This paper presents a comprehensive review of thin-layer drying-curve models available in the literature and their comparisons for single-layer drying applications from 2003 to 2013. In this regard, a total of 67 models are selected and classified under 28 performance assessment criteria for comparison purposes. These models are then evaluated by considering the following parameters: (1) product type; (2) pretreatment type; (3) drying parameters, such as temperature, air velocity, layer thickness, microwave power levels, amount of solar radiation, vacuum pressure, frequency of sound wave, excitation amplitude, relative humidity, bed depth, product shape, pH, salt content, absolute pressure, etc.; and (4) drying method employed. Furthermore, the best models obtained are employed for product drying applications and compared for different drying methods, drying parameters, and dried products.

**Keywords** Drying; Drying models; Food; Performance evaluation; Thin layer

**INTRODUCTION**

Drying is recognized as a crucial unit operation to dry out moist bodies by removing their moisture and reducing their moisture content to desired levels through diffusion within the body and evaporation from the surface. It is, at the same time, known as one of the oldest and most common forms of food preservation methods. Its use, over centuries, has been extended to various sectors, ranging from the pharmaceutical to lumber industries. Its use, over centuries, has been extended to various sectors, ranging from the pharmaceutical to lumber industries. It is of paramount importance to develop appropriate models to study the behavior of drying processes and their transport phenomena, including moisture diffusion and evaporation.

The models developed in the literature are used for designing new drying systems as well as selection of optimum drying conditions and for accurate prediction of simultaneous heat and mass transfer phenomena during the drying process.\[1-390\]

Under these considerations, based on the experimental data taken from the thin-layer drying experiments, the thin-layer drying curve models can be applied in the case of (i) a single product exposed to the drying air or one layer of the grains and (ii) a multilayer of many grain thicknesses if the temperature and the relative humidity of the drying air can be applied for drying process calculations as being in the same thermodynamic state at any time of the drying process. It is then important to emphasize that the thickness of a thin layer can go up if the velocity of drying air rises and also if the thermodynamic state of the drying air approaches the equilibrium state in heat and mass transfer with grain dried in this layer.\[390\] As a result, such mathematical models appear to be useful tools for the prediction of drying kinetics of heat-sensitive bio-origin materials.\[112\] The drying curves can be processed for drying rates to find the most convenient model for the drying process under given conditions.\[76\] The principle of modeling is based on having a set of mathematical equations that are detailed and simplified enough that they can adequately characterize the system.\[46\] Comprehensive models use simultaneous heat and mass transfer equations with variable food properties and shrinkage and these equations are a system of two nonlinear, coupled partial differential equations.\[46\] The thin-layer equations have been used to estimate drying times of several products and to generalize drying curves. In the development of thin-layer drying models for agricultural products, the moisture content of the material at any time after it has been subjected to a constant relative humidity and temperature conditions is generally measured and correlated to the drying parameters.\[1\]

In addition, they are absolutely required to select and evaluate the appropriate drying technique for a specific product. These procedures help the producer understand whether or not high-quality products are produced during the thin-layer drying process and if the efficiency of the thin-layer drying system increases. Although modeling studies in thin-layer drying are important, there is no theoretical model which is both practical and can unify the calculations. Therefore, experimental studies are important in thin-layer drying and thin-layer drying equations are...
important tools in the mathematical modeling of drying. They are practical and give sufficiently good results.\cite{200}
For every dryer, the process conditions—such as the drying chamber temperature, pressure, air velocity (if the carrier gas is air), relative humidity, and the product retention time—have to be determined according to feed, product, purpose, and method.\cite{200} Considering all these parameters, the designers who want to establish and construct a thin-layer dryer should take into account the experimental results collected from the thin-layer experiments. Accordingly, this will provide improved performance of thin-layer dryers and increase the efficiency of the thin-layer drying process while minimizing the harmful effects that reduce product quality as well as the drying behavior of the process. It should be emphasized that the experimental data collected incorrectly from thin-layer drying experiments will affect the system’s performance and process efficiency as well as the selection of the best model to describe thin-layer drying behavior. The selection of the best model is a very important procedure describing the behavior of the thin-layer drying process. However, before selecting the best model, the researchers should precisely and accurately perform experimental studies and measure the parameters correctly using devices with high accuracy, and collect the experimental data in a reliable way. Before the researchers use the experimental data in the calculations of the parameters in the thin-layer drying curve models, they should check the raw data in terms of the uncertainty analysis. It is observed that most of the researchers in the area of drying technologies have not applied an uncertainty analysis to their experimental studies. This is a really important lack in the modeling and analysis of thin-layer drying processes. Accordingly, the uncertainty analysis should be taken into consideration not only in the modeling and analysis of the thin-layer drying processes, but also in designing and performing cost analysis of the thin-layer dryers.

