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The Pharma Innovation

ISSN (E): 2277- 7695
ISSN (P): 2349-8242
NAAS Rating: 5.23
TPI 2022; SP-11(1): 1157-1159

www.thepharmajournal.com
Received: 28-11-2021
Accepted: 30-12-2021

Bhawna S Shirsat
Ph. D. Scholar, Department of Agril. Processing and Food Engg. SV, CAET & RS, FAE, IGKV, Raipur, Chhattisgarh, India

S Patel
Head, Department of Agril. Processing and Food Engg., SV CAET & RS, FAE, IGKV, Raipur, Chhattisgarh, India

PH Bakane
Associate Professor, Department of Agricultural Process Engineering, Dr. PDKV, Akola, Maharashtra, India

Corresponding Author
Bhawna S Shirsat
Ph. D. Scholar, Department of Agril. Processing and Food Engg. SV, CAET & RS, FAE, IGKV, Raipur, Chhattisgarh, India

Mathematical modeling of drying kinetics of ginger slices

Bhawna S Shirsat, S Patel and PH Bakane

Abstract
The aim of this study was to determine the best model for predicting the drying kinetics of osmotically dehydrated ginger (*Zingiber officinale*) slices. Ginger slices were osmotically dehydrated to remove the water followed by air drying single layer 3 mm, double layer 6 mm and triple layer 9 mm at different temperatures (40-70ºC) and air velocity (1.3m/s) in a convective dryer. In order to estimate and select the most appropriate drying model, four different models were applied to the experimental data and the results were compared. The goodness of fit was determined by using the coefficient of determination (R^2), reduced chi square (χ^2), and root mean square error (RMSE). Among the applied models, the Midilli model was the best model in explaining thin layer drying behavior of the osmotically dehydrated ginger slices in compared with other models based on the experimental temperature range.

Keywords: mathematical modelling, drying kinetics, ginger slices

Introduction
Ginger (*Zingiber officinale roscoe*) is a member of the Zingiberaceae family. It is widely used as antioxidant and spice for food and beverage [1, 2]. Zingiberaceae plant are widely cultivated in India, China, Malaysia, Thailand, Philippines, and Indonesia [3]. Drying is an important process to preserve agricultural products. The purpose of this process is to reduce the moisture content to a level that allows safe storage over an extended period [3]. Aromatic and medicinal plants, can be presented in two basic forms; namely fresh and dried. Dried form makes easier process of storage and transport in compared with fresh herbs. Therefore, it becomes the most popular way of preserving herbs [4]. Drying process influences the physicochemical and quality characteristic of products [6], thus, modeling of drying kinetic is one tool for process control. Evaluation of drying kinetics as a function of drying conditions can be drying simulation for predicting the suitable drying conditions. Moreover, many mathematical models have been used to describe the drying process of food products [7]. The present study was to determine the best model in predicting drying kinetics of osmo-dehydrated ginger slices using convective dryer.

Material and Methods
Experimental set-up for convective drying
A laboratory model convective tray dryer (Fig.1) was used to carry out the air drying experiments of osmotically dehydrated samples. The main components of the dryer are drying chamber, heating unit, and a fan.

These experimental trays were placed over the dryer trays in a single column. Osmotically dehydrated ginger slice samples (100 g) were loaded on each of the experimental trays and spread uniformly. The layer thickness of the ginger slices was kept as per the plan (single/double/triple layer). The ginger slices were uniformly spread over the tray so as to maintain the loading density of about 0.5 kg/

Drying chamber of dryer

Each experimental run was conducted with the osmotically dehydrated samples in the laboratory tray dryer at four different drying air temperatures (40, 50, 60 and 70 °C) and three bed thickness of single, double and triple layer i.e., the bed thickness were 3 mm, 6 mm, and 9 mm, respectively. The air velocity during drying was maintained constant (1.3 m/s) throughout the experiment.

Determination of characteristics Drying Curve

The moisture ratio (MR) at each moisture content level was determined by the following equation (Zarein *et al.* 2015):

$$MR = \frac{M - M_\infty}{M_o - M_\infty} \quad ...(1)$$

Where, MR is the moisture ratio, M is the moisture content at any time (%), M_o is the initial moisture content (%) and M_∞ is the equilibrium moisture content (%). Subsequently, plot data MR versus time was done to obtain the curve.

Selection of the Appropriate Model

The experimental drying curves were fitted to three models with different moisture ratio equations (Table 1).

