Influence of pre-drying treatments on physicochemical and organoleptic properties of explosion puff dried jackfruit chips

Jianyong Yi¹ · Linyan Zhou¹ · Jinfeng Bi¹ · Qinqin Chen¹ · Xuan Liu¹ · Xinye Wu¹

Revised: 10 November 2015 / Accepted: 24 November 2015 / Published online: 2 December 2015
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Abstract The effects of hot air drying (AD), freeze drying (FD), infrared drying (IR), microwave drying (MV), vacuum drying (VD) as pre-drying treatments for explosion puff drying (EPD) on qualities of jackfruit chips were studied. The lowest total color differences (ΔE) were found in the FD-, MV- and VD-EPD dried chips. Volume expansion effect (9.2 %) was only observed in the FD-EPD dried chips, which corresponded to its well expanded honeycomb microstructures and high rehydration rate. Compared with AD-, IR-, MV- and VD-EPD, the FD-EPD dried fruit chips exhibited lower hardness and higher crispness, indicative of a crispier texture. FD-EPD dried fruits also obtained high retentions of ascorbic acid, phenolics and carotenoids compared with that of the other puffed products. The results of sensory evaluation suggested that the FD-EPD was a more beneficial combination because it enhanced the overall qualities of jackfruit chips. In conclusion, the FD-EPD could be used as a novel

combination drying method for processing valuable and/or high quality fruit chips.

Keywords Volume ratio · Color · Texture · Rehydration · Microstructure · Sensory evaluation

Introduction

Jackfruits (*Artocarpus heterophyllus* L.) belong to the family Moraceae and are widely grown in many tropical areas (Saxena et al. 2013). Jackfruits are tropical fruits rich in dietary fiber, protein, potassium, vitamin B, vitamin C and many other nutrients (Jagtap et al. 2010). Due to a low yield of edible portion (around 35 % of the whole fruit), transportation and storage of fresh jackfruits are not particularly economical (Saxena et al. 2012b). Although many preservation/processing methods have been developed to preserve these perishable fruits, a large amount of jackfruits still get spoiled during peak harvest season.

Fruit chips have become increasingly popular in the diet of modern consumer due to a pleasant crispy mouth feel (Zou et al. 2013). In addition, rich in many phytonutrients and easy to carry are also the reasons for their increasing market share. Many processing technologies have been applied for producing fruit chips, such as deep fat frying, vacuum frying, freeze drying, steam puff drying, and microwave vacuum drying. Besides these fruit chip production technologies, explosion puff drying (EPD) is an emerging technology with unique advantages. The EPD contributes to a typical porous structure and an appealing crispy texture, which is one of the most important qualities for fruit chips. Other favorable characteristics of the EPD finished product are found in flavor, color, rehydration, as well as competitive production costs (Du et al. 2013).

Highlight

- Pre-drying significantly affects qualities of explosion puff dried jackfruit chips.
- Volume expansion effect was only observed in the FD-EPD dried chips.
- FD-EPD yields chips with superior porous microstructure and crispier texture.
- FD-EPD can be used for processing valuable and high quality fruit chips.

Electronic supplementary material The online version of this article (doi:10.1007/s13197-015-2127-2) contains supplementary material, which is available to authorized users.

✉ Jinfeng Bi
jinfengbi_caas@163.com

¹ Institute of Food Science and Technology, Chinese Academy of Agricultural Science (CAAS)/Key Laboratory of Agro-Products Processing, Ministry of Agriculture, Beijing 100193, China

During EPD decompression phase, a product undergoes an irreversible adiabatic transformation. This decompression induces a partial auto-evaporation of the internal water, creating engenders mechanical constraints with the product, which has a viscoelastic behavior (Louka and Allaf 2002; Lyu et al. 2015). meanwhile, a complex alveolation phenomenon occurs. The maintenance of the product microstructure at this expanded state depends on the further dehydration and hardening, which is determined by the temperature and moisture content of a material. The moisture content affects the amount of steam generated during the puffing phase. Furthermore, a large amount of generated steam could completely disintegrate fruit tissues, whereas in the opposite case products are not well expanded (Louka and Allaf 2002). Consequently, relatively low initial moisture content of around 25–50 % wet basis is a prerequisite to start the puff procedure (Bi et al. 2015). In other words, it is not efficient to use the EPD alone to finish drying of fresh fruits, which moisture content, in most cases, are higher than 80 % wet basis.

