**Network for Research and Development in Africa**
International Journal of Pure and Applied Science Research
ISSN: 2384-5918. Volume 11, Number 5
Pages 52-68 (September, 2019)
www.arcnjournals.org

# A Review of Mathematical Modelling of Thin-Layer Sun Drying of Agricultural Products

**Kauji, A.M.[1], Shittu, S.K.[2], and Bawu, B.M.[1]**
[1]Department of Agricultural Engineering, Ramat Polytechnic Maiduguri, Nigeria
[2]Department of Agricultural and Environmental Engineering, Bayero University Kano, Nigeria

***Abstract:*** *The drying of agricultural products is a complex operation that demands much energy and time. In practice, drying increases product shelf-life and reduces the bulk and weight of the product, thus simplifying transport. Occasionally, drying may lead to a great decrease in the volume of the product, leading to a decrease in storage space requirements. Studies have shown that dependence purely on experimental drying practices, without mathematical considerations of the drying kinetics, can significantly affect the efficiency of drying, increase the cost of production, and reduce the quality of the dried product. Present work involves the study of thin layer drying characteristics of different agricultural products under open sun drying process. The drying data fitted into different thin layer drying models. The performance of these models was investigated by comparing the coefficient of determination ($R^2$), reduced chi-square($X^2$) and root mean square error (RMSE) between the observed and predicted moisture ratio. On the basis of highest value of correlation coefficient (R) and coefficient of determination ($R^2$) and lowest value of reduced chi- square($X^2$) and root mean square error (RMSE) appropriate model will be selected.*

***Keywords****: Agricultural, Drying, Modeling, Layer, and Product*

## 1.0 INTRODUCTION

Food is the basic necessity requires by human beings for comfortability of living. Food production and consumption imbalance is the major problem faced by human beings. Increase of food supply and limitation of population growth are cited as two solutions for the imbalance of food. Although, both the solutions require considerable amount of capital and time to achieve (Murthy, 2009). Another solution to the food production and consumption imbalance is the reduction in the postharvest losses occurring in the developing countries. Therefore, the only method to reduce the postharvest losses is through food preservation, and drying is the method that is being adopted since many centuries ago (Blaise *et al.,* 2009; Murthy, 2009).

Therefore, drying can be defined as a thermo-physical process (Silva *et al.,* 2014) that consists of reduction or removal of moisture content from a wet material by the application of heat energy (Cakmak and Yildiz, 2012; Chatta *et al.,* 2018; El-Sebaii and Shalaby, 2012; Gulcimen and Karakaya, 2016; Polatoğlu and Beşe, 2017). Drying of agricultural products is one of the oldest methods of food preservation (Al-Mahasneh *et al.,* 2013; Chatta *et al*., 2018; Doymaz, 2011; Ismail, 2016; Silva *et al*., 2014). The objectives of drying include: safe storage over an extended period of time (Fargali *et al.,* 2008), ease of handling and reduction in cost of transportation (Cakmak and Yildiz, 2012; Doymaz, 2005, 2012; Torki-harchegani *et al.,* 2016;

Tripathy and Kumar, 2009).

Moreover, more than 80% of the food in the developing countries are produced by the small farmers. These food products are preserved through sun drying by the farmers, i.e., natural sun drying is being practiced (Murthy, 2009). It is known that there is no electricity to use refrigeration in many rural areas in the developing countries for the preservation of the food products. Therefore, the only food preservation method available for the rural people is sun drying technique as in the case for many areas of Africa, Asia, Caribbean, and Latin America (Blaise *et al*., 2009).

Therefore, open sun drying is simply defined as the drying process which consists of spreading the crop in a thin layer on the ground (Jain and Tiwari, 2003) and expose the crop directly to solar radiation, wind and other ambient conditions (C¸akmak and Cengiz, 2011; Fargali *et al*., 2008). Sun drying has been in practice since long time ago for preserving food and agricultural crops (Saleh and Badran, 2009). Although, there are several demerits with the open sun drying process which include: loss of produce due to animals and birds; spoilt products due to moisture, wind, rain and dust; deterioration in the harvested crops due to fungi, decomposition and insect attacks. Moreover, sun drying process is time consuming, labour intensive and requires large space for drying the produce (Dilip and Pathare, 2007; Mghazli *et al*., 2017; Oyerinde, 2016; Sahdev, 2014; Sahdev *et al.,* 2017; Sharma *et al.,* 2009).

