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Convective drying of sweet pepper (*Capsicum annuum* L. 'Tres Cantos') and yellow onion (*Allium cepa* L. 'Yellow Granex F1')

Secado convectivo de chiltoma criolla (*Capsicum annuum* L. 'Tres Cantos') y cebolla amarilla (*Allium cepa* L. 'Yellow Granex F1')

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ABSTRACT

In this study, the drying kinetics of sweet pepper (*Capsicum annuum* L. 'Tres Cantos') and yellow onion (*Allium cepa* L. 'Yellow Granex F1') 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 volumetric 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. The drying process took place in a falling rate period. It was found that the changes in air velocity had essentially no effect on the drying process. In addition, a non-linear regression analysis was employed to determine the characteristic drying curve.

Keywords: Sweet pepper; Onion; Drying; Shrinkage; Characteristic drying curve

RESUMEN

En este estudio, se investigó experimentalmente la cinética de secado de chiltoma criolla (*Capsicum annuum* L. 'Tres Cantos') y cebolla amarilla (*Allium cepa* L. 'Yellow Granex F1') 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 volumétrico de la literatura para incluir el efecto del encogimiento en el proceso de secado. A partir de las curvas de secado, no se observó ningún período de velocidad constante. El proceso de secado tuvo lugar en un período de velocidad decreciente. Se encontró que los cambios en la velocidad del aire esencialmente no tenían efecto sobre el proceso de secado. Además, se empleó un análisis de regresión no lineal para determinar la curva característica de secado.

Palabra claves: Chiltoma; Cebolla; Secado; Encogimiento; Curva característica de secado

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1. INTRODUCTION

Drying is defined as a process of moisture removal due to simultaneous heat and mass transfer. It is also one of the conservation methods of foods, which is most often used and is the most energy-intensive process in the food industry (Mujumdar, 2015). Furthermore, drying is one of the oldest methods of food preservation and is a complex food processing operation mainly because of undesirable changes in the quality of dried foods. Longer shelf-life, product diversity, and substantial volume reduction are the reasons for the popularity of dried fruits and vegetables.

In recent years, research efforts have been directed towards investigating the drying characteristics of various fruits and vegetables, mostly concerning process parameters and the development of mathematical models. For instance, Zalpouri *et al*. (2023) reported the drying of onion (*Allium cepa* L. 'Punjab Naroya') puree using two different drying methods (refractance window drying and convective drying). It was observed that irrespective of the drying method, the moisture ratio decreased, and drying time and effective moisture diffusivity increased with the thickness of the onion puree. In addition, the Lewis model and Wang and Singh model provided the best fit for refractance window drying and convective drying, respectively. Kaur *et al*. (2022) studied the drying kinetics of sweet pepper (*Capsicum annuum* L. var. *bachata*) in a convection hot air dryer at different temperature conditions (40, 50, and 60 °C) with an air velocity of 1.5 m/s. The Page model was found to be the most appropriate model for explaining the slices' drying behaviour.

In addition, Sasongko *et al*. (2020) evaluated the effects of drying temperature and relative humidity on both the drying rate and onion quality. Fresh onions (*Allium cepa* L. var. *bima*) were dried for 120 min under various temperatures (40, 50, 60, and 70 °C) and at an air velocity of 0.54 m/s. The results demonstrated that the drying rate of sliced onion can be expressed using Fick's model. Furthermore, decreasing the relative humidity of air can enhance the driving force for drying at either low or medium temperatures. Speranza *et al*. (2019) investigated the drying of sweet pepper (*Capsicum annuum* L. var. *senise*) using two drying methods (solar drying and forced air-drying). For solar drying, samples were dried for about seven days with an average temperature of 45-17 °C (day-night) and a relative humidity of 25-50%. For forced air-drying, samples were dried for 48 h at 55 °C. Solar-dried samples showed retention of glucose, while fructose levels decreased.

Kiranoudis *et al*. (1992) proposed an empirical mass transfer model for describing the drying kinetics of onion and green pepper. The proposed model is based on a drying constant (K), which is a function of process parameters (i.e., characteristic dimension, temperature, moisture content, and air velocity). Experiments were performed at five air temperatures and three air velocities. They have proved that air velocity does not significantly affect the drying rate.

Onion and sweet pepper are most widely consumed as a component of the diet in Nicaragua, along with the tomato. These foods are cost-effective and have a high nutritional profile (MEFCCA, 2022). Both onion and sweet pepper offer varied aromas, colours, flavours, and nutritional and medicinal value. In the last few years, they gained attention due to the presence of a plurality of beneficial chemical compounds, such as vitamins, phenolic compounds, antioxidants, and among others (Kaur *et al*., 2022; Sasongko *et al*., 2020). These beneficial chemical compounds are highly influenced by temperature changes; thus, to retain the chemical compounds, appropriate drying methods and storage are compelled. At present, convective drying is the most used for fruit and vegetable drying.

