Impact of pulsed electric field treatment on drying kinetics, mass transfer, colour parameters and microstructure of plum

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Abstract The aim of the present study was to scrutiny the impact of pulsed electric field (PEF) as a pre-treatment method on the convective drying kinetics, cell disintegration, colours and microstructural changes of fresh plums. In this study, the PEF intensities of 1–3 kV/cm, pulses number 30 and 70 °C drying temperature was applied to detect the drying kinetics. The specific energy consumption generated by PEF treatment was 10–90 kJ/kg. It was explored that the cell disintegration index increased from 0.147 to 0.572 with increased electric field intensity from 1 to 3 kV/cm. Further, we found that high cell disintegration leads to increase in drying rate and shorten drying time. The rates of water diffusion coefficient also increase with increasing PEF intensity from 0.27 to $16.47 \times 10^{-9} \text{ m}^2/\text{s}$. PEF pre-treatment followed by convective drying results in enhanced lightness and chroma as compared to untreated plum. Furthermore, the microscopic analysis by scanning electron microscopy at $200 \times$ revealed that the PEF treatment at 3 kV/cm had caused shrinkage in the plum tissues which might be responsible for higher diffusion rate of water in the plum. In this work was investigated that

drying kinetics and mass transfer after PEF treatment to improve quality of dried plum.

Keywords Pulsed electric field · Plum · Diffusion coefficient · Cell disintegration index · Drying kinetics

Introduction

Drying is a common method to improve the shelf life of food by reducing microbial activity and dilapidation of chemical reactions for storage permanence and curtail packaging. It diminishes the weight of transportation of fruits and some vegetables (Niu et al. 2019). Drying is useful for making intermediate products known as additives for manufacturing industrial foods such as soup, jam-jelly, fruit snacks, fruit-cake, instant drinks, cereals, colouring and gel-forming essence with improving food quality. It also increases the availability of carbohydrates, vitamins, fibres, minerals and fat in per unit weight of dried product compared to fresh product (Hong et al. 2016). Solar drying method is commonly used for fruit and vegetable preservation which cause dissemination of contagious dust particles along with microbial infectivity. However, this is weather dependent method therefore, it takes long time for drying beside inferior food quality (Bezyma and Kutovoy 2005). The other thermal drying techniques evoke deleterious effects over the quality of food products (Figiel and Michalska 2016).

Important criterions in the preference of drying technique are energy utilisation and quality of manufactured food items which could reduce the expenses, drying time as well as damage to the dried products (George et al. 2004). Nowadays, pulsed electric field (PEF) as anon-thermal technique has dragged various attentions as a pre-drying

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treatment. The significance of pre-drying treatment is to decrease energy, costs and to improve nutritional quality of dried food products. PEF is also used in food processing which helps to develop ingredients and novel product to consumers (Wang et al. 2016; Wei et al. 2018; Zhang et al. 2017). It enhances the permeability of cell membrane by electroporation and also increases the rates of mass transfer through plant cell membranes (Amami et al. 2005; Wang et al. 2016).

The efficacy of electroporation increased drying rate which depends on electric conductivity, electric field strength, duration of pulsed treatment and temperature (Patras et al. 2017). Several studies have been reported with PEF as pre-drying treatment to ameliorate both drying processes and quality of food items (Liu et al. 2016; Ostermeier et al. 2018). It was reported that the PEF pre-drying treatment might enhanced diffusion coefficient of potato tissues compared to untreated (Lebovka et al. 2007b). In another studies, PEF pre-drying treatment showed a significant decrease in drying time, energy consumption and an increase in drying rate together with the yield of products (Wiktor et al. 2016). Therefore, the PEF as a pre-drying technique has not only affects the drying time but also improved the drying rate, colour and microstructure of drying food items.

According to our best knowledge, no study has been reported on the effects of PEF pre-treatment on the drying characteristics and microstructure of plum. Therefore, the current study was designed to investigate the PEF pre-treatment effect followed by oven drying on drying kinetics, cell disintegration and microstructure of cell membrane.

Materials and methods

Sample preparation

In this study, the fresh and flawless *Victoria* plums were purchased from the local market in Guangzhou, China. The plums were kept in the refrigerator at 4 °C and used within a week. Plums were cut with a sharp knife having a diameter of 35 mm and 5 mm height for PEF treatments.