However, with all these disadvantages, sun drying is still practiced by small farmers or rural people due to its low cost set up, its simplicity, requires little expertise and requires only direct sun light which is cheap, non-pollutant, environmental friendly, abundant and renewable (Hii *et al.,* 2008; Jayashree and Visvanathan, 2013; Karaaslan *et al.,* 2016).

Furthermore, Thin-layer drying can be described as the procedure of drying single layer of a particles or slices of a product (Blanco-cano *et al.,* 2016; Pandey *et al.,* 2015). Due to the thin-layer drying, the temperature distribution is considered uniform. The main mechanisms of drying include: surface diffusion on the pore surfaces which occurs during the constant rate period of drying; liquid or vapour diffusion due to moisture concentration differences which occurs during the falling rate period of drying and capillary action in granular and porous foods due to surface forces. Generally, hygroscopic materials dry in constant rate and subsequent falling rate periods and drying stops when equilibrium is reached (Pandey *et al*., 2015).

## 2.0 MATHEMATICAL MODELLING OF THIN LAYER DRYING

In mathematical modelling of drying, the thin-layer drying equations are important tools. The thin-layer equations have been used to estimate the drying time of many agricultural products, to simulate moisture movement and mass transfer during the drying of agricultural products, in the design of dryers and to generalized the drying curve (Aregbesola *et al.,* 2015; Jayashree and Visvanathan, 2013; Toĝrul and Pehlivan, 2004; Vijayan *et al.,* 2016). The thin-layer drying models that describe the drying phenomenon of agricultural products are usually categorized into three (3), namely: theoretical, semi-theoretical and empirical (Pandey *et al*., 2015; Sharada, 2013; Vijayan *et al*., 2016).

The theoretical models clearly describe the drying behaviours of agricultural products and can be used for all process conditions, but may include assumptions about moisture mechanisms which may cause considerable error (Pandey *et al*., 2015). One of the theoretical models used in drying is the Fick's second law equation which has been used widely for thin-layer drying process. Semi-theoretical models are generally derived from Fick's second law (Pandey *et al*., 2015). The empirical and semi-theoretical models consider external resistance to moisture transfer resistance between product and air but a theoretical model takes into account only internal resistance to moisture transfer. An empirical model gives a better fit to the experimental data without any understanding of the transport processes involved whereas the theoretical model gives a better understanding of the transport processes involved in the drying (Pandey *et al*., 2015). The most commonly used thin-layer drying models are given in the table below.

**Table 1.1 models used in thin layer drying of agricultural products**

| Model number | Model name | Model | Reference |
|---|---|---|---|
| 1 | Newton | MR=exp(-kt) | (O'Callaghan *et al.,* 1971) |
| 2 | Page | MR = exp(−kt$^n$) | (Diamante and Munro, 1993) |
| 3 | Modified page | MR=exp[-(kt)$^n$] | (Overhults *et al.,* 1973; White *et al.,* 1978) |
| 4 | Henderson and Pabis | MR=a exp(-kt) | (Zhang and Litchfield, 1991) |
| 5 | Modified Henderson and Pabis | MR=a exp(-kt)+b exp(-gt)+c exp(-ht) | (Karathanos, 1999) |
| 6 | Two term | MR=a exp($k_0$t)+b exp(-$k_1$t) | (Sharaf-Eldeen *et al.,* 1980) |
| 7 | Two term exponential | MR=a exp(-kt)+(1-a)exp(-kat) | (Sharaf-Eldeen et al., 1980) |
| 8 | Approximation of diffusion | MR=a exp(-kt)+(1-a)exp(-kbt) | (Yaldiz *et al*., 2001) |
| 9 | Verma et al. | MR=a exp(-kt)+(1-a)exp(-gt) | (Lalit *et al.,* 1985) |

| | | | |
|---|---|---|---|
| 10 | Logarithmic | MR=a exp(-kt)+c | (Yagcioglu & A., 1999) |
| 11 | Wang and Singh | $MR=1+at+bt^2$ | (Wang and Singh, 1978) |
| 12 | Midilli & Kucuk | $MR= a.\exp(-kt^n)+bt$ | (Akpinar and Bicer, 2007) |

