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DETERMINATION OF SUITABLE THIN-LAYER DRYING MODELS FOR BREWER'S YEAST (*Saccharomyces cerevisiae*)

DETERMINACIÓN DE MODELOS DE SECADO EN CAPA DELGADA PARA LA LEVADURA CERVECERA (*Saccharomyces cerevisiae*)

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ABSTRACT

Mathematical models of thin-layer drying for brewer's yeast (*Saccharomyces cerevisiae*) were studied and verified with experimental data. Twelve (12) different mathematical drying models were compared according to three (3) statistical parameters, i.e., correlation coefficient, root mean square error and chi (χ^2)-square. The thin-layer drying kinetics of brewer's yeast was experimentally investigated in a laboratory tunnel dryer and the mathematical modelling, using thin-layer drying models present in the literature, was performed. Experiments were performed at air temperature of 40, 50 and 60 ºC at an airflow rate of 1.2 m/s. Drying curves obtained from the experimental data were fitted to the thin-layer drying models. The results show that the Page model is the most appropriate model for predicting the drying behaviour of the thin-layer brewer's yeast.

Keywords: Brewer's yeast; Thin-layer drying; Drying modelling; Multiple regressions

RESUMEN

Modelos matemáticos del secado en capa delgada para la levadura cervecera (*Saccharomyces cerevisiae*) fueron estudiados y verificados con datos experimentales. Doce (12) diferentes modelos matemáticos de secado fueron comparados de acuerdo a tres parámetros estadísticos, i.e., coeficiente de correlación, error de la raíz cuadrada de la media y chi (χ^2)-cuadrado. La cinética de secado en capa delgada de la levadura cervecera fue experimentalmente estudiada en un secador de túnel de laboratorio y la modelación matemática, usando los modelos de secado en capa delgada presente en la literatura, fue realizada. Los experimentos se realizaron a una temperatura de secado de 40, 50 y 60 ºC y a una velocidad de aire de 1.2 m/s. Las curvas de secado obtenidas de los datos experimentales fueron ajustadas a los modelos de secado en capa delgada. Los resultados muestran que el modelo de Page es el modelo más apropiado para predecir el comportamiento de secado en capa delgada de la levadura cervecera.

Palabras clave: Levadura cervecera; Secado en capa delgada; Modelado del secado; Regresiones múltiples

INTRODUCTION

When brewing beer, yeast (*Saccharomyces cerevisiae*) is produced as a by-product. This product is usually treated as waste. Brewer's yeast, however, contains valuable ingredients, such as amino acids, proteins and minerals. These ingredients can be re-used in several food products. For instance, people has been used brewer's yeast to make medicine. Brewer's yeast is a source of B vitamins and protein. Thanks to its dietetic and probiotic properties as well as to the presence of high quality, easily available proteins, natural vitamins (mainly of group B) and amino acids necessary for the animals to grow (lysine, methionine, threonine, cystine, tryptophan), dried brewer's yeast is one of the most valuable natural products used in animal feeding.

Due to the high sensitivity of most biological materials to high temperatures and water activities, such as brewer's yeast, its preservation is a challenge in the related industries. It is necessary to maintain its activities over a period of time in order to prolong its shelf life. During thermal drying, the yeast may undergo numerous changes, such as destruction of cell membranes, denaturation of proteins or enzymes, or even death (Adamiec *et al*., 1995).

Drying is commonly used in chemical, food and pharmaceutical industries, and it is defined as a process to reduce the moisture content and prolong shelf life of products. Biological products are especially very sensitive to drying processes. The whole changes that is either wanted or unwanted, may affect product quality. The drying characteristics of brewer's yeast have been examined by many researchers and various models for the prediction of drying rate have been performed with moderate success (Luna-Solano *et al*., 2005). Different industrial dryers are available in industries; in which fluidised bed dryers with batch or continuous operations are widely used for industrial drying of yeast (Hovmand, 1995).

Bayrock and Ingledew (1997a) studied drying of compressed *S. cerevisiae* in a fluidised bed dryer as well as its exposure to moist heat in classical thermal death time experiments. They reported that dehydration (not moist heat, dry heat, or oxidation) was responsible for viability decreases during the fluidised bed drying. It was also determined that the viability decreased sharply in the falling-rate drying period. However, it is difficult to develop an accurate model for the process. For a more predictive model, diffusive transport limitation of moisture inside the granules should be considered. It requires mathematical description of the distribution of moisture and temperature inside the granules.

