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Convective drying of papaya (*Carica papaya* L. 'Red Maradol') and banana (*Musa acuminata* (AAA Group) 'Gros Michel')

Secado convectivo de papaya (*Carica papaya* L. 'Red Maradol') y banano (*Musa acuminata* (AAA Group) 'Gros Michel')

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ABSTRACT

In this study, the drying kinetics of papaya (*Carica papaya* L. 'Red Maradol') and banana (*Musa acuminata* (AAA Group) 'Gros Michel') was experimentally investigated in a lab-scale tunnel dryer. The drying experiments were performed at three air temperatures (50, 60, and 70 °C) and three air velocities (1.0, 1.5, and 2.0 m/s). A surface area shrinkage linear model from the literature was used to include the shrinkage effect on the drying process. From the drying curves, no constant rate period was observed and drying occurred in a falling rate period. It was found that the changes in air velocity had a slight effect on the drying process. In addition, a non-linear regression analysis was employed to determine the characteristic drying curve.

Keywords: Papaya; Banana; Drying; Shrinkage; Characteristic drying curve

RESUMEN

En este estudio, se investigó experimentalmente la cinética de secado de papaya (*Carica papaya* L. 'Red Maradol') y banano (*Musa acuminata* (AAA Group) 'Gros Michel') en un secador de túnel a escala de laboratorio. Los experimentos de secado se realizaron a tres temperaturas del aire (50, 60 y 70 °C) y tres velocidades del aire (1.0, 1.5 y 2.0 m/s). Se utilizó un modelo lineal de encogimiento del área superficial de la literatura para incluir el efecto de encogimiento en el proceso de secado. A partir de las curvas de secado, no se observó ningún período de velocidad constante y el secado se produjo en un período de velocidad decreciente. Se encontró que los cambios en la velocidad del aire tenían un ligero efecto en el proceso de secado. Además, se empleó un análisis de regresión no lineal para determinar la curva característica de secado.

Palabra claves: Papaya; Banano; Secado; Encogimiento; Curva característica de secado

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1. INTRODUCTION

Drying is one of the oldest unit operations used by the food processing industry. Drying is a process of reducing the moisture of foods to low levels for improved shelf life by adding one or more forms of energy to the foods. Most commonly, heat is added to the foods by hot air, which also carries the moisture away from the foods. The drying process involves simultaneously heat and mass transfer within the foods and the medium used to transfer energy to the foods. In addition to preserving the foods, drying reduces the weight and bulk of the foods, thus lowering transportation and packaging costs. The present demand for high-quality products in the food market requires dried foods that maintain at a very high level the nutritional and organoleptic properties of the initial fresh foods (Mujumdar, 2015).

Many foods, namely fruits and vegetables, have been dried successfully including papaya and banana. For instance, Kumar *et al*. (2019) studied the thin-layer drying kinetics of banana (*Musa acuminata* × *balbisiana* (ABB Group) 'Monthan') and the influence of convective drying on nutritional quality and sensory characteristics. The blanched banana slices were dried at three temperatures (45, 55, and 65 °C) and at an airflow rate of 0.12 to 0.16 m/s using a lab-scale electrical cabinet dryer. The moisture ratio decreased exponentially with an increase in drying time. Page and Logarithmic models are the most appropriate ones to describe the drying behaviour. Improved rehydration ratio and resistant starch content were observed at the temperature of 55 °C. Fernández Valdés *et al*. (2015) analysed the drying kinetics of papaya (*Carica papaya* L. 'Red Maradol') using two different drying methods (osmotic dehydration and hot-air flow drying). Papayas were diced in a piece of size 2.5 × 2.5 × 1.0 ± 0.02 cm. The sliced papaya was dehydrated at 60 °C for 10 hours and dried at 60 °C for 5 hours. The results indicate that there is no difference between the two drying methods. However, the moisture removal was less pronounced by osmotic dehydration due to an increase in sucrose content within the cell cytoplasm.