The past decade has seen an increasing interest in the effects of EPD on many fruits and vegetables, such as apple (Bi et al. 2015; Yi et al. 2015), pepper (Tellez-Perez et al. 2015), maize (Mrad et al. 2014), jujube (Du et al. 2013), mango (Zou et al. 2013), peach (Lyu et al. 2015), strawberry (Alonzo-Macias et al. 2014), banana (Setyoprato et al. 2012), carrot and onion (Louka and Allaf 2002), etc. It is worth noting that, prior to EPD processing, hot air drying (AD) is in most case used as a pre-drying technology for reducing the moisture content of a raw material, namely combined hot air-explosion puff drying (AD-EPD). However, collapse and shrinkage of fruit tissues often occur during the AD pre-drying stage, leading to adverse effects on final product qualities, e.g. volume, color, texture. In addition, the degradation of nutritional and bioactive compounds cannot be ignored during AD (Frias and Oliveira 2001). The objective of this work was to study the effects of different drying methods, as novel pre-drying treatments for EPD, on the physicochemical and organoleptic properties of jackfruit chips.

Materials and methods

Materials and sample preparation

Fully ripened fruits of *Artocarpus heterophyllus* L. were purchased from Xinfadi agro-product market in Beijing, China. All the jackfruits used in this study were of the same batch. The edible jackfruit bulbs were selected manually to obtain those in good condition and without deterioration. It was then followed by washing, peeling, cutting into $3.0 \times 1.5 \times 1.5$ cm slices. Prior to FD and combined freeze-explosion puff drying (FD-EPD), the fresh fruit slices were frozen and allowed to store at -40 °C for 24 h. Fresh jackfruit slices were used for

the other drying methods. About 200 g of frozen or fresh jackfruit slices were used for each drying process.

Drying process

Hot air drying was conducted by a convective dryer (DHG-9123A, Jinghong Laboratory Instrument Co. Ltd., Shanghai, China). Fresh jackfruit slices were dried at 65 °C at an air velocity of 1.2 m/s to the final moisture content. Freeze drying (FD) was performed in an experimental freeze dryer (Alphal-4Lplus, CHRIST Co., Osterode am Harz, Germany), which had a drying area of 0.4 m². The FD dehydration was set at 50 Pa with condenser temperature of -55 °C. The temperature of second drying was 25 °C.

All the combination drying processes consisted of three steps. Firstly, the frozen or fresh jackfruit slices were dried to a moisture content of approximate 30 % wet basis. For AD-EPD and FD-EPD drying, the samples were pre-dried by AD and FD at the same condition as the abovementioned AD and FD, respectively. For combined infrared-explosion puff drying (IR-EPD), the samples were dried at 75 °C at a total input power of 1125 W/m², using a laboratory short- and medium-wave infrared dryer (Infrared Technology Co. Ltd., Taizhou, China). The dryer consists of three infrared lights with powers of 0.48, 0.60 and 0.90 kW, and wavelengths of 3.15, 3.10 and 1.40 μ m, respectively. For combined microwave-explosion puff drying (MV-EPD), the samples were dried at a dissipated power/load ratio around 2.2 W/g fresh fruit, using a laboratory microwave dryer (Sanle microwave technology Co. Ltd., Nanjing, China). For combined vacuum-explosion puff drying (VD-EPD), the samples were dried at 65 °C under a continuous vacuum of 40 Pa, using an experimental vacuum dryer (Yaoshi Instrument Equipment Co., Shanghai, China). All the parameters of the pre-drying treatments were optimized in a previous study (Wang et al. 2014). The samples were tightly wrapped in polyethylene films and equilibrated in a thermostatically chamber at 20 °C for 24 h. Secondly, the above equilibrated semi-dried samples were removed to an experimental explosion puff dryer (Qin-de New Material Scientific Development Co. Ltd., Tianjin, China), which were depicted in the previous study (Yi et al. 2015). A schematic diagram of the explosion puff dryer is shown in supplementary material. Prior to explosion puffing, the samples were equilibrated at 90 °C for 5 min under an atmospheric pressure. Meanwhile, the vacuum tank was evacuated to approximate 3 kPa (absolute pressure). Then, the decompression valves were opened to obtain a rapid pressure drop (< 0.2 s) to vacuum in the processing vessel. Hereafter, the jackfruit slices were dried under a continuous vacuum at 65 °C until reaching a final moisture content of lower than 7.0 % db. Final moisture contents were determined and confirmed by drying the chips at 105 °C for 24 h. Before chemical analysis, all the chips were equilibrated in a desiccator

over P_2O_5 for 48 h. Each drying process was performed in triplicate.