PEF treatment

PEF treatment was performed using PEF generator (PEF equipment from the School of Food Science and Engineering, SCUT, China), with high voltage up to 15 kV/cm and the capacitance of 1 µF. In this study the electric field intensity of 1, 2, and 3 kV/cm voltage, 30 pulses were applied; the system provided unipolar square wave form pulses. Treatment cell was filled with tap water which

works as a conductor and to distribute uniform conductivity. The total mass inside the chamber was set to be 1.5 kg. The initial conductivity of the sample was 239 µS/cm. The specific energy was in the ranged from 10 to 90 kJ/kg. Every step of the experiment was performed in triplicate forms. The calculation of specific energy was carried out according to Eq. (1) (Ostermeier et al. 2018).

$$W = \frac{(\frac{1}{2} \times V^2 \times C) \times n}{m} \quad (1)$$

In which W, V, C, n and m is specific energy (kJ/kg), voltage (kV/cm), the capacitance of PEF, pulse number and mass (kg) in the treatment chamber respectively.

Electric conductivity measurement

The electric conductivity of the sample before and after treatment was measured using an electronic INESA, China. The rod of the meter is made up of stainless steel. The measuring electrode of the equipment was washed with distilled water before the measurement of electric conductivity.

Convective drying process

The convective drying process was performed at 70 °C using hot air oven after the treatment sample was taken out from the cell and wiped with tissue paper and weighed. For analysis of moisture content, the weight of the sample was measured at 30-min intervals. The moisture content of the sample was rated by applying hot air oven method stated by AOAC (Horwitz 1980). The moisture content was expressed in the dry basis of a gram of water/g of dry solid.

Mathematical modelling of drying kinetics

Mathematical modelling for drying experiments is a helpful method to elaborate the relationship between applied parameters in drying and their results. The empirical moderation (Page model) of the simple exponential system was applied to fit experimental results (Azoubel et al. 2015).

$$DR = \frac{X - X_e}{X_0 - X_e} \exp(-k \text{ drying} * t^n) \quad (2)$$

X, X_e, X₀, k, n and t is the moisture content at time t, equilibrium moisture content and initial moisture content, drying constant, Page's parameter and process time respectively. The real-time moisture content of the plum differs because of physical versatility. Therefore, for the comparison of moisture content of plum and to scoop this versatility, the dimensionless moisture ratio of plum during drying was calculated by Eq. (3) in this whole experiment.

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (3)$$

In which M_t is the moisture content at drying time t (dry basis), M_e is the equilibrium moisture content, M_0 is the initial moisture content.

The percent residuary moisture content (MC) of the sample was calculated. The rate of moisture should be range from 0 to 100%. The percent moisture content on a dry basis and the wet basis was calculated by Eqs. (4) and (5).

$$MC = \frac{\text{mass of water}}{\text{moisture at time } t} \times 100 = wb \quad (4)$$

$$\frac{wb}{1 - wb} = db \quad (5)$$

Cell disintegration

The membrane disintegration was determined by electric conductivity of the sample and measured by conductivity meter before and after PEF treatment. The membrane disintegration was calculated based on an intact and destroyed sample. The conductivity of totally destroyed sample was achieved by heating the sample at 80 °C for 15 min. The following equation was used to calculate the membrane disintegration (Lebovka et al. 2002):

$$Z = \frac{d - di}{dd - di} \quad (6)$$

where z denotes the membrane disintegration, d measured electric conductivity, dielectric conductivity of intact and dd is electric conductivity of the totally destroyed sample.

Diffusion coefficient

The water diffusion coefficient was determined by applying the Fick's 2nd law of diffusion. The diffusion coefficient is featured in a way to get the acquaintance on the impact of PEF treatment and mass transfer. Plum fruits are rich in plumpness with waxy coating and plumpness contains more quantity of water. So, that moisture diffusion in plum flesh was analysed. While the drying process moisture removed from interior flesh and epidermis to drying environment. The correlation between moisture ratio and diffusion coefficient can be expressed as Eq. (7).

$$MR = 8/\pi^2 \sum_{n=1}^{\infty} \left(1/n^2 \exp\left(-\frac{\pi^2 D_{eff}}{L} t\right) \right) \quad (7)$$

