Mathematical Modelling of the Drying Characteristics of Milled Sorghum Residue

ABSTRACT

During milling of cereal grains, bran which is separated from the starchy endosperm of the grain is a major by-product. In this study, milled sorghum residue was dried in a cabinet dryer under different conditions (temperature and air velocity). The obtained drying data were fitted into ten existing mathematical models and obtained the best model while, the effective moisture diffusivity and activation energy of the drying process was determined using Arrhenius type approach. The result shows that the initial moisture content obtained for the sorghum residue using standard oven drying method were 41.28 ± 0.33%, 49.52 ± 0.63 % and 47.06 ± 0.42 % on wet basis for the wet residue of variety A, B and C, respectively, at equilibrium point, the final moisture content of about 12.93 ± 0.14 – 14.31± 0.07 as temperature ranges from 40 °C to 70 °C and air velocity ranges from 0.8 m/s to 1.2 m/s. During the drying process, the drying rate falls more rapidly as it was initially high as a result of more moisture in the sorghum residue and the drying rate decreases slowly until reaching the reduced moisture content. The obtained values of effective moisture diffusivity (D_{eff}) ranges between 9.89 x 10^{-10} and 22.21 x 10^{-10} m^2/s, 9.45 x 10^{-10} and 20.62 x 10^{-10} m^2/s and 8.56 x 10^{-10} and 20.76 x 10^{-10} m^2/s for variety A, B and C, respectively. However, the result of the modelling shows that the drying characteristics of variety A and B of the sorghum residue can be predicted using Midilli *et al.* model while the drying behaviour of Variety C can be predicted using Hii *et al.* model.

Keywords: Cereal, sorghum residue, drying, modelling, effective moisture diffusivity

1. INTRODUCTION

Cereal is a member of the grass family (*Gramineae*) cultivated for the edible components of its grain or the kernel. Strictly speaking, it is a caryopsis which is composed of the fruit coat (pericarp) and a seed. The fruit coat adheres tightly to the seed coat surrounding the remainder of the seed consisting of germ and endosperm (Delcour and Hoseney, 2010).

There are many types of cereals grown worldwide, each sharing some structural similarities. It is grown in large quantities due to its importance as an economic commodity and providing food and energy worldwide more than any other type of crop. Due to this, cereal grains are also known as staple crops. Not only cereal processing forms a large and important part of the food production chain, they provide versatile and essential nutrients to numerous populations. Cereal grains are easy to store once their enzymatic activity is in check and may be used to produce a myriad of food products (Tsadik and Emire, 2015; Amadou *et al.,* 2013).

Sorghum is the fifth most important cereal crop in the world after rice, wheat, and barley, while maize is the most grown cereal in terms of production quantity in Sub-Saharan Africa (FAOSTAT, 2020; Mabhaudhi *et al.*, 2016; Sobowale *et al.*, 2019). It remains one of the most versatile cereal crops on the continent, serving as a staple and main meal for millions of people (FAOSTAT, 2020; Sobowale *et al.*, 2019; Adebo *et al.*, 2018). It is an important source of calories, variety of nutrients and beneficial food components (Schober and Bean, 2008; Taylor and Daodu, 2017; Odunmbaku *et al.*, 2018). With the increasing world population, decrease in water supply and the effects of climate change, this drought resistant food crop is vital for human utilization and will be an important crop for the future.

Amongst all the available food processing techniques, fermentation is an age-long process, known to improve nutritional qualities, palatability and consumer appeal (Adebo *et al.*, 2017a,b; Rosales *et al.*, 2018; Adebo *et al.*, 2020). Derived fermented food products continue to constitute an important part of our daily diet and are estimated to provide about a third of world food supplies (Xiang *et al.*, 2019) . These foods are known to confer beneficial effects, including therapeutic and functional properties, in addition to possessing antimicrobial, antioxidant, probiotic and cholesterol-lowering attributes, and are a source of some other important bioactive compounds (Adebo *et al.*, 2020; Galati *et al.*, 2014; Adebiyi *et al.*, 2018; Tamang, 2007; Farhad *et al.*, 2010; Taylor and Doudu, 2015). Accordingly, fermented sorghum-based foods have a long history and strong cultural ties to the African people in particular.

Cereal grains are usually milled to remove the fibrous bran. During milling, bran which is separated from the starchy endosperm of the grain is a major by-product. Although the micronutrients are generally present in higher concentrations in the outer part of the grain, it is often undervalued and used as animal feed (Slavin *et al.,* 2001; Hemery *et al.,* 2011a). The term "bran" is usually applied to the outer layers of the grain and its composition depends widely on the grain type, kernel size, shape, and maturity, size of the germ, thickness of the pericarp, duration and condition of grain storage, conditioning process of the grain before milling, during milling and the milling machinery used (Alan *et al.,* 2012; Zitterman, 2003). In wheat grain milling, the bran obtained is about 15% with composite multi-layered materials like outer and inner pericarp, testa, hyaline layer, aleurone layer and part of starchy endosperm residue (Hemery *et al.,* 2011a, b) and in barley the milling by-product yield is approximately 30–40% (Marconi *et al.,* 2000). However, various studies show the utilization of cereal bran in food products, the level of incorporating the bran as such is very low (5–10%) due to the negative effects on overall acceptability of the product. The world production of rice bran is increasing annually but only part of the production is employed to extract rice bran oil or utilized in animal feed only an insignificant amount is used as food additives. With the increasing concern about the safety of synthetic antioxidant usage, natural antioxidants from plant extracts as an alternative has become a rage. Consequently, rice bran extract has been proven as an effective natural preservative in various food systems (Min *et al.,* 2011). Likewise, other valuable food ingredients with specific health benefits are also abundantly present in the by-product of cereal industry which can be extracted from a low-cost material.

Foods products have a high moisture content of more than 50% which makes them highly susceptible to numerous microorganisms such as bacteria causing spoilage. Immediate preservation should be carried out to prevent biological deterioration after harvesting or processing due to their perishable characteristics. Drying or dehydration preserves food products in a stable and safe condition by reducing water activity, extending the shelf life much longer than that of fresh produce (Zhan *et al.*, 2006), drying is one such method to do it especially in developing countries like India where cold storage facilities are poorly established. Also, the high amount of moisture contained in most agricultural material highly contributes to its perishability. The aim of this study therefore was to mathematically model the drying characteristics of milled sorghum residue.

2. MATERIALS AND METHODS

2.1 Samples Collection and Preparation

Sorghum grains was obtained from Oba market in Akure, Nigeria. The sorghum was manually sorted and cleaned to remove husk, dirt, damaged grains and other foreign particles, to obtain the residue. The gruel was prepared using improved traditional method of Akingbala *et al.* (2004). The sorghum sample was sorted, steeped in tap water for 72 hrs. After decanting the steeping water; they were milled in an attrition mill, the residue was separated from the residue through a locally manufactured sieve. The water content in the residue was reduced to the possible level by gravity and stored in refrigeration system to equilibrate the moisture content and prevent spoilage. Before the experimentation, the initial moisture content of each experimental material was determined using standard oven dry method (dried at 105 C for 24 hrs) and the obtained values were recorded on wet basis.

2.2 Experimental Equipment and Materials

The equipment and materials used for carrying out the experiment were: Cabinet dryer, microwave, weighing balance, desiccator, stop watch, petri dish, attrition milling machine, container for fermentation, thermometer, distilled water, thimble, cotton wool and sieve

2.3 Drying Experiment

The extracted sorghum residue was filled into sample holder and its initial weight and temperature was determined using weighing scale and digital thermometer. The drying system was powered on for about 1h to ensure the proper circulation of heat in the drying system, the weight loss and temperature was measured after every 30 minutes interval to determine drying rate and other drying parameters. Effect of some parameters such as drying temperature on the quality of the drying was determined. The dried sample were measured after cooling and store in desiccator to avoid reabsorption of moisture. Drying tests were replicated three times for each of this power (40, 50, 60 and 70 C) with each sample. Samples were weighed on an electronic balance (Make-Citizen Model No.CY-500gm). After drying test, equilibrium moisture content of the sample was determining by the same procedure used for measurement of initial moisture content. Moisture content of sample during drying period was calculated at each drying time of constant time interval and presented as the moisture ratio (MR). Average values of each drying test were used for the drying curve of each sample for three drying power

2.4 Determination of Moisture Content

The moisture content of the whole Maize gruel-residue was determined using American Society of Agricultural Engineers (ASAE) standard method (ASAE, 1983). Weighed amount of the samples were dried in a hot-air oven at 105±2℃ and weighed every time after cooling the samples in a desiccator till it appears it contains no more moisture and constant weight was obtained. Weight loss on drying to a final constant weight is recorded as moisture content of the material. Moisture content (wet basis) was calculated respectively using the following method

$$MC_{wb}(\%) = \frac{Mw-Md}{Mw}\times 100 \quad (1)$$

Where; an MC$_{wb}$ (%) is the moisture content (wet basis) %, Mw is the mass of wet product and Md is the mass of dry product.

