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Superheated Steam for Drying Avocado Pulp: Kinetic Model and Changes in Polyphenol Content

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Avocado contains a variety of essential nutrients and important phytochemicals. At present, the drying method is widely used to increase the commercial life and availability of avocado pulp. In this study, the drying characteristics of avocado pulp by freeze drying (FD) and superheated steam drying (SHD) methods were evaluated. The SHD process occurred faster than FD, respectively, by 4 and 15 h. The loss of polyphenols and antioxidant activity of avocado flesh on drying process was relatively high, depending on the drying method and temperature. SHD has a lot of superiority that is a suitable drying method for avocado pulp. The empirical data on avocado pulp drying were used to build mathematical models that simulate moisture ratios against operating times. The statistical values revealed that the Wang and Singh model and the Page model were appropriate to depict dehydration behaviour for avocado pulp by FD, whereas the Page and Modified Page models were appropriate for the SHD method.

1. Introduction

Avocado is well-known for its nutritional value and health benefits. Its pulp contains more insoluble, soluble fibers and proteins than most other fruits. Avocado pulp is famous for its high levels of lipids (12 – 24 %), and rich in polar lipids, which are important in plasma membranes (Araújo et al., 2018). It also contains mostly mono-unsaturated fatty acids (> 70 %), minerals (e.g. potassium and phosphorus), vitamins (e.g. β-carotene, vitamin A, C, E, K, and B vitamins), antioxidants, pigments, tannins, and phytoestrogens, which are beneficial to mental and physical wellness. Avocado pulp contains a high phenolic compounds concentration with various subgroups, hence it has been reported to have various health benefits (Çin and Özçelik, 2020).
Avocados are commonly used as fresh fruits, but the oxidation catalyzed by polyphenol oxidase and peroxidase causes rapid discoloration (browning), which pose a major problem in avocado production. Many methods have been studied for minimizing browning of pulp, such as the use of preservative compounds, controlled temperature, oxygen, pH, cold storage or heat treatments (Ospina et al., 2019). However, they are difficult to control the conditions or dosage, and the effects of some preservatives on health are either negative or not yet clear. The modern food industry is oriented towards the preservation methods that help maintain the structure and nutritional properties, sensory attributes, and in particular, thermally labile compounds (e.g. vitamins, antioxidants) based on emerging physical techniques. Freeze drying (FD) is the superior technique for thermo-sensitive food materials to limit heat changes when compared to other conventional dry techniques, which are frequently utilized in fruit drying. This drying technique allows food to retain its nutrition, actual color and shape of the original raw material, resulting in a high-quality product (Guerrero et al., 2022). On the other hand, the main disadvantage of FD is their high cost due to the specialized equipment needed, high energy intensive and lengthy processing time (Liapis and Bruttini, 2020). Superheated-steam drying (SHD) is a technology with great potential that can make good shortcomings of current drying methods. It uses steam at temperatures greater than the saturation (boiling) point as the drying medium (Romdhana et al., 2015). The main advantages of SHD are nonpoisonous, no fire risk, energy savings, improved pollution control, short drying times, no resistance to diffusion, enhanced water mobility within the particle pore, restrained exposure to O_2 free environment (Calín-Sánchez et al., 2020). It is gradually being used to replace traditional drying methods for high quality products.

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Although numerous investigations on techniques for drying avocados have been conducted, the study only provided the properties of the sample obtained after the drying process was completed, no information on drying kinetics was provided (Rafidah et al., 2014). The polyphenol compounds have been reported being the most accountable compound for the antioxidant properties in avocado (Abd Elkader et al., 2022). In order to gain a deeper insight into the drying kinetics and changes in the components during the avocado pulp drying by SHD and FD, this research investigated the drying process and antioxidant capacity of avocado pulp by applying the FD and SHD methods through moisture loss rate, polyphenol content and antioxidant activity during the drying process. The study also built up the mathematical model to describe the drying kinetics and design a practical scale for drying avocado pulp by FD and SHD.

2. Experimental

2.1 Materials

Avocados of the variety Hass were provided by farms in Dak Lak, Vietnam. Fruit was kept at room temperature for 2 to 7 days until it reached pre-ripeness, peel color is from bright green to purplish and pulp texture is firm but yielded slightly to finger pressure. The pre-ripe avocado is cleaned with water at room temperature, before removing its skin and seeds. The avocado flesh was cut into cubes of 1x1x1 cm, and the drying process was carried out immediately afterwards to limit oxidation.