Bayrock and Ingledew (1997b) also studied the effects of moisture levels, drying rates and yeast cell viabilities for two commercial compressed yeasts dried in a modified fluidised bed dryer. They found that death mechanisms for fluidised bed drying appear to be quite different from that reported for spray drying.

Mathematical modelling of drying is crucial for the optimisation of operating parameters and performance improvements of the drying systems. In order to simulate drying, some researchers have used a liquid diffusion model, based on the assumption that the moisture transfer from the solids is in the liquid phase (Mujumdar, 2007). However, this modelling type is complex and not suitable for practical aims. Most researchers have performed empirical or semi-empirical models for simulation of drying, given in Table 1. The primary advantage of empirical or semi-empirical models in drying simulations is their easiness to apply. Most of the models in Table 1 are derived by simplifying the general solutions of the Fick's second law or the modification of the simplified models. Therefore, most of them are not arbitrarily chosen models; on the contrary, they are based on the physiological bases (Erbay and Icier, 2009).

The purpose of this study was to investigate the suitability of several empirical and semi-empirical models available in the literature in defining the thin-layer drying behaviour of brewer's yeast (*S. cerevisiae*).

MATERIALS AND METHODS

Material

Yeast used in the experiments was spent brewer's yeast *Saccharomyces cerevisiae* obtained as a by-product of lager production. It was provided as slurry from Compañía Cervecera de Nicaragua, S.A., Managua, Nicaragua. After collection from fermentation vessel at the end of the 5th fermentation, it was brought to laboratory as soon as possible for experiments.

The spent yeast slurry obtained from the brewery consisted of thick, viscous cream-like slurry of 54 % total solids. The slurry was gently mixed and stirred for 15 minutes to obtain a homogenous consistency of solids. Then, the yeast slurry was filtered at 83 kPa using a laboratory vacuum pump over a period of about 30 minutes or until the sample was completely filtered. The moisture content of the resulting yeast cake was 72 % on a wet basis (Picado *et al*., 2006).

Experimental apparatus

A schematic arrangement of the experimental apparatus is shown in Fig. 1. The equipment may be divided into four main sections as follows: gas supply and dehumidification section, heating section, drying chamber, and analysing equipment. The blower (B) supplies a gas flow--a broad range of flow rates are possible by changing the rpm setting through the frequency inverter (FI). The air passes through an adsorption column (AC) containing a dehumidificant (silica gel) to obtain a process air of low humidity content (less than 1.0 % relative humidity) measured by a hygrometer. The air velocity is measured by an anemometer. After dehumidification, the air is pre-heated with electrical resistance (ER) heaters of up to 2 kW each. Temperature is controlled by means of a temperature controller (TC) that supplies heat by means of an electrical resistance heater as its final control element. Before entering the drying chamber, a static mixer homogenises temperature by mixing the gas. The sample is put in a sample holder (SH) inside the drying chamber and is supported on a weighing balance (WB) through an oil-sealed shaft. The cross-sectional area and depth of sample holder are 30.65 mm× 109.8 mm and 3 mm, respectively. The drying chamber has a uniform cross-sectional area of 90 mm× 110 mm. The sample's weight history is recorded on a computer (C). It is possible to take a reading every 12 seconds.