Since research on local varieties and cultivars of fruits and vegetables is limited, it was therefore deemed valuable to conduct a study on the drying characteristics of sweet pepper (*Capsicum annuum* L. 'Tres Cantos') and yellow onion (*Allium cepa* L. 'Yellow Granex F1'), which both are considered important cultivars in Nicaragua (MEFCCA, 2022).

2. MATERIALS AND METHODS

2.1 Materials

Freshly harvested, uniformly sized and blemish-free sweet pepper (*Capsicum annuum* L. 'Tres Cantos') and yellow onion (*Allium cepa* L. 'Yellow Granex F1') were procured from a local vegetable market in Managua, Nicaragua. Before drying, the materials were sorted, washed, blotted off, hand-peeled (onion), seed removed (sweet pepper), 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).

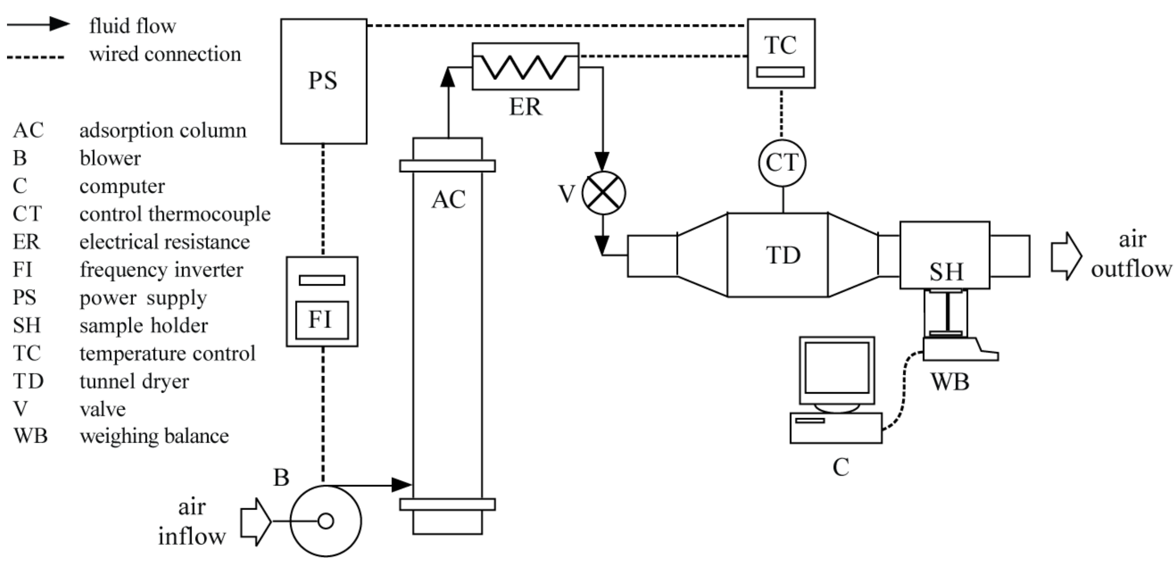

Fig. 1 A schematic diagram of the experimental drying system.

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 is an important phenomenon that appears during the drying of foods (e.g., fruits, vegetables). Shrinkage in ideal conditions is often defined as volume reduction equivalent to the volume of evaporated moisture (e.g., water) regardless of the drying methods used and thus the relationship between shrinkage and evaporated moisture content is linear as follows (Lozano *et al*., 1983):

$$\frac{V}{V_0} = a + b\left(\frac{X}{X_0}\right) \tag{4}$$

where V is the volume, and a and b are constants to be experimentally determined for each food material. The subscript 0 denotes the initial value. If the shrinkage in volume equals the volume of moisture lost by evaporation during all the stages of the drying, the change of the surface area with the shrinkage can be calculated as follows (Suzuki *et al*., 1976):

$$\frac{A}{A_0} = \left(\frac{V}{V_0}\right)^{2/3} \tag{5}$$

In this context, it was assumed that the shrinkage takes place equally in all directions and thus Eq. (5) enables us to consider 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:

$$\phi = \frac{X_i - X_{eq}}{X_{cr} - X_{eq}} \quad (6)$$

and

$$f = \frac{N_v}{N_w} \quad (7)$$

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 sweet pepper and yellow onion are shown in Figs. 2 and 3, respectively. The moisture content of the food samples 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 other words, the driving force for heat and mass transfer is enhanced at high temperatures, which results in a higher reduction of moisture content. As seen in Fig. 2, an increase in air velocity at 70 °C did not influence the drying process of sweet pepper. Similar behaviour was observed for yellow onion at 50 and 70 °C (see Fig. 3). These results are in good agreement with earlier observations (Bimbenet *et al*., 1984).

