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Analysis of drying properties and vacuum-impregnated qualities of edamame (*Glycine max* (L.) Merrill)

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ABSTRACT
To develop a novel dehydrated edamame leisure food, the best edamame from different drying processes was selected to impregnate by different solutions in a vacuum. Microwave drying (MD), pulse-spouted microwave vacuum drying (MVD), vacuum infrared drying (VID), and hot air-drying (AD) were researched, when the drying quality of edamame samples was analyzed for microstructure, color, texture, and flavor. MVD product was found to be the most suitable sample for impregnation. Vacuum impregnation was undertaken with this dried edamame at different impregnated solutions (sucrose, trehalose, and maltose solutions). Through magnetic resonance imaging (MRI) analysis, it was found that three solutions were uniformly distributed in cotyledons after vacuum impregnation. There are some differences in flavor among the impregnated samples in electronic nose. The water state (bound, immobilized and free) in the samples was analyzed during MVD by low-field nuclear magnetic resonance (NMR). The water mobility was found strong in the samples in most of the drying process, and with the progression, the free water gradually disappeared. In the impregnated edamame, the water mobility was much weaker, thus the impregnated edamame can be assumed more suitable for snacks with a longer shelf-life.

KEYWORDS
Edamame; moisture state; pulse-spouted microwave vacuum drying; sugar solution; vacuum impregnation

Introduction

Edamame (*Glycine max* (L.) Merrill) is also named vegetable soybean or green soybean, which is harvested as it reaches almost 80% of maturity.[1,2] Mature edamame is yellow in color and is named as soybean which is a main oil seeds in the world. Edamame originated in China and is also widely cultivated in America, Brazil, Japan, and other temperate countries.[3] Since edamame is very rich in protein, fat, phospholipids, calcium, iron, vitamins, and other nutrients, it is popularly consumed after blanching in Korea, Japan, China, and other far-east countries.[4,5] However, the harvest period of edamame is short. A good drying and processing method can extend its storage time, thus the dehydrated and impregnated edamame with a sweet flavor was developed as a novel edamame leisure food, which has a vast development space.[6]

Drying method has a great influence on the quality of dehydrated products. There are several drying methods and each method can be suitable for a specific product considering the quality and energy requirement. The vacuum infrared drying (VID), microwave drying (MD), and hot air-drying (AD) have been used for drying of agricultural products. Pulse-spouted microwave vacuum drying (MVD) is one of the recent drying methods, which not only solves the problem of uneven drying in MD process but also gives a puffing effect.[7] According to the advantage of MVD, the products from MVD were used to be impregnated in vacuum by different impregnating solutions. In general, impregnated dried food has been researched for many fruit and vegetables, such as apple slices,[8,9] carrots,[10] and so on.[11] Compared with salted and pickled processes, vacuum impregnation can preserve the nutrition of fresh materials better.[12] At present, the drying process was almost vacuum freeze-drying, which cost too much energy and processing time.[13] Pulse-spouted MVD is a high-efficiency drying method; thus, this work investigates the feasibility of using MVD process for drying and impregnation of edamame to achieve the best quality of the product.

Materials and methods

Raw materials

Uniformly sized deep-frozen edamame with 70.5% of water content was obtained from All Nice Food Ltd.

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Co. in the city of Jiaxing, China. All the edamame used for drying was from the same batch.

Main equipment

Pulse-spouted MVD, a laboratory-scale pulse-spouted microwave-assisted vacuum dryer developed in our laboratory was used for drying the fresh edamame as a new drying method. In this dryer, there are six basic systems: (1) a cylindrical multimode microwave cavity; (2) a circular duct vacuum drying chamber; (3) a pulsed-spouted system; (4) a heat supply system; (5) a water load system; and (6) a vacuum system. The detailed information of this device was introduced in the study of stem lettuce slices' drying by Wang et al.[14,15]

In MVD, compressed air is controlled by electric–magnetic valve, thus the intermittent spouting of the materials is realized. In general, the spouting time is short, and in this experiment, if MD is for 60 s, the electric–magnetic valve would work 2–3 s. Since the vacuum pump works continuously, the vacuum environment cannot be vanished, and spouting process is aimed to make the materials' moisture removed uniformly with time. Infrared temperature measurement system was set up in the materials. When the drying temperature was higher than a set value, the microwave power will adjust in real time. Meanwhile, VID equipment and hot AD equipment were also used in this experiment for comparison purpose. In impregnating process, the best dried edamame was selected, and a vacuum heating device was used for vacuum impregnating. The storehouse was connected with a vacuum pump, and there were three electric heating plates, when the temperature of every heating plate and the material is detected by a temperature sensor, respectively. The temperature of material can be set and controlled by a programmable logic controller (PLC) system.