In this article, we aim to review the potential thin-layer drying-curve models available in the literature and compare them for single-layer drying applications from 2003 to 2013. We identify 67 potential models and classify and compare them under 28 performance assessment criteria. We also aim to evaluate these models by considering the following parameters: (1) product type; (2) pretreatment of the product; (3) drying parameters, such as temperature, air velocity, layer thickness, microwave power levels, amount of solar radiation, vacuum pressure, frequency of the sound wave, excitation amplitude, relative humidity, bed depth, product shape, pH, salt content, absolute pressures, etc.; and (4) drying method employed.

THIN-LAYER DRYING-CURVE MODELS

It is generally noted that, in terms of the comparative evaluation of the advantages and disadvantages of thin-layer drying models, the curve models used for thin-layer drying are mainly theoretical, semi-theoretical, and empirical types. The most widely used theoretical models are derived from Fick’s second law of diffusion. Similarly, semi-theoretical models are generally derived from Fick’s second law and modifications of its simplified forms (other semi-theoretical models are derived by analogues with Newton’s law of cooling). They are easier and need fewer assumptions due to their use of some experimental data.\cite{200} The empirical models also have similar characteristics to semi-theoretical models. They strongly depend on the experimental conditions and give limited information about the drying behaviors of the product.\cite{200} The empirical method is based on experimental data and dimensional analysis. They are easily applied to drying simulation, as they depend on experimental data.\cite{1} The theoretical method takes into account not only the external conditions, but also the mechanism of internal movement of moisture and the consequent effects.\cite{46} The semi-theoretical and empirical models consider only the external resistance to moisture transfer between the product and air.\cite{3,62} Accordingly, the solution of Fick’s second law is used widely as a theoretical model in thin-layer drying of food products. Semi-theoretical models are only valid under the drying and product conditions for which these models were developed. Empirical models are used for the water absorption process as well as the single-layer drying process, which can adequately describe the drying kinetics.\cite{204} Under these considerations, it can be said that the complexity of the models are mainly based on the number of constants. According to the open literature, the number of the model constants varies between one constant (e.g., see Newton model) and six constants (e.g., see Modified Henderson and Pabis Model, and Multiple Multiplicative Factor (MMF)) (see Table S1, available online in the Supplementary Material). When the number of model constant is taking into consideration, the Newton model with one constant is the simplest model, and the Modified Henderson and Pabis model and Multiple Multiplicative Factor (MMF) are the most complex models. In the literature,\cite{47,59,123,152,182} it is seen that Newton model was found to be the most suitable thin layer curve equation (see Table S3, available online). On the other hand, the Modified Henderson and Pabis model was determined to be the best model in the literature,\cite{2,73,95,130,141,195,213,293,322,330,348,351} while the Multiple Multiplicative Factor (MMF) was not designated as a most suitable model (see Table S3). As understood from these explanations, it is impossible to select the model describing the thin-layer drying curve by taking into consideration the number of the model constants. That is, the number of the model constants is not a selection criterion for determination of the best model indicating the drying behavior of the products. However, it is expected
that the model should give accurate results for optimization of drying behavior and conditions of the products. When the thin-layer drying curve models in the literature are taken into consideration, it is observed that the Midilli-Kucuk model with four constants is mostly found to be the most suitable model for thin-layer drying processes. In addition, the following thin-layer drying curve models have been commonly selected to be the most suitable models: the Page model (with two constants), the Logarithmic model (with three constants), the two-term model (with four constants), the Wang and Singh model (with two constants), the approximation of diffusion model (with three constants), the Modified Henderson and Pabis model (with six constants), the Modified Page model (with two constants), the Henderson and Pabis model (with two constants), the two-term exponential model (with two constants), the Verma et al. model (with three constants), and the Weibull model (with two-four constants) (see Table S3).