**2.1 MATHEMATICAL MODELLING OF THIN-LAYER SUN DRYING OF GRAINS**

An experiment was conducted by Alves *et al*. (2019) on the drying of cowpea bean grain using solar energy. Drying was performed during the day with samples exposed to the sun; during the night, the samples were left on a laboratory bench. The cowpea bean grains at initial moisture contents of 65.42% d.b were dried to final moisture content of 6.73% d.b within 54.4 h (3270min). The mean values of temperature and relative humidity in the external environment were 26.92 ± 2.9 ºC and 67.87 ± 12.3%, respectively. The drying rates occurred at the falling rate period. The models Approximation of Diffusion, Page, Verma, Logarithmic and Two Terms were fitted to the drying kinetics and all of them fitted well to the experimental data, with coefficients of determination ($R^2$) higher than 0.98, mean square deviations (MSD) less than 0.01 and chi-square ($\chi^2$) values lower than 0.0001. The effective diffusivity values were of the order of $10^{-11}$ $m^2/s$ for the cowpea bean samples. In an experiment to study the drying behaviour of rough rice in Ivory Coast, Ahou *et al*. (2014) dried aromatic rough rice under open sun at three different seasons (i.e. small dry season S1, harmattan season S2 and great dry season S3). The temperature and relative humidity for the three seasons S1, S2 and S3 are $30.7^0$C, 69.26%; $31.52^0$C, 45.86% and $32.42^0$C, 60.66% respectively. The rough rice was dried from an initial moisture content of 19% d.b to a final moisture content of 12% d.b. The drying data were fitted to ten different mathematical models. Among the models, the Two-term model was found to best explain thin layer open sun drying behaviour of the rice. The performance of these models was investigated by comparing the determination of coefficient ($R^2$), sum square error (SSE) and root mean square error (RMSE) between the observed and predicted moisture ratios. The results showed that the Two-term model was found to be the most suitable for describing drying curve of rough rice, in all study season, with $R^2$ SSE RMSE ranging respectively from 0.9931 to 0.9957, from 0.0041 to 0.0093 and from 0.0143 to 0.0215. In this study, it was noticed that value of diffusion coefficients for the examined samples changed between $8.34 \times 10^{-12}$ and $4.52 \times 10^{-11}$ $m^2/s$, and the activation energy was estimated to 68.255 Kj/mol.

Al-Mahasneh *et al*. (2013) investigated the drying kinetics of roasted green wheat under open sun using Fuzzy and conventional modelling. The assumption of open sun drying adequacy to prevent deterioration was tested in this study. In this experiment, green beans were roasted by exposing them to direct fire for about 15 minutes before sun drying. The roasted green beans at an average moisture content of 43.2% (w.b) were sun dried to a safest moisture content of below 10% (w.b) in 5.5 hours. During the drying experiment, the ambient temperature varied between 26 and 32◦C. The experiment occurred in falling rate period of drying. The drying data were fitted into eight common thin-layer drying models. Goodness of fit for each model was evaluated using coefficient of determination ($R^2$) and root mean square error (RMSE). Among the conventional thin layer drying models, the two-term exponential model was found to best fit the roasted green wheat sun drying data with $R^2$, and root mean square error values of 0.988 and 0.038, respectively. Fuzzy modelling, however, provided better modelling capabilities compared to conventional models. The effective diffusivity was also evaluated for roasted green wheat kernels and found to be $1.7 \times 10^{-11}$ $m^2/s$. The results showed that open sun drying for 5.5 h was effective and adequate to reduce moisture content to a safe level and to prevent deterioration of this product.