Drying processes for fresh edamame

The frozen edamame was thawed for 10–15 min in cold water, surface water was drained and then used for drying.

In MVD, almost 1,000 g of thawed edamame was put in the drying chamber, and then the vacuum system, pulsed-spouted system, and MD system were run. Microwave power was set as 1–3 W/g (w. b.), with the highest temperature control of no more than 80°C. With the same drying experiment, the vacuum system was stopped, and the spouted operation was applied, thus a normal pressure MD was realized.

In VID, almost 1,000 g of thawed edamame was put in infrared drying chamber, and then the infrared drying system and vacuum system ran. The infrared power was set as 1–3 W/g, with the highest temperature control of no more than 80°C. In AD, the temperature of the air flow was set as 75°C, and the air flow speed was around 1 m/s. For all three drying methods, the moisture content of final products was no more than 7% (d. b.).

Impregnating process

The edamame with high drying efficiency and good quality was selected for impregnation. The impregnated solution was prepared with sugar 150 g, water 50 g, and salt 5 g in 70–80°C. The sugar was sucrose, trehalose, and maltose, respectively, in three different impregnating processes. The selected edamame was impregnated under vacuum condition of −0.09 MPa for 15 min in a vacuum heating device, and the temperature was set as 75°C, when all the sucrose, trehalose, and maltose have a good solubility and then impregnated at atmospheric pressure at the same temperature for 15 min. Thus, the impregnating process was realized from vacuum to atmospheric pressure conditions.[16]

Quality evaluations of dried products

Color

The product color was measured using a CR-400 model color meter (Konica Minolta, Inc., Osaka, Japan). The color value was reported in CIE-lab scale as L^*, a^*, b^*, where L^* represents lightness, with 0 for black and 100 for white, a^* is from green to red, and b^* is from blue to yellow.[17] Five replicates were performed for each batch of samples. The total color difference (ΔE) between thawed and dried edamame was calculated using the following equation:[18,19]

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2}$$

Here, L_0^*, a_0^*, and b_0^* are the color parameters of thawed deep-frozen edamame. Color value reflects the difference among different dehydrated edamame and fresh ones. If the color difference based on the fresh samples is small, the drying quality in color is good.

Microstructure

The microstructures of dried edamame obtained from MD, MVD, AD, and VID processes were measured using a scanning electron microscope (S-4800, Hitachi, Tokyo, Japan). Surface and section of the edamame cotyledon was selected as the focus zones. The space distribution in the structure is another key factor to judge the dried product quality. How the microstructure of the dried product affected the impregnating ability of the dried edamame for different impregnated solutions was observed. If the space distribution is uniform, it would indicate the suitability of the solution for impregnation.[20]

Texture

The textural properties of the dried samples were measured using a texture analyzer (model TA-XT2, Stable Micro System Ltd., Leicestershire, UK). The dried edamame from different drying methods was analyzed in compression mode (40% compression) at pretest, test, and post-test probe speeds of 1, 1, and 10 mm/s, respectively. The hardness is the amount of maximum force required to break the sample.[21] For the same drying batch, measurements were taken individually on five different samples and the average values were reported. For different dehydrated samples, if the maximum compression force is small, texture distribution is good, which is suitable for impregnation.

Moisture state analysis

Low-field nuclear magnetic resonance (NMR) is an analytical method which through the transverse relaxation time T_2 of hydrogen protons in a constant magnetic field provides information on the mobility of the water molecules. In a magnetic field, some nuclear magnetic energy levels of hydrogen protons can be formed. When in the perpendicular direction of the magnetic field some pulse electromagnetic waves are introduced, some of the hydrogen proton in low-energy state will jump to high energy state, and resonance occurs.[22] If the pulse electromagnetic waves are withdrawn, the hydrogen proton would go back to the original low-energy state. In a certain distance, two activated hydrogen protons with same frequency but different moving trends change their directions to the same level, and the time of the process is called as T_2. The hydrogen protons in water molecules constitute the main semaphore of T_2 in normal vegetables. NMR technology can provide the detailed information of water state composition by free water (FW), immobilized water (IW), and bond water (BW) in drying.[23,24] If T_2 is larger, the water molecules are freer. Magnetic resonance imaging (MRI) is the extension of NMR. If the semaphore in T_2 is obvious, the corresponding zone is bright in the image.[25] In this work, the NMR instrument used was PQ001 NMR analyzer (Shanghai Niumag Corporation, China). For MVD samples, water state information of the samples in different times was detected by NMR. At the same time, the impregnated edamame with different solutions was analyzed by NMR and MRI, thus the impregnated quality and uniformity can be known.