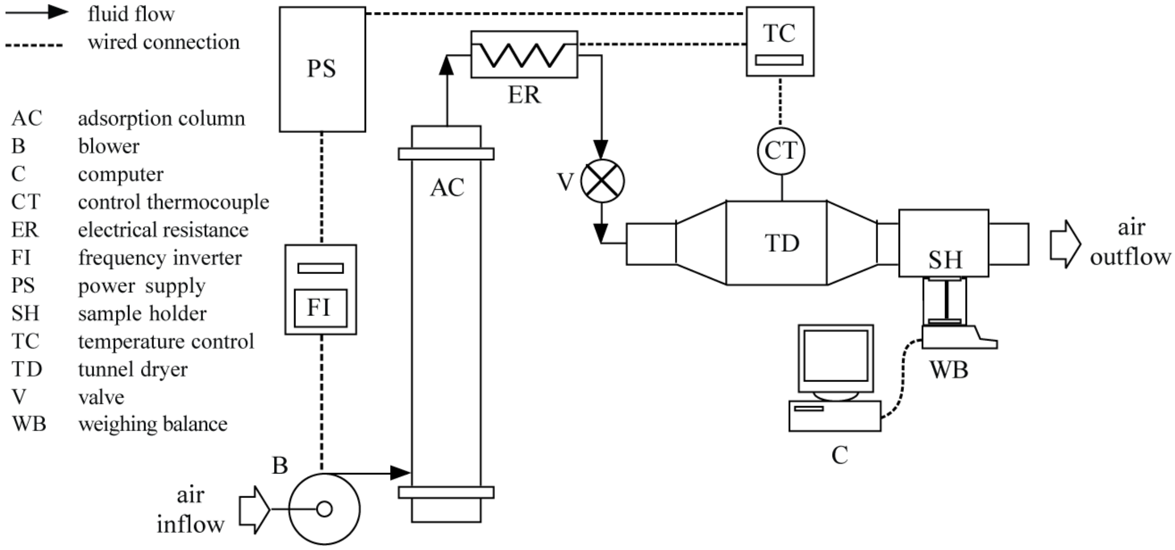

Fig. 1 A schematic diagram of a tunnel drying system.

Experimental procedure

The experiments were performed at an airflow rate of 1.2 m/s and at three different temperatures: 40, 50 and 60 °C. Before starting an experiment, the apparatus was run for at least half an hour to obtain steady-state conditions. The sample was loaded evenly in the sample holder, which covered the whole drying area as a thin-layer. The sample holder was put into the tunner dryer. The drying time and mass of the sample were recorded. The test was stopped until the mass was invariable. After drying by the apparatus 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 the drying kinetics.

Mathematical modelling of drying curves

The moisture content of drying sample at time *t* can be transformed to be moisture ratio (*MR*):

$$X_i = \frac{m_i - m_s}{m_s} \tag{1}$$

$$MR = \frac{X_i - X_e}{X_0 - X_e} \tag{2}$$

where X_i, m_i and m_s are moisture content at any time (kg water/kg dry matter), mass of a sample at any time (kg) and oven-dry mass of sample (kg), respectively; MR, X_0 and X_e are moisture ratio (dimensionless), initial moisture content (kg water/kg dry matter) and equilibrium moisture content (kg water/kg dry matter), respectively. The drying data obtained were fitted to twelve (12) thin-layer drying models detailed in Table 1 using the non-linear least square regression analysis. Regression analysis was performed using Matlab's Curve Fitting Toolbox. Generally, the correlation coefficient (*r*) is the primary criterion for selecting the best model to describe the drying curve equation and the highest *r* value is required. In addition to *r*, the root mean square error (RMSE) and chi square (χ^2) are used to determine the best fit. The highest *r* and the lowest χ^2 and RMSE values required to evaluate the goodness of fit. These statistical values can be calculated as follows:

$$r = \frac{N\sum_{i=1}^{N} MR_{pred,i}\, MR_{\exp,i} - \sum_{i=1}^{N} MR_{pred,i} \sum_{i=1}^{N} MR_{\exp,i}}{\sqrt{\left(N\sum_{i=1}^{N} MR^2_{pred,i} - \left(\sum_{i=1}^{N} MR_{pred,i}\right)^2\right)\left(N\sum_{i=1}^{N} MR^2_{\exp,i} - \left(\sum_{i=1}^{N} MR_{\exp,i}\right)^2\right)}} \tag{3}$$

$$\chi^2 = \left[\sum_{i=1}^{N} \left(MR_{\exp,i} - MR_{pred,i}\right)^2\right](N-n)^{-1} \tag{4}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N} \left(MR_{\exp,i} - MR_{pred,i}\right)^2\right]^{1/2} \tag{5}$$

where $MR_{exp,i}$ is the *i*th experimental moisture ratio, $MR_{pred,i}$ is the *i*th predicted moisture ratio, *N* is the number of observations and *n* is the number of constants within the drying model.

Table 1 Thin-layer drying models (Erbay and Icier, 2009).