Physicochemical characterization

The jackfruit chips were ground using a tissue blender (JYL-D022, Joyoung Co. Ltd., Shandong, China). Exact 20 g of the jackfruit powder was weighed and mixed with 20 mL distilled water, and the mixture was centrifuged at 6000 g for 10 min. Total soluble solid (TSS) content of the supernatant was measured by a refractometer (DBX-55, Atago Co. Ltd., Tokyo, Japan) (Lyu et al. 2015). Titratable acidity (TA) of the supernatant was determined by titrating a sample with 0.05 mol/L NaOH, and the result was calculated as citric acid equivalents (Zou et al. 2013). Prior to chemical analysis, 2.0 mL of the supernatant was diluted with 8.0 mL of distilled water. Ascorbic acid (AA) content was determined using a 2,6-dichloroindophenol titrimetric method (Bi et al. 2014). Total phenolic (TP) content was determined according to the procedure described by Du et al. (2013), and the result was expressed as gallic acid equivalents (GAE). Total carotenoid (TC) content was determined according to the procedure described by Saxena et al. (2012a), and the result was expressed as β -carotene equivalents (CE). All the chemical tests were performed in triplicate.

Color analysis

Color of the jackfruit chips was analyzed by a colorimeter (D25L, Hunter Associates Laboratory Inc., Reston, USA). Instrumental color data were expressed as CIE L , a , b coordinates, which defined the color in a three-dimensional space: L (lightness-darkness), a (redness-greenness) and b (yellowness-blueness) (Oberoi and Sogi 2015). ΔE represents total color difference and it was calculated according to eq. 1:

$$\Delta E = \sqrt{(L_0 - L^*)^2 + (a_0 - a^*)^2 + (b_0 - b^*)^2} \quad (1)$$

where L^* , a^* , b^* are the color of fruit chips, and L_0 , a_0 , b_0 are the color of fresh fruits, respectively. Three measurements were made at three different locations (top, middle and bottom) on the surface of each sample, and the test was conducted in quadruplicate.

Texture analysis

Texture of the jackfruit chips was measured using a TA.XT2i/50 Texture Analyzer (Stable Micro System Ltd., Godalming, UK) fitted with a ball probe (p/0.25S) (Lyu et al. 2015). The pre-test, test and post-test speed were 1.0 mm/s, 1.0 mm/s, 2.0 mm/s, respectively. The test distance was 50 % and the trigger force was 5.0 g. A force-time curve was recorded and analyzed by the software of Texture Exponent 32 (Surry, UK)

to calculate the peak compression force and number of compression peaks, which represent the hardness and crispness of a material, respectively. Twelve measurements were performed for each treatment.

Volume ratio and bulk density determination

The bulk volume of the jackfruit chip was measured using a Volscan Profiler (Stable Micro-System, England) (Lyu et al. 2015). The volume ratio (VR) was calculated using eq. 2 (Oberoi and Sogi 2015):

$$VR = V_a / V_b \quad (2)$$

where V_a , V_b , refer to volume (mL) of a sample after and before drying, respectively. The bulk density was calculated as the weight of a chip divided by its corresponding volume. The volume ratio and bulk density determination were carried out in triplicate.

Rehydration property analysis

Rehydration property analysis was performed according to the method reported by Vega-Gálvez et al. (2015) and Maqsood et al. (2015) with small modification. Each jackfruit chip was weighed, placed in a tea drainer, and then immersed in a water bath at 25 °C for various lengths of time. At different time intervals, the samples were removed from the water. Excess water from the surface was gently wiped off using tissues and weighed. This step was repeated until the difference between two consecutive recordings was smaller than 0.001 g. The rehydration ratio (RR) was calculated according to eq. 3:

$$RR = M_r / M_0 \quad (3)$$

where M_0 and M_r are the sample mass before and after rehydration at specific time intervals (g), respectively. The rehydration property analysis was carried out in triplicate.

Microstructure

Morphological characterization of the fruit chip microstructure was performed using a scanning electron microscopy (S-570, HITACHI Co. Tokyo, Japan) at 150 kV accelerated voltage and 10–15 mm working distance. The samples were coated with 10 nm gold to make it conductive. A typical micrograph was selected to represent the microstructure of each treatment.