In addition, water activity reflects the saturated vapor pressure of moisture, which will influence the storage quality. The different impregnated edamame and raw materials are detected by water activity meter; thus, the product storage quality can be analyzed.

Electronic nose analysis

Electronic nose is an electronic system that uses the response of gas sensor array to recognize the odor.[26] The electric nose (Ruifen Trading Co., Shanghai, China) was used in this experiment, there are four basis systems: (1) sampling system and gas collecting system; (2) sensor array; (3) sensor detection curve; and (4) intelligent recognition system. There are 14 sensors in the sensor array system. For each product, 5–8 g of sample was placed in an airtight bottle to determine the flavor by electronic nose. The process air flow was 1 L/min and testing and cleaning times were 120 s. Through principal component analysis, two kinds of components were selected to judge the odor difference among the samples. To compare with fresh edamame, the dried samples from different drying methods were analyzed. At the same time, the impregnated edamame with different sugar solutions was researched. Tests were performed in triplicate.

Results and discussion

Drying quality

Drying time and color difference

The drying time of edamame by different drying methods and the corresponding color parameters of the products are shown in Table 1. MD and infrared drying have advantage in drying time, especially MVD, which has the shortest drying time of 1.33 h. MD is an absorbing microwave power process in whole volume, and vacuum is a favorable condition for dehydration, thus the MVD had the best drying efficiency.[27]

In the case of color of the products, the dried edamame was much brighter than fresh samples which was reflected by L^* value. Except for MD, the other products' green index was similar to that of fresh samples which is reflected by a^* value (Table 1), and the appearance should be caused by that the moisture always cannot evaporate in time with the rapid drying speed in MD. Similar result in ginger's drying research by MD and AD was reported by Lv et al.[28] The b^* values of MD and MVD have no significant difference, and they are much more similar to the fresh edamame than other two drying processes. It indicates that the chlorophyll can be preserved well in vacuum MD process. For the total color difference of different products, the samples from MVD had the smallest value. Thus, it can be said that this drying method produces best dried

Table 1. Drying time and color difference of the edamame from different drying methods.

Sample	Drying time (h)	L^*	a^*	b^*	Color difference ΔE
Fresh	–	74.05 ± 0.15^{a}	-14.29 ± 0.18^{c}	29.13 ± 0.13^{a}	–
MD	2.00	83.53 ± 0.05^{d}	-7.76 ± 0.26^{a}	29.77 ± 0.19^{b}	11.53 ± 0.06^{d}
MVD	1.33	80.53 ± 0.11^{b}	-12.44 ± 0.09^{b}	30.22 ± 0.08^{b}	6.83 ± 0.10^{a}
VID	1.42	80.46 ± 0.05^{b}	-12.20 ± 0.04^{b}	31.24 ± 0.12^{c}	7.07 ± 0.07^{b}
AD	8.50	82.97 ± 0.10^{c}	-12.31 ± 0.18^{b}	33.11 ± 0.54^{d}	9.97 ± 0.19^{c}

Note: the same letters of a, b, c indicated no significant difference, and the different letters between them mean there is a significant difference, $P < 0.05$.

product in terms of color preservation which is a very important parameter of quality.

Microstructure changes in different drying processes

In the case of microstructure, surface and section figures of the edamame cotyledon obtained from MD, MVD, AD, and VID are shown in Figs. 1 and 2. The surface microstructure of the dried edamame cotyledon from MD was in disorder, and the surface was rough. In the samples dried by MVD, the product surface was flat, when the microstructure should be puffed. In this drying process, the pressure difference between the vacuum environment and edamame tissue was obvious, thus the surface did not collapse, which is helpful to be impregnated. In AD product, the inside edamame cotyledon surface was collapsed exhibited by its wavy shape, and the epidermal structure of cells was clear. In VID product, the inside edamame cotyledon surface was rough. However, it was almost clear for the cell structure. Whether the microstructure of the tissue dried by VID is better than that from MVD, it should be researched according to the image obtained from sections.