In addition, Udomkun *et al*. (2014) monitored the quality changes of papaya (*Carica papaya* L. 'Pluk Mai Lie') during drying. Convective hot air drying was conducted at four temperatures (50, 60, 70, and 80 °C), during which time the product was sampled and subjected to a non-destructive optical (i.e., a laser light back-scattering) analysis. As expected, drying temperatures significantly affected the quality attributes of dehydrated papayas. Increasing drying temperature resulted in a decrease in moisture content, lightness and chroma values, whereas hue and shrinkage values were increased. Demirel and Turhan (2003) investigated the air-drying behaviour of Dwarf Cavendish and Gros Michel banana cultivars. Banana slices from each cultivar were divided into three groups. The first group includes intact banana slices (untreated slices). The second group slices were kept in a 0.1% ascorbic acid/citric acid (1:1) mixture for 1 min (acid-treated slices). The third group samples were dipped into 1% sodium bisulphite solution for 2 min (bisulphite treated samples). Pretreatments and increasing temperature decreased the browning, and the colour change in the untreated samples was acceptable. Pretreatments and temperature did not affect the shrinkage. The type of cultivars did not affect the drying behaviour.

In Nicaragua, many different types of bananas vary in colour, shape, and size. As a result of the abundance and wide availability of this fruit, it provides a cheap snack that needs no preparation whatsoever. In addition, papaya is one of the largest fruits found in Nicaragua. There are several papaya cultivars grown in Nicaragua that vary in shape and size, but most of them are large. Both papaya and banana fruits are an essential complement to the daily food and nutrition of a large part of Nicaraguan families and represent an alternative for the diversification of farms and the peasant family economy (INATEC, 2018).

This study aimed to determine the effect of drying air temperature and air velocity on the drying kinetics of papaya (*Carica papaya* L. 'Red Maradol') and banana (*Musa acuminata* (AAA Group) 'Gros Michel'), including the shrinkage effect, and to determine the characteristic drying curve.

2. MATERIALS AND METHODS

2.1 Materials

Freshly harvested, uniformly sized and blemish-free papaya (*Carica papaya* L. 'Red Maradol') and banana (*Musa acuminata* (AAA Group) 'Gros Michel') were procured from a local vegetable market in Managua, Nicaragua. Before drying, the fruits were sorted, washed, blotted off, hand-peeled, seed removed (papaya), and manually cut into slices.

2.2 Experimental drying system

A schematic arrangement of the experimental drying system is shown in Fig. 1. The system can be divided into four main sections as follows: gas supply and dehumidification section, heating section, drying chamber section, and analysing equipment section. The blower (B) supplies a gas flow--a broad range of flow rates is possible by changing the rpm setting through the frequency inverter (FI). The gas passes through an adsorption column (AC) containing a dehumidificant (e.g., silica gel) to obtain a process gas of low humidity content (less than 1.0 % relative humidity) measured by a hygrometer. The gas velocity is measured by an anemometer. After dehumidification, the gas is pre-heated with electrical resistance (ER) heaters of up to 2 kW each. Temperature is controlled by means of a temperature controller (TC), which supplies heat by means of an electrical resistance heater as its final control element. Before entering the drying chamber section, a static mixer homogenises the temperature by mixing the gas. The sample is put in the sample holder (SH) inside the drying chamber section and is supported on a weighing balance (WB) through an oil-sealed shaft. The cross-sectional area and depth of the sample holder are 45 mm × 75 mm and 5 mm, respectively. The drying chamber section has a uniform cross-sectional area of 100 mm × 200 mm. The sample's weight history is recorded on a computer (C). It is possible to take a reading every 12 seconds (Mendieta *et al*., 2015).