For prolong drying times, Eq. (7) was again modify and simplified to a straight-line equation as Eq. (8).

$$MR = 8/\pi^2 \left(\exp\left(-\frac{\pi^2 D_{eff}}{L^2} t\right) \right) \quad (8)$$

In which, D_{eff} , h and t indicate effective moisture diffusivity, thickness drying time respectively. The natural log of Eq. (3) was given as Eq. (9). Hence, the slope (k) was obtained from binomial regression of $\ln MR$ vs drying time curves. Diffusion coefficient was determined by Eq. (10).

$$\ln(MR) = \ln 8/\pi^2 - \frac{\pi^2 D_{eff}}{L^2} t \quad (9)$$

$$D_{eff} = -\frac{L^2}{\pi^2} K \quad (10)$$

Colour measurement

The colour of the fresh and dried sample was analyzed using colourimeter (Chroma-meter, CR-400, Konica, Japan). The surface of the sample was measured, and the colour was represented by the CIE lab model (L^* , a^* , b^*), where values of L^* , a^* and b^* designate precision of colour. The measurement of colour was performed in triplicates from the randomly selected plum. The chroma (C^*) plum was calculated using Eq. (11), and the change of total colour difference (ΔE) was calculated using Eq. (12).

$$C^* = \sqrt{(a^2 - b^2)} \quad (11)$$

Here C^* indicates the saturation of colour.

$$\Delta E = \sqrt{(L^* - L^* 0^2) + (a^* - a^* 0^2) + (b^* - b^* 0^2)} \quad (12)$$

In which L^* , a^* and b^* indicate lightness, red/green and yellow/blue colour respectively. The ΔE indicates colour differences from PEF treated and untreated plum.

Microstructure analysis

The microstructure of randomly chosen plum was detected after the drying process using scanning electron microscopy (Quanta 200, thermo fisher scientific, UK) from the centre facility lab of SCUT. Prior to microscopic observation, samples were cut into small pieces with a sharp blade. The microstructure examination of dried plum was performed at 20 kV, with 200 × magnifications. Further, the specimens were viewed at different magnification, and images of the representative area were saved for future analysis.

Statistical analysis

All the data obtained were subjected to analysis of single ANOVA. A value of $P < 0.05$ considered as statistically significant. The data were analysed with T test. The results of all manual statistical analyses were confirmed with SPSS software package (version 20.0). Each set of the tests

were repeated, and differences were analyzed by using multiple range tests.

Result and discussion

Effect of PEF on membrane disintegration

Membrane disintegration index (Z_p) is one of the most important parameters for mass transfer during drying of food. The membrane disintegration leads to membrane permeabilisation which causes transfer of water molecules from plant tissue in the course of dehydration. The elevated membrane disintegration provoked more water and solute exchange via the cell wall of plant tissues (Knorr and Angersbach 1998).

The pulsed electric field causes the membrane disintegration of the cell that increased the permeability of membrane. The results of this study showed that increasing PEF intensities and specific energy consumption leads to

increased membrane disintegration index (Fig. 1a, b), this study was based on the electric conductivity of intact and PEF treated plum at different intensities. It has been applied previously to study membrane permeabilisation on various vegetable tissues (Ostermeier et al. 2018). Our results found that disintegration of membrane increases with increasing PEF treatment intensity and the ascent of specific energy. The membrane disintegration index value was 0.147 at 1 kV/cm with specific energy 10 kJ/kg. Meanwhile it increased from 0.463 to 0.572 after increasing the PEF intensities to 2 and 3 kV/cm with specific energy 40 to 90 kJ/kg, respectively. The standard membrane disintegration for the intact and destroyed membrane is $Z = 0$ and $Z = 1$ (Lebovka et al. 2002), respectively. In this regards the maximum membrane disintegration (0.572) was observed at 3 kV/cm. Our result are in complete agreement with previously reported data on other plant tissues like, apples, grapes, sugar beets, onions, and goji berry [$(Z_p > 0.8)$] were reported by applying PEF ≤ 3 kV/cm] (Dermesonlouglou et al. 2018; Puértolas et al. 2013).