In cotyledon section, the microstructure difference among various drying processes was obvious. The tissue structures of the edamame dried by MD were arranged closely with no obvious pores, which indicated that the cell walls might have been compressed by the microwave power in drying process. In MVD product, the cells were arranged with tiny pores uniformly, and the

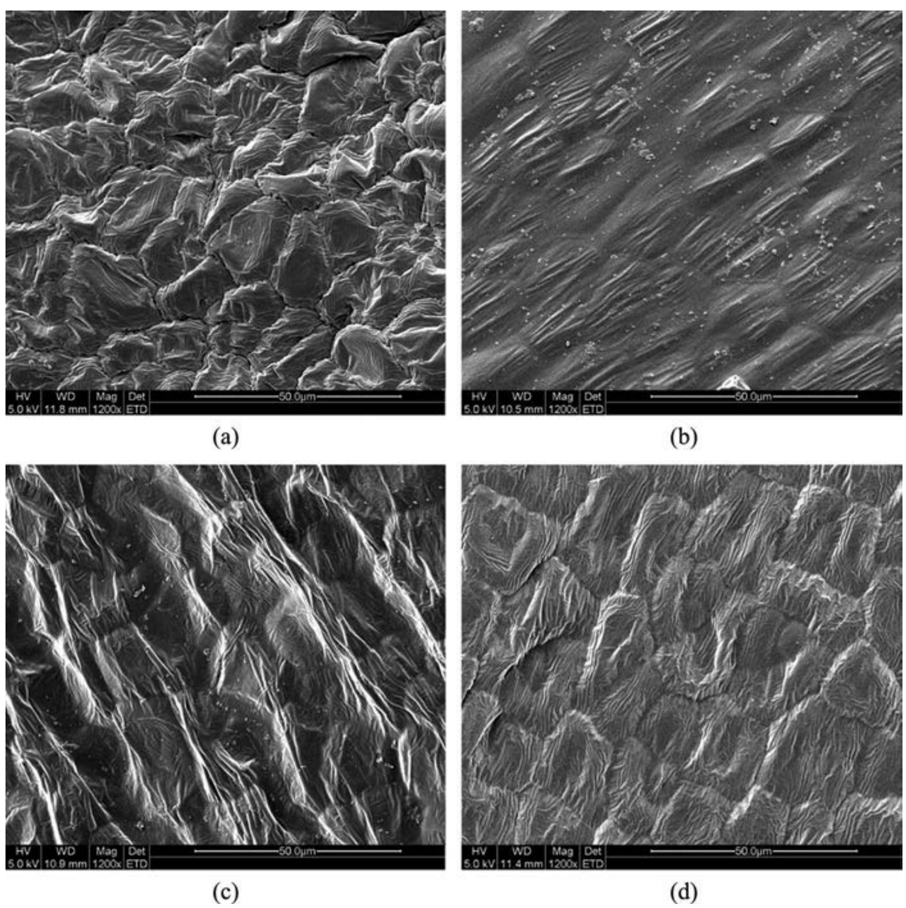

Figure 1. Surface microstructure of edamame cotyledon from different drying methods (magnification ×1200): (a) MD, (b) MVD, (c) AD, and (d) VID.