## 2.2 MATHEMATICAL MODELLING OF THIN-LAYER SUN DRYING OF FRIUTS

Santos *et al*. (2018) evaluated the drying kinetics of passion fruit seeds exposed to three drying conditions: full sun, half shade and shade (laboratory). The passion fruit seeds were dried at the initial moisture content of 0.7 (d.b) to a final moisture content of 0.4 (d.b.) at the end of drying. The drying period was 7h for the three situations studied. The temperature was measured by means of a chemical thermometer (wet and dry bulb). Twelve (12) thin-layer models were fitted to the experimental data. For the validation of the drying equations, analysis of nonlinear regression of the mathematical models of drying to the experimental data was performed. The values of the coefficient of determination ($R^2$), mean relative error (P), estimated mean error (SE), and chi-square ($X^2$) were used as criteria to verify the fitting degree of the mathematical models studied. The Wang and Singh model was the model that best fit the experimental data, with $R^2$ values closer to 1, $X^2$ and SE closer to 0 and smaller P. The sun drying condition obtained a greater efficiency in the water removal of passion fruit seeds. An investigation on the sun drying behaviour of cornelian cherry fruits was conducted by Polatoğlu and Beşe (2017). The drying process of cornelian cherry took place in the falling rate period as shown by the drying rate curve. For explaining the thin layer drying kinetics of cornelian cherry, about twelve thin-layer mathematical models were used. The approximation of diffusion model was found to be the most appropriate model for the process. The Fick's diffusion model was used to calculate the effective moisture diffusion coefficients ($D_{eff}$) of cornelian cherry. The value of ($D_{eff}$) was obtained as $1.20 x 10^{-11}$ $m^2/s$. The vitamin C degradation of dried cornelian cherry was determined as about 51.1%.

Thin layer drying experiments were conducted by Olabinjo *et al*. (2017) to compute the drying characteristics of fermented cocoa beans in open sun and indirect natural convection solar dryer. The drying experiments were conducted at the same time for comparison. Three different thin layers drying of the fermented cocoa beans were examined under field conditions of Akure, Nigeria. The drying process took place only in the falling rate period. The drying curves obtained from the experimental data were fitted to thirteen (13) different thin layer mathematical models. All the models were compared according to three evaluation parameters. These include coefficient of determination ($R^2$), Root mean square error (RMSE) and Chi-square ($X^2$).The results showed that the Midilli and Kucuk model, best described the drying curve of fermented cocoa beans under open sun with $R^2$ = 0.9866, $X^2$=0.0024 and RMSE=0.0023. Olawoye *et al*. (2017) performed an experiment on Modelling of thin-layer drying characteristic of unripe Cardaba banana (Musa ABB) slices. The drying kinetics of Carbada banana were investigated using sun and hot air-drying at the temperature. The drying rate of the convective hot air oven was kept constant at 1.2 $m^2$/s. The Cardaba samples had a thickness of 5 mm and the initial moisture content of about 79.80% w.b (395.05% d.b) were dried to the final moisture content of 13.61% d.b for drying using sun. The drying curves of the Cardaba banana slices contained no constant rate of drying but took place in the falling rate period. Twelve thin-layer drying models were used to fit the drying data and compared according to their coefficients of determination ($R^2$), root mean square error (RMSE) and reduced $\chi^2$ to estimate drying curves. Among the thin-layer models, Wang and Singh model with $R^2$ of 0.9953, RMSE of 0.0223 and $\chi^2$ of $4.94 \times 10^{-4}$ was found to best explain the drying behaviour of the Cardaba banana slices. Effective moisture diffusivity of Cardaba banana slices increased from $1.46 \times 10^{-8}$ to $4.25 \times 10^{-8}$ $m^2$/s, resulting to activation energy of 38.46 kJ/mol.

The drying kinetics of pineapple was studied by Olanipekun *et al*. (2015), and the model that best describes it was selected. Pineapple slices were dried in a hot-air oven, microwave and under direct sunlight. Drying took place entirely in the falling rate-drying period. Seven mathematical models were fitted into the experimental data. The goodness of fit was determined using the coefficient of determination ($R^2$), reduced chi-square ($\chi^2$), root mean square error (RMSE) and sum square error (SSE). The Page model best explained the sun-drying behaviour of the pineapple. The effective moisture diffusivity increased from $6.89 \times 10^{-10}$ to $5.1 \times 10^{-8}$ $m^2$/s. Doymaz (2012) investigated the sun drying behaviour of seedless and seeded grapes. The drying study showed that the times taken for drying of seedless and seeded grapes of berry size of 1.72 cm and 2.20 cm thicknesses from the initial moisture contents of 78.2% and 79.5% (w.b.) to final moisture content of around 22% (w.b.) were 176 and 228 h in open sun drying, respectively. The temperature of ambient air ranged from 32 to 46 °C. The drying data were fitted to 12 thin-layer drying models. The performance of these models were compared using the determination of coefficient ($R^2$), mean relative percent error (P), reduced chi-square ($\chi^2$) and root mean square error (RMSE) between the observed and predicted moisture ratios. The results showed that Midilli et al. model was found to satisfactorily describe the sun drying curves of seedless and seeded grapes. The effective moisture diffusivity values were estimated from Fick's diffusion model by $1.02\times10^{-11}$ and $1.66\times10^{-11}$ $m^2$/s for seeded and seedless grapes.