2.2 Drying procedure

Avocado was freeze dried by a domestic freezer at -18 °C for 24 h. Avocado cubes were then dried in a vacuum freeze drying unit FreeZone® 12 Liter Freeze Dry Labconco (USA) under vacuum (100.10^{-3} mbar) at a condenser temperature of -50 °C. For drying with SHD, the experiments were conducted in drying cabinet which is cylindrical in shape with 400 mm in diameter and 700 mm in length. In each batch, the pulp of avocado fruit was put on the tray with 300 x 650 mm of width x length. The mass of avocado was around 3 kg/batch. Avocado pulp was dried at 140, 150, 160, 170 °C. The drying agent is superheated steam produced by heating the saturated steam at a pressure of 1.05 bar to the required temperature under isobaric conditions. The drying processes were performed until the samples reached constant mass. Avocado was placed on a poly (tetrafluoroethylene) netting in all experiments.

2.3 Analytic methods

Moisture content was estimated by the gravimetric method, avocado pulp was dried at 105 °C until it reached a constant weight (AOAC, 2000). Total polyphenols content was estimated using the spectrophotometric method and Folin – Ciocalteu as a reagent. The content of PPs was expressed as milligram of gallic acid equivalents per gram of dried weight (mg GAE/ g DM) (Trujillo-mayol et al., 2020). Antioxidant activity: DPPH was measured using the spectrophotometric technique of Brand-Williams et al. (1995). The changes in PPs content and antioxidant activity were shown by the ratio of the value at the assessment time to initial value.

2.4 Mathematical modeling

Due to equilibrium moisture content being relatively smaller than instantaneous moisture content, the moisture ratio of avocado pulp in drying process was determined by the following formula (Pala et al., 1996):

$$MR = \frac{M_t}{M_0} \quad (1)$$

In there, M_t and M_o (kg water/ kg dry matter) are the instantaneous moisture content at time t of drying and moisture content of raw avocado pulp.

The moisture ratio curves were obtained from five semi-theoretical models by multiple non-linear regression technique in order to demonstrate the drying characteristics of avocado pulp. The mathematic models to describe drying kinetics were presented below (Pianroj et al., 2018):

Wang and Singh: $MR = 1 + at + bt^2$ (2)

Newton: $MR = \exp(-\mathrm{kt})$ (3)

Modified Page: $MR = \exp(-(kt)^n)$ (4)

Page: $MR = \exp(-kt^n)$ (5)

Henderson and Pabis: $MR = a\exp(-\mathrm{kt})$ (6)

The goodness of fit between observed and theoretical result was selected by various statistical parameters, namely coefficient of determination R^2, reduced chi-square χ^2 and root mean square error RMSE.

3. Results and discussion

The fresh avocado pulp had a moisture content of 76.04 %, a crude fat content of 15.02 %, an ash content of 1.05 %, a carbohydrate content of 3.42 %, phenolic content of 364 mg GAE/ 100 g dm, and an IC50 value of 61.32 g/g dm.

3.1 Freeze drying of avocado pulp

At the early stage of the drying process, from 0 to 3 h, the moisture content of avocado pulp reduced rapidly (Figure 1). After that, the rate of drying reduced gradually over time due to the reduction in free moisture. After 9 h, the drying rate did not change significantly because the critical moisture content had been passed, and the moisture was no longer evaporated when it reached the equilibrium moisture content of 0.5 %. The FD avocado pulp process took 15 h, due to the avocado's high fat content that attributed to the hydrophobic character which imposed a resistance to the flow of moisture. Moisture was difficult to diffuse in the matrix of avocado pulp. The existence of large macromolecules such as lipid and protein resulted in the formation of two different forms of water. One inside the macromolecules, immobilized by hydrogen binding and another outside the macromolecule forming a hydration shell with a high density of hydrogen binding (Laage et al., 2017). As a result, water had a greater binding energy, resulting in a longer drying time than for other fruits.

(a) (b)