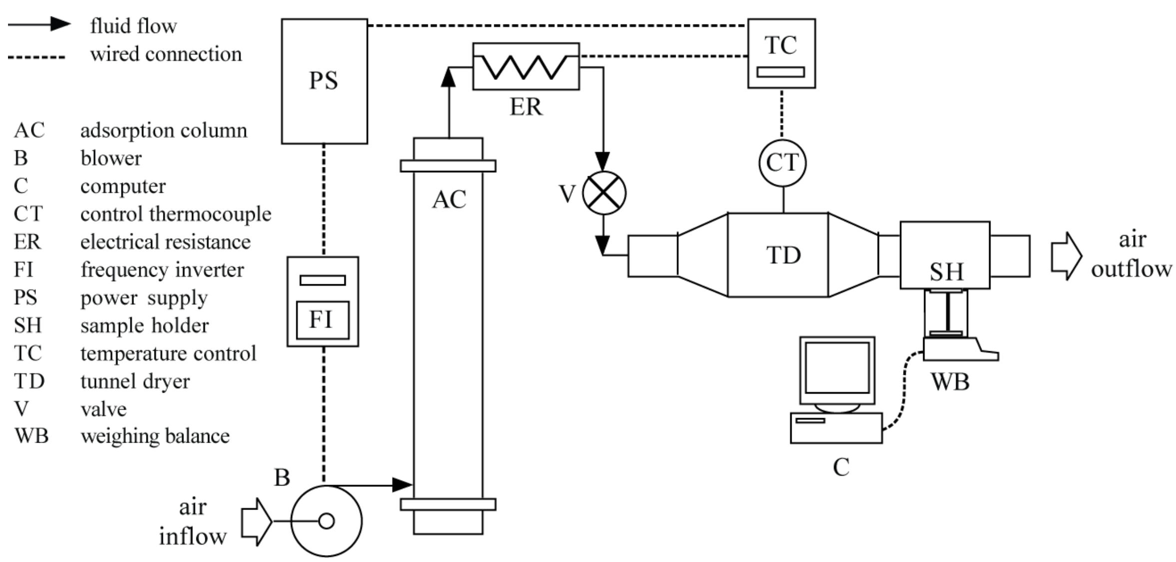

Fig. 1 A schematic diagram of the experimental drying system.

2.3 Experimental procedure

The drying experiments were performed at three air temperatures (50, 60, and 70 °C) and three air velocities (1.0, 1.5, and 2.0 m/s). Before starting an experiment, the system was run for at least half an hour to obtain steady-state conditions. The sample was uniformly distributed into the sample holder, thus covering the whole drying area. The sample holder was put into the drying chamber section. The drying time and mass of the sample were recorded. The test was stopped until the mass was invariable. After drying by the system above, the sample was further dried in an oven at 110 °C for 24 hours to determine its oven-dry mass (m_s). The initial mass, drying mass and oven-dry mass were determined with a precise analytical balance. All the drying experiments were performed in triplicate. Post-processing of these data yields drying kinetics.

2.4 Drying kinetics

The moisture content is computed as follows:

$$X_i = X_{i-1} + \frac{1}{m_s}\left(\frac{m_i - m_{i-1}}{t_i - t_{i-1}}\right) \tag{1}$$

where X is the moisture content at any time (dry basis), m is the mass of the sample at any time, and t is the time. The drying rate is defined as:

$$N_v = -\frac{m_s}{A_s}\frac{dX}{dt} \tag{2}$$

where N_v is the drying rate at any time and A_s is the drying area. Using the moisture content data as a function of time and a centred approximation of the derivative, it is possible to determine the drying rate as follows (Picado *et al.*, 2006):

$$N_v\left(X_i\right) = -\frac{m_s}{A_s(X_i)}\left(\frac{X_{i+1} - X_{i-1}}{t_{i+1} - t_{i-1}}\right) \tag{3}$$

The processing of the experimental data is performed using a program written in MATLAB®, this program reads the experimental data obtained and plots the drying curves and drying rate curves according to Eqs. (1) and (3).

Shrinkage of foods during drying takes place simultaneously with moisture diffusion and thus can affect the drying rate. Ideally, it can be considered that the shrinkage of foods is equal to the volume of the removed moisture. Therefore, an empirical correlation can be obtained that relates the shrinkage to the moisture content of foods. In the scope of this study, shrinkage is represented by a correlation that relates the changes in the surface area as a function of the moisture content as follows (Yadollahinia *et al*., 2009):

$$\frac{A}{A_0} = a + b\left(\frac{X}{X_0}\right) \tag{4}$$

where a and b are constants to be experimentally determined for each food. The subscript 0 denotes the initial value. Equation (4) enables us to include the shrinkage effect on the drying rate of foods [i.e., $A_s = A_s(X)$].