Fig. 1 **a** Cell membrane disintegration index (z_p) values for PEF treated plum at 1, 2 and 3 kV/cm, **b** cell membrane disintegration index (z_p) values for PEF treated plum with specific energy

consumption of 10, 40, and 90 kJ/kg, **c** drying rate of PEF treated and untreated plum and moisture content at 70 °C. **d** drying rate of PEF treated and untreated plum at 70 °C drying temperature

The disintegration of the membrane was found to increased with increasing electric field intensities and pulse number (Dermesonlouoglou et al. 2018).

Effect of PEF on drying kinetics of plum

The drying curve and mathematical design were expressed and calculated to characterise PEF treated and untreated plum with different specific energy at the same temperature. The effect of drying temperature as well as PEF treatment at different intensities 1, 2 and 3 kV/cm on drying rate and moisture content are shown in Fig. 1c. It was observed that increasing PEF intensity results in enhanced drying rate and reduced the drying time (Fig. 1d). The values of R^2 were 0.97 to 0.99 for untreated and treated plum, respectively suggesting a good fit between moisture ratio and drying time (Table 1). Our results endorsed by EL-Mesery and Mwithiga (2012), i.e. based on page model with regards to convective drying using onion at a static temperature. As shown in Fig. 2A, the analysed data of the moisture ratio against drying time indicates that moisture ratio is decreasing with increasing drying time of PEF treated plum. All these data were analysed by drawing the linear curve. Further, we found that increasing PEF intensities to 1, 2, and 3 kV/cm results in decreased moisture ratio and increased specific energy consumption compared to untreated plum. In this study, gradual decrease in drying time and moisture ratio were found in PEF treated plum at 1, 2 and 3 kV/cm with gradual increase in specific energy 10, 40 and 90 kJ/kg respectively. As reported by Wiktor et al. (2016) on PEF treated carrot at 5 kV/cm, 10 to 100 pulses resulted in

8–80 kJ/kg specific energy consumption, respectively. These findings state that the number of pulses were one of the most effective parameters which are responsible for shortening of drying time and raising specific energy consumption. Indeed, this behaviour indicates that there are different PEF treatment model and parameters for specific materials and devices. It also depends upon the structure of the raw materials. The analogous result has been observed previously Arevalo et al. (2004).

The measured drying results based on percent dry basis and wet basis are shown in (Fig. 2b, c). The moisture content of the sample decreased with increased drying time. The PEF treated and untreated plums were dried up to 270 min and it was found that plum treated at highest intensity (3 kV/cm) was losing the most moisture by 28% compared with untreated plum on a wet basis. The same trend was found on dry basis plum treated at 3 kV/cm (moisture by 22%) compared to untreated plum. The pattern of moisture loss was depended on treatment intensity at the same temperature, which could have happened due to elevated tissue permeability. The plant tissue compressed while drying because of higher cell membrane disintegration. The PEF treatment causes tissue damage before the drying process that finally leads to dysregulation of water movement, and thus the shrinkage occurred quickly. These results support the previous studies by Janositz et al. (2011), Lebovka et al. (2007a), which suggested that potatoes treated by PEF resulted in higher cell disintegration and increased in drying rate. These remarkable similarities among them were due to the fact that increase in specific energy consumption rises the cell disintegration index and the drying rate as well. Our results may be

Table 1 Electric conductivity (EC), diffusion rate and regression values during drying for PEF treated plum and optical properties of PEF treated and untreated plum after and before drying