Sensory evaluation

Sensory evaluation was conducted with a 15-member consumer panel (staff and students) at Chinese Academy of Agricultural Science according to the protocols described by

Zou et al. (2013). The quality attributes tested were color, odor, texture, flavor and overall quality. All samples were served in labeled and capped glass containers, randomly coded with digit numbers, and presented to each panelist at the same time. A 9-point hedonic scale was used with a score of 1–9, where 1 represents dislike extremely and 9 represents like extremely.

Statistical analysis

Statistical analysis was conducted using the software SPSS Statistics (v.17.0, SPSS Inc., Chicago, USA), applying one-way analysis of variance (ANOVA) and Tukey's test. Significant differences were defined at $p < 0.05$.

Results and discussion

Drying times

The effects of different drying methods on the drying times are shown in Fig. 1. The longest drying time was found in the FD, followed by the FD-EPD process. The drying times of the explosion puffing and the following vacuum drying were fixed due to the same initial moisture content after equilibration. Therefore, the total drying times were mainly dependent on pre-drying methods. When infrared drying (IR), microwave drying (MV), and vacuum drying (VD) were used as the pre-drying treatments, the total drying times of jackfruit chips were significantly shortened by 42.8 %, 46.9 % and 19.9 %, respectively, compared with the traditional

AD-EPD. Different pre-drying treatments were conducted to decrease the initial puffing moisture content of fresh jackfruit slices, which consumed 52.8 %, 82.8 %, 20.5 %, 20.1 % and 45.8 % of the total drying time, for the AD-, FD-, IR-, MV- and VD-EPD, respectively.

Physicochemical characteristics

As shown in Table 1, all the final moisture contents of the jackfruit chips were lower than 7.0 g/100 g db. The highest TSS content was found in the FD dried product. No significant differences were found in the TSS contents among the AD-, FD-, IR-, MV- and VD-EPD finished jackfruit chips. The decrease in the TSS content of the jackfruit chips might be due to leaching of tissue solutions during the pre-drying stage; while during the FD, the solution leaching might be avoided because no liquid water was presence during sublimation phase. The variations in the TA contents showed a similar trend as the TSS contents, indicating that the TA contents might be also affected by the solution leaching.

Ascorbic acid, phenolics and carotenoids are important nutritional or bioactive compounds in jackfruits, which are regarded as well-known antioxidants and play important roles in increasing health benefit. The FD dried chips always showed the highest content of AA, TP, and TC, compared with all the other drying methods (Table 1). The high retention of these compounds in FD dried products was attributed to the absence of oxygen and the low drying temperature during the FD processing, which resulting in retarding most of degradation reactions (Ratti 2001). In addition, the contents of these compounds were higher in the FD-EPD finished products than in the AD-, IR-, MV- and VD-EPD finished product, which could be also due to the degradation retarding effects of FD pre-drying as discussed above. The lowest AA, TP and TC contents were showed in the AD dried products. According to some previous reports, the degradation behaviors of ascorbic acid, phenolics (Djendoubi Mrad et al. 2012) and carotenoids (Demiray et al. 2013) are most significantly dependent on drying temperature, and in most cases, following a first- or pseudo first-order degradation kinetics during drying. In addition, Djendoubi et al. (2012) found that the TP reduction of pear dried at 30 °C for 10 h was higher than that dried at 70 °C for 2 h, indicating that both temperature and drying time should be considered for the nutritional and bioactive compound degradation. In this study, the samples dried by the AD-EPD stayed at 65 °C for approximate 3 h during the AD pre-drying, while the IR- and MV-EPD dried sample stayed at 75 °C for approximate 40 min. The longer drying time for the AD pre-drying, compared with the IR and MV pre-drying, might render a low retention of these chemical compounds. On the other hand, during the VD pre-drying, the vacuum environment was in

Fig. 1 Effect of pre-drying treatments on the total drying time of jackfruit chips. AD: hot air drying; FD: freeze drying; AD-EPD: combined hot air-explosion puff drying; FD-EPD: combined freeze-explosion puff drying; IR-EPD: combined infrared-explosion puff drying; MV-EPD: combined microwave-explosion puff drying; VD-EPD: combined vacuum-explosion puff drying. Drying times are presented as mean values and standard deviations ($n = 3$). Significant differences ($p < 0.05$) among the total drying times of the different drying methods are indicated with different lower case letters