The characteristic drying curve (CDC) concept, first introduced by van Meel (1958) and subsequently popularised by Keey (1978), relies on an appropriate transformation of the drying rate curve coordinates to look for a single normalised drying rate curve, which does not depend on external parameters (e.g., gas conditions). The variable transformations proposed by van Meel (1958) are:

$$\phi = \frac{X_i - X_{eq}}{X_{cr} - X_{eq}} \tag{5}$$

and

$$f = \frac{N_v}{N_w} \tag{6}$$

where ϕ is the characteristic moisture content, f is the relative drying rate, X_{eq} is the equilibrium moisture content, X_{cr} is the critical moisture content, and N_w is the drying rate at the constant rate period. The general form of the CDC is given by $f = f(\phi)$.

By plotting f vs. ϕ at the different temperatures tested, a group of curves is obtained whose behaviour, if common, describes a characteristic drying curve to which a mathematical function (e.g., a polynomial function) can be determined. It is assumed that a unique relationship between f and ϕ can be found for a specific material.

3. RESULTS AND DISCUSSION

3.1 Drying characteristics

The variation of moisture content with drying time at three air temperatures (50, 60, and 70 °C) and three air velocities (1.0, 1.5, and 2.0 m/s) for papaya and banana are shown in Figs. 2 and 3, respectively. The moisture content of the fruits decreased exponentially with the drying time. As expected, an increase in drying air temperature reduces the time required to reach any given level of moisture content. In the case of papaya, high air temperatures may result in undesirable nutritional and textural quality degradation, such as case hardening (Kurozawa *et al*., 2012). The case-hardening phenomenon was also reported for banana (Katekawa *et al*., 2007). As seen in Fig. 2, an increase in air velocity at 70 °C did not influence the drying process of papaya. In the case of banana, the air velocity had a slight influence on the drying process at the three temperatures (see Fig. 3).

The correlation constants of Eq. (4) employed for calculating the surface shrinkage are shown in Table 1. In the scope of this study, Eq. (4) enables us to include the shrinkage effect on the drying rate of papaya and banana.

Table 1 Correlation constants of the linear model representing the surface area shrinkage at various drying conditions (Kurozawa *et al*., 2012; Katekawa *et al*., 2007)

Fruit	***a***	***b***	R^2
Papaya	0.3011	0.6583	0.9919
Banana	0.5673	0.4100	0.9867

Drying rates were estimated based on Eqs. (3) and (4) and are shown in Figs. 4 and 5 for papaya and banana, respectively. As seen in Figs. 4 and 5, an influence of air temperature on drying rate is observed. As expected, an increase in air temperature increases the drying rate because higher air temperature causes a higher moisture evaporation. In addition, no constant rate period was observed in the drying of papaya and banana. The drying process took place in a falling rate period, which indicates that diffusion was the dominant physical mechanism governing the movement of moisture in the samples during drying. These results are in good agreement with earlier observations (Jannot *et al*., 2004; Hawlader *et al*., 2007).

