long with 15–20 beans per pod. Its name comes from its peculiar smell as it has a skunky or gaseous, methane-like aroma. Stink beans are called by local names in different regions, e.g., Yongchak in India, Peteh or Petai in Malaysia and Singapore, and Sataw or Sator in Thailand and Indonesia [17,47–49]. They are classified into two types, namely sataw kow and sataw dahn. The former is rounder, nuttier, and less stinky. Unlike twisted sataw kow, sataw dahn's bean pods are straight, hence the name dahn or gradahn (plank) [50]. Previous studies indicate that sataw is rich in vitamin A, calcium, phosphate, sulfidic acid, polyphenolic compounds, and antioxidant capacity [47,51–58]. It possesses antidiabetic and antihypertensive bioactive peptides [47,59] and active organic compounds including flavonoids, saponins, and tannins [47,50,53]. Stink beans exhibit the highest

concentrations of phytochemicals and biological activity and likely compete in functional food markets [47,49]. Stink bean peels demonstrate a potential to remove azo dye [60].

Stink beans are widely consumed in various Asian cuisines as both raw and cooked foods [47]. At present, the preservations are in forms of pickled stink beans in sour brine normally eaten with chili sauce and fresh frozen stink beans with an even stronger aroma. Most recipes still prefer the fresh stink bean to fresh frozen ones. In the monsoon season, there are abundant stink beans, resulting in a price drop. By contrast, their supplies are insufficient during the off-season and thus not available for consumption throughout the year. Additionally, the major problem for fresh stink beans is that the high water content leads to deterioration, so they become rotten. To prolong their production chain on the market, dehydration is the most common way to preserve stink beans by reducing the water activity and expand product distributions with an extended shelf life. Nowadays, stink beans are developed in forms of powders [17] and freeze-dried products [18], but there is no report about the rehydration of dried stink bean.

This research work firstly compares the dehydration as well as rehydration characteristics of stink beans from microwave drying with those from convective drying and freeze drying. The dehydration time is successfully reduced by lowering the pressure in the microwave drying system previously used to dry fish [24] and durian [25]. Finally, it is demonstrated that the rehydration time is shortened by soaking the dehydrated products in water of increasing temperatures.

2. Materials and Methods

2.1. Dehydration of Stink Bean

Fresh samples of stink bean were collected in a local market in Thasala district, Nakhon Si Thammarat, Thailand. After their removal from their pods and shells, the stink beans were cut into half-seeds for drying. These stink beans initially contained 73.08% moisture, comparable to those in previous reports [17,47,51]. Three different dehydration methods were carried out in equipment shown in Figure 1 and are detailed as follows.

- (1) Convective drying: Approximately 1185 g of stink beans was placed on the trays and dried in a convective oven at the Food Technology laboratory of Walailak University, Thailand at 60 °C for 6 h. The drying time was determined based on the characteristics of drying curves in preliminary experiments. To achieve moisture content down to 5%, a drying time shorter than 6 h would require an increase in temperature, which is the critical cause of the degradation of the nutritional value of plants and seeds [17]. The total phenolic compound reduces significantly if the temperature exceeds 60 °C [61]. The temperature of 60 °C was therefore selected to ensure that nutritional quality is retained.
- (2) Freeze drying: Stink beans of about 400 g were dried for 72 h at about −70 °C in a freeze dryer (Christ, gamma 2–16 LSCplus, Osterode am Harz, Germany), operated at the maximum fan speed.
- (3) Microwave drying: Stink beans of about 200 g were dried in a 600 W microwave drying system, previously designed and constructed for fish and durian drying [24,25], at 35 °C for 10 h and at 40 °C for 6 h. The drying time was determined based on the period needed to reduce the moisture content down to 15%. A microwave vacuum dryer was also developed by reducing the pressure in the microwave cavity with a rotary pump [44]. This low-pressure microwave drying was carried out under the pressure of around 400 Pa at 35 °C until reaching a comparable moisture.

Figure 1. Equipment for drying stink beans in this research; (a) Convective drying, (b) Freeze drying, and (c) Microwave drying.