Number	Model	Model equation
1	Lewis	$MR = \exp(-kt)$
2	Page	$MR = \exp(-kt^n)$
3	Modified Page	$MR = \exp(-kt)^n$
4	Henderson & Pabis	$MR = a\exp(-kt)$
5	Logarithmic	$MR = a\exp(-kt) + c$
6	Two-term	$MR = a\exp(-k_1 t) + b\exp(-k_2 t)$
7	Two-term exponential	$MR = a\exp(-kt) + (1-a)\exp(-kat)$
8	Diffusion approach	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$
9	Verma	$MR = a\exp(-kt) + (1-a)\exp(-gt)$
10	Modified Henderson & Pabis	$MR = a\exp(-kt) + b\exp(-gt) + c\exp(-ht)$
11	Demir	$MR = a\exp\left[(-kt)^n\right] + b$
12	Weibull	$MR = \exp\left[-\left(\frac{t}{a}\right)^b\right]$

Model constants can be obtained by performing multiple regression analysis. These drying models are relatively easy to use in multiple regression analysis, because they could be linearised. However, some models must be solved with nonlinear regression techniques and it is too hard to find the solutions to such nonlinear models if there are many constants.

RESULTS AND DISCUSSION

Curve fitting computations have been carried-out on the twelve (12) drying models relating the drying time and moisture ratio with the experimental condition for drying temperatures of 40, 50 and 60 °C and an airflow rate of 1.2 m/s. The results of statistical analysis on them are given in Tables 2-4. The acceptability of the drying model has been based on a value for the correlation coefficient that should be close to one, and low values for RMSE and χ^2.

According to this evaluation, the most suitable model in describing drying process of thin-layer brewer's yeast is the Page model. The Page model exhibits a better suitability with the experimental data not only because of the lower number of coefficients, but also due to the form of the model equation.

Table 2 Results of statistical analysis for the drying temperature T = 40 °C.

Model	Coefficients	*r*	*RMSE*	χ2
Lewis	k = 6.899 E-5	0.9947	2.65 E-2	7.02 E-4
Page	k = 6.983 E-6, n = 1.234	0.9997	6.29 E-3	3.96 E-5

Modified Page	k = 6.128 E-5, n = 1.126	0.9947	2.65 E-2	7.04 E-4
Henderson-Pabis	a = 1.079, k = 7.402 E-5	0.9968	2.07 E-2	4.28 E-4
Logarithmic	a = 1.083, k = 7.039 E-5, c = -0.0154	0.9975	1.83 E-2	3.33 E-4
Two-term	a = 0.8815, k_1 = 7.402 E-5, b = 0.1976, k_2 = 7.399 E-5	0.9968	2.07 E-2	4.31 E-4
Two-term exponential	a = 1.779, k = 9.446 E-5	0.9996	7.06 E-3	4.98 E-5
Diffusion Approach	a = 1.30, k = 5.644 E-5, b = 0.536	0.9972	1.93 E-2	3.72 E-4
Verma	a = 1.60, k = 9.134 E-5, g = 1.82 E-4	0.9995	7.69 E-3	5.92 E-5
Modified Henderson-Pabis	a = 1.113, k = 7.601 E-5, b = 6.161 E-6, g = 1.445 E-4, c = -0.1494, h = 7.601 E-5	0.9978	1.72 E-2	2.95 E-4
Demir	a = 1.079, k = 7.11 E-3, n = 1.041 E-2, b = 5.522 E-6	0.9968	2.07 E-2	4.31 E-4
Weibull	a = 1.511 E+4, b = 1.233	0.9997	6.29 E-3	3.96 E-5

Table 3 Results of statistical analysis for the drying temperature T = 50 °C.