Table 1: Mathematical models used for osmo-dehydrated ginger drying study

Model Name	Model Equation
Page	$MR = \exp(-kt^n)$
Midilli Kucuk	$MR = a\exp(-kt^n) + bt$
Modified Page	$MR = \text{Exp}(-(kt)^n)$
Approximation Diffusion (Two-term exponential)	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$

a, b, k and n = model coefficients, t = drying time, min

To determine the suitability of the model on the drying process, three statistical parameters were tested on the obtained data, i.e. the coefficient of determination (R^2), root mean square error (RMSE), and chi-square (χ^2). The most suitable model is the model that has the highest R^2 value and the lowest RMSE and χ^2 values. These three parameters can be calculated through the following equation [2, 3, 4]:

$$R^2 = \frac{\left[\sum_{i=1}^{N}(MR_{exp,i} - MR_{exp})(MR_{pre,i} - MR_{pre})\right]}{\sum_{i=1}^{N}(MR_{exp,i} - MR_{exp})^2 \sum_{i=1}^{N}(MR_{pre,i} - MR_{pre})^2} \quad \ldots (2)$$

$$E_{RMS} = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2\right]^{1/2} \quad \ldots (3)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N - z} \quad \ldots (4)$$

Results and Discussion

To describe the drying data obtained while drying of osmo-dehydrated ginger slices through different set of experiments, some of the well-known models were used. The moisture ratio (MR) calculated from the moisture content of samples during drying were fitted to the four different drying models (Page, Midilli Kucuk, Modified Page, and Approximation diffusion) given in Table 2. The obtained statistical regression results including the drying model coefficients are given in Table 2. The comparison criteria used to evaluate goodness of fit, including highest values of R^2, the lowest value of reduced mean square of the deviation χ^2 and root mean square error, RSME of osmo-convectively dried ginger slices which were calculated using Eqn. (2) through Eqn. (4) are also presented.

The values of coefficients and statistical parameters obtained for four different temperatures (40, 50, 60, and 70 °C) and three sample layer thicknesses (3, 6 and 9 mm) are summarized in Table 2. For all the models, the value of R^2 varied from 0.984 to 0.996, indicating a good fit. Model developed by Midilli *et al.* (2002) gives the highest R^2 value and lowest RMSE value for all the temperatures and thicknesses. R^2 and χ^2, RMSE values for Midilli *et al.* (2002) model were 0.996 and 0.0003, 0.0059, respectively

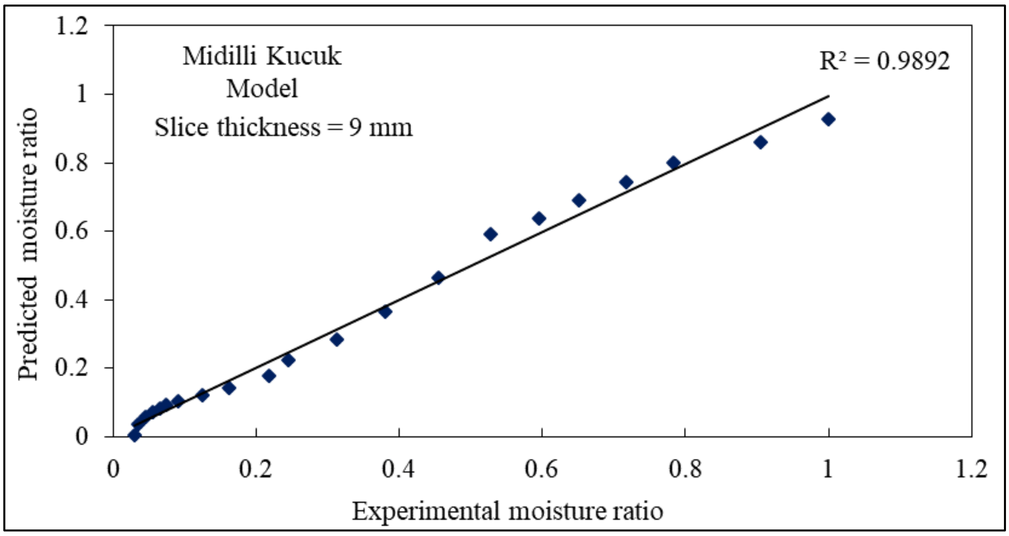

Fig 3: Comparison of experimental and predicted moisture ratios using Midilli Kucuk model for the ginger layer thickness of 9 mm at various temperatures

Conclusions

This study revealed that the Midilli Kucuk model is the best model for representing the drying kinetic of osmo-dehydrated ginger slices using convective dryer.

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