Table 1 Physicochemical characteristics of the jackfruit chips dried by different methods (dry basis)

Samples	Moisture content (g/100 g)	TSS (g/g)	TA (%)	AA (mg/g)	TP (mg GAE/g)	TC ($\mu\text{g CE/g}$)
AD	$6.13 \pm 0.12^{\text{ab}}$	$0.79 \pm 0.03^{\text{a}}$	$0.30 \pm 0.02^{\text{ab}}$	$0.27 \pm 0.04^{\text{a}}$	$0.84 \pm 0.06^{\text{a}}$	$2.47 \pm 0.13^{\text{a}}$
FD	$6.54 \pm 0.08^{\text{c}}$	$0.86 \pm 0.01^{\text{b}}$	$0.35 \pm 0.02^{\text{b}}$	$0.57 \pm 0.02^{\text{d}}$	$1.54 \pm 0.02^{\text{c}}$	$6.60 \pm 0.11^{\text{d}}$
AD-EPD	$5.94 \pm 0.20^{\text{a}}$	$0.81 \pm 0.02^{\text{ab}}$	$0.29 \pm 0.03^{\text{a}}$	$0.33 \pm 0.03^{\text{ab}}$	$1.02 \pm 0.04^{\text{b}}$	$2.76 \pm 0.25^{\text{a}}$
FD-EPD	$6.47 \pm 0.14^{\text{bc}}$	$0.83 \pm 0.02^{\text{ab}}$	$0.34 \pm 0.02^{\text{ab}}$	$0.47 \pm 0.02^{\text{c}}$	$1.24 \pm 0.03^{\text{d}}$	$4.45 \pm 0.14^{\text{c}}$
IR-EPD	$6.08 \pm 0.17^{\text{ab}}$	$0.82 \pm 0.01^{\text{ab}}$	$0.32 \pm 0.01^{\text{ab}}$	$0.34 \pm 0.03^{\text{ab}}$	$1.13 \pm 0.03^{\text{c}}$	$3.89 \pm 0.28^{\text{b}}$
MV-EPD	$6.42 \pm 0.14^{\text{bc}}$	$0.81 \pm 0.02^{\text{ab}}$	$0.31 \pm 0.01^{\text{ab}}$	$0.35 \pm 0.05^{\text{ab}}$	$1.14 \pm 0.04^{\text{cd}}$	$4.31 \pm 0.10^{\text{cd}}$
VD-EPD	$5.88 \pm 0.09^{\text{a}}$	$0.82 \pm 0.02^{\text{ab}}$	$0.31 \pm 0.02^{\text{ab}}$	$0.38 \pm 0.03^{\text{bc}}$	$1.17 \pm 0.02^{\text{cd}}$	$4.39 \pm 0.25^{\text{cd}}$

Data are expressed as mean value $\pm$ standard deviation ($n = 3$)

TSS total soluble solid, TA titratable acidity, AA ascorbic acid, TP total phenolics, TC total carotenoids. For abbreviation of the drying methods, please see Fig. 1. Different superscript lower case letters in the same column indicate significant differences at $p < 0.05$

favor of preventing oxidative degradation, possibly contributing to the higher retention of AA, TP and TC.

Color

Color is one of the most obvious quality attributes for fruit chips and it can be used as a quality indicator to evaluate the extent of deterioration during thermal processing (Horuz and Maskan 2015). As shown in Fig. 2, the color of jackfruit chips was significantly affected by pre-drying methods. Substantial

decreases in the L^* values were found in the AD dried and all the puffed jackfruit chips, while the L^* value of the FD dried jackfruit chips was higher than that of the fresh jackfruits. Krokida et al. (2001) also found that the L^* values of apple, banana, potato and carrot were increased after FD dehydration, indicating that FD rendered whiter or paler appearances for these products, which was in line with this study. Among the five puffed fruit chips, the highest L^* value was observed in the FD-EPD dried samples, while the lowest L^* value was showed in the AD-EPD and IR-EPD dried samples. The

Fig. 2 Color values of the jackfruit chips dried by different methods. For abbreviation of the drying methods, please see Fig. 1. Data are presented as mean values and standard deviations ($n = 4$). Different lower case letters indicate significant differences at $p < 0.05$

influence of the pre-drying methods on a^* values were minimal, but all the b^* values of the jackfruit chips substantially increased after drying, indicating an increasing yellowness. Actually, appealing golden yellow appearances of the jackfruit chips were obtained after FD-, IR-, MV- and VD-EPD drying. However, the AD-EPD dried product showed a light brown appearance, indicating the occurrence of Maillard reaction or caramelization (Saxena et al. 2012a).