The correlation constants of Eq. (4) employed for calculating the volumetric shrinkage are shown in Table 1. In the scope of this study, Eq. (5) enables us to consider the shrinkage effect on the drying process of sweet pepper and yellow onion.

Table 1 Correlation constants and ANOVA of the linear model representing the volumetric shrinkage at various drying conditions (Mazza and Lemaguer, 1980; Kumar *et al*., 2019)

Material	*a*	*b*	R^2	*SSE*	*RMSE*
Yellow Onion	0.0936	0.9108	0.9971	0.0021	0.0153
Sweet Pepper	0.0600	0.8180	0.9050	0.5890	0.1180

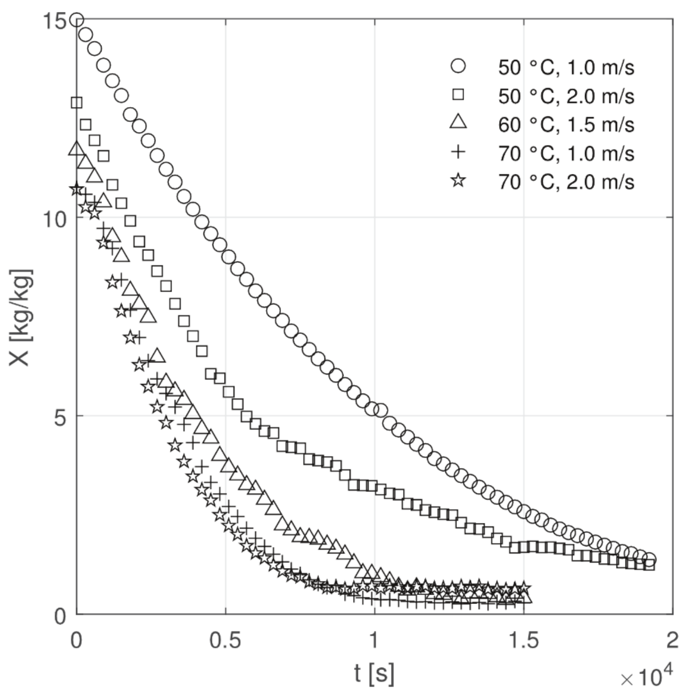

Fig. 2 Drying curves of sweet pepper at various temperatures and velocities.

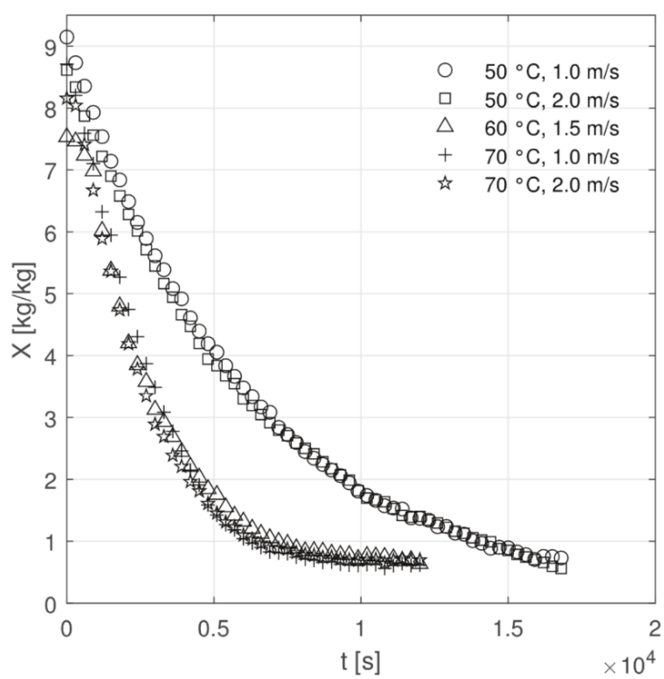

Fig. 3 Drying curves of yellow onion at various temperatures and velocities.

Drying rates were estimated based on Eqs. (3) to (5) and are shown in Figs. 4 and 5 for sweet pepper and yellow onion, 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.