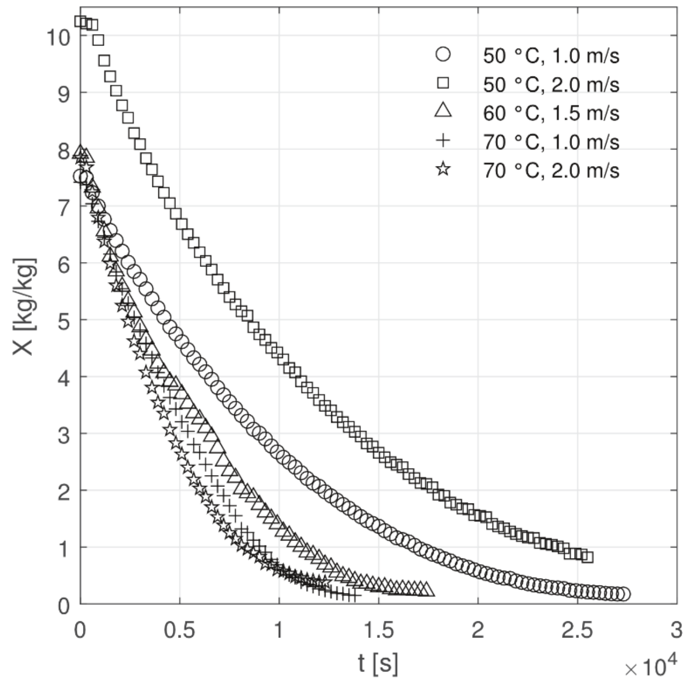

Fig. 2 Drying curves of papaya at various temperatures and velocities.

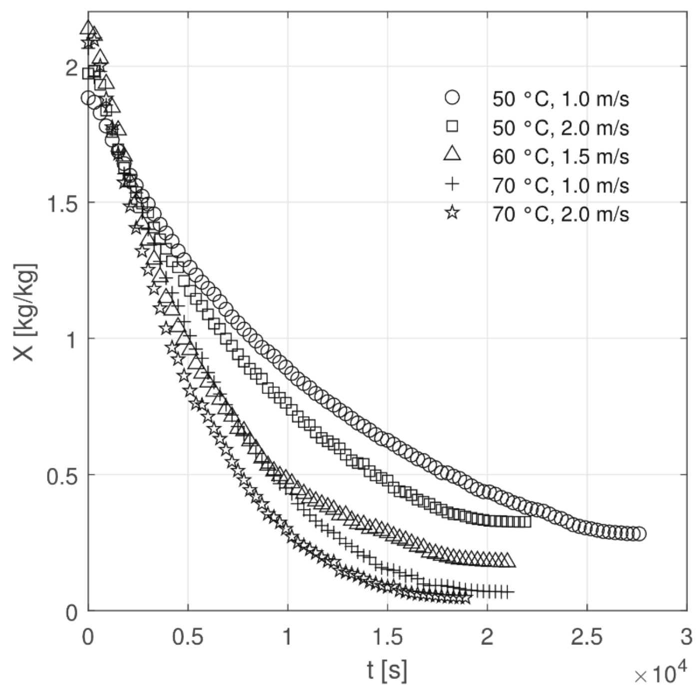

Fig. 3 Drying curves of banana at various temperatures and velocities.

Generally, the drying of most foods (namely, fruits and vegetables) is defined only by the falling rate period (Mujumdar, 2015). The drying rate (N_v) and moisture content (X) are normalised by the constant drying rate (N_w) and critical moisture content (X_{cr}), respectively. However, for papaya and banana no constant drying rate period was observed, and another approach must be found to normalise the drying data. In this case, X_{cr} and X_{eq} have been taken equal to X_0 and the value of X corresponding to $- dX/dt = 0$, respectively. N_w is equal to the drying rate at the beginning of the falling rate period (Bellagha *et al*., 2002; Jannot *et al*., 2004).

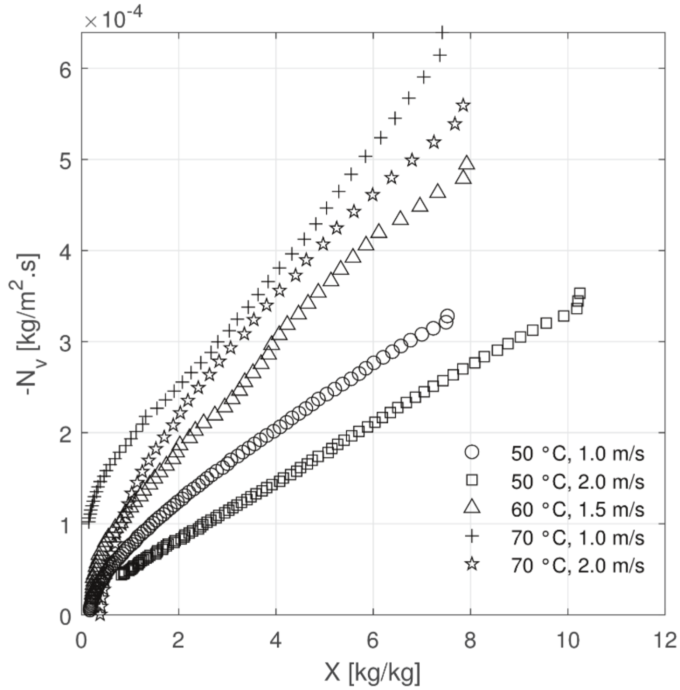

Fig. 4 Drying rate curves of papaya at various temperatures and velocities.