## 2.3 MATHEMATICAL MODELLING OF THIN-LAYER SUN DRYING OF VEGETABLES

The thin layer drying behaviour of groundnut was investigated under open sun drying (OSD) and indoor forced convection drying (IFCD) modes by Sahdev *et al*. (2017). The groundnut samples were dried from initial moisture content of 38% (w.b.) to the safe storage moisture content of 8%-10% (w.b.). Four mathematical models were compared for describing the groundnut drying process. The performance of thin layer drying models was investigated by comparing the statistical parameters such as coefficient of correlation (R), reduced chi-square ($\chi^2$), root mean square error (RMSE), and mean bias error (MBE) between experimental and predicted moisture ratios. Henderson and Pabis model was observed to give the highest value of R and lowest values of $\chi^2$, RMSE and MBE for the groundnut drying under both OSD and IFCD modes. The values of statistical parameters under Lewis model were also found to be very close to Henderson and Pabis model. Therefore, Henderson and Pabis and Lewis models were found to be the best for describing the drying behaviour of groundnut under both given drying conditions. Ismail (2016) investigated the effects of open-air sun drying and pre-treatment on drying characteristic of cherry tomato (Lycopersicum esculentum). The sun drying times were determined as 26h for natural cherry tomato and 22 h for pre-treated cherry tomato samples. The pre-treated cherry tomato samples were dried in slightly shorter time than the natural cherry tomato samples. There were no any constant rate drying period occurred, so the drying process took place in the falling rate period. About seven theoretical drying models were applied to experimental data and all the models were compared according to statistical parameters; i.e. coefficient of determination ($R^2$), chi-square ($\chi^2$) and root mean square error (RMSE). Among the seven models used, it was observed that Verma et al. model is the best mathematical model represented the open-air sun drying behaviour of cherry tomatoes. Based on Fick's second law, the values of effective moisture diffusivity for treated and natural cherry tomatoes samples are found to be $4.76\times10^{-10}$ and $4.42\times10^{-10}$ $m^2/s$ respectively.

Oyerinde (2016) conducted drying experiment using direct sun drying and indirect passive solar dryer to simulate the drying processes of tomato slices. Tomato slices of 3mm thickness were placed on perforated stainless steel trays in a thin layer and dried to equilibrium moisture content. All samples were dried from an initial moisture content of 95.4 %w.b to 10.2 %w.b for sun dried samples and 8.5 %w.b for solar dried samples. Ambient temperature (dry bulb) varied from 22.0 $^0$C – 32.5 $^0$C and relative humidity from 70.8 % – 97.0 %, while solar radiation varied from 231.14 $W/m^2$ – 912.41$W/m^2$ during the drying period. Drying time was 15 hours over a period of 3 days for sun dried samples. To explain the drying characteristics of tomatoes slices, ten semi-theoretical and empirical models found in literature were applied and fitted to the experimental data. From the statistical analysis, it was concluded that the Page model best predicted the drying data for both sun and solar dried samples. Effective moisture diffusivity was $5.07\times10^{-7}m^2/s$ for sun dried samples, while activation energy ranged from 32.38 to 33.53 kJ/mol for samples dried under open sun drying. Fadhel *et al*. (2014) studied and analysed the drying of red pepper known as "Baklouti" by three different solar processes. These three drying processes include: natural convection solar drier, greenhouse and open sun. During the drying experiments, the temperature of ambient air ranged from 18.21 to 33.57°C. On the other hand, the solar radiation ranged from 812 to 902 $W/m^2$ and the relative humidity of ambient air ranged from 53.5 to 91.9%. Drying time (including nights) is about 118 hours in open sun. Six thin-layer drying models (Newton, Henderson and Pabis, Modified Henderson and Pabis, Wang and Singh, Logarithmic and Two- term) were fitted to the experimental data to select a suitable drying equation. The Logarithmic was found to best describe the drying behaviour of pepper for open sun, greenhouse and solar drier drying. Fudholi *et al*. (2013) evaluated the drying of the Malaysian red chili (Capsicumannuum L.) under open sun and solar drying processes. Red chilies were dried down from approximately 80% (wb) to 10% (wb) moisture content within 33h using solar dryer and 65h using open sun drying. The drying process was conducted during the day at the average solar radiation of 420W/$m^2$ and air flow rate of 0.07 kg/s. Solar drying yielded a 49% saving in drying time compared with open sun drying. A nonlinear regression procedure was used to fit three drying models. These models were compared with experimental data on red chilies dried by open sun drying and those dried by solar drying. The fit quality of the models was evaluated using their coefficient of determination ($R^2$), mean bias error (MBE), and root-mean-square error (RMSE) values. The Page model resulted in the highest ($R^2$) and the lowest (MBE) and (RMSE) which make it the best fit.