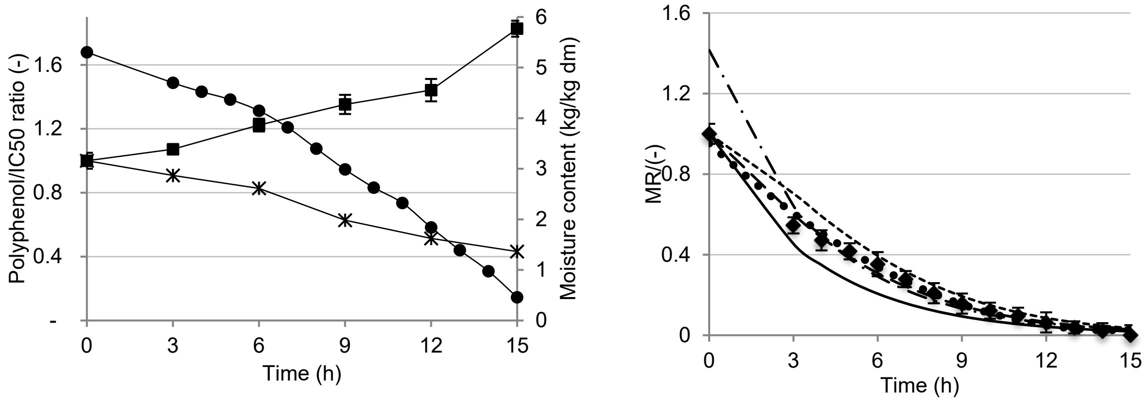

Figure 1: Change of (a) avocado pulp properties, (b) drying kinetics simulation using the empirical model in FD (♦ experimental, ••• Wang and Singh, — Newton, ···· Page, ---- Modified Page, – · – Henderson and Pabis, ●: Moisture content, ∗: Polyphenol ratio, ■: IC 50 ratio)

The drying models demonstrating the changes in moisture ratio of avocado pulp against time by the FD method are given in Figure 1, and the statistical indicators are provided in Table 1. The results revealed that the moisture ratio declined consistently with drying time. In general, all values of R^2 were greater than 0.95, suggesting that the results were well-fitting. According to the findings, the Wang and Singh model was proven to be the most adequate to predict the phenomenon of avocado pulp dehydration by the FD method, because, in addition to giving comparatively the highest R^2 values of all models, it also had the lowest values of χ^2 and RMSR. The Wang and Singh model was revealed to be the most accurate model for the description of the pineapple FD by Izli et al. (2018).

Total polyphenols content significantly reduced, at the end, that was only approximately 43 % of the initial drying (Figure 1). During the freezing process, there was a phenomenon of water evaporation or ice sublimation on the food surface, which occurred when the water pressure of the ice was greater than the vapor pressure of the environment, and the temperature of the evaporator was lower than the surrounding air (Sun, 2005). It resulted in excessive surface desiccation, an opaque dehydrated surface and the moisture losses, the dryness of frozen food, leading to easily causing oxidation and irreversible denaturation. This phenomenon, known as freezer burning, increased oxygen contact with the food surface area, resulting in a reduction of antioxidant compounds, sensory attributes, product quality, and weight loss (Zaritzky, 2008). Along with that, the rapid freezing process at -50 °C could break the bonds in the compounds, change structure, leading to a reduction in the activity and concentration of biological compounds. The antioxidant activity of drying avocado pulp strongly decreased that might be caused by the reduced amount of polyphenols in the drying process.

During the FD operation at the vacuum chamber pressure of 100.10^{-3} mbar and condenser temperature of -50 °C, the drying of the cubed avocado pulp took 15 h. The polyphenol content and antioxidant activity of avocado pulp reduced during drying.

3.2 Superheated steam drying of avocado pulp

At the same drying air velocity, the higher the drying air temperature, the more accelerated the drying process will be (Figure 2). This could be because the driving force of diffusion from the interior areas to the surface was greater at higher temperatures, effectively overcoming impediments in the drying process and resulting in more uniform drying. The results showed that moisture evaporation took place quickly, and the moisture content after drying was below 5 % at all temperature conditions after only 4 drying h, much faster than FD methods. At the first hour, the moisture evaporation rate was very fast compared to the following, and reached the critical moisture content. In drying at temperatures above 150 °C, mono-carbohydrates, phenolic compounds and other compounds spontaneously decompose into CO_2, H_2O and organic crosslinks within macromolecules (Niksa and Krishnakumar, 2015). It can destroy the molecular structure of avocado organelles, and consequently increased free moisture content, and decreased resistance of moisture. The drying process by superheated steam was faster than by the FD method.