The overall color differences of the jackfruit chips were reflected from their ΔE values. Interestingly, the lowest ΔE values were not observed in the FD dried products, but in the FD-, MV- and VD-EPD dried chips, which were 4.53, 5.19 and 6.04 respectively. Such low ΔE values indicated colors that were more similar to the fresh jackfruits. In addition, no differences were found in the ΔE values among the FD-, MV- and VD-EPD dried chips, which were all lower than that of the AD, FD and AD-EPD dried products. The high ΔE value that showed in the FD dried chips was mainly attributed to the increase in the L^* value as discussed above.

Volume ratio and bulk density

The volume ratio and bulk density of the jackfruit chips are shown in Fig. 3. The volume ratio of the FD dried jackfruit chips was significantly higher than that of the AD-, IR- and MV-EPD dried products, but lower than that of the FD-EPD dried chips, which volume was increased by 9.2 % compared with the fresh samples. The lowest volume ratio was observed in the AD dried samples. During the explosion puff drying, the internal water of the jackfruit slices was heated to 90 °C before decompression, which was far above the water boiling point in the following vacuum environment (4–5 kPa). Then, driven by the pressure difference (≥ 0.1 MPa), the water in the cell vaporized immediately and exploded rapidly to the outer

vacuum environment during the sudden pressure drop. The decompression, involving the sudden releasing of the internal water, formed a puffy and porous structure, and increased the bulk volume of the sample (Bi et al. 2015; Louka and Allaf 2004). Among the five combination drying methods, FD-EPD was the only combination which obtained a volume ratio higher than one, indicative of the expansion of bulk volume compared with the volume of fresh samples. A plausible explanation was that, instead of severe tissue shrinking during AD pre-drying stage, the FD pre-drying fortified the cell/tissue structure and maintained the volume of the jackfruit slices, which might bring positive effects on the volume expansion during the puffing, possibly by presenting more capillary paths for releasing internal water vapor (Chen et al. 2013). In contrast, obvious volume shrinkage (reduced about 40–55 % in volume, data not shown) was observed after the AD-, IR-, MV- and VD pre-drying. Nevertheless, these volume reductions were neutralized to a certain extent by the expansion effects of the following explosion puff processing, resulting in an increase in bulk volume.

The variation in bulk density of the jackfruit chips showed an opposite trend as the volume ratio, because it was calculated based on the final weight and volume of a sample. The highest density was observed in the AD dried chips, while the lowest densities were obtained in the FD and FD-EPD dried products, which showed no significant difference between each other.

Texture

The texture (hardness and crispness) of the jackfruit chips dried by different methods is shown in Fig. 4. The maximum compression force represents the hardness of a sample, while the number of peaks reflects crispness. For the AD dried chips,

Fig. 3 Volume ratio (a) and bulk density (b) of the jackfruit chips dried by different methods. For abbreviation of the drying methods, please see Fig. 1. Data are presented as mean values and standard deviations ($n = 3$). Different lower case letters indicate significant differences at $p < 0.05$

Fig. 4 Maximum compression force (a) and number of compression peaks (b) of the jackfruit chips dried by different methods. For abbreviation of the drying methods, please see Fig. 1. Data are presented as mean values and standard deviations ($n = 12$). Different lower case letters indicate significant differences at $p < 0.05$

the compression force reached the maximum point at 63.9 N, then dropped to zero point with only few small jag appearance (number of compression peaks). Such textural profiles revealed that the AD dried products acquired a hard texture. For the AD-, FD-, IR-, MV- and VD-EPD dried jackfruit chips, the force reached 44.4, 30.2, 45.9, 38.2 and 36.6 N, respectively, and showed dozens of small peaks until reaching the zero point. These results indicated that, compared with the AD dried samples, the puffed samples obtained a crispier texture. In general, the hardness of the MV- and VD-EPD dried fruit chips were lower than that of the AD- and IR-EPD dried chips, possibly due to the puffing effects of MV and VD drying (Rakesh and Datta 2011). The FD dried fruit chips showed the lowest hardness among all the samples, indicating that the FD dried fruit chips obtained a relatively soft texture. It has been reported that FD could maintain the dimensional cell wall structure of a plant material during drying, avoiding shrinkage and collapse of parenchyma cells, thus leading to a more porous structure (Rahman 2001). However, the fact that this type of structure showed a relatively low hardness and crispness, indicating that the porous structure obtained from the FD might, in some cases, lack of enough strength to trigger a new peak before next collapsing during texture measurement, i.e. compressing of the material.