The effect of sample thickness, method of drying and drying air temperature on the drying characteristics and kinetics of okra slices were investigated by Afolabi and Agarry (2014). The samples (10mm and 20mm thick) were dried under open sun and solar dryer. The okra slices dried perfectly within 216 – 240 h, under open sun. The samples dried in the falling rate period with no constant rate period. Four thin-layer semi- empirical mathematical drying models (Newton, Page, Henderson and Pabis, and Logarithmic models) were fitted to the experimental drying curves. The models were compared using the coefficient of determination ($R^2$) and the root mean square error (RMSE). The logarithmic model has shown a better fit to the experimental data obtained as relatively compared to other tested models. The transport of water during drying was described by application of Fick's diffusion model and the effective moisture diffusivity was estimated. The value ranges from 0.253 to 0.901 × 10-10 $m^2$/s for open sun drying. Jayashree and Visvanathan (2013) conducted an experiment titled "Mathematical modelling for thin layer sun drying of ginger (Zingiber officinale Rosc.)". In the experiment, ginger were dried during the month of April, 2009 at Agricultural Engineering College and Research Institute, Coimbatore (Tamil Nadu). Ginger rhizomes were mechanically washed, partially peeled, spread in single layer on cemented yard and dried from initial moisture of 594.01% (d.b.) (dry basis) to a final moisture content value of 9.82% (d.b.). During the days of the experiment, the temperature of the drying air varied from 30.3°C to 38.1°C while the average relative humidity varied from 62.47% to 35.09%, which corresponded to the time when the average solar intensity obtained was maximum (889.38 W $m^2$) and the average wind speed varied from 0.5 m/s to 1.3 m/s. Drying of ginger was completed in eight days. Drying characteristics curves, showed no constant rate period and all the drying process occurred in the falling rate period. Thin layer modelling of drying data showed that diffusion approximation model best described the drying process. The effective moisture diffusivity for drying of ginger was calculated as $1.91 \times 10^{-7}$ $m^2$/s. Sun dried ginger rhizomes were evaluated for its quality and it was found that the essential oil, oleoresin, moisture and crude fibre contents were 2.0%, 4.6%, 9.82% and 2.5%, respectively.

**3.0 Mathematical modelling approach**

The mathematical modelling of drying agricultural product is done based on the drying characteristics obtained from the experimental investigation. To get the drying characteristics of the product, thin layer drying requires some important parameters which include the following(Pandey *et al*., 2015);

**3.0.1 Important parameters**

**3.0.1.1 Moisture content**

The quantity of moisture present in a material can be expressed either on the wet basis or dry basis and expressed either as decimal or percentage. The moisture content on the wet basis is the weight of moisture present in a product per unit weight of the undried material, represented as,

$$M_{wb} = \frac{W_0 - W_d}{W_0} \quad 1$$

Percentage wet basis (wb) is expressed as,

**Percentage $M_{wb}$ = $M_{wb}$ x 100** 2

While the moisture content on the dry basis is the weight of moisture present in the product per unit weight of dry matter in the product and represented as,

$$M_{db} = \frac{W_0 - W_d}{W_d} \quad 3$$

Percentage dry basis (db) is expressed as,

**Percentage $M_{db}$ = $M_{db}$ x 100** 4

The moisture contents on the wet and dry basis are inter-related according to the following equations,

$$M_d = \left(\frac{M_w}{100 - M_w}\right) \times 100 \quad 5$$

$$M_w = \left(\frac{M_d}{100 + M_d}\right) \times 100 \quad 6$$

The moisture content on the wet basis is used normally for commercial purposes, while the moisture content on the dry basis has tended to be employed for engineering research designation, because the weight change associated with each percentage point of moisture reduction on the dry basis is constant as against the wet basis where the amount of water involved in a moisture content reduction of one percent changes as drying progresses, because the weight of water and total crop weight change.