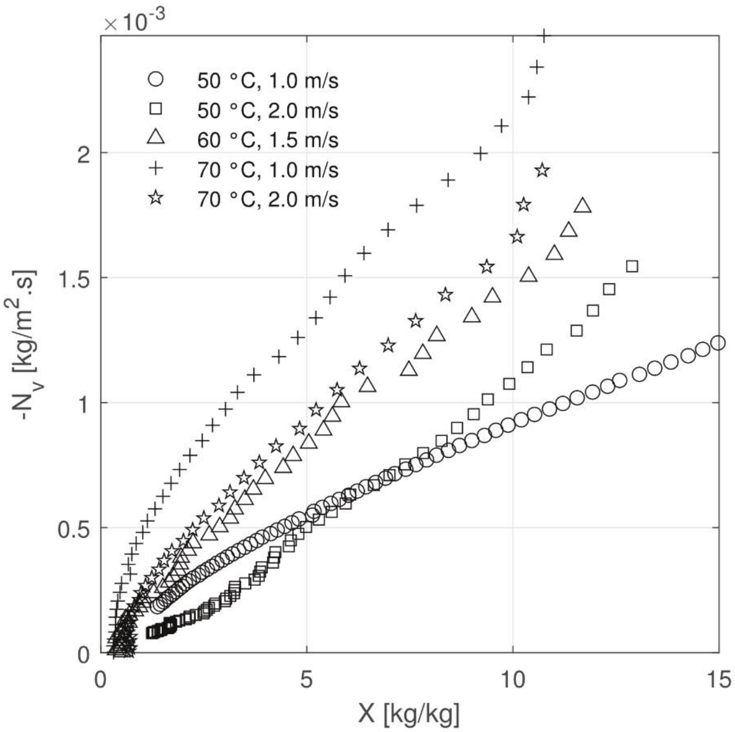

Fig. 4 Drying rate curves of sweet pepper at various temperatures and velocities.

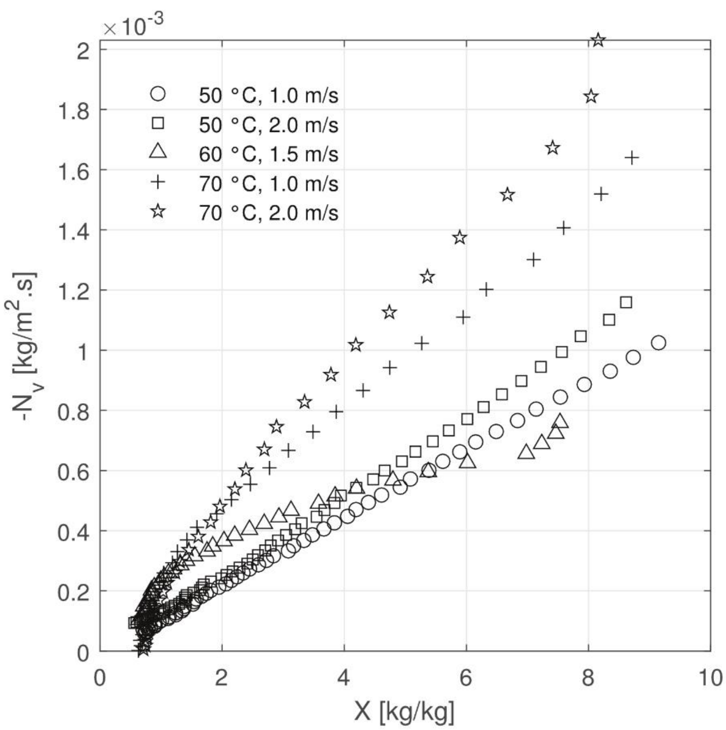

Fig. 5 Drying rate curves of yellow onion at various temperatures and velocities.

In addition, no constant rate period was observed in the drying of sweet pepper and yellow onion. The drying process took place in a falling rate period, which indicates that the moisture removal is controlled by diffusion inside the food samples. These results are in good agreement with earlier observations (Mazza and Lemaguer, 1980; Vega, 2008). Generally, the drying of most foods (namely, fruits and vegetables) is defined only by the falling rate period (Kiranoudis *et al*., 1992).

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 sweet pepper and yellow onion 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).

In Figs. (6) and (7), experimental drying data are plotted to represent $f = f(\phi)$ for sweet pepper and yellow onion, 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 sweet pepper and yellow onion characteristic drying curves.