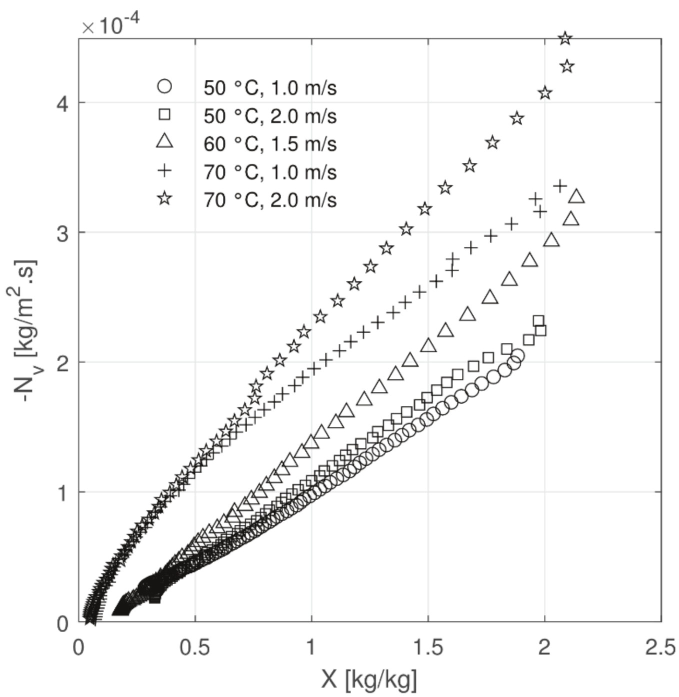

Fig. 5 Drying rate curves of banana at various temperatures and velocities.

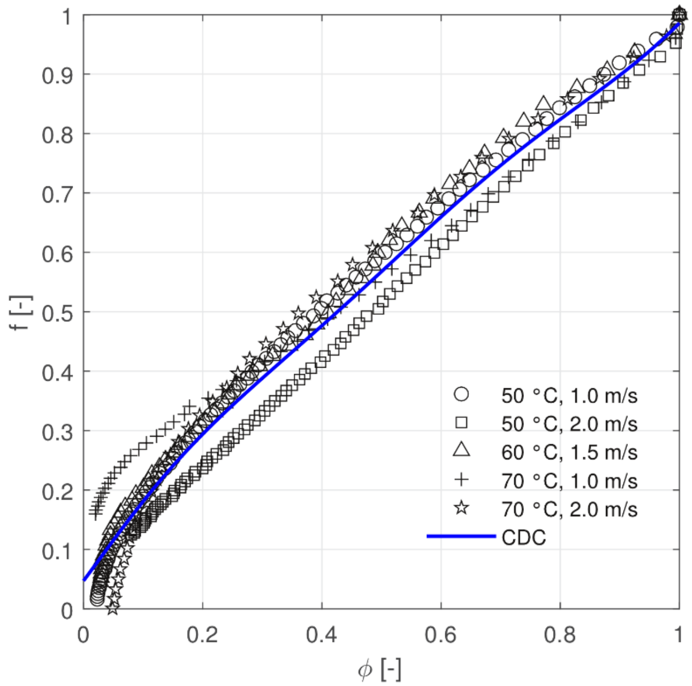

Fig. 6 Characteristic drying curve of papaya.