2.5 Determination of Moisture Ratio

Moisture ratio of samples during drying was determined using the following equation:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (2)$$

As the Me value is very small compared to Mo and Mt values, the Me value can be neglected and the moisture ratio was simplified and it can be expressed as

$$MR = \frac{M_t}{M_0} \quad (3)$$

Where Mt is the Moisture content at time t, kg moisture, Me is the Equilibrium moisture content, kg moisture, Mo is the Initial moisture content, kg moisture and MR is a dimensionless moisture ratio.

2.6 Determination of Drying Rates

Agricultural products (which are hygroscopic) has always some residual moisture after the drying while for non-hygroscopic material drying continued up to zero moisture content. Because of hygroscopic products moisture is trapped in closed capillaries. The rate of moisture flow is only approximately proportional to its vapor pressure difference with the environment because of the crop resistance to moisture flow. There are two main drying rate regimes for agricultural products, namely the constant drying rate period and the falling drying rate period. Therefore, the draying rate was determined using equation 4

$$\text{Drying rate (DR)} = \frac{M_{t+dt} - M_t}{dt} \quad (4)$$

Where Mt+dt is the moisture content at t +dt (g water / g wet base), Mt is the moisture content at a specific time (%) and t is the drying time (minute)

2.7 Fitting of Mathematical Model

In the empirical models a direct relationship is derived between moisture ratio, drying time and the parameters associated with it have no physical meaning. Non-linear regression was performed using the least square method in Microsoft excel (Solver analysis). To select a suitable model for describing the drying process of extracted residue, the drying curves were fitted with 10 thin layer drying model equations (Table 1). Statistical parameters such as the coefficient of determination (R^2), reduced chi-square (χ^2), Root mean square error (RMSE), standard error of estimate (SEE) and sum of squared error (SSE) were used as the criteria th goodness of fit of the model. The best model was selected using the highest value of coefficient of determination (R^2), and the lowest value reduced chi-square (χ^2) as the primary criterion for selecting the best model to describe the drying characteristics and the lowest in value of the Root mean square error (RMSE), standard error or estimate (SEE) and sum of squared error (SSE) will be used for the validation of the model. The equation of statistical parameter are given below,

$$R^2 = \frac{\sum_{i=1}^{n}(MR_i - MR_{pre,i})\sum_{i=1}^{n}(MR_i - MR_{pre,i})}{\sqrt{\sum_{i=1}^{n}(MR_i - MR_{pre,i})\sqrt{\sum_{i=1}^{n}(MR_i - MR_{pre,i})}}} \quad (5)$$

$$\chi^2 = \frac{\sum_{i=1}^{n}(MR_i - MR_{pre,i})^2}{N-n} \quad (6)$$

$$MBE = \frac{1}{N}\sum_{i=1}^{n}(MR_{pre,i} - MR_{esp,i}) \quad (7)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{n}(MR_i - MR_{pre,i})^2\right]^{\frac{1}{2}} \quad (8)$$

Where, R^2 is the coefficient X^2 is the Chi Square, RMSE is the root mean square error, $MR_{pre,i}$ is the predicted moisture ratio, $MR_{esp,I}$ is the experimental observed moisture ratio, I is the ith predicted moisture ratio, N is the number of observation and n is the number of constants

Table 1: Some thin layer drying models.

Model Name	Model Equation	References
Newton	$MR = exp(-kt)$	Togrul and pehlivan (2004)
Page	$MR = exp(-kt^n)$	Kaleemullahand Kailappan (2006)

Modified page	$MR = exp\,[-(kt)^{n}]$	Sogi *et al.* (2006)
Henderson and pabis	$MR = a \cdot exp(-kt)$	Kashaninejad *et al.*, (2007);
Logarithmic	$MR = aexp(-kt) + c$	Celma *et al.* (2007);
Two-two	$MR = aexp(-k_0 t) + bexp\,(-k_1 t)$	Wang *et. al.* (2007).,
Two-term exponential	$MR = aexp(-kt) + (1 + a)\,exp(-kc$	Midili and Kucuk (2003);
Wang and singh	$MR = 1 + at + bt2$	Wang and Singh (1978)
Approximation of diffusion	$MR = aexp(-kt) + (1 - a)\,exp(-k$	Wang *et al.* (2007);
Modified Henderson and pabis	$MR = aexp(-kt) + bexp\,(-gt) + c$	Karathanos (1999)
Verma *et al.*	$MR = aexp(-kt) + (1 + a)\,exp(-gt$	Doymaz (2005);
Midilli and Kucuk	$MR = aexp\,(-kt^{n} + bt)$	Midilli *et al.* (2002)

Where MR =moisture ratio; a, b, c, g, h, k, k_1, k_2 and n = drying constants; t = drying time (h)

2.8 Determination of Effective Diffusivities

The experimental moisture ratio was expressed by using Ficks diffusion equation. The solution of this equation developed by Crank (1975), and the form of Eq. (9) was applicable for particles with slab geometry by assuming uniform initial moisture distribution:

$$\ln MR = \ln \frac{8}{\pi^2} - \frac{\pi^2 D_{eff}}{4L^2} t \qquad (9)$$

where Deff is the effective diffusivity (m^2/s); L is the half thickness of slab (m). The linear solution of the equation is obtained by using a simple approach that assumes that only the first term in the series equation is significant (Tutuncu & Labuza, 1996). Then, Equation (10) is obtained by taking the natural logarithm of both sides. It shows that the time to reach given moisture content will be directly proportional to the square of the half-thickness and inversely proportional to Deff.

Diffusivities are typically determined by plotting experimental drying data in terms of ln(MR) versus time in Eq. (9), and the plot gives a straight line with a slope of

$$slope = \frac{\pi D_{eff}}{4L^2} \qquad (10)$$

2.9 Determination of Activation energy

The activation energy was obtained from temperature dependence of the effective diffusivity which was represented by an Arrhenius type equation as shown in equation 11 (Madamba *et al.,* 1996).

$$D_{eff} = D_o \exp\left(\frac{-E_a}{R(T+273.)}\right) \qquad (11)$$

where Do is the pre-exponential factor of the Arrhenius constant (m2/s), Ea is the activation energy (kJ/mol), R is the universal gas constant (kJ/molK), T is the temperature

3. RESULTS AND DISCUSSION

3.1 Drying Curve

3.1.1 Moisture content and moisture ratio

The initial moisture content obtained for the sorghum residue using standard oven drying method were 41.28 ± 0.33%, 49.52 ± 0.63 % and 47.06 ± 0.42 % on wet basis for the wet residue of variety A, B and C respectively, was dried in the cabinet dryer for until the material reached the equilibrium point with final moisture content of about 12.93 ± 0.14 – 14.31± 0.07 as temperature ranges from 40 °C to 70 °C and air velocity ranges from 0.8m/s to 1.2m/s. The variation in the moisture content and moisture ratio profile of the sorghum residue with time during the drying process under the influence of four different temperatu (40 °C, 50 °C, 60 °C, and 70 °C) in the cabinet dryer is shown in Figure 1 and 2 respectively for the three varieties of sorghum. The figu hows that the moisture content of the residues decreases progressively with increase in the drying time (Figure and similar trend was observed for moisture ratio (Figure 2). However, the increase in the drying temperature (40 °C to 70 °C) lead to an increase in the amou hoisture loss by the residue over the drying time considered in this study, therefore, a significant reduction in the moisture profile (Variation in the moisture content and moisture ratio with time) was recorded as the effect of temperature and similar trend was obtained for all the air velocity that was considered in this study. This explains the fact that the surface moisture evaporates very fast at higher temperature due to high heat and mass transfer during the thin layer drying. It can be pointed out that the drying process is very high at the initial stage of the drying process, but it decreases exponentially when all the surface moisture evaporat he drying heat diffuses inside the material. Similar result was reported for some other agricultural product such as carrot (Aghbashlo *et al.*, 2011), tomato (Ruiz-Celma *et al.*, 2012), and corn (Odjo *et al.*, 2012).