2.2. Characterization of Dehydrated Stink Bean

The moisture content in dried stink beans was characterized according to method 950.46 of Association of Official Analytical Chemists (AOAC) [62]. The crude protein was determined from the amount of nitrogen content using the Combustion Method (Leco TruSpec CN, protein factor 6.25). The surface morphology of dried stink beans was imaged by a field-emission scanning electron microscope (FESEM: Zeiss Merlin compact, Carl Zeiss Microscopy GmbH, Jena, Germany). With the reduction in water, the specific energy consumptions were estimated from the ratio of total electrical power supplied to the amount of water removed by the microwave and convective drying processes.

2.3. Rehydration of Dehydrated Stink Bean

The dried stink beans were immersed in 50 mL distilled water at a controlled temperature of 38 °C. The rehydration was terminated after the weight of stink beans was constant. As the rehydration time was recorded, the stink beans were removed from the water and characterized. In the case of microwave drying, the comparison of colors of dehydrated and rehydrated products was aided by smartphone colorimetry. The application Colorimeter (Research Lab Tools) was employed on an Android smartphone (Oppo A5 2020), previously calibrated with the HunterLab's MiniScan EZ spectrophotometer in the Batik color measurement [63]. The Commission internationale de l'éclairage (CIE) L^*

(lightness), a^* (redness to greenness), and b^* (yellowness to blueness) were averaged from three points on each seed. The rehydration time and appearance of stink beans rehydrated at 38 °C, 50 °C, and 70 °C were also compared. The rehydration process in commercial products is typically carried out at temperatures below 80 °C [64]. The temperature of 38 °C was selected to test the rehydration near ambient conditions, whereas 50 °C was selected based on previous reports on the rehydration of food materials [29,64]. The studies on stink beans reveal that the cooking and leaching of material into the rehydration solution occur rapidly at temperatures over 70 °C. The highest temperature used in this work was therefore 70 °C. The rehydration temperature was also comparable to the studies in [46].

3. Results and Discussion

3.1. Characterization and Rehydration of Stink Beans Dehydrated by Different Methods

The comparison of moisture contents in Table 1 highlights the advantage of freeze drying with negligible water left after 72 h. By using convective drying, the dehydration time can be substantially reduced and the moisture content is lower than 5% within 6 h. Microwave drying at 35 °C for 10 h leaves the moisture over 13% in the stink beans. Interestingly, an increase in the temperature from 35 to 40 °C in drying decreases dehydration time, and a moisture content of 12% is obtained after microwave drying for 6 h. The relatively high moisture in products by microwave drying can be explained based on the classification of water into free, multilayer, and monolayer states. The free water is weakly bound and therefore conveniently evaporated by every method. Prolonged heating removes the water in multilayer and monolayer states. Compared to other methods, microwave drying tends to leave more hydration monolayer at cell walls [27]. However, a lower temperature of microwave drying generally results in high-quality dried products, such as preserving higher phenolic compounds [65].

Table 1. Drying characteristics of dehydrated stink beans from different drying processes.

Drying Methods	Dehydration Time (h)	Starting Weight (g)	Specific Energy Consumption (MJ/kg)	Moisture Content w.b. (%)
Convective Drying at 60 °C	6	1185	75 ± 6	4.23 ± 0.21
Freeze Drying at −70 °C	72	400	N/A	0
Microwave Drying at 35 °C	10	200	146 ± 9	13.6 ± 0.7
Microwave Drying at 40 °C	6	200	102 ± 8	11.6 ± 0.6

The specific energy consumptions of microwave and convective drying are shown in Table 1. The values over 100 MJ/kg are rather high for microwave drying but comparable to a previous report on shiitake mushroom drying [43]. In contrast to the comparison from carrot drying by Gilandeh et al. [14], the specific energy consumptions by microwave dehydration are higher than those by the convective drying of stink beans in this report. Such a difference is related to the much larger size of this convective oven. The oven is capable of dehydrating more than 1 kg of stink beans, whereas the loading for the microwave oven is only around 200 g. A combination of microwave with hot air drying was recommended to increase the dehydration efficiency [23]. The initial convective drying followed by microwave heating reduces the drying time, while the quality of dried products is maintained.

Table 2 shows the external appearance of dehydrated stink beans. All products slightly change their shape and colors. The green color becomes distinctly darker in the case of stink beans from microwave drying. Corresponding to the highest moisture content, the product from microwave drying at 35 °C is closest to the fresh stink beans. Freeze drying results in a very brittle product with the smallest deformation. The deformation after microwave drying is a slightly more than that caused by freeze drying, but significantly lower than convective drying. These findings are consistent with the report from other fruits and vegetables [23].