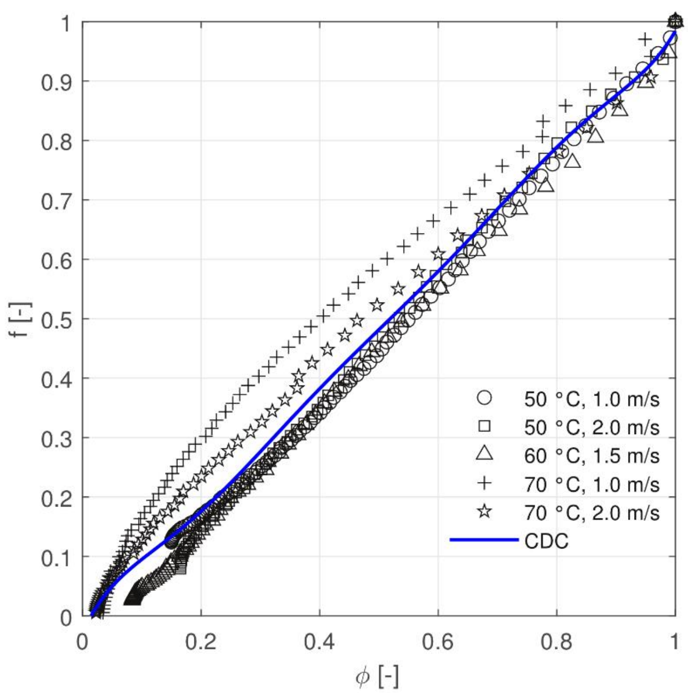

Fig. 7 Characteristic drying curve of banana.

In Figs. (6) and (7), experimental drying data are plotted to represent $f = f(\phi)$ for papaya and banana, respectively. Figures (6) and (7) show that all drying curves obtained with the characteristic moisture content (ϕ) and relative drying rate (f), for the different tested conditions, fall into a tight band, thus indicating that the effect of variation in different conditions is small over the range tested.

The regression analysis was performed using MATLAB®'s Curve Fitting Tool to find the best equation for papaya and banana characteristic drying curves.

For papaya (*Carica papaya* L. 'Red Maradol'):

$$f = -9.68\phi^7 + 39.01\phi^6 - 59.67\phi^5 + 42.82\phi^4 - 13.78\phi^3 + 0.89\phi^2 + 1.35\phi + 0.05 \quad (7)$$

For banana (*Musa acuminata* (AAA Group) 'Gros Michel'):

$$f = 57.13\phi^7 - 204.04\phi^6 + 290.17\phi^5 - 208.98\phi^4 + 79.75\phi^3 - 15.15\phi^2 + 2.13\phi - 0.03 \quad (8)$$

4. CONCLUSIONS

The drying kinetics of papaya (*Carica papaya* L. 'Red Maradol') and banana (*Musa acuminata* (AAA Group) 'Gros Michel') was experimentally investigated in a lab-scale tunnel dryer. The drying experiments were performed at three air temperatures (50, 60, and 70 °C) and three air velocities (1.0, 1.5, and 2.0 m/s). A surface area shrinkage linear model from the literature was used to include the shrinkage effect on the drying process. The moisture content of the fruits decreased exponentially with the drying time. As expected, an increase in drying air temperature reduces the time required to reach any given level of moisture content. No constant rate period was observed in the drying of papaya and banana and drying occurred in a falling rate period. This indicates that diffusion was the dominant physical mechanism governing the movement of moisture within the fruits during drying. It was found that the changes in air velocity had a slight effect on the drying process. In addition, a non-linear regression analysis was employed to determine the characteristic drying curve. The characteristic drying curve can be used to optimise dryer design and process parameters.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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NOTATION

a	Constant	(-)
A	Surface area	(m^2)
A_s	Drying area	(m^2)
b	Constant	(-)
f	Relative drying rate	(-)
m	Mass	(kg)
N_v	Drying rate	($kg\ m^{-2}\ s^{-1}$)
N_w	Drying rate at the constant rate period	($kg\ m^{-2}\ s^{-1}$)
R^2	Coefficient of determination	(-)
t	Time	(s)
T	Temperature	(K)
X	Moisture content, dry basis	($kg\ kg^{-1}$)

Greek Letters

ϕ	Characteristic moisture content	(-)

Subscripts

i	ith value	eq	Equilibrium value
cr	Critical value	s	Solid
eff	Effective value	0	Initial value

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