MODEL SELECTION AND ASSESSMENT

In the thin-layer drying method, sensible heat from heated air is transferred to wet products by convection. Heated air is ventilated through the thin layer of the wet material and carries with it the water vapor evaporated from the material. Researchers have developed numerous thin-layer drying models for various agricultural products (see Table S1). Thin-layer drying generally means to dry as a single layer of sample particles or slices. Because of this thin structure, the temperature distribution can be easily assumed to be uniform and thin-layer drying is very suitable for lumped parameter models. Recently, thin-layer drying equations have been found to have wide application due to their ease of use and the fact that they require less data, unlike in complex distributed models with wide application due to their ease of use and the fact that they require less data, unlike in complex distributed models have been commonly used to define this model by researchers (see Table S1). The most used form of the Page model is given in Eq. (50); it has been commonly used in the literature and has been incorrectly defined in Eqs. (28), (51), and (61)–(67). The Page model has two model constants and it has been determined to be the second-best suitable model after the Midilli-Kucuk model for various products according to evaluation criteria (see Table S3). The Modified Page model is generally used in a form as given in Eqs. (88) and (69), respectively, and is sometimes called the Modified Page-I, Modified Page-II, or Overhults et al. model. The Modified Page model has two model's constant and it has been determined to be the eighth-best suitable model (see Table S3). The Henderson and Pabis model, occasionally called the single term, generalized exponential, approximation of diffusion, McCormick, or Brooker et al. model, is highly cited in the literature and Eq. (159) is commonly used to define this model by researchers (see Table S1). However, Eqs. (127) and (153) have not been correctly defined. The Henderson and Pabis model has two model constants and has been found to be the ninth-best suitable model (see Table S3). The Logarithmic model is occasionally called the asymptotic or Yagcioglu et al. model and is the third-best suitable model (see Table S3). It has three model constants. The commonly used form of the logarithmic model is given in Eq. (193) and incorrectly used in Eqs. (194), (195), and (197). The Midilli-Kucuk model is sometime called the

- Step 1: Calculate the values of correlation coefficient, the coefficient of determination, modelling efficiency, adjusted R², the reduced chi-square, the root mean square error, the mean relative percentage error, the mean bias error, the standard error of estimate, the residual sum of squares, the reduced sum square error, the residuals, and the others in Table S2 for each model selected for the analysis. For the details of the equations of these criteria, please see Table S2.

- Step 2: Determine and select the highest values of the correlation coefficient, the coefficient of determination, modelling efficiency, adjusted R².

- Step 3: Determine and select the lowest values of the reduced chi-square, the root mean square error, the mean relative percentage error, the mean bias error, the standard error of estimate, the residual sum of squares, the reduced sum square error, the residuals, and the others in Table S2.

- Step 4: Determine the drying curve model that has the highest values of the criteria in Step 2 and the lowest values of the criteria in Step 3. This model can be assumed to be the best model describing the thin-layer drying curve.