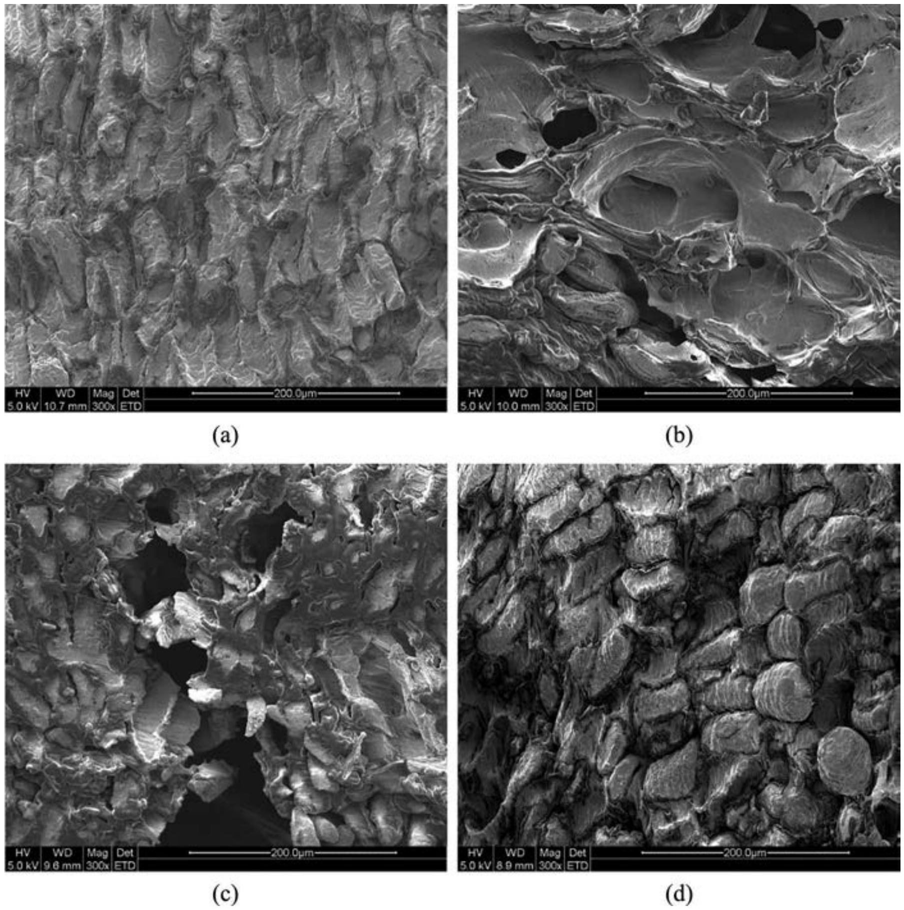

Figure 2. Section microstructure of edamame cotyledon from different drying methods (magnification × 300): (a) MD, (b) MVD, (c) AD, and (d) VID.

diameter was almost 50–100 μm (Fig. 2b), which indicated that under vacuum condition, the moisture moved quickly and the inside pressure was enough to protect the basic structure of the edamame. This is helpful to obtain the expansion effect and crispy characteristics of the dried product. In general, vacuum impregnation is caused by differential pressure. The air in porous materials would be changed by the liquid solution, when the impregnating process is realized.[29] Thus, expansion effect was facilitated by impregnation. The edamame dried from AD had bigger pores in local areas, and the microstructure was arrayed closely. In AD, the drying speed is slow, and the water vapor could not dissipate quickly, thus there is a bigger expansion of pores. In VID product, the tissue structures of the edamame were arranged closely and the pores were not obvious, which will affect the crispy characteristics of the dried products. In summary, the information from surface and internal microstructure indicated that MVD rendered the best expansion effect and crispy characteristics of the product. So, this will be considered the most suitable for further research work.

Crispy characteristics

In terms of texture, the dried edamame was detected by a texture analyzer. Fig. 3 presents the maximum compression force for the fracture of the samples obtained from different drying methods. The less the maximum compression force is, the better for the crispy

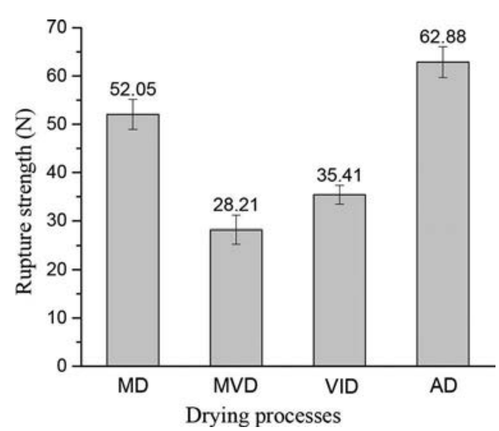

Figure 3. Maximum compression force for the edamame from different drying methods.

characteristics. It can be shown from the result that the maximum compression force of AD product was maximum, which is 62.88 N. This should be caused by no expansion of the product in AD process. For the similar reason, the maximum compression force of the product from MD was larger than that of the VID and MVD products. Since there were some errors among the samples of same batch, each batch samples were tested five times. In the confidence intervals of 95%, there were significant differences among the maximum compression force for the fracture of the AD, VID, and MD products, and the texture of the MVD product was better than the others. This is similar to the expansion effect. These results were consistent with the study of the microstructural characteristics obtained from SEM images in Fig. 2.