Treatment	Pulse number	EC ($\mu\text{S}/\text{cm}$)	Diffusion $\times 10^{-9}$ (m^2/s)	R^2
0 kV/cm	30	239 $\pm$ 0.09	0.27	0.975
1 kV/cm	30	293 $\pm$ 0.03	11.7	0.989
2 kV/cm	30	408 $\pm$ 0.07	12.15	0.990
3 kV/cm	30	448 $\pm$ 0.04	16.41	0.985
Color attributes of treatment (after drying)				
	L^*	a^*	b^*	C^*
Control	43.71 $\pm$ 0.67 ^c	1.141 $\pm$ 0.08 ^a	1.96 $\pm$ 0.07 ^a	2.27 $\pm$ 0.08 ^a
1 kV/cm	46.61 $\pm$ 0.17 ^a	0.24 $\pm$ 0.03 ^d	0.71 $\pm$ 0.05 ^c	1.53 $\pm$ 0.06 ^b
2 kV/cm	44.44 $\pm$ 0.20 ^b	0.91 $\pm$ 0.09 ^b	1.23 $\pm$ 0.01 ^b	0.75 $\pm$ 0.03 ^d
3 kV/cm	44.08 $\pm$ 0.51 ^b	0.89 $\pm$ 0.03 ^c	0.65 $\pm$ 0.02 ^c	1.12 $\pm$ 0.05 ^c
Color attributes of treatment (before drying)				
Control	47.23 $\pm$ 0.28 ^c	4.65 $\pm$ 0.08 ^c	1.19 $\pm$ 0.07 ^b	4.80 $\pm$ 0.09 ^c
1 kV/cm	47.21 $\pm$ 0.33 ^c	4.64 $\pm$ 0.10 ^c	1.18 $\pm$ 0.07 ^b	4.89 $\pm$ 0.10 ^c
2 kV/cm	47.29 $\pm$ 0.09 ^b	4.85 $\pm$ 0.02 ^a	1.25 $\pm$ 0.02 ^a	5.08 $\pm$ 0.13 ^a
3 kV/cm	47.59 $\pm$ 0.13 ^a	4.76 $\pm$ 0.01 ^b	1.25 $\pm$ 0.02 ^a	4.92 $\pm$ 0.14 ^b

All values are indicated mean $\pm$ standard deviation. Values with different letters in the same column (a–d) are significantly different ($P < 0.05$) from each other

Fig. 2 **a** Moisture ratio of PEF treated and untreated plum at 70 °C, **b** moisture content on wet basis, **c** moisture content on dry basis, for untreated and PEF treated plum

different due to the structural variations in potatoes and plum and application of PEF parameters.

Effect of PEF on diffusion coefficient

The current study showed that the PEF pre-treatment at 1, 2 and, 3 kV/cm of plum enhanced the drying rate (Fig. 3a, b). This rate of drying was increased with increasing applied PEF intensities and increasing specific energy up to 90 kJ/kg. The water diffusion coefficient of plum treated by PEF showed a higher rate of diffusion compared to the untreated plum as shown in Table 1. The effective water diffusivity increased to 11.7 , 12.15 and $16.47 \times 10^{-9} \text{ m}^2/\text{s}$ with increasing treatment intensities and specific energy by 10, 40, and 90 kJ/kg, respectively compared with untreated plum ($0.27 \times 10^{-9} \text{ m}^2/\text{s}$) (Fig. 3a, b). It stated that the PEF pre-treatment increased the water diffusion coefficient up to 60% compared to untreated plum. Moreover, this finding is supported by previous studies of diffusion coefficient

during drying. The effective water diffusion coefficient on PEF treated carrot and okra at 0.60 and 4 kV/cm were found to be $1.17 \times 10^{-9} \text{ m}^2/\text{s}$ to $5.10 \times 10^{-9} \text{ m}^2/\text{s}$ and $8.05 \times 10^{-10} \text{ m}^2/\text{s}$, respectively (Amami et al. 2008) (Adedeji et al. 2008). These findings suggested that the rate of diffusion coefficient differs by changing the PEF treatment intensities. The another study also stated that the rate of water diffusion coefficient differs from 0.94 to $1.07 \times 10^{-9} \text{ m}^2/\text{s}$ by changing the PEF treatment intensities 1.85 to 5 kV/cm (Wiktor et al. 2016). The rate water diffusion coefficient is affected by drying temperature, PEF designing, applied voltage, membrane disintegration, drying methods, and lipid composition of the membrane with the type of material used. As investigated by Deng et al. (2018), George et al. (2018), diffusion coefficient ($1.33 \times 10^{-10} \text{ m}^2/\text{s}$ to $8.97 \times 10^{-10} \text{ m}^2/\text{s}$) vary with drying method (HAD, PVD) at the same temperature. As expected, diffusion increases with increasing PEF intensity. This incident was just because the water agitation was

Fig. 3 **a** The effective moisture diffusion coefficients $Deff$ for PEF treated and untreated plum at different electric field intensities, **b** Variation of $\ln MR$ vs. drying time, single temperature and PEF 1, 2 and 3 kV/cm during drying at 70 °C

accelerated after applying the highest intensity (3 kV/cm) which causes tissue disintegration that leads to increased water diffusion $16.47 \times 10^{-9} m^2/s$. Thus, diffusion is predominantly depended on drying parameter, temperature, and physiochemical properties of the material.