Model	**Coefficients**	***r***	***RMSE***	**χ2**
Lewis	k = 9.628 E-5	0.9999	3.37 E-3	1.13 E-5
Page	k = 9.562 E-5, n = 1.001	0.9999	3.37 E-3	1.14 E-5
Modified Page	k = 9.628 E-5, n = 1.001	0.9999	3.37 E-3	1.14 E-5
Henderson-Pabis	a = 1.003, k = 9.654 E-5	0.9999	3.34 E-3	1.11 E-5
Logarithmic	a = 1.003, k = 9.755 E-5, c = 2.65 E-3	0.9999	2.82 E-3	7.95 E-6
Two-term	a = 0.01501, k_1 = 2.896 E-5, b = 0.9919, k_2 = 9.899 E-5	0.9999	2.68 E-3	7.20 E-6
Two-term exponential	a = 0.001352, k = 7.113 E-2	0.9999	3.42 E-3	1.17 E-5
Diffusion Approach	a = 1.125 E-3, k = 6.907 E-3, b = 0.01392	0.9999	3.42 E-3	1.17 E-5
Verma	a = 1.092 E-3, k = 2.064 E-2, g = 9.618 E-5	0.9999	3.42 E-3	1.17 E-5
Modified Henderson-Pabis	a = 0.1383, k = 1.321 E-4, b = 0.8679, g = 9.262 E-5, c = -9.946 E-4, h = 6.855 E-4	0.9999	3.16 E-3	9.98 E-6
Demir	a = 1.003, k = 9.749 E-5, n = 1.001, b = 2.751 E-3	0.9999	2.83 E-3	3.35 E-4
Weibull	a = 1.039 E+4, b = 1.001	0.9999	3.37 E-3	1.14 E-5

Table 4 Results of statistical analysis for the drying temperature T = 60 °C.

Model	**Coefficients**	***r***	***RMSE***	$\chi 2$
Lewis	k = 1.407 E-4	0.9917	3.65 E-2	1.33 E-3
Page	k = 1.758 E-5, n = 1.228	0.9977	1.93 E-2	3.71 E-4
Modified Page	k = 1.383 E-4, n = 1.017	0.9917	3.66 E-2	1.34 E-3
Henderson-Pabis	a = 1.067, k = 1.494 E-4	0.9937	3.22 E-2	1.03 E-3
Logarithmic	a = 1.094, k = 1.251 E-4, c = - 6.181 E-2	0.9975	2.01 E-2	4.06 E-4
Two-term	a = 1.067, k_1 = 1.494 E-4, b = 0.1794, k_2 = 11.14	0.9937	3.24 E-2	1.05 E-3
Two-term exponential	a = 1.748, k = 1.889 E-4	0.9974	2.04 E-2	4.17 E-4
Diffusion Approach	a =17.6, k = 8.012 E-5, b = 0.9678	0.9980	1.79 E-2	3.21 E-4
Verma	a = 19.24, k = 2.311 E-4, g = 2.39 E-4	0.9978	1.89 E-2	3.58 E-4
Modified Henderson-Pabis	a = 1.067, k = 1.494 E-4, b = 0.1794, g = 9.482, c = 0.9869, h = 3.734	0.9937	3.26 E-2	1.06 E-3
Demir	a = 1.093, k = 2.061 E-4, n = 0.6065, b = - 0.0617	0.9975	2.02 E-2	4.08 E-4
Weibull	a = 7431, b = 1.228	0.9977	1.93 E-2	3.71 E-4

The Page model is the modification of the Lewis model by adding a dimensionless empirical constant (n) to get a more accurate model. Generally, n is named as the model constant.

The results of the statistical analyses also show that the second most accurate models among the two (2) parameters are the two-term exponential and Weibull models, and among the three (3) parameter models the Verma model. All of these models are semi-empical models based on the solution of liquid diffusion equation. The worst fit in this study belongs to the Lewis and modified Page models.

A thin-layer drying curve based on the Page model is presented along with the experimental data in Fig. 2 at a temperature of 60 °C and an airflow rate of 1.2 m/s. There is no constant rate of drying period in this curve and the entire drying process occurred in the falling-rate period. These results are in good agreement with earlier observations (Picado *et al*., 2006).

For all drying conditions, great amount of moisture is removed in duration of first 1-2 hours of drying. The moisture removal from thin-layer brewer’s yeast slows down gradually and, after first 4 h, moisture content of the brewer’s yeast gets closer towards the equilibrium moisture content.

Validation of the Page model has also been confirmed in this study by comparing the predicted moisture ratios to the experimental values at a temperature of 50 °C, see Fig. 3. The predicted data is banded around the straight line that showed the suitability of the Page model in describing the drying behaviour of the thin-layer brewer’s yeast.