**3.0.1.2 Equilibrium moisture content (Me)**

A crop has a characteristic water vapour pressure at a particular temperature and moisture content. The equilibrium moisture content is the moisture content at which the product is neither gaining nor losing moisture. It is a dynamic equilibrium which changes with relative humidity and temperature.

**3.0.1.3 Moisture ratio (MR)**

Moisture ratio is one of the important criteria to determine the drying characteristics of agricultural product. MR can be determined according to external conditions. If the relative humidity of the drying air is constant during the drying process, then the moisture equilibrium is constant too. In this respect, MR is determined as in Eq. (7).

$$MR=\frac{M_t-M_e}{M_o-M_e} \quad 7$$

If the relative humidity of the drying air continuously fluctuates, then the moisture equilibrium continuously varies so MR is determined as in Eq.(8) given by (Diamante and Munro, 1993).

$$MR=\frac{M_t}{M_o} \quad 8$$

**3.0.1.4 Drying rates**

Drying rate may be defined as the amount of moisture lost per unit of drying surface area per unit of drying time. This can be expressed as;

Drying rate ( R ) =

$$\frac{M_{t+dt}-M_t}{dt} \quad 9$$

**3.0.2. Periods of Drying**

There are two main drying rate regimes for agricultural products, namely the constant drying rate period and the falling drying rate period.

**3.3.2.1 Constant drying rate period**

During the constant drying rate period, drying takes place from the surface of the product and is simply the evaporation of moisture from the free-water surface. The rate of moisture removal during this period is mainly dependent on the surrounding conditions and only affected slightly by the nature of the product. At the end of the constant drying period is the critical moisture content.

**3.3.2.2 Falling drying rate period**

Below the critical moisture content is the falling drying rate period. This drying rate regime is dependent essentially on the rate of diffusion of moisture from within the product to the surface and also on moisture removal from the surface.

Figure 1 shows a plot of moisture content (W) versus time ($\theta$) generally obtained by experimentally drying a solid. This curve represents a typical case when a wet solid loses moisture initially by evaporation from a saturated surface on a solid, followed by a period of evaporation from a saturated surface of gradually decreasing area and finally when the latter evaporated in the interior of the solid. Figure 1a indicates that the drying rate is subject to variation with time or moisture content, further better illustrated by graphically or numerically differentiating the curve and plotting *dW*/*d*θ versus *W,* as shown in Figure 1b*,* or as *dW*/*d*θ versus θ, as shown in Figure 1c*.* These rate curves illustrate that the drying process is not a smooth, continuous one in which a single mechanism controls throughout. Figure 1*c* has the advantage of showing how long each drying period lasts.

The section *AB* on each curve represents a warming-up period of the solids. Section *BC* on each curve represents the constant-rate period. Point *C,* where the constant rate ends and the drying rate begins falling, is termed the critical-moisture content. The curved portion *CD* on Figure 1a is termed the falling-rate period and, as shown in Figure 1*b* and *c,* is typified by a continuously changing rate throughout the remainder of the drying cycle. Point *E* (Figure 1b) represents the point at which all the exposed surface becomes completely unsaturated and marks the start of that portion of the drying cycle during which the rate of internal moisture movement controls the drying rate. Portion *CE* in Figure 1.1b is usually defined as the first falling-rate drying period; and portion *DE,* as the second falling-rate period (Perry, 2007).