3.1.2 Drying Rate of the Residue

Figure 3 represents the drying rate versus drying time for the three varieties of sorghum residue during convective drying in the cabinet dryer while the graphical representation of the drying rate against the reduced moisture content was presented in Figure 4, show the effect of different temperatures of the drying air (40 ºC - 70 ºC) and air velocity (0.8m/s – 1.2 m/s) on the drying rate of the residues. The curves clearly depict two major drying periods: (1) the drying rate falls more rapidly as it was initially high as a result of more moisture in the sorghum residue and (2) the drying rate decreases slowly until reaching the reduced moisture content and the moisture content at which the changes between this two period occur is known as transition moisture content. The first period corresponds to the evacuation of the free water and the bound water is evacuated during the second period. However, the constant drying rate period was not observed Also, it was observed that the drying rate increased with increase in the temperature and this corroborates the results of some studies mushroom (Arumuganathan *et al.*, 2009), olive pomace (Meziane, 2011) and barberry (Gorjian *et al.*, 2011).

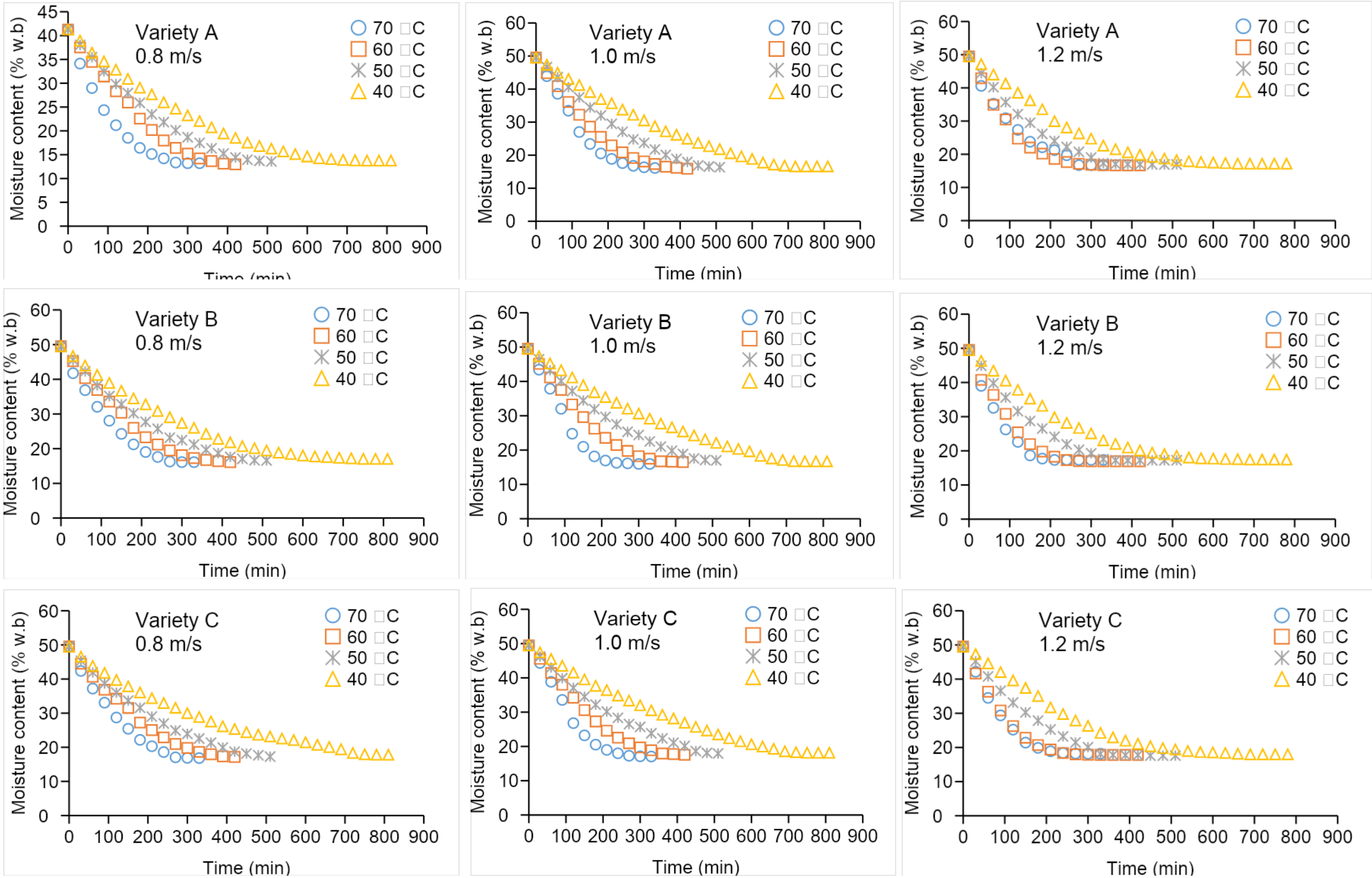

Variety A
0.8 m/s
Variety A
1.0 m/s
Variety A
1.2 m/s
Variety B
0.8 m/s
Variety B
1.0 m/s
Variety B
1.2 m/s
Variety C
0.8 m/s
Variety C
1.0 m/s
Variety C
1.2 m/s
70 □C
60 □C
50 □C
40 □C
Moisture content (% w.b)
Time (min)

Figure 1: Moisture content versus drying time at different temperature and air velocity for variety A, B and C