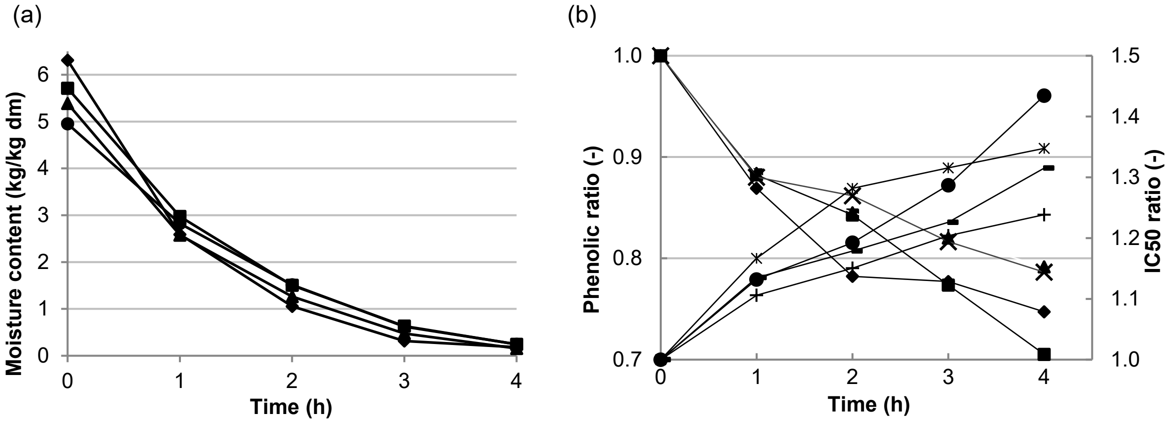

*Figure 2: Change of (a) moisture content, (b) ratio of polyphenol content and antioxidant activity during SHD of avocado pulp ((a)●: 140 °C, ■: 150 °C, ▲: 160 °C, ♦: 170 °C; (b): ♦:140 °C, ■:150 °C, ▲:160 °C, ×:170 °C; IC50 ratio: *:140 °C, ●:150 °C, +:160 °C, - :170 °C)*

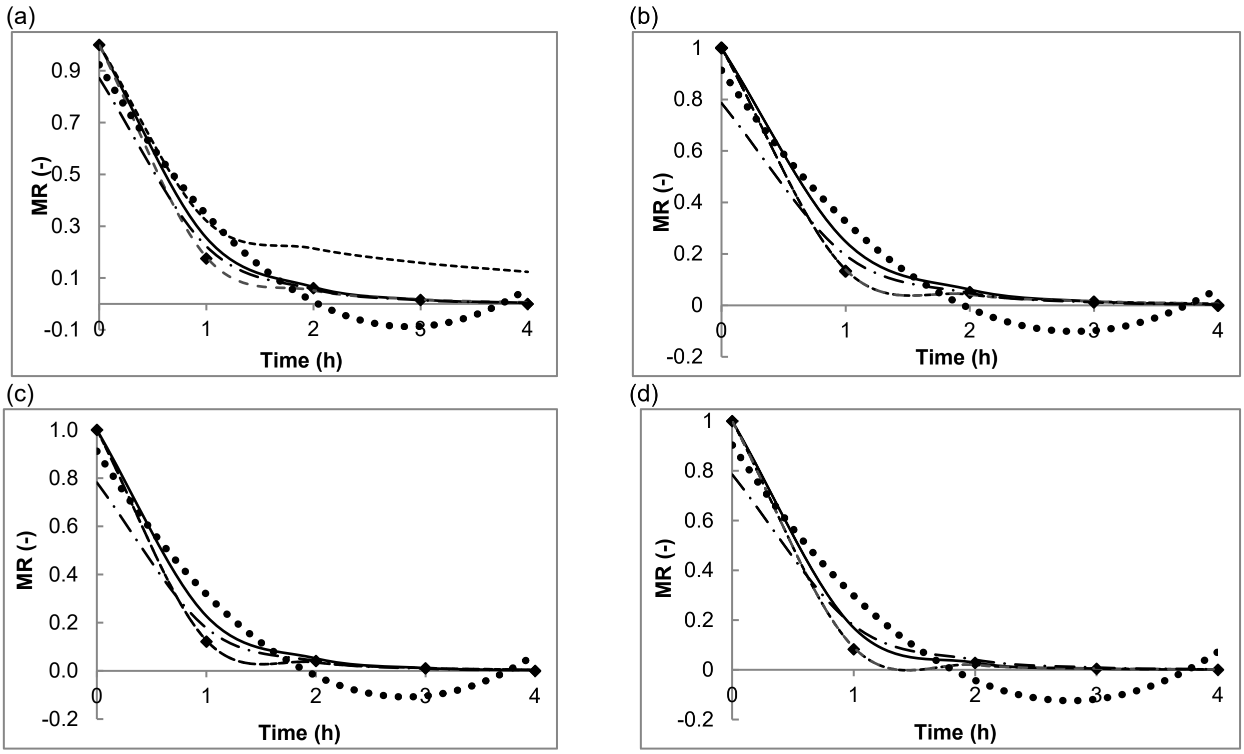

Figure 3: Drying kinetics simulation using the empirical model in SHD, (a) 140 °C, (b) 150 °C, (c) 160 °C, (d) 170 °C (♦ experimental, ••• Wang and Singh, — Newton, - - - Page, – – – Modified Page, – · – Henderson and Pabis)