Flavor analyzed by electronic nose

In Fig. 4, through electronic nose analysis, the principal components of the odor in the edamame from different drying methods detected in triplicate are presented. There is some error noticed between the same sample, which might be caused by the differences of the storage time in airtight bottles and other factors before analysis. Principal component analysis was applied to determine if there were differences in the aroma-active volatile components from the different edamame samples.[30] In this detection, two kinds of the main flavor components were analyzed, when 96.2% and 2.1% of the flavor difference was reflected in these two components, respectively. In general, the edamame dried from AD process had a beany flavor, which is not desirable in snacks.[31] There was less flavor difference for the product from AD to VID than to others. The flavor difference between the products of MVD and MD was not obvious, and the product flavor of MVD was the farthest from that of AD in the figure. Thus, the flavor of the product from MVD was welcome in this sense. At the same time, it indicated that MD can make the edamame's beany flavor decreased, especially under vacuum condition.

State of moisture in the product dried from MVD process

For MVD, water mobility information of the samples in different drying times was detected by low-field NMR, and the T_2 curves are shown in Fig. 5. In general, every sample had three peaks in the T_2 curve. The left peak reflected the BW information, which meant that the transverse relaxation time was short. Similarly, the middle peak meant IW, and the right peak meant FW. The peak area reflected the semaphore of water in a certain state. At the start, FW and IW were detected as the main water state in a fresh edamame. With the advancement of drying, the T_2 peaks for all the moisture state moved to the left, and the right peak decreased, which meant FW was removed or moved to the other two states. When dried for 40 min, 3 peaks of the T_2 curves turn to 2, which meant that by 40 min, FW was almost disappeared. In the final stage, the material moisture decreased to less than 7% (db), and the main water states were BW and IW at this low level of moisture.

Impregnating quality

Vacuum impregnation method is a physical process. First, the dried materials and impregnating solution was set under vacuum condition, the gas in the materials was drawn out, and then normal pressure was returned, during which the impregnating process would be realized. Compared with salting and pickling processes, vacuum impregnating process has a high processing speed, best flavor, and nutrition retention.[32] So, the impregnated food is desirable in snacks.

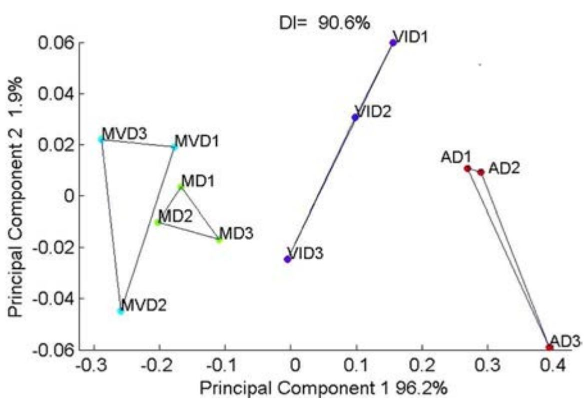

Figure 4. Principal component analysis of edamame from different drying methods.

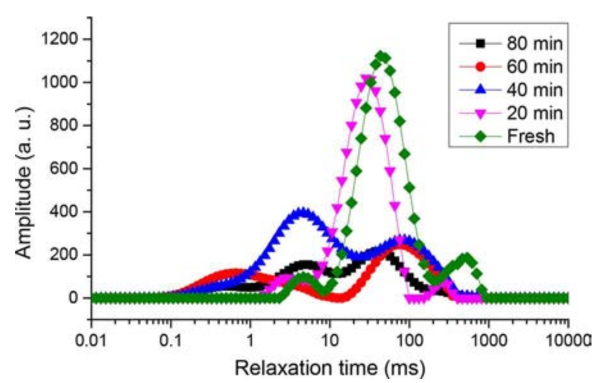

Figure 5. NMR information of the edamame in MVD drying process.

Table 2. Solution and sugar mass in 100 g of impregnated edamame.