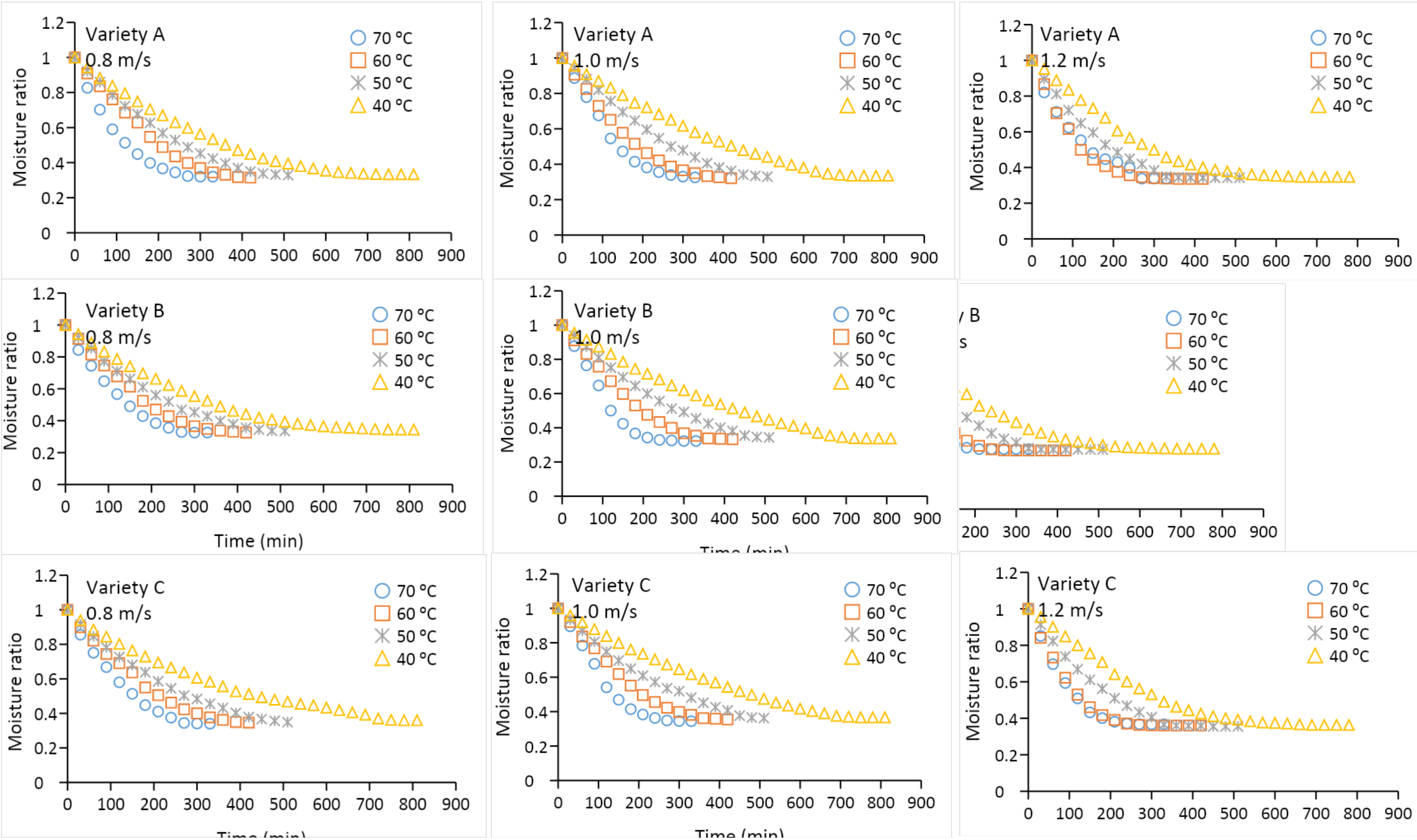

Variety A
0.8 m/s
Variety A
1.0 m/s
Variety A
1.2 m/s
Variety B
0.8 m/s
Variety B
1.0 m/s
Variety C
0.8 m/s
Variety C
1.0 m/s
Variety C
1.2 m/s
70 °C
60 °C
50 °C
40 °C
Moisture ratio
Time (min)
0
0.2
0.4
0.6
0.8
1
1.2
0
100
200
300
400
500
600
700
800
900

Figure 2: Moisture ratio versus drying time at different temperature and air velocity for variety A, B and C

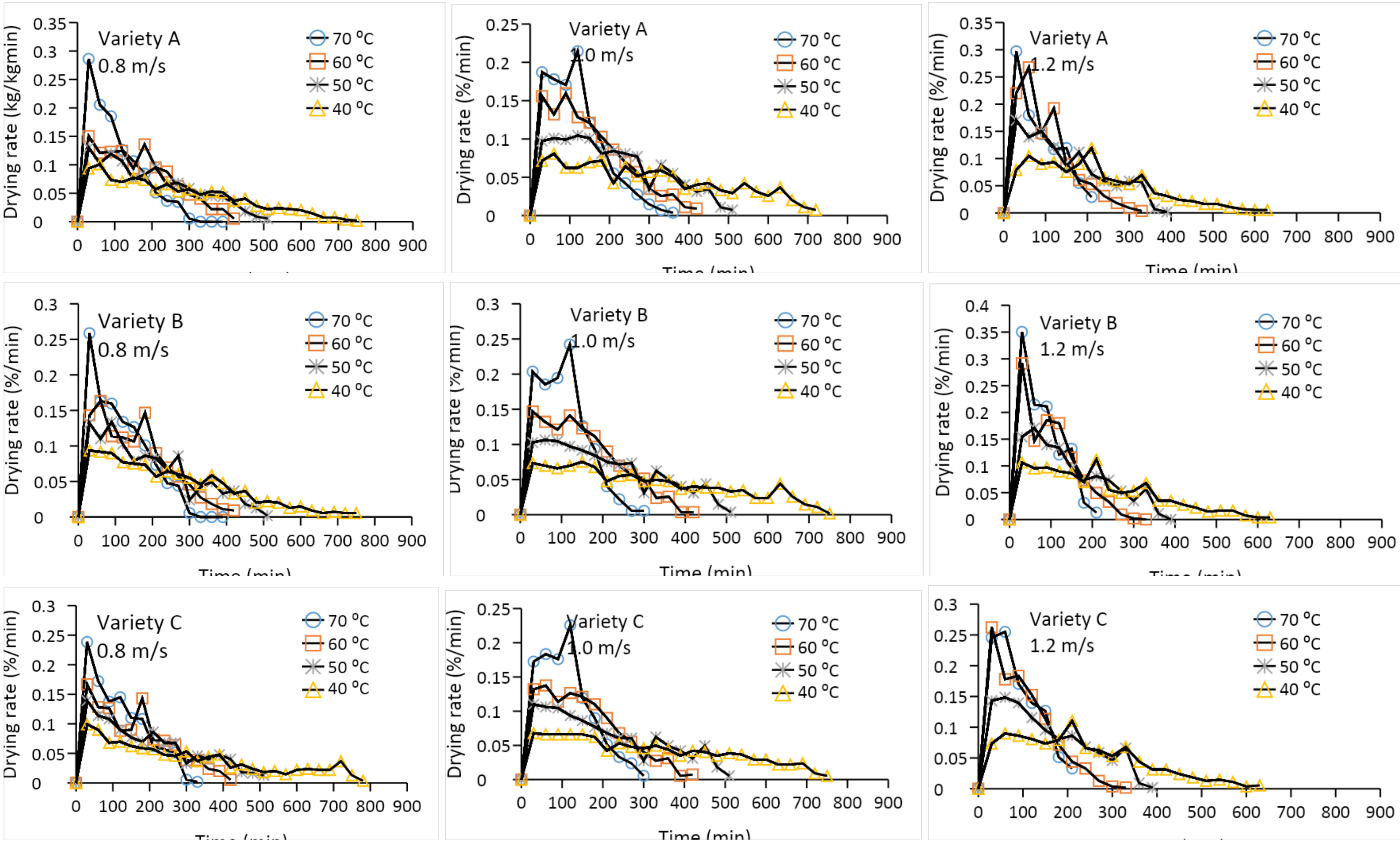
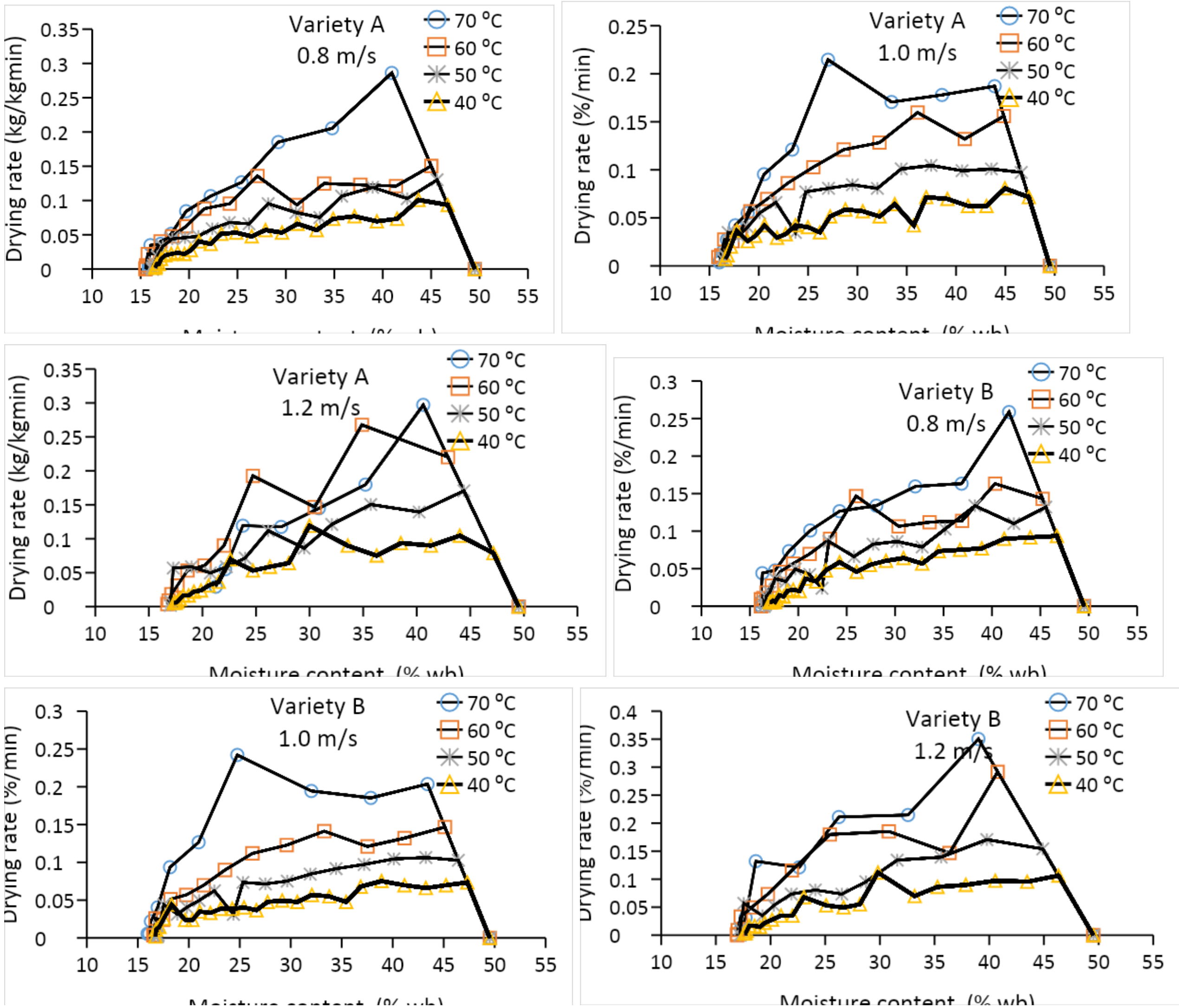