Microstructure

The representative microscopic images of the jackfruit chips are shown in Fig. 5. Typical homogenous honeycomb

microstructures were clearly observed in the FD dried chips (Fig. 5b). The distribution and size of pores in the FD dried fruit chips were similar to the cellular microstructure of the fresh jackfruits (Fig. 5a), indicating that the influence of FD drying on the cell structure of jackfruits was minimal. A substantial increase in the cell and/or cavity size was found in all the puffed samples. The expansions were difficult to quantify due to the large differences in the pore size within the jackfruit chips, but explosion puff drying formed loose structures with cavity diameter of nearly two to three times as large as that in the FD dried samples. Numerous large and heterogeneous voids were also found in apple chips by Lewicki and Pawlak (2003), indicative of the formation of irregular microstructure after puffing. Nevertheless, the microstructures of the FD-EPD dried fruit chips (Fig. 5e) were more homogenous and puffy than that of the samples dried by the other combination methods. Dense microstructures without obvious porous structure were observed in the AD dried jackfruit chips (Fig. 5c). In addition, un-puffed areas with high density cell materials (marked with arrows) were clearly visible in the AD- and IR-EPD dried chips, as well as in some parts of the MV-EPD dried sample, proving that some areas, which were similar to the microstructures of the AD dried products, were not well expanded during explosion puff processing. These dense areas might contribute to the fortification of the structural strength of the AD- and IR-EPD dried chips, which could be responsible for their high hardness value. Moreover, these un-puffed areas which obtained in the AD- and IR-EPD dried samples were in line with the results of volume ratio (Fig. 3).

Fig. 5 Representative microscopic image of the (a) fresh jackfruit fruit and the jackfruit chips dried by (b) hot air drying; (c) freeze drying; (d) combined hot air-explosion puff drying; (e) combined freeze-explosion

puff drying; (f) combined infrared-explosion puff drying; (g) combined microwave-explosion puff drying; (h) combined vacuum-explosion puff drying

Fig. 6 Rehydration properties of the jackfruit chips dried by different methods. For abbreviation of the drying methods, please see Fig. 1. Data are presented as mean values and standard deviations ($n = 3$)

The extent of shrinkage sets up porosity of a dry plant material, which means that the material shrinkage is closely related to a reduction in the number and size of pores (Chen et al. 2013; Lewicki 1998). In the case of the AD-, IR-, MV and VD-EPD process, obvious volume shrinkages were observed during the pre-drying stages, resulting in a limited and heterogeneous volume expansion during the explosion puff processing, which was in line with their intermediate hardness and crispness (Fig. 4).

Rehydration

The effects of different drying methods on the rehydration behaviors of the jackfruit chips are shown in Fig. 6. The rehydration rates of the jackfruit chips decreased in the sequence of FD, FD-EPD, VD-EPD, and MV-EPD finished products, followed by the AD-EPD, IR-EPD and AD dried products. A rapid moisture uptake is due to surface and capillary suction, and the rehydration kinetics of a dried fruit is strongly related to porosity, and filling of capillaries and cavities near the surface yields quick saturation (Rahman 2001). Generally,

at a certain temperature, the more porous the products are, the faster the products rehydrate. The FD drying was assumed to have a positive effect on maintaining porous cell structure (Krokida et al. 1998). In this study, this effect might lead to the presence of more capillary paths in the FD dried products (Fig. 5). Consequently, these paths could facilitate water infiltration during immersing, rendering a quicker rehydration rate and higher rehydration capacity for the FD dried products. Interestingly, though the FD-EPD dried chips also obtained a fine porous structure, it did not exhibit the same high rehydration rate compared with the FD dried product. It was hypothesized that, in the case of the FD-EPD dried products, the puffing structure might not be able to absorb water quickly due to the size of the porous structure was too large to facilitate a fast capillary effect (Hawladar et al. 2006), which might be an explanation for their relatively low rehydration rate compared with the FD dried chips. Low rehydration rates were found in the AD- and IR-EPD dried chips, and this might be attributed to the existence of some un-puffed areas (Fig. 5), leading to limited number of capillary paths for water imbibition.