Effect of PEF on colour attributes of plum

Colour is one of the most vital features of food that attract to consumers. Drying process leads to a change in the colour (Wiktor et al. 2016). PEF treatments at 1, 2 and 3 kV/cm with the same pulse number were applied to see the alteration in colour, and total colour changed was represented for all dried plum (Table 1). The lightness of plum treated at 1 kV/cm was inscribe higher value of L^* (46.61 ± 0.17), as compared to plum treated at 2 kV/cm and 3 kV/cm value of L^* (44.44 ± 0.20 , 44.08 ± 0.51). The lightness of plum treated by PEF was slightly decreasing after drying from the initial due to reducing in the red pigments and emergence of dark pigment by

Maillard reaction (Wang et al. 2017). The redness (a^*) and yellowness (b^*) of the plum decrease after drying and perceive dark brown colour compared to fresh plum (Table 1). A study on kiwifruit drying indicated that the significant decrease in the values of L^* , a^* and b^* at 60 °C, due to a reduction of non-enzymatic browning which takes place during drying (Orikasa et al. 2014). Further studies on strawberry suggested that PEF intensity of more than 1 kV/cm reduces the lightness. The highest intensity leads to membrane permeabilisation which might have released more enzymes like peroxidase and another polyphenol oxidase (Tylewicz et al. 2017). The value of a^* in all dried sample was decreased, it might be happened due to the loss of carotenoids mainly capsanthin family that is responsible for red colour (Montoya-Ballesteros et al. 2014). The β -carotene and some other carotenoids are responsible for yellow colour, so the high unsaturation makes it perceptible to oxidation and loss of this molecules in the thermal drying process (Topuz et al. 2011).

The colour difference was calculated, depending on ΔE value, the colour difference between PEF treated and untreated plums can be assessed as reported by Mtaoua et al. (2017) as reported that ΔE value > 2 indicate well visible with naked eye. According to this finding, all the plums treated with PEF are visible as compared to fresh plums. Although, the increased value of ΔE was recorded in dried sample, which endorse that total colour changes also occurred while drying.

Effect of PEF treatment on microstructure

The microstructure is an important factor in perceiving the cellular mechanisms. This mechanism is very useful to understand and upgrade drying techniques and properties of food products (Karunasena et al. 2014). The impact of PEF on the microstructure of plum after drying was shown in Fig. 4. Shrinkage in the membrane was seen in the plum treated by PEF as compared to untreated plum. The PEF treatment at different intensities with the same pulses number showed differences in the shrinkage of the membrane. The PEF treatment at 1 and 2 kV/cm showed less shrinkage, whereas the highest shrinkage was observed at 3 kV/cm in the membrane. This gradual increament in the shrinkage might be due to the PEF induced eletroporation. Moreover, the electroporation process in the tissues is either reversible or non-reversible this phenomenon is not clearly understood. Therefore, further studies are required to understand this process. The microstructural shrinkage of cell wall occurred during PEF treatment combined with convective drying. The PEF treatment at high intensity causes more damage to the cell membrane and vice versa (Wiktor et al. 2016).

Fig. 4 SEM image of the dried plum for control, PEF treated at 1, 2 and 3 kV/cm

Conclusion

In this study, the impact of PEF treatment on cell disintegration index, drying kinetics, diffusion rate, colour and microstructure of plum were examined. There was an increase in PEF treatment ($3 \text{ kV/cm} > 2 \text{ kV/cm} > 1 \text{ kV/cm}$) leads to increased cell disintegration up to 0.57. This higher cell disintegration facilitated both drying rate and moisture loss. The water diffusion coefficient was also increased with increasing PEF intensity at uniform temperature. Further, this research confers that higher diffusion coefficient has higher moisture diffusion on a wet and dry basis of plum. The PEF treatment with the highest intensity (3 kV/cm) at uniform temperature results in increased drying rate and reduced drying time. Additionally, this study suggests that the Fick's steady state law is suitable for designate convective drying of plum at a constant temperature. Furthermore, the PEF treatment also affects the colour during drying process. The findings in the current work confer constitutive knowledge for choosing suitable drying technology for plum.

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