Figure 3: Drying rate versus drying time at different temperature and air velocity for variety A, B and C


Variety A
0.8 m/s
Variety A
1.0 m/s
Variety A
1.2 m/s
Variety B
0.8 m/s
Variety B
1.0 m/s
Variety B
1.2 m/s
70 °C
60 °C
50 °C
40 °C
Drying rate (kg/kgmin)
Drying rate (%/min)
Moisture content (% wb)

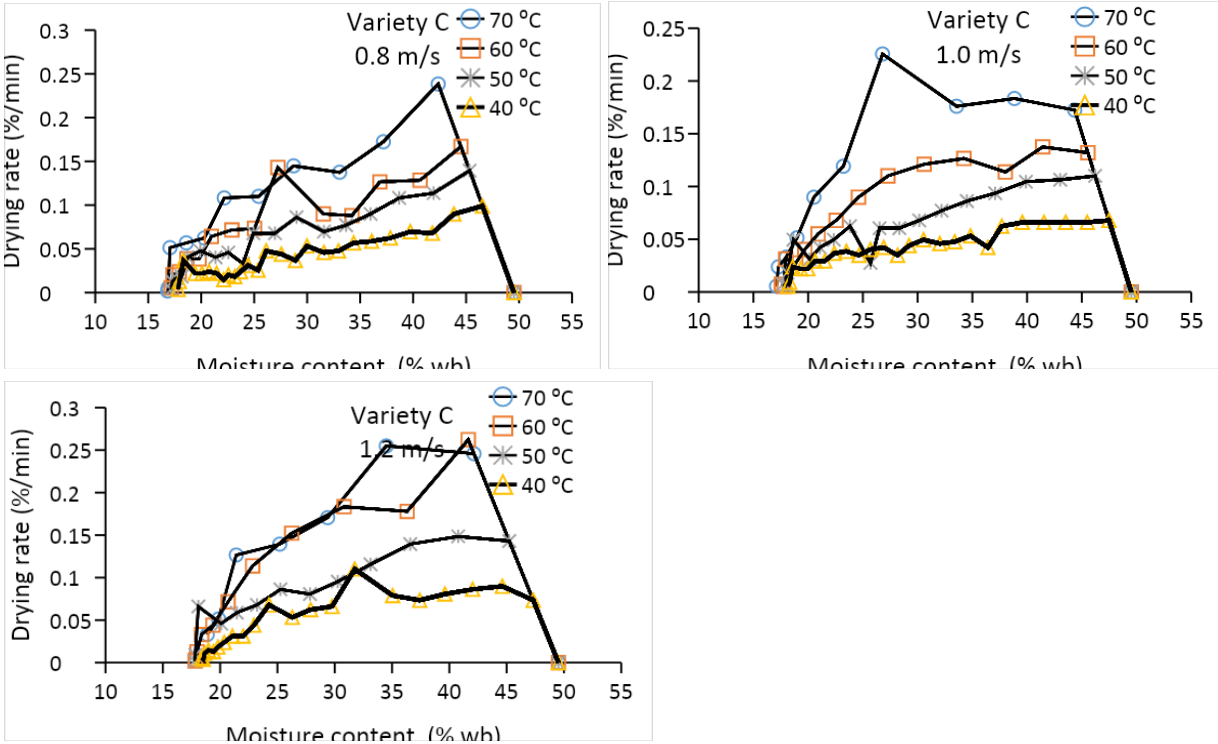


Figure 4: Drying rate versus moisture content at different temperature and air velocity for variety A, B and C

3.2 Modelling of the Drying Curve

The moisture ratio of the sorghum residue during the drying experimentation was calculated as the ratio of the moisture content of the moisture content at every time and the initial moisture content and the data obtained were fitted to ten thin layer existing mathematical models using nonlinear regression approach and the degree of accuracy and precision of the selected thin layer mathematical models were measure and compared using goodness of fit parameter such as coefficient of determination (R^2), root mean square error (RMSE), and the reduced chi-square (χ^2). The result of the fitted model which include the goodness of fit parameter and the fitted model constant for different air temperatures and air velocity are presented in Table 2 which shows that the coefficient of determination (R^2), root mean square error (RMSE), standard error of estimate (SEE), the reduced chi-square (χ^2), and sum of square of error (SSE) values were obtained as $0.8865 \leq R^2 \leq 0.9998$, $0.00035 \leq \text{RMSE} \leq 0.1111$, $0.0000062 \leq \chi$ $2 \leq 0.0154$, respectively. The best model was selected based on the high values of determination coefficient and the low values of root mean square error (RMSE), and the reduced chi-square (χ^2). Among the models considered, the Midilli *et al.*; Wang and Smith;, Modified Henderson and Pabis; Page model gave the best values of coefficient of determination (R^2) above 0.9972 with root mean square error (RMSE), the reduced chi-square (χ^2), values lower than 0.011, and 0.00019 respectively for variety A. The Midilli *et al.*; Wang and Smith;, Modified Henderson and Pabis; Hii *et al.* and Logarithmic model gave the best values of coefficient of determination (R^2) above 0.9961 with root mean square error (RMSE), and the reduced chi-square (χ^2), vaues lower than 0.013, and 0.00025 respectively for variety B whilst The Midilli *et al.*; Wang and Smith;, Modified Henderson and Pabis; Hii *et al.*; Logarithmic model gave the best values of coefficient of determination (R^2) above 0.9986 with root mean square error (RMSE), and the reduced chi-square (χ^2), vaues lower than 0.0078, and 0.000092 respectively for variety C. These models appear then the most adequate in describing the drying processes of sorghum under the experimental conditions studied. However, the Midilli *et al.* model gave comparatively higher coefficient of determination ($R^2 \geq 0.997$) values in most cases, with lower value of root mean square error, the reduced chi-square for variety A and B, while Hii *et al.* model gave comparatively higher coefficient of determination values in most cases, with lower value of root mean square error and the reduced chi-square for variety C. Thus, models were chosen as the most reliable model in predicting the drying behaviour of sorghum residue under different condition in the cabinet dryer.