Applying this procedure, most of the models are presented in Table S1. Table S1 shows thin-layer drying models developed by researchers for various agricultural products depending on product type, pretreatment of the product, drying parameters, and drying methods. It is observed that 67 thin-layer drying models have been used to estimate drying curves. Note that there is a complexity in drying methods such as name, equation, and nomenclature. The Newton model, commonly used by the researchers, is sometimes called the Lewis, exponential, or single exponential model, and is the simplest model because of the one-model constant. Equation (25) has been usually used to define this model by researchers (see Table S1). The most used form of the Page model is given in Eq. (50); it has been commonly used in the literature and has been incorrectly defined in Eqs. (28), (51), and (61)–(67). The Page model has two model constants and it has been determined to be the second-best suitable model after the Midilli-Kucuk model for various products according to evaluation criteria (see Table S3). The Modified Page model is generally used in a form as given in Eqs. (88) and (69), respectively, and is sometimes called the Modified Page-I, Modified Page-II, or Overhults et al. model. The Modified Page model has two model's constant and it has been determined to be the eighth-best suitable model (see Table S3). The Henderson and Pabis model, occasionally called the single term, generalized exponential, approximation of diffusion, McCormick, or Brooker et al. model, is highly cited in the literature and Eq. (159) is commonly used to define this model by researchers (see Table S1). However, Eqs. (127) and (153) have not been correctly defined. The Henderson and Pabis model has two model constants and has been found to be the ninth-best suitable model (see Table S3). The Logarithmic model is occasionally called the asymptotic or Yagcioglu et al. model and is the third-best suitable model (see Table S3). It has three model constants. The commonly used form of the logarithmic model is given in Eq. (193) and incorrectly used in Eqs. (194), (195), and (197). The Midilli-Kucuk model is sometime called the
Midilli or Midilli et al. model; it was developed in 2012 and is commonly used in the literature. The Midilli-Kucuk model has four model constants and has been found to be the best model at high ratio by researchers (see Table S3). In the literature, Eq. (232) is generally used to define the Midilli-Kucuk model, while Eqs. (202), (209), (222), (227), (233), (241), (242), and (244) have been incorrectly used by researchers (see Table S1). Also, some researchers have developed thin-layer drying models (model numbers are 10, 11, and 12; see Table S1) based on the Midilli-Kucuk model. On the other hand, Eqs. (246) and (252) have been written incorrectly (see Table S1). The two-term model is sometime called the two-factor, two terms exponential-I, exponential two terms, Henderson, double logarithmic, two-term exponential, Sharaf-Eldeen et al., or Sharma et al. model. It has four model constants and Eq. (261) has been generally used to define it by the researchers. The two-term model is one of the most used models in the literature to describe the drying behavior of products and it is the fourth-best thin-layer drying model (see Table S3). In Eqs. (257)–(260), the two-term model has been defined as wrong (see Table S1). The two-term exponential model is occasionally called the two-term exponential-II model; it, too, has been commonly used in the literature as defined in Eq. (311) and given as the wrong expression in Eqs. (312), (314), and (326)–(332). The two-term exponential model has two model’s constant and is found to be the ninth-best suitable model by researchers (see Table S3). The Verma et al. model is called the modified two-term exponential, and has been commonly used in the literature. It has three model’s constant and been found to be the eleventh-best suitable model by researchers to determine thin-layer drying curve equations for products (see Table S3). The Verma et al. model is generally defined by Eq. (353) and is wrongly written in Eqs. (350) and (354) (see Table S1). The approximation of diffusion model is sometimes called the diffusion approach or simplified diffusion; it has four constants and is the sixth-best model between thin-layer drying models (see Table S3). It is highly used and commonly defined by Eq. (355) by the researchers in the literature; however, it is incorrectly given in Eqs. (371) and (372) (see Table S1). The Modified Henderson and Pabis model is sometimes called a three-term exponential model; it has six constants and, with the Wang and Singh model which has two constants, they are the seventh- and fifth-best suitable models defining thin-layer drying curve equations, respectively (see Table S3). Also, they are commonly used in the literature and generally given by Eqs. (374) and (424), respectively (see Table S1). On the other hand, the Wang and Singh model is not correctly used in Eqs. (425), (426), (433), (434) and (439). The Weibull model has two model’s constants and it is the twelfth-best suitable model found by researchers. It is defined in two different forms, as given in Eqs. (455)–(458) and Eqs. (459)–(464) (see Table S1). The Thompson model, which has two constants, and the Simplified Fick’s diffusion (SFFD) model, which has three constants, are highly used in the literature and commonly defined by Eq. (401) and Eq. (447), respectively. The Thompson model is presented in two different forms given as in Eqs. (398)–(404) and Eqs. (406)–(408) in the literature and it is wrongly defined in Eq. (405). The Thompson and simplified Fick’s diffusion models have been found to be the first- and third-best suitable models in the literature (see Table S3). Also, the simplified Fick’s diffusion model has been incorrectly defined in Eq. (455). Moreover, the exponential-hyperbolic decay model, the modified Page-I model, the modified Midilli-Kucuk model (number of the model is 10; see Table S1), the Demir et al. model, the Abbasi et al. model (modified Midilli-Kucuk), the Hii et al. model, the Aghbashlo et al. model, the Akbulut and Durmuş model, the Jaros and Pabis-II model, the modified Page-II model, the Diamente et al. model, the Law et al. model, the Tutuncu and Labuza model, the parabolic model, the modified Henderson and Perry model, the Jena-Das model, the Das et al. model, the Balbay and Şahin model, the Ranjbaran and Zare model, the Alibas model, the exponential model, the polynomial model, the cubic model, the logistic model, the quadratic model, the Yun et al. model, the Kaleta et al. model, and the Pillai model have been found to be the most suitable thin-layer drying model in the respective literature [11,26,30,37,55,134,136,142,156,192,198,204,216,226,233,259,268,270,301,306,314,316,317,320,321,327,332,335,350,351,352,356,357,376,386] (see Table S3).