Table 2. External appearance and rehydration time of dried stink bean from different drying processes.

Drying Methods	Dehydration Time (h)	Appearance		Rehydration Time in 38 °C Water (min)
		Dehydrated Product	After Rehydration	
Convective Drying at 60 °C	6			90
Freeze Drying at −70 °C	72			120
Microwave Drying at 35 °C	10			65
Microwave Drying at 40 °C	6			65

Surface morphologies of dehydrated stink beans are compared by FESEM images. The freeze-dried product tends to lose texture elasticity and exhibits some small pores on the surface in Figure 2b. Freeze drying is known to preserve the structure of dried products. However, greater degradation of aromatic contents due to prolonged drying and the cost of the system must be taken into account for commercial production [66]. Microwave drying results in several large micropores scattered on the surface, as shown in Figure 2c. With similar micropores but a larger distribution, the stink bean after convective drying in Figure 2a has a rougher surface. According to the report of fruits and vegetables drying by microwave [23], the number of pores is reduced but the pores are generally larger than those obtained from the freeze drying and convective drying methods. Such porous structures facilitate the rehydration of dried food [2]. It was reported that drying at elevated temperature led to large pores, increasing the grain rehydration [67].

After immersion in 38 °C water for different periods of time, photographs of dehydrated stink beans are shown in Table 1. All dehydrated stink beans were successfully restored to their original half-seed shape. The decision to terminate the rehydration is validated by the softness at the surface and the light green color of fresh stink beans. In addition, the rehydrated products regain the distinct aroma of fresh stink beans. According to the mass spectrometry-based electronic nose profiles by Asikin et al. [48], dominant volatile aroma components including alcohol, aldehyde as well as sulfur compounds in stink beans are varied and likely affect the perception and acceptance of consumers. The rehydration time is varied and can be related to the morphology of dehydrated stink beans. Structure degradation and collapse reduce the water absorption capacity, whereas the

pores allow more water diffusion. With the smallest pore size, the freeze-dried products need as long as 120 min to rehydrate. The rehydration time is reduced to 90 min in the case of convective drying, and stink beans dehydrated by microwave take only 65 min. From this finding, it is fitting to correlate the rehydration time to the moisture content. It can be understood that the freeze dried stink beans require the longest rehydration time, followed by those from convective drying. The remaining moisture in the dried products is generally undesirable but beneficial in reducing rehydration times for these dried stink beans. The results confirm that microwave drying does not cause severe structural change and the food characteristics are preserved in rehydrated products [10].

Figure 2. FESEM images of dried stink beans from (a) Convective drying (60 °C), (b) Freeze drying (−70 °C), (c) Microwave drying (35 °C), and (d) Microwave drying (40 °C).

3.2. Reduction in Dehydration and Rehydration Times

As microwave drying is generally appropriate for low-moisture foods, it takes a long time to dehydrate fresh stink beans with the moisture exceeding 70%. In addition to the increase in temperature shown in 3.1, the dehydration time by microwave can be shortened by the reduction in pressure during drying. Vacuum pressure and higher microwave power produce more pores without increasing shrinkage [41]. It follows that the diffusion of water through rehydrated products is increased.

The low pressure of 400 Pa during microwave drying gives rise to dark green products comparable to those dehydrated by microwave at the increased temperature of 40 °C. As compared in Table 3, the reduction in pressure from 101 kPa to 400 Pa decreases the dehydration time from 10 h to 6 h. However, the rehydration still needs around 65 min. In both cases, the color of seed coats greatly changes after the rehydration. As compared in Table 4, the CIE L^* value is almost doubled, consistent with the change from dark to lighter in color. The effect of pressure during microwave drying is shown by the CIE a^* and b^* values. As a result of drying at a lower pressure of 400 Pa, a^* is smaller and b^* is larger corresponding to the color closer to that of fresh stink beans. Moreover, the shape

and size are fully restored, indicating that structural damages by microwave drying are not severe. As shown in Figure 3, stink beans after low-pressure microwave drying have a more uniform surface and smaller pores than those dried at ambient pressure.

Table 3. External appearance and rehydration time of dried stink bean from microwave drying with ambient and low pressures.