Table 2: The goodness of fit parameter and model constant for the best models

Variety	Air velocity (m/s)	Temperature	Best model	Model constant	R^2	RMSE	X
A	0.8	70 °C	Midili *et al.*	k = 0.4183, b = 0.04, a = 0.9989, n = 1.0089	0.9998	0.0029	1.215E-05
		60 °C	Midili *et al.*	k = 0.1909, b = 0.0308, a = 0.9857, n = 1.2826	0.9986	0.0083	8.758E-05
		50 °C	Wang and smith	a = -0.1516, b = 0.0084	0.9995	0.0048	2.548E-05
		40 °C	Wang and smith	a = -0.1105, b = 0.0046	0.9997	0.0040	1.705E-05
	1.0	70 °C	Midili *et al.*	k = 0.3206, b = 0.0454, a = 0.9994, n = 1.2374	0.9983	0.0091	0.0001172
		60 °C	Midili *et al.*	k = 0.2362, b = 0.0322, a = 0.997, n = 1.1829	0.9997	0.0035	1.544E-05
		50 °C	Modified henderson pabis	k = 1.5021, a = 0.1002, g = 0.013, b = -0.3054, h = -0.5045, c = 0.003	0.9993	0.0056	4.365E-05
		40 °C	Page	k = 0.0935, n = 1.0199	0.9996	0.0038	1.629E-05
	1.2	70 °C	Midili *et al.*	k = 0.3811, b = 0.0254, a = 0.9994, n = 0.8648	0.9973	0.0105	0.0001659
		60 °C	Modified henderson pabis	k = 2.2518, a = 0.3389, g = 0.8789, b = 0.0353, h = -2.1143, c = 0.1904	0.9972	0.0108	0.0001854
		50 °C	Midili *et al.*	k = 0.2435, b = 0.0319, a = 0.9946, n = 1.119	0.9989	0.0069	6.113E-05
		40 °C	Midili *et al.*	k = 0.1388, b = 0.0239, a = 1.0004, n = 1.2071	0.9989	0.0068	5.414E-05
B	0.8	70 °C	Modified henderson pabis	k = 0.9873, a = 0.3153, g = 0.0241, b = -0.3415, h = -0.0149, c = -0.0079	0.9989	0.0070	8.63E-05
		60 °C	Midili *et al.*	k = 0.2148, b = 0.033, a = 0.991, n = 1.2349	0.9984	0.0087	9.636E-05
		50 °C	Modified henderson pabis	k = 1.0677, a = 0.1682, g = 0.1596, b = -0.126, h = -0.2233, c = -0.0655	0.9994	0.0049	3.356E-05
		40 °C	Midili *et al.*	k = 0.1249, b = 0.0191, a = 0.9914, n = 1.1425	0.9994	0.0049	2.799E-05

	1.0	70 ^{0}C	Hii *et al.*	k = 0.397, g = -0.0101, a = 0.7148, c = 0.2754, n = 1.5287	0.9977	0.0108	0.0001806
		60 ^{0}C	Midili *et al.*	k = 0.2126, b = 0.0345, a = 0.992, n = 1.2528	0.9994	0.0054	3.814E-05
		50 ^{0}C	Wang and smith	a = -0.1408, b = 0.0075	0.9996	0.0046	2.33E-05
		40 ^{0}C	Logarithmic	k = 0.1067, a = 0.9354, c = 0.0701	0.9997	0.0030	1.025E-05
	1.2	70 ^{0}C	Midili *et al.*	k = 0.5338, b = 0.0574, a = 0.9987, n = 1.0276	0.9976	0.0101	0.0001524
		60 ^{0}C	Modified henderson pabis	k = 2.335, a = 0.305, g = 1.0826, b = 0.0288, h = -2.4126, c = 0.1548	0.9960	0.0125742	0.000253
		50 ^{0}C	Midili *et al.*	k = 0.2544, b = 0.0327, a = 0.9994, n = 1.1002	0.9991	0.0060098	4.575E-05
		40 ^{0}C	Midili *et al.*	k = 0.1497, b = 0.023, a = 0.996, n = 1.1446	0.9994	0.0049076	2.827E-05
C	0.8	70 ^{0}C	Hii *et al.*	k = 0.2997, g = -0.3591, a = 0.9768, c = 0.02, n = 1.0025	0.9991	0.0062	5.889E-05
		60 ^{0}C	Modified henderson pabis	k = 24.5943, a = 0.0389, g = 7.2432, b = -0.0231, h = -30.8404, c = 0.0195	0.9986	0.0078	9.148E-05
		50 ^{0}C	Hii *et al.*	k = 0.1664, g = -0.3786, a = 0.9942, c = 0.004, n = 0.9587	0.9996	0.0042	2.281E-05
		40 ^{0}C	Logarithmic	k = 0.1597, a = 0.7121, c = 0.2849	0.9994	0.0041	1.944E-05
	1.0	70 ^{0}C	Hii *et al.*	k = 0.3731, g = -0.0058, a = 0.6797, c = 0.3133, n = 1.515	0.9987	0.0078	9.458E-05
		60 ^{0}C	Hii *et al.*	k = 0.2152, g = -0.037, a = 0.8077, c = 0.1863, n = 1.2786	0.9995	0.0048	3.197E-05
		50 ^{0}C	Hii *et al.*	k = 0.1509, g = -0.6119, a = 1.0034, c = 0.0004, n = 0.9525	0.9994	0.0049	3.131E-05
		40 ^{0}C	Page	k = 0.0883, n = 0.9963	0.9998	0.0024	6.148E-06
	1.2	70 ^{0}C	Midili *et al.*	k = 0.4412, b = 0.058, a = 1.0021, n = 1.0994	0.9991	0.0061	5.572E-05
		60 ^{0}C	Hii *et al.*	k = 0.5096, g = -0.0147, a = 0.6878, c = 0.3059, n = 1.2115	0.9988	0.0068	6.738E-05
		50 ^{0}C	Hii *et al.*	k = 0.2339, g = -0.0643, a = 0.8554, c = 0.1407, n = 1.1472	0.9989	0.0068	6.292E-05

40 ^{0}C	Hii *et al.*	k = 0.1267, g = -0.0073, a = 0.7125, c = 0.2802, n = 1.3633	0.9993	0.0052	3.351E-05

3.3 Effective Moisture Diffusivity

The result of the effective moisture diffusivity of the three varieties of sorghum residue is presented in Table 3. The obtained values of D_{eff} ranges between 9.89 x 10^{-10} and 22.21 x 10^{-10} m^2/s, 9.45 x 10^{-10} and 20.62 x 10^{-10} m^2/s and 8.56 x 10^{-10} and 20.76 x 10^{-10} m^2/s for variety A, B and espectively. The reported D_{eff} values were within the general range of 10^{-11} to 10^{-9} m^2/s for food materials (Doymaz, 2011). The lowest moisture diffusivity value (9.89 x 10^{-10} m^2/s, 9.45 x 10^{-10} and 8.56 x 10^{-10} for variety A, B and C respectively) of the sorghum residue in cabinet dryer was estimated at the lowest air temperature of 40 °C, and the lowest air velocity of 0.8 m/s while the highest moisture diffusivity value (22.21 x 10^{-10} m^2/s, 20.62 x 10^{-10} m^2/s and 20.76 x 10^{-9} m^2/s for variety A, B and C respectively) is achieved at air temperature of 70 °C and air velocity of 1.2 m/s. However, it was observed that D_{eff} values increased greatly with increasing drying temperature from 40 C to 70 °C and increase in air velocity from 0.8 – 1.2 m/s. When sorghum residue at higher temperature, increased heating energy would increase the kinetic energy of water molecules leading to higher moisture diffusivity (Xiao *et al.*, 2010). The values of D_{eff} are comparable with the reported values of 6.27 to 35.0 X 10^{-10} m^2/s for orange slices at 40–80 °C (Rafiee *et al.*, 2010), 1.19 to 4.27 X 10^{-9} m^2/s for pumpkin fruits at 40–80 °C (Tunde-Akintunde and Ogunlakin, 2011), 1.015 to 2.650 X 10^{-9} m^2/s for tomato leathers at 60–100 °C (Demiray and Tulek, 2012) and 1.1 X 10^{-10} to 1.26 X 10^{-9} m^2/s for the drying of terebinth in the temperature range of 40–80 °C (Amiri-Chayjan and Kaveh, 2014).

The activation energy (Ea) for the residue varied from 20.77 – 22.98 kJ/mol, 21.18 – 22.75 kJ/mol and 21.65 – 24.23 kJ/mol as the air velocity varied from 0.8 m/s to 1.2 m/s for different sorghum varieties (Variety A, B, and C respectively), The values of energy of activation for the sorghum residue fall in the range reported (12.7-110 kJ/mol) by Aghbashlo *et al.* (2009) for most food, fruit, and vegetable materials. Also, values of the activation energy for the sorghum varieties are comparable to the the value reported for other agricultural material (Tunde-Akintunde and Ogunlakin, 2010; Ioannou *et al.*, 2011; Chen *et al.*, 2012; Rodriguez *et al.*, 2013; and Lee and Zuo, 2013).

Table 3: Effective moisture diffusivity and activation energy of the sorghum residue during drying.