Impregnated sample	Solution mass (g/100 g)	Sugar mass (g/100 g)
Sucrose	55.8 ± 0.9	41.9 ± 0.7
Trehalose	61.5 ± 1.9	46.1 ± 1.4
Maltose	51.9 ± 1.4	38.9 ± 1.1

Impregnated mass

The dehydrated edamame from MVD was selected for impregnation. The impregnated solution and impregnating processes were detailed in the "Materials and methods" section. With 105°C hot air flow drying, it was found that the impregnated solution mass in 100 g of dried edamame had some differences between different impregnated solutions (Table 2). Trehalose-impregnated edamame has the most impregnated mass, which may be due to the fact that the difference of trehalose solubility in water is very obvious at different temperatures. If the temperature decreased, the trehalose could crystallize and combine with the dry matters together. In general, the impregnated solution mass took more than half of the impregnated edamame. The sugar content was more than 38%, and there is some salt in solution, thus it is presumed that the impregnated edamame can be stored for a long time safely.

The edamame impregnated by different sugar solutions is shown in Fig. 6. The samples impregnated by sucrose solution appeared green. The difference of the solubility in different temperatures is related to the sugar's crystalline property. Sucrose has the solubility of more than 200% at room temperature, thus its crystalline property is not obvious (Fig. 6a). However, trehalose's solubility variation in different temperatures is large and crystalline speed is quick, thus trehalose's crystalline phenomenon is clear with no adhesion among these samples (Fig. 6b). The edamame impregnated by maltose solution appeared fresh green (Fig. 6c).

Water state and impregnation uniformity

Water state of the edamame impregnated with different solutions was detected by NMR and MRI analyzers. Each group contained 3–5 g of uniform impregnating edamame. The detecting parameters was the same as the detecting process of the edamame in MVD drying process, and the water state information is shown as T_2 curves (Fig. 7) and MRI (Fig. 8). The signal amplitude among the samples had some differences. However, the amplitude was much smaller than that of most of the samples in MVD drying process, which indicated that the water content was much less than that in most of the samples in drying process. For the peaks, every sample had three peaks, which indicated that FW still persists in impregnated edamame. If FW is kept at a minimum level, the impregnated edamame will be much more suitable for snacks, and because of the high sugar concentration, impregnated products can be stored safely.

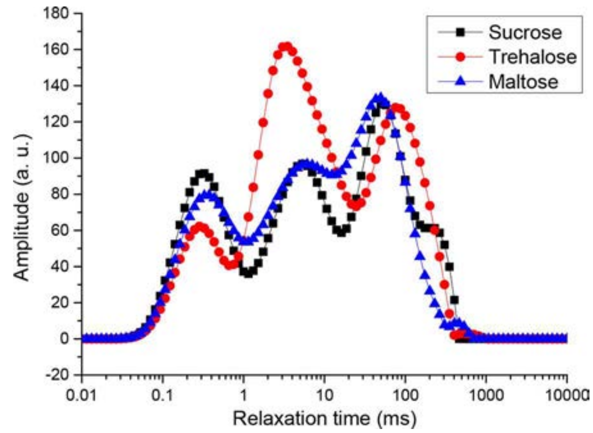

Figure 7. Moisture T_2-spectrum of the impregnated dried edamame with different solutions.

The water distribution of the impregnated edamame can be reflected from Fig. 8. Since the water is impregnated as sugar solution, the impregnating uniformity can be obtained in the image. In general, the higher the brightness, the stronger the signal of hydrogen proton, which meant that the water content is higher than other places.[33] For all the samples, among the cotyledons, there was some impregnated solution entrapped, especially for the edamame impregnated by trehalose

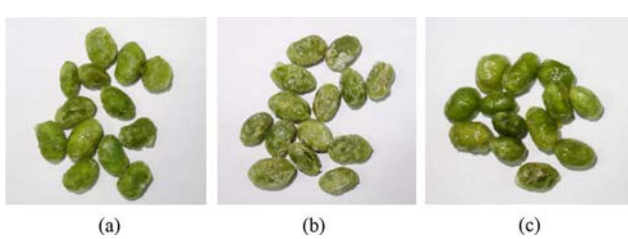

Figure 6. Representative pictures of impregnated edamame by different impregnating solutions. (a) Sucrose solution, (b) trehalose solution, and (c) maltose solution.

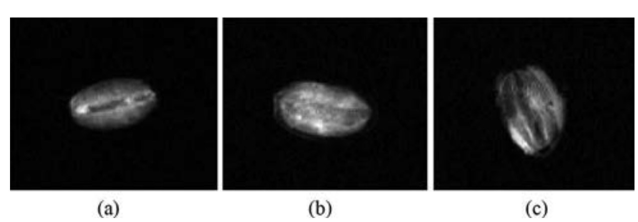

Figure 8. MRI of the impregnated edamame with different solutions. (a) Sucrose solution, (b) trehalose solution, and (c) maltose solution.