The evaluation criteria given in Table S2 are highly important to determine the best suitable models in thin-layer drying studies. It is determined that there are 28 performance evaluation criteria in the literature to evaluate thin-layer drying models. As seen in Table S2, evaluation criteria have complexity such as name, equation, and nomenclature in the literature. The highest values of correlation coefficient, coefficient of determination, modeling efficiency, and adjusted $R^2$ and the lowest values of reduced chi-square, root mean square error, mean relative percentage error, mean bias error, standard error of estimate, residual sum of squares, reduced sum square error, residuals and the other evaluation criteria given in Table S2 give the best suitable model for thin-layer drying. The commonly used forms of correlation coefficient, coefficient of determination, modeling efficiency, reduced chi-square, root mean square error, mean relative percentage error, mean bias error, standard error of estimate, residual sum of squares are given in Eqs. (527), (560), (718), (609), (673), (787), (761), (733), and (544), respectively (see Table S2). The most used evaluation criteria that have the most complexity in the literature for thin-layer drying models are coefficient of determination, reduced
chi-square, root mean square error, mean relative percentage error, standard error of estimate, mean bias error, and reduced sum square error, respectively (see Tables S2 and S3).

CONCLUSIONS

Studying the drying behavior and determining the drying times of moist products are considered two significant areas of drying, and research has focused on model development in these areas. There was a strong need to identify, classify, evaluate, and compare these thin-layer drying-curve models.

In this article, a comprehensive review of 67 models under 28 performance assessment criteria is undertaken, and an evaluation of these models is performed by considering the following parameters: (a) product type; (b) pretreatment type; (c) drying parameters, such as temperature, air velocity, layer thickness, microwave power levels, amount of solar radiation, vacuum pressure, frequency of sound wave, excitation amplitude, relative humidity, bed depth, product shape, pH, salt content, absolute pressure, etc.; and (d) drying method utilized. The most used evaluation criteria, which have the most complexity in the literature for thin-layer drying models, are coefficient of determination, reduced chi-square, root mean square error, mean relative percentage error, standard error of estimate, mean bias error, and reduced sum square error, respectively.

Based on the assessment carried out, some single-layer drying-curve models, such as Midilli-Kucuk, Page, logarithmic, two-term, Wang and Singh, approximation of diffusion, Modified Henderson and Pabis, Modified Page, Henderson and Pabis, two-term exponential, Verma et al., and Weibull et al., offer better results for the criteria considered and applications and products selected. Before selecting the model for use, it is important for researchers to properly conduct the drying experiments and measure the drying quantities and parameters/properties in an adequately correct manner with an uncertainty analysis. Furthermore, there are several parameters—such as the drying air (possibly other types of gases or fluids) temperature, pressure, velocity, relative humidity, shape and type of drying materials, retention time, design and geometry of the shelves, flow configuration, drying medium conditions, etc.—which should be considered for better management of drying processes.

NOMENCLATURE

ANO, f(x), MR, Moisture ratio
M_R, MC, mr, R,
RU, RH, RX, X',
X, X_R, X_r, y, Y',
\Delta M, \Phi

Empirical constants in models

Sample length (m)
Drying constants (min^{-1})

Effective moisture (m^2 s^{-1})
Drying time
Root mean square error, mean square deviation
Percent mean relative deviation modulus, mean relative deviation modulus, mean relative percentage deviation
Absolute relative error
Standard deviation
Modeling efficiency
Mean relative percentage deviation
Estimated mean error
Mean relative error
Mean bias error
Root mean square error
Mean square error, root mean square error
Moisture content
Half-slice thickness, sample thickness (m)
Moisture content (kg/kg, db)
Mean absolute error
Mean bias error
Critical moisture content (dry basis)
M_e
Equilibrium or final product moisture on dry basis (g water/g dry solid)
M_o
Initial product moisture on dry basis (g water/g dry solid)
M_s
Moisture at the product surface on dry basis (g water/g dry solid)
Mean percent error
Mean relative deviation between moisture levels, mean relative deviation modulus
Mean relative error
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SUPPLEMENTAL MATERIAL

Supplemental data for this article can be accessed on the publisher’s website.

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