No significant differences were found in the rehydration capacity among the FD, FD-EPD, MV-EPD and VD-EPD dried samples, but they were higher than that of the AD- and IR-EPD dried products. The damages of cell structures could significantly affect the rehydration behavior (Lewicki 1998). During the AD, IR, MV and VD pre-drying stages, irreversible cell damage and misalignment might be occurred inside the materials, resulting in the loss of cellular integrity and capillary contraction. However, compared with the AD- and IR-EPD dried chips, a superior porous microstructure for the MV- and VD-EPD dried chips (see Fig. 5) could be responsible for their higher rehydration capacity.

Sensory evaluation

The effects of pre-drying treatments on the sensory quality of the jackfruit chips are shown in Table 2. The highest color scores were found in the FD- and MV-EPD dried products.

Table 2 Sensory evaluation of the jackfruit chips dried by different methods

Samples	Color	Odor	Texture	Flavor	Overall quality
AD	4.0 ± 0.8 ^a	6.8 ± 0.8 ^a	3.6 ± 0.4 ^c	6.2 ± 1.1 ^a	4.2 ± 0.8 ^a
FD	5.2 ± 0.5 ^{ab}	6.2 ± 0.7 ^a	5.9 ± 0.8 ^c	6.3 ± 1.0 ^a	6.3 ± 0.6 ^c
AD-EPD	4.9 ± 0.7 ^{ab}	5.6 ± 0.9 ^a	4.9 ± 0.6 ^d	6.5 ± 0.8 ^a	5.3 ± 0.6 ^{ab}
FD-EPD	7.7 ± 0.9 ^d	6.2 ± 1.6 ^a	8.2 ± 0.4 ^a	6.2 ± 0.9 ^a	8.2 ± 0.5 ^d
IR-EPD	5.8 ± 0.3 ^{bc}	7.0 ± 1.1 ^a	5.5 ± 0.4 ^{cd}	5.9 ± 1.0 ^a	5.5 ± 0.8 ^{ab}
MV-EPD	7.5 ± 0.4 ^{cd}	6.1 ± 0.8 ^a	6.7 ± 0.3 ^{bc}	6.2 ± 0.7 ^a	6.4 ± 0.4 ^c
VD-EPD	7.6 ± 1.5 ^d	6.4 ± 1.6 ^a	7.2 ± 0.6 ^b	6.0 ± 0.6 ^a	6.5 ± 0.3 ^c

For abbreviation of the drying methods, please see Fig. 1. Data are expressed as mean value ± standard deviation ($n = 15$). Different superscript lower case letters in the same column indicate significant differences at $p < 0.05$

A low color score was obtained in the AD dried product due to an unpleasant light brown appearance, which was reflected by the b^* values (see Fig. 2). The FD-EPD dried samples showed the highest texture score, followed by the MV- and VD-EPD dried samples. No significant differences were found in the odor and flavor scores among the five different combination drying methods. In other words, pre-drying treatments only significantly influenced two of the sensory parameters of the EPD finished products. According to the results of overall quality scores, the FD-EPD dried jackfruit chips obtained a superior sensory quality than the other drying methods.

Conclusion

Jackfruit chips were produced by explosion puff drying which was combined with five different pre-drying treatments that were, hot air drying (AD), freeze drying (FD), infrared drying (IR), microwave drying (MV), and vacuum drying (VD). The FD-EPD minimized the color deterioration and yielded a color that was more similar to the fresh jackfruits. Volume expansion effect was only observed in the FD-EPD dried chips, which corresponded to its well expanded honeycomb microstructures and high rehydration rate. FD-EPD dried chips also showed a relative low hardness and the most number of peaks, indicating a puffy structure and a crispy texture. In addition, the FD-EPD dried chips also exhibited relatively high retentions of ascorbic acid, phenolics and carotenoids. The results of sensory evaluation suggested that the FD-EPD was a more beneficial combination since it enhanced the overall quality of jackfruit chips. Considering the relatively high production cost of FD, it is suggested that the FD-EPD could be used as a novel combination drying method for processing valuable and/or high quality fruit chips.

Acknowledgments The authors would like to acknowledge the Special Fund for Agro-scientific Research in the Public Interest Program (No. 201303077) of the Chinese Minister of Agriculture (MOA).

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