Journal of the Ghana Institution of Engineering (2023) 23:4
https//doi.org/10.56049/jghie.v23i4.104

ORIGINAL RESEARCH

Thin-layer mathematical modelling of maize in a biomass-powered inclined bed dryer

Paxwell D. Adjei[1,*], Joseph O. Akowuah[1], George Obeng-Akrofi[2], Edward A. Awafo[3]

Received: 13th March, 2023 / **Accepted:** 26th June, 2023
Published online: 27th November, 2023

Abstract

In this study, the drying kinetics of maize dried in a biomass-powered inclined bed dryer were studied using ten (10) thin-layer mathematical drying models. The drying system recorded an average plenum temperature of 73.54 ˚C during the drying experiment compared to an average ambient temperature of 28.41 ˚C. Maize grains with an initial average moisture content of 23.25 % on a wet basis were reduced to 13.61 % average final moisture content over a drying period of 2 hours 40 minutes. The results revealed a moisture extraction rate, drying rate, and drying efficiency of 6.70 kg/h, 9.50 kg/h, and 71.37 %, respectively. The two-term model best describes the thin-layer drying kinetics of maize in the biomass-powered inclined bed dryer based on the coefficient of determination (R^2) and root mean square error (RMSE) values of 0.998 and 0.00738, respectively. The two-term model showed a better fit between the experimental and the predicted moisture ratios. The drying process occurred in the falling rate period with an effective moisture diffusivity of 4.65×10^{-9} m^2/s and activation energy of 21.31 kJ/mol. The two-term model was able to imitate the behaviour of the drying process of maize in the drying system. The model would assist in predicting the drying time for different moisture contents of maize in the scale-up of the drying system and, accordingly, help farmers and agro-processors in planning drying schedules. The drying kinetics of other staples like cassava and rice are recommended for further studies using the biomass-powered inclined bed dryer.

Keywords: Thin-layer Drying, Kinetic Modelling, Effective Moisture Diffusivity, Activation Energy

Introduction

Maize is Ghana’s most important cereal grain, accounting for approximately half of the total cereal production (Darfour and Rosentrater, 2016). In 2019, Ghana recorded a production output of 3.06 million metric tonnes of maize (MoFA, 2020). Maize is often linked to household food security, with low-income households considered food insecure if they do not have maize on reserve, regardless of other commodities available (Tweneboah, 2000). Ghana's average yields are below what is achievable, and post-harvest losses are significantly high (Alhassan and Kumah, 2018).

Drying is a critical post-harvest unit operation along the maize production value chain practised by farmers in Ghana. These farmers are ordinarily smallholders relying mainly on sunlight to dry their grains. However, these smallholder farmers frequently experience grain losses due to insect infestation, mould growth, and discolouration due to improper grain drying (Akowuah *et al*., 2015). Post-harvest loss of maize is a threat to food security; it causes financial loss to farmers and countries at large and it’s a disincentive especially for the youth regarding their interest to go into farming.

The use of mechanical dryers offers many opportunities that overcome challenges encountered using sun-dependent drying methods. The energy source for these dryers is usually diesel or liquefied petroleum gas (LPG) and according to Kaaya and Kyamuhangire (2010), such drying systems consume a lot of energy and are also quite expensive to operate. This calls for a cost-effective energy source for mechanical drying systems. Biomass-powered dryers utilise biomass such as maize cobs, palm nut shells, bamboo and other agro-residues that are abundant, freely available, and easily accessible in farming communities.

Given the importance of drying kinetics, the modelling of thin-layer drying of grains is essential for conceptualizing the basic transport mechanism and is a requirement for the successful simulation or scale-up of the entire process for optimization of the drying conditions (Inyang *et al*., 2018). The modelling of the drying process is one of the most crucial aspects of drying technology. The design and optimization of dryers benefit greatly from the ability to predict the kinetics of drying agricultural products under various conditions. In order to achieve optimal performance, grain drying simulation, thus, imitation of a drying system or process' behaviour is useful in the design process (Afriyie *et al*., 2013; Akowuah *et al*., 2021). Many researchers have created various drying models for a variety of crops (Page 1949; Wang and Singh, 1978) but these studies focused on solar drying and mechanical drying technologies using electricity, diesel and liquefied petroleum gas heat sources. This study sought to investigate the thin-layer mathematical modelling of maize in a newly developed prototype inclined bed dryer utilising biomass as the main source of energy for drying maize.