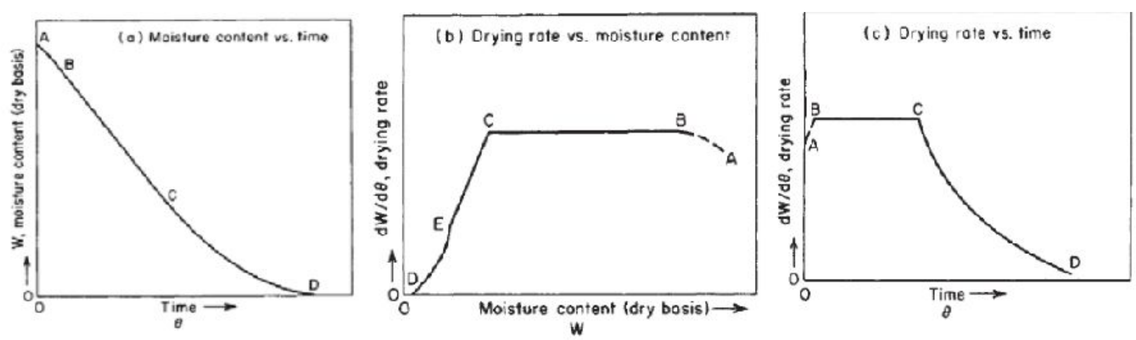


**Figure 1 drying period curves** (Perry, 2007)

### 3.1 Determination of appropriate model

Mathematical modelling of the drying of food products often requires the statistical methods of regression and correlation analysis. Linear and nonlinear regression analyses are important tools to find the relationship between different variables, especially, for which no established empirical relationship exists. Thin layer drying equations require MR variation versus time (t). Therefore, MR data plotted with time (t) and regression analysis is performed with the selected models to determine the constant values that supply the best appropriateness of models. The validation of models can be checked with different statistical methods. The most widely used method is determining correlation coefficient (r), coefficient of determination ($r^2$), reduced chi-square ($\chi^2$) test and root mean square error (RMSE) analysis (Pandey et al., 2015).

**Correlation coefficient (r)-**

$$r = \frac{\sum_{i=1}^{N} MR_{pre,i}\, MR_{exp,i} - \sum_{i=1}^{N} MR_{pre,i} \sum_{i=1}^{N} MR_{exp,i}}{\sqrt{\left(N\sum_{i=1}^{N} (MR_{pre,i})^2 - \left(\sum_{i=1}^{N} MR_{pre,i}\right)^2\right)\left(N\sum_{i=1}^{N} MR_{exp,i} - \left(\sum_{i=1}^{N} MR_{exp,i}\right)^2\right)}} \qquad 10$$

**Coefficient of determination ($r^2$)-** (Akpinar, 2008)

$$R^2 = \frac{\sum_{i=1}^{n}\left(MR_i - MR_{pre,i}\right) \cdot \sum_{i=1}^{n}\left(MR_i - MR_{exp,i}\right)}{\sqrt{\left[\sum_{i=1}^{n}\left(MR_i - MR_{pre,i}\right)^2\right] \cdot \left[\sum_{i=1}^{n}\left(MR_i - MR_{exp,i}\right)^2\right]}} \quad 11$$

**Reduced chi-square ($\chi^2$)-**

$$X^2 = \frac{\sum_{i=1}^{n}( MR_{exp,i} - MR_{pre,i})^2}{N-n} \quad 12$$

**Root mean square error (RMSE)-**

$$\mathrm{RMSE} = [\sum_{i=1}^{N} \frac{1}{N} ( MR_{exp,i} - MR_{pre,i})^2]^{\frac{1}{2}} \quad 13$$

The highest correlation coefficient (r) and coefficient of determination ($r^2$), and the lowest chi square ($X^2$) and root mean square error (RMSE) values are required to select the best suitable model to explain the thin layer drying process. Once the drying curves obtained from the experimental data, then it will be fitted to the different semi-theoretical thin layer drying models (shown in table 1.1). The model which satisfies these requirements will be selected to represent the thin layer behaviour of the product.

**4.0 Conclusions**

A comprehensive review of the fundamental principles and theories required for the mathematical modelling of thin layer drying has been presented. For different agricultural product, different thin layer model was selected as per the statistical approach.

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**Nomenclature**

| | |
|---|---|
| a, b, c, g, h, n | Empirical constants in the drying models |
| k, $k_0$, $k_1$ | Empirical constants in the drying models |
| n | Number of constants |
| N | Number of observations |
| MR | Moisture ratio |
| MRexp | Experimental moisture ratio |
| MRpre | Predicted moisture ratio |
| M | Moisture content, (% dry basis) |
| Me | Equilibrium moisture content, (% dry basis) |
| $M_0$ | Initial moisture content, (% dry basis) |
| Mt | Moisture content at t, (% dry basis) |
| $M_{t+dt}$ | Moisture content at t+dt, (% dry basis) |
| t | Time, (min or hour) |
| T | Temperature, ($^0$C) |
| $T_{abs}$ | Absolute temperature, ($^0$K) |

Abbreviations:

wb: Wet Basis

db: Dry basis

RMSE: Root mean square error