Variety	Air velocity (m/s)	Parameters	70 °C	60 °C	50 °C	40 °C
A	0.8	Deff (x 10^{-10}m²/s)	19.69	16.92	12.98	9.89
		Do (m²/s)	3.07E-06			
		Ea (J/mol)	20.89			
	1.0	Deff x 10^{-10}m²/s	20.76	16.02	13.91	10.04
		Do m²/s	3.00E-06			
		Ea (J/mol)	20.77			
	1.2	Deff x 10^{-10}m²/s	22.21	15.49	13.97	9.75
		Do m²/s	6.77E-06			
		Ea (J/mol)	22.98			
B	0.8	Deff x 10^{-10}m²/s	20.34	16.05	12.57	9.45
		Do m²/s	5.95E-06			
		Ea (J/mol)	22.76			
	1.0	Deff x 10^{-10}m²/s	20.46	15.75	13.25	9.84
		Do m²/s	3.41E-06			
		Ea (J/mol)	21.19			
	1.2	Deff x 10^{-10}m²/s	20.62	15.20	13.64	9.44
		Do m²/s	4.45E-06			
		Ea (J/mol)	21.94			
C	0.8	Deff x 10^{-10}m²/s	19.62	15.03	12.05	8.56
		Do m²/s	9.62E-06			
		Ea (J/mol)	24.23			
	1.0	Deff x 10^{-10}m²/s	19.56	14.83	12.43	9.08
		Do m²/s	4.56E-06			
		Ea (J/mol)	22.15			
	1.2	Deff x 10^{-10}m²/s	20.76	14.41	13.63	9.43
		Do m²/s	3.95E-06			
		Ea (J/mol)	21.65			

4. CONCLUSIONS

The following conclusion were made based on the findings of this study, titled: Mathematical Modelling of the Drying Characteristic of Milled Sorghurm Residue

1. The initial moisture content obtained for the sorghum residue using standard oven drying method were 41.28 ± 0.33%, 49.52 ± 0.63 % and 47.06 ± 0.42 % on wet basis for the wet residue of variety A, B and C respectively
2. The equilibrium point with final moisture content of about 12.93 ± 0.14 – 14.31± 0.07 as temperature ranges from 40 °C to 70 °C and air velocity ranges from 0.8m/s to 1.2m/s

3. The equilibrium point with final moisture content of about 12.93 ± 0.14 – 14.31± 0.07 as temperature ranges from 40 °C to 70 °C and air velocity ranges from 0.8m/s to 1.2m/s
4. The drying rate falls more rapidly as it was initially high as result of more moisture in the sorghum residue and the drying rate decreases slowly until reaching the reduced moisture content therefore the residue should be dried under a temperature of 70 C and air velocity of 1.2 m/s to attain the lowest moisture content and save time;
5. The obtained values of D_{eff} ranges between 9.89 x 10^{-10} and 22.21 x 10^{-10} m^2/s, 9.45 x 10^{-10} and 20.62 x 10^{-10} m^2/s and 8.56 x 10^{-10} and 20.76 x 10^{-10} m^2/s for variety A, B and C respectively
6. Midilli *et al.* model gave comparatively higher coefficient of determination ($R^2 \geq$ 0.997) values in most cases, with lower value of root mean square error, the reduced chi-square for variety A and B, while Hii *et al.* model gave comparatively higher coefficient of determination values in most cases, with the lowest value of root mean square error and the reduced chi-square for variety C

Reference

Adebiyi, J. A., Obadina, A. O., Adebo, O. A. and Kayitesi, E. (2018). Fermented and malted millet products in Africa: Expedition from traditional/ethnic foods to industrial value added products. *Crit. Rev. Food Sci. Nutr.,* 58, 463–474.

Adebo, O. A. and Medina-Meza, I. E. (2020). Impact of fermentation on the phenolic compounds and antioxidant activity of whole cereal grains: A mini review. Molecules, 25, 927.

Adebo, O. A., Njobeh, P. B., Adebiyi, J. A., Gbashi, S. and Kayitesi, E. (2017a) Food metabolomics (Foodomics), a new frontier in food analysis and its potential in understanding fermented foods. In Functional Food–Improve Health through Adequate Food; Hueda, M.C., Ed.; *InTech: Rijeka, Croatia*, pp. 211–234.

Adebo, O. A., Njobeh, P. B., Adebiyi, J. A., Gbashi, S., Phoku, J. Z., and Kayitesi, E. (2017b). Fermented pulse-based foods in developing nations as sources of functional foods. In Functional Food–Improve Health through Adequate Food; Hueda, M.C., Ed.; *InTech: Rijeka, Croatia*,; 77–109.

Adebo, O. A., Njobeh, P. B., Mulaba-Bafubiandi, A. F., Adebiyi, J .A., Desobgo, S. C. Z. and Kayitesi, E. (2018). Optimization of fermentation conditions for ting production using response surface methodology. *J. Food Process Preserv.,* 42, e13381.

Aghbashlo, M., Kianmehr, M. H. and Arabhosseini, A. (2009). Modeling of thin-layer drying of potato slices in length of continuous band dryer. *Energy Convers. Manage*. 50, 1348–1355.

Aghbashlo, M., Kianmehr, M. H., Arabhosseini, A. and Nazghelichi, T. (2011). Modelling the carrot thin-layer drying in a semi-Industrial continuous band dryer. *Czech J. Food Sci*. 29, 528–538.

Akingbala, J., Rooney L.W. and Faubion J. M. (2004). A laboratory procedure for the preparation of Ogi, a Nigerian fermented Food. *Journal of Food Science* 12: 57-64

Alan, P. A., Ofelia, R. S., and Patricia T. M. (2012). Cereal bran and whole grain as a source of dietary fibre: technological and health aspects. *Int J Food Sci Nutr* 63:882–892. https://doi.org/10.3109/09637486.2012.676030

Amadou I, Gounga ME, Le G-W (2013). Millets: nutritional composition, some health benefits and processing—A review. *Emir J Food Agric* 25:501–508. https://doi.org/10.9755/ejfa.v25i7.12045

Amiri Chayjan, R. and Kaveh, M. (2014). Physical parameters and kinetic modeling of fix and fluid bed drying of terebinth seeds. *J. Food Process Preserv*. 38, 1307–1320.

Arumuganathan, T., Manikantan, M. R., Rai, R. D., Anandakumar, S. and Khare, V. (2009). Mathematical modeling of drying kinetics of milky mushroom in a fluidized bed dryer. *Int. Agrophys*. 23, 1–7.

ASAE (1983). Transactions of the ASAE. 26 (4): 1258-1263. (doi: 10.13031/2013.34113)

Celma A. R., Rojas S., Lopez F., Montero I. and Miranda T. (2007). Thin-layer drying behaviour of sludge of olive oil extraction. *Journal of Food Engineering,* 80: 1261-1271.

Chen, D., Zheng, Y. and Zhu, X. (2012). Determination of effective moisture diffusivity and drying kinetics for poplar sawdust by thermogravimetric analysis under isothermal condition. *Bioresource Technol*. 107, 451–455.

Crank, J. (1975). The Mathematics of Diffusion, 2nd edition. Clarendon Press, Oxford

Delcourm J, A. and Hoseney, R. (2010). Principles of cereal science and technology. AACC International press, USA

Demiray, E. and Tulek, Y. (2014). Drying characteristics of garlic (Alliumnm sativum L) slices in a convective hot air dryer. *Heat Mass Transf.* 50 (6):779–786

Demiray, E., and Tulek, Y. (2012). Thin-layer drying of tomato (Lycopersicum esculentum Mill. cv. Rio Grande) slices in a convective hot air dryer. *Heat and Mass Transfer*, 48(5), 841-847. http://dx.doi.org/10.1007/s00231-011-0942-1.

Doymaz I. (2005). Sun drying of figs: An experimental study. *Journal of Food Engineering*, 71; 403-407.

Doymaz, I. (2011). Thin-layer drying characteristics of sweet potato slices and mathematical modelling. *Heat and Mass Transfer*, 47(3), 277-285. http://dx.doi.org/10.1007/s00231-010-0722-3.

FAOSTAT (2020). Food and Agriculture Organization Statistics. Available online: http://www.fao.org/faostat/en/ #data/QC (accessed on 31 March 2020).

Farhad, M., Kailasapathy, K. and Tamang, J. P. (2010). Health aspects of fermented food. In Fermented Foods and Beverages of the World; Tamang, J.P., Kailasapathy, K., Eds.; CRC Press: London, UK,; pp. 391–414.

Galati, A., Oguntoyinbo, F. A., Moschetti, G., Crescimanno, M. and Settanni, L. (2014). The cereal market and the role of fermentation in cereal-based food production in Africa. *Food Rev. Int.,* 30, 317–337.