Figure 3 depicts the drying kinetic curves of avocado pulp at four different temperature conditions in drying process by the SHD method. It was obvious that at all temperatures, the Wang and Singh model exhibited the lowest correlation, while the other models agreed well with the practical value, which was shown by the values of R^2, χ^2, and RMSE in Table 1. The Page and Modified Page models performed a better fitting with practical data. These models were also the most appropriate model for simulation of the drying kinetic of various fruits and vegetables e.g. banana, date palm, green bean, mango, onion, kiwi, etc. (Onwude et al., 2016).

The reduction of polyphenols content and antioxidant activity at 160 and 170 °C were similar and lower than the other two temperatures (Figure 2). In comparison to FD, the reduction rate of polyphenols and IC50 was significantly lower. This was explained by the shorter drying time and the less favorable conditions for oxidation reactions. In SHD, oxidizing reactions were inactivated, because there was no free oxygen in superheated steam, resulting in the decomposition of quickly oxidized nutrients at a very low rate. But the appearance of derivatives and decomposition of polymeric molecules caused a rise in monomer formation, which negatively impacted content of antioxidants and antioxidant activity of the dried product (Lee et al., 2005). On the other hand, Maillard reaction products could form during drying, such as melanoidins, which might be responsible for improved antioxidant activity (Echavarría et al., 2012). In FD, the reactions that produced new compounds with antioxidant activity were more difficult to occur. Besides that, high drying temperatures allowed for irreversible protein denaturation, reducing the activity of oxidizing enzymes, as a result, limiting the change of substances, biological activity, and color in the product after drying. The SHD method ensured a greater level of polyphenols and antioxidant activity than other methods.

Table 1: Values of statistical parameters of drying model in FD and SHD avocado pulp

Drying condition	Model name	FD	SHD, 140 °C	SHD, 150 °C	SHD, 160 °C	SHD, 170 °C
R^2	Wang and Singh	0.9908	0.9287	0.9113	0.9084	0.8937
	Newton	0.9510	0.9912	0.9784	0.9804	0.9912
	Page	0.9806	0.9891	0.9834	0.9834	0.9566
	Modified Page	0.9721	0.9891	0.9834	0.9875	0.9566
	Henderson and Pabis	0.9510	0.9912	0.9784	0.9804	0.9793
RMSE	Wang and Singh	0.025567	0.101449	0.114329	0.116536	0.127059
	Newton	0.083612	0.036014	0.051550	0.047644	0.038687
	Page	0.062424	0.127142	0.005246	0.004064	0.005123
	Modified Page	0.025825	0.005475	0.005246	0.004064	0.005123
	Henderson and Pabis	0.117835	0.061432	0.099769	0.100932	0.105635
$\chi 2$	Wang and Singh	0.000704	0.012865	0.016339	0.016290	0.020180
	Newton	0.007529	0.001621	0.003322	0.003322	0.001871
	Page	0.062424	0.020206	0.000003	0.000003	0.000003
	Modified Page	0.000718	0.000003	0.000003	0.000003	0.000003
	Henderson and Pabis	0.014953	0.004717	0.012442	0.127340	0.013948

The process of drying avocado pulp with superheated steam at 140 – 170 °C was extended for 4 h to achieve equilibrium moisture content. The results showed that, compared with the FD method, the convectional drying method of avocado pulp with superheated steam gives much better results, namely a faster moisture evaporation rate, shorter drying time, and lower loss of polyphenols and antioxidant activity. The findings also indicated that, at the investigated temperatures, the drying agent temperature of 160 °C gave high efficiency in terms of nutrition.

4. Conclusion

The preliminary influence of the drying method on avocado pulp was investigated based on moisture and antioxidant activity. The superheated-stem drying method had many advantages over the freezing drying method in drying avocado pulp. The SHD process had a shorter drying time, and a significantly lower reduction in polyphenol content and antioxidant activity than the FD method. The model with the highest R^2 and lowest χ^2 and RMSE showed the best correlation with the empirical value, which were Wang and Singh in FD, Page and Modified Page in SHD. These models enable mathematical expressions for the drying rate and the operating time in the avocado pulp drying process.

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