Pressure during Microwave Drying	Dehydration Time (h)	Appearance and CIE L*a*b* Color Space		Rehydration Time (min)
		Dehydrated Product	After Rehydration	
Ambient pressure (101 kPa)	10			65
		$L^* = 21 \pm 4, a^* = -3.7 \pm 5, b^* = 16 \pm 1$	$L^* = 45 \pm 2, a^* = -8.3 \pm 4, b^* = 40 \pm 8$	
Low pressure (400 Pa)	6			65
		$L^* = 24 \pm 2, a^* = -13 \pm 1, b^* = 24 \pm 4$	$L^* = 45 \pm 2, a^* = -22 \pm 1, b^* = 48 \pm 1$	

Table 4. Moisture and crude protein in dried stink beans dehydrated by microwave at 35 °C with two different pressures compared to fresh stink beans.

Stink Bean	Moisture Content w.b. (%)	Crude Protein (%)
Fresh	73.1 ± 3.7	31.02
Microwave drying at 101 kPa	15.7 ± 0.8	31.23
Microwave drying at 400 Pa	11.3 ± 0.6	30.41

(a)

(b)

Figure 3. FESEM images of stink beans dehydrated by microwave at 35 °C with (a) ambient pressure (101 kPa), and (b) low pressure (400 Pa).

The moisture content of 11.3% in Table 4 highlights the effect of low pressure on the microwave drying of stink beans that more water content is removed within a shorter time. The crude protein in stink beans dehydrated by using ambient and low pressures is comparable around 30%. As the combined uncertainty from the sample preparation and protein analysis method can be as high as 1%, these protein values are considered unchanged from those of the fresh stink bean, highlighting that the relatively low temperature in microwave drying could preserve the high protein present in stink beans [47]. In this work, the crude protein of dried stink beans is measured exclusively in the case of microwave drying at 35 °C because the proteins are likely degraded by drying at higher temperatures [68,69]. As demonstrated by Miranda et al. [61], the protein in quinoa seeds was reduced by 10% after convective drying at 40–80 °C. The report on squid shreds indicated that microwave drying slightly affected the protein content [42].

Finally, the rehydration time is significantly reduced by increasing the water temperature. As shown in Table 5, the products fully restore their original shape and color after immersion in 50 °C and 70 °C for, respectively, 40 min and 30 min. The measurements on seed coats in Table 5 show some similar trends to those in Table 3. The rehydrated products exhibit increases in L^* and b^* values. However, the a^* value is only reduced in the case of 50 °C, suggesting that the major change after rehydration is not the greenness but the lightness component. Furthermore, both values are increased with increasing temperature in the rehydration. The reduction in rehydration time is consistent with the suggestion in the literature that a higher temperature increases water absorption as well as the rehydration rate [28]. After a rapid rise in water due to the initial moisture difference, the reductions in viscosity and the surface tension of water at elevated temperature are increasingly influential in the later stage of rehydration [29].

Table 5. External appearance and rehydration time of dried stink bean using different water temperatures.

Temperature of Water in Rehydration (°C)	Appearance and CIE $L^*a^*b^*$ Color Space		Rehydration Time (min)
	Dehydrated Product	After Rehydration	
38	$L^* = 34 \pm 1, a^* = -19 \pm 2, b^* = 36 \pm 3$	$L^* = 46 \pm 2, a^* = -16 \pm 1, b^* = 48 \pm 3$	65
50	$L^* = 33 \pm 3, a^* = -29 \pm 3, b^* = 37 \pm 1$	$L^* = 48 \pm 7, a^* = -33 \pm 2, b^* = 51 \pm 4$	40
70	$L^* = 31 \pm 3, a^* = -21 \pm 5, b^* = 35 \pm 5$	$L^* = 59 \pm 7, a^* = -20 \pm 4, b^* = 50 \pm 2$	30

4. Conclusions

The stink bean was demonstrated as a rehydrated food produced from microwave drying. Microwave drying at 35 °C gave rise to a moisture content of 14%, higher than that in convective and freeze-dried products, after 10 h. The dehydration time was successfully decreased to 6 h by either increasing the temperature to 40 °C or decreasing the pressure to 400 Pa. This study revealed that stink beans can be dried by using microwaves in a much shorter time compared with freeze drying. With uniform porous characteristics, the dehydrated stink beans can restore their shape, color, and aroma after immersion in water for 65 min. The rehydration time can be reduced to 30 min by increasing the water temperature to 70 °C. The results from the rehydration suggest that the microwave drying process is potentially useful for producing a variety of rehydrated foods with superior quality.

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