Gorjian, Sh., Tavakoli Hashjin, T., Khoshtaghaza, M. H. and Nikbakht, A. M. (2011). Drying kinetics and quality of barberry in a thin layer dryer. J. Agric. Sci. Technol. 13, 303–314.

Hemery, Y., Chaurand, M., Holopainen, U., Lampi, A. M., Lehtinen, P., Piironen, V., Sadoudi, A., and Rouau, X. (2011a). Potential of dry fractionation of wheat bran for the development of food ingredients, part I: influence of ultra-fine grinding. *J Cereal Sci* 53:1–8. https://doi.org/10.1016/j.jcs.2010.09.005

Hemery, Y., Holopainen, U., Lampi, A. M., Lehtinen, P., Nurmi, T., Piironen, V., Edelmann, M. and Rouau, X. (2011b). Potential of dry fractionation of wheat bran for the development of food ingredients, part II: electrostatic separation of particles. *J Cereal Sci* 53:9–18. https://doi.org/10.1016/j.jcs.2010.06.014

Ioannou, I., Guiga, W., Charbonnel, C. and Ghoul, M. (2011). Frozen mirabelle plum drying: Kinetics, modelling and impact on biochemical properties. Food Biophys. Process. 89, 438–448.

Kaleemullah, S., and Kailappan, R. (2006). Modelling of thin-layer drying kinetics of red chillies. *Journal of Food Engineering*, 76(4), 531-537. http://dx.doi.org/10.1016/j.jfoodeng. 2005.05.049.

Karathanos V. T. (1999). Determination of water content of dried fruits by drying kinetics . *Journal of Food Engineering 39:337-344.*

Kashaninejad M., Mortazavi A., Safekordi A. and Tabil L. G. (2007). Thin-layer drying characteristics and modeling of pistachio nuts. *Journal of Food Engineering,* 78:98-108.

Lee, J. H. and Zuo, L. (2013). Mathematical modeling on vacuum drying of Zizyphus jujuba Miller slices. *J. Food Sci. Technol.* 50, 115–121.

Mabhaudhi, T., O'Reilly, P., Walker, S. and Mwale, S. (2016). Opportunities for underutilised crops in Southern Africa's post-2015 development agenda. *Sustainability,* 8, 302.

Marconi, E., Graziano, M. and Cubadda, R. (2000). Composition and utilization of barley pearling by-products for making functional pastas rich in dietary fiber and b-glucans. *Cereal Chem* 77:133–139. https://doi.org/10.1094/CCHEM.2000.77.2.133

Meziane, S. (2011). Drying kinetics of olive pomace in a fluidized bed dryer. *Energy Conserv. Manage*. 52, 1644–1649

Midilli A. and Kucuk H. (2003). Mathematical modeling of thin layer drying of pistachio by using solar energy. *Energy Conversion Management 44, (11): 11-22.*

Midilli A., Kucuk H. and Yapar Z (2002). A new model for single layer drying. *Drying Technology, 20(7): 1503-1513.*

Min, B., McClung, A. M. and Chen, M. H. (2011). Phytochemicals and antioxidant capacities in rice brans of different colour. J Food Sci 76:117–126. https://doi.org/10.1111/j.1750-3841.2010.01929.x

Minaei, S., Motevali, A., Ahmadi, E., and Azizi, M. H. (2012). Mathematical models of drying pomegranate arils in vacuum and microwave dryers. *Journal of agricultural Science and Technology*, 14, 311-325

Odjo, S., Malumba, P., Dossou, J., Janas, S. and Bera, F. (2012). Influence of drying and hydrothermal treatment of corn on the denaturation of salt-soluble proteins and color parameters. *J. Food Eng*. 109, 561–570.

Odunmbaku, L. A., Sobowale, S. S., Adenekan, M. K., Oloyede, T., Adebiyi, J. A. and Adebo, O. A. (2018). Influence of steeping duration, drying temperature, and duration on the chemical composition of sorghum starch. *Food Sci. Nutr.,* 6, 348–355.

Rafiee, S., Sharifi, M., Keyhani, A., Omid, M., Jafari, A. and Mohtasebi, S. S. (2010). Modeling effective moisture diffusivity of orange slices (Thompson Cv.). *Int. J. Food Prop*. 13, 32–40.

Rodriguez, I., Clemente, G., Sanjuan, N. and Bon, I. (2014). Modelling drying kinetics of thyme (Thymus vulgaris L.): Theoretical and empirical models, and neural networks. *Food Sci. Technol. Int*. 20, 13–22.

Ruiz Celma, A., Cuadros, F. and Lopez-Rodriguez, F. (2012). Convective drying characteristics of sludge from treatment plants in tomato processing industries. *Food Biophys. Process*. 90, 224–234

Schober, T. J. and Bean, S. R. (2008). Sorghum and maize. In Gluten-Free Cereal Products and Beverages; Arendt, E.K., Bello, F.D., Eds.; Elsevier: Amsterdam, The Netherlands,; pp. 101–118.

Slavin, J. L., Jacobs, D. and Marquart, L. (2001). Grain processing and nutrition. *Crit Rev Biotechnol* 21:49–66. https://doi.org/10.1080/10408690091189176

Sobowale, S. S., Adebo, O. A., and Mulaba-Bafubiandi, A. F. (2019). Production of extrudate pasta from optimal-sorghum-peanut flour blend and influence of composite flours on some quality characteristics and sorption isotherms. *Trans. Royal Soc. S. Afr.,* 74, 268–275.

Sogi D. S., Shivahare U. S., Garg S. K and Bawa S. A. (2003). Water sorption isotherms and drying characteristics of btomato seeds. *Biosystems Engineering,* 84(3): 297-301.

Tamang, J. P. (2007). Fermented foods for human life. In Microbes for Human Life; Chauhan, A.K., Verma, A., Kharakwal, H., Eds.; I.K International Publishing House Pvt: New Delhi, India, 2007; pp. 73–87

Taylor, J. R. N. and Duodu, K. G. (2015). Effects of processing sorghum and millets on their phenolic phytochemicals and the implications of this to the health-enhancing properties of sorghum and millet food and beverage products. J. Sci. Food Agric. 95, 225–237

Taylor, J. R. N. and Duodu, K. G. (2017). Sorghum and millets: Grain quality characteristics and management of quality requirements. In Cereal Grains; Wrigley, C., Batey, I., Miskelly, D., Eds.; Elsevier: Amsterdam, The Netherlands,; pp. 317–351.Rosales, E., Pasoz, M. and Sanroman, M. A. (2018). Solid-state fermentation for food applications. In Current Developments in Biotechnology and Bioengineering; Pandey, A., Larroche, C., Soccol, C., Eds.; Elsevier: Amsterdam, The Netherlands,; pp. 319–355.

Togrul I. T. and Pehlivan D. (2004). Modeling of thin layer drying kinetics of some fruits under open air sun drying process. *Journal of Food Engineering* 65 (3): 413-425.

Tsadik, Y. Y. G. and Emire, S. A. (2015). Development of value added products from byproducts of Ethiopian wheat milling industries. *J Food Process Technol* 6:8. https://doi.org/10.4172/2157-7110.1000474

Tunde-Akintunde, T. Y. and Ogunlakin, G. O. (2011). Influence of drying conditions on the effective moisture diffusivity and energy requirements during the drying of pretreated and untreated pumpkin. *Energy Conserv. Manage*. 52, 1107–1113

Wang C. Y and Singh R. P. (1978). A single layer drying equation for rough rice. *American society Agricultural engineering, paper No. 78-3001, St. Joseph, MI, USA.*

Wang Z., Sun J., Liao X., Chen F., Zhao G., Wu J. and Hu X. (2007). Mathematical modeling on hot air drying of thin layer apple pomace. *Food Research International,* 40: 39-46.

Xiang, H., Sun-Waterhuse, D., Waterhouse, G. I. N., Cui, C. and Ruan, Z. (2019). Fermentation-enabled wellness foods: A fresh perspective. *Food Sci. Hum. Well,* 8, 203–243.

Zitterman, A. (2003). Bran. In: Caballero B, Trugo LC, Finglas PM (eds) Encyclopedia of food science and nutrition, 2nd edn. Academic press, Amsterdam, pp 1844–1850