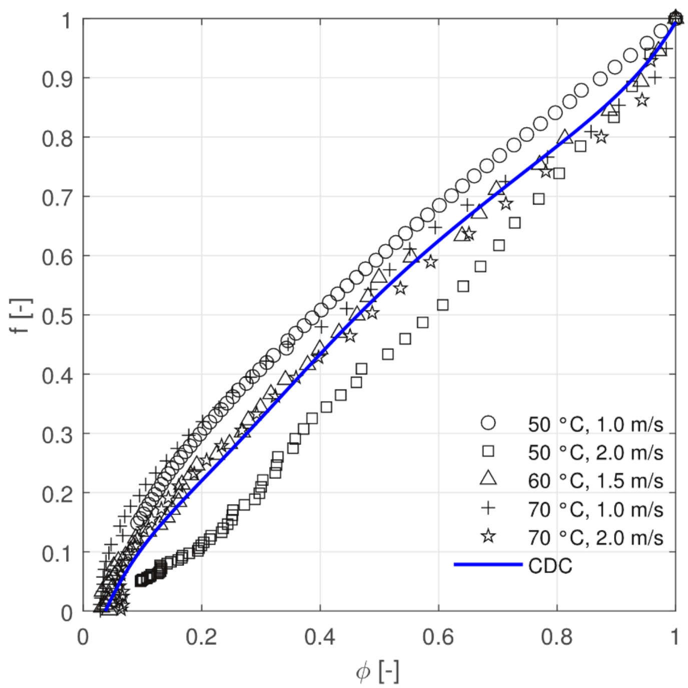

Fig. 6 Characteristic drying curve of sweet pepper.

For sweet pepper (*Capsicum annuum* L. 'Tres Cantos'):

$$f = 25.46\phi^7 - 99.89\phi^6 + 161.88\phi^5 - 137.80\phi^4 + 64.89\phi^3 - 16.67\phi^2 + 3.21\phi - 0.10 \quad (8)$$

For yellow onion (*Allium cepa* L. 'Yellow Granex F1'):

$$f = 188.59\phi^7 - 728.53\phi^6 + 1144.67\phi^5 - 939.35\phi^4 + 429.97\phi^3 - 108.50\phi^2 + 14.78\phi - 0.64 \quad (9)$$

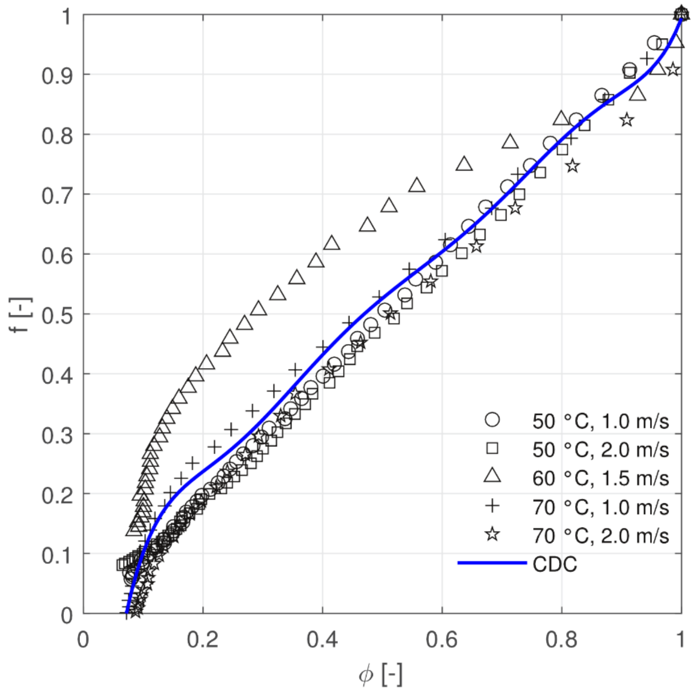

Fig. 7 Characteristic drying curve of yellow onion.

4. CONCLUSIONS

The drying kinetics of sweet pepper (*Capsicum annuum* L. 'Tres Cantos') and yellow onion (*Allium cepa* L. 'Yellow Granex F1') 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 volumetric shrinkage linear model from the literature was used to include the shrinkage effect on the drying process. The moisture content of the food samples 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 sweet pepper and yellow onion. The drying took place in a falling rate period, which indicates that the moisture removal is controlled by diffusion inside the sweet pepper and yellow onion. It was found that the changes in air velocity had essentially no effect on the drying process. In addition, a non-linear regression analysis was employed to determine the characteristic drying curve. The characteristic drying curve is extremely valuable in understanding idiosyncrasies associated with the drying of each unique food and can be used to facilitate dryer design and promote efficient dryer operation by simulation and optimisation of the drying process.

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_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	(-)
RMSE	Root-mean-square error	(-)
SSE	Sum of squared estimate of errors	(-)
t	Time	(s)
T	Temperature	(K)
V	Volume	(m^3)
X	Moisture content, dry basis	(kg kg^{-1})

Greek Letters

ϕ	Characteristic moisture content	(-)

Subscripts

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

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