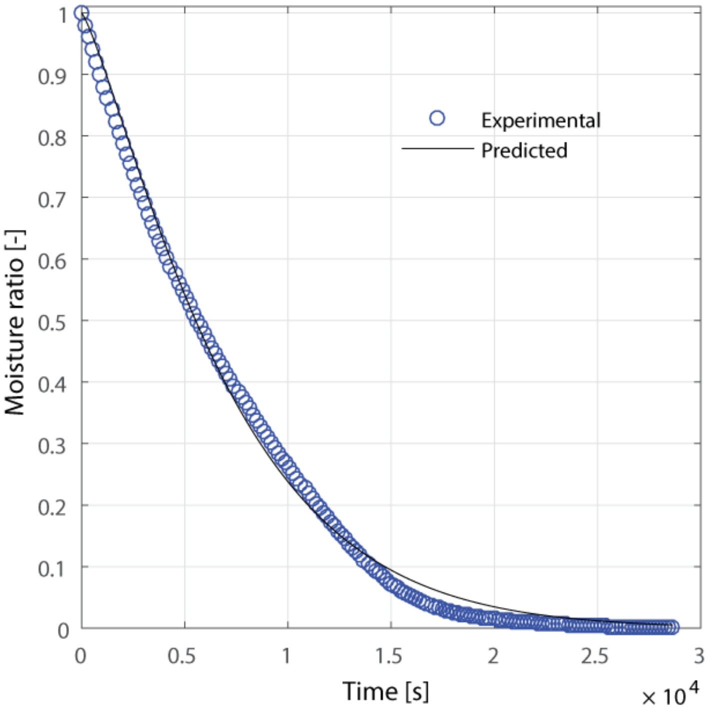

Fig. 2 Comparison between experimental and predicted moisture ratio with respect to time (s) at a temperature of 60 °C and an airflow rate of 1.2 m/s.

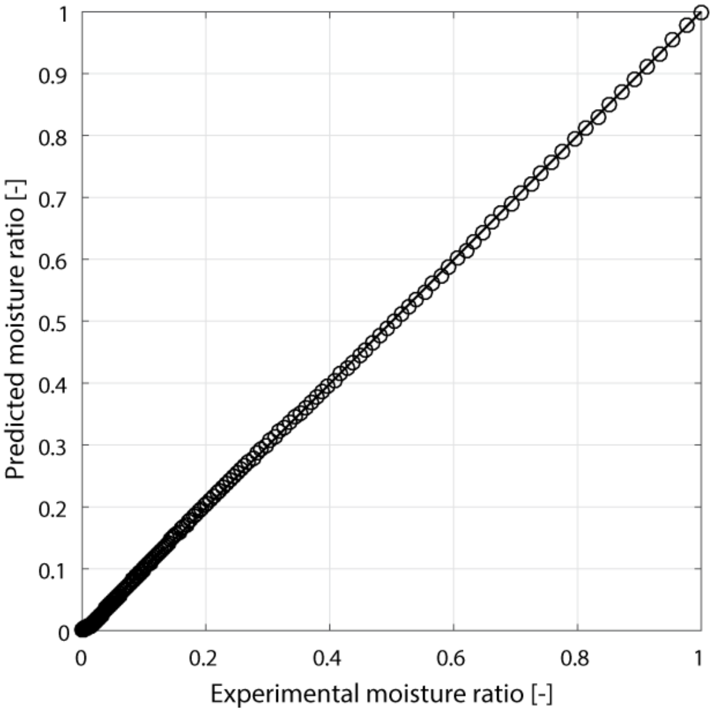

Fig. 3 Comparison of the experimental and predicted moisture ratios at a temperature of 50 °C and an airflow rate of 1.2 m/s.

As it is generally difficult and complex to obtain the analytical solution of the liquid diffusion equation, it is mostly empirical and semi-empirical models are used for this purpose. Moreover, the most of these models are simplified versions or modified version of simplied versions of the solution of liquid diffusion equation. Therefore, these models are acceptable for the purpose of simulation of drying thin-layer brewer's yeast.

CONCLUSIONS

In this study, suitability of twelve (12) drying models in defining thin-layer drying behaviour of brewer's yeast has been examined by using statistical analysis. For this purpose, drying models have been fitted to experimental data by means of the coefficients within the models for the drying air temperatures of 40, 50, and 60 °C and at an airflow rate of 1.2 m/s. The results show that the Page model is the most appropriate model for drying behaviour of thin-layer brewer's yeast (*Saccharomyces cerevisiae*).

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