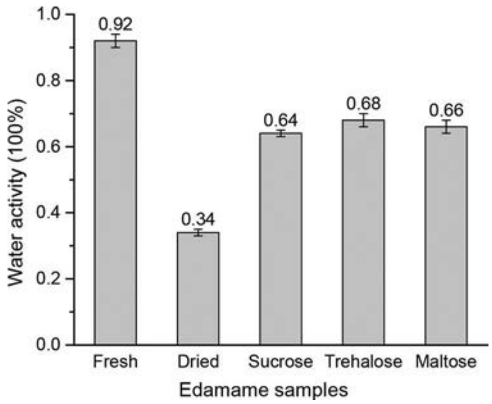

Figure 9. Water activity of the different edamame samples. Fresh and dried sample mean the raw materials, and sucrose, trehalose, and maltose mean the edamame impregnated by the sucrose, trehalose, and maltose solutions, respectively.

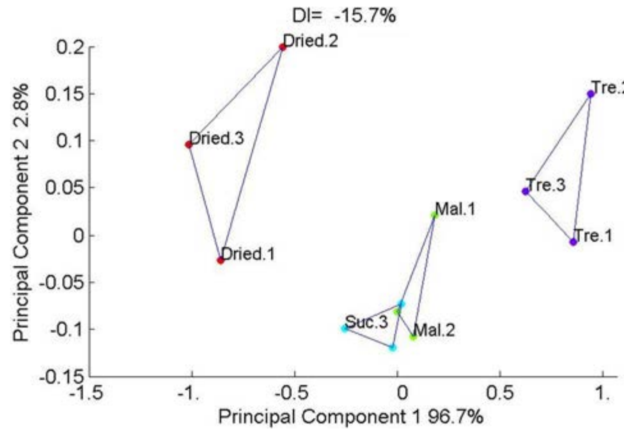

Figure 10. Principal component analysis of edamame from different impregnating methods. Dried, dried edamame from MVD; Suc, edamame impregnated by sucrose solution; Tre, edamame impregnated by trehalose solution; Mal, edamame impregnated by maltose solution.

solution, and in the cotyledons, the water distribution was mostly uniform, so the impregnated process was found successful.

The water activity of the different impregnated edamame and raw materials is shown in Fig. 9. For fresh edamame, the water activity is high. Compared with the dried edamame from MVD, the water activity of impregnated edamame is higher, but no more than 7.0, when most of the bacteria and molds cannot live, thus the impregnated edamame from different processes can be stored in safety for a long time.

Flavor

Sucrose solution, trehalose solution, and maltose solution not only have some differences in sweetness but also in flavor. In general, the edamame impregnated by sucrose solution was sweetest among all the samples. The sweetness difference of trehalose solution and maltose solution was not obvious. However, their flavor has much difference. For flavor, through electronic nose analysis, the principal components of the odor in the edamame from different drying methods are shown in triplicate (Fig. 10). With the same as the detection of dried edamame from different drying methods, two kinds of the main flavor components in impregnated edamame were analyzed, when 96.2% and 2.8% of the flavor difference were reflected in these two components, respectively.

Dried edamame from MVD was fresh but without beany flavor. When impregnated by different solutions, the flavor was different. The edamame impregnated by sucrose solution and maltose solution had no obvious difference. However, they were different from the edamame impregnated by trehalose solution and dried edamame from MVD. The flavor between edamame impregnated by trehalose solution and dried edamame from MVD had significant difference. The sample having the best flavor should depend on different consumers.

Conclusion

Good drying quality of the edamame is needed to realize the impregnating process. The dried sample from MVD has the best drying quality in microstructure, color, texture, and flavor among the samples from MD, MVD, VID, and AD. So, MVD product was suitable for impregnation.

Sucrose solution, trehalose solution, and maltose solution were all suitable for vacuum impregnation, and the solution can be impregnated in the cotyledons uniformly. However, the flavor of impregnated edamame was different in electronic nose, and the sample, which has the best flavor should depend on different consumers.

In MVD, the water information is strong in the front 40 min with much alive FW, and with the development of drying process FW disappeared. However, in the impregnated edamame, the water mobility information is much weaker, thus the impregnated edamame can be stored for a long time safely.

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