*Corresponding author: adjeipaxwell@gmail.com

[1]Department of Agricultural and Biosystems Engineering, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana

[2]Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, Iowa USA

[3]Department of Agricultural and Bioresources Engineering, University of Energy and Natural Resources, Sunyani, Ghana

Materials and Methods

Study area

The study was conducted at the Department of Agricultural and Biosystems Engineering, Kwame Nkrumah University of Science and Technology, Kumasi. The study area is located at 6° 415 'N and 1°34 'W in latitude and longitude, respectively, approximately 270 kilometres north of Ghana's capital (GSS, 2014). KNUST is in the Kumasi Metropolis of the Ashanti Region. The area has a bimodal rainfall distribution with an annual mean rainfall of 1484 mm (GSS, 2014).

Dryer description

The biomass-powered inclined bed dryer was designed and fabricated at the Department of Agricultural and Biosystems Engineering, KNUST, Kumasi, Ghana. The drying system consists of a combustion unit, a blower unit, and a drying chamber

The blower unit connects the combustion chamber to the

ISSN: 0855-0743/

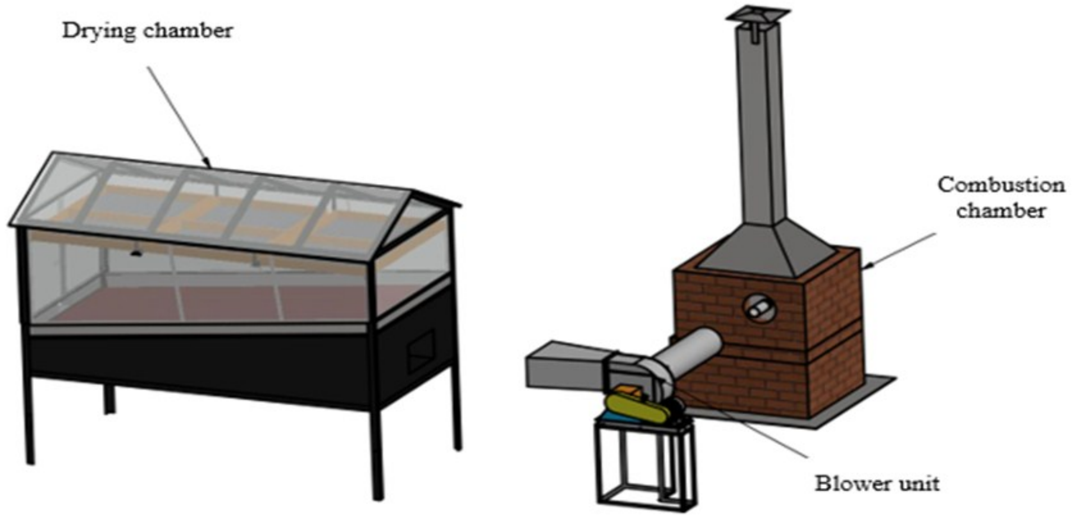

Figure 1 Schematic illustration of the biomass-powered inclined bed dryer

Figure 2 Experimental set-up of drying maize in the biomass-powered inclined bed dryer

drying chamber. Heated air generated in the combustion chamber using biomass fuel (bamboo) is sucked by the blower and delivered into the plenum for maize drying. The drying chamber consists of a plenum with a 7˚ (degrees) inclined removable drying bed made from 0.003 m thickness mild steel metal bars, and a transparent perspex sheet housing with vents as shown in Figure 1. The dryer bed is rectangular in shape with 2.5 m length, 1.3 m width, and 0.1 m depth. At the lower end of the dryer bed is the outlet for offloading after drying. The inclination of the dryer bed additionally allows easy offloading of the maize through the exit after drying.

Experimental procedure

Freshly harvested yellow maize (*Honampa* variety) with predetermined moisture content from KNUST Agricultural Research Station farm at Anwomaso (GPS Coordinates 6.70098, -1.53569) was used for the experimental study. A quantity of 200 kg of maize was measured using the weighing scale and spread over the dryer bed to ensure uniformity as shown in Figure 2. The combustion of the biomass fuel started 15 minutes before the start of the blower to allow enough heating of the heat exchanger before the suction of heated air through the blower unit to the plenum. The temperature in the drying system was determined at 10 minutes intervals using temperature sensors (Tinytag Plus 2 data logger, TGP-4520). The moisture content of the drying maize was measured three (3) times at 20 minutes intervals until a final moisture content of 13 % to 14 % (w.b) was obtained. The experiment was repeated in three (3) replicates and the average measurement was determined.

Dryer performance indices

The dryer performance was evaluated based on moisture extraction rate, drying rate, and the drying efficiency represented mathematically from Equation (1) to Equation (3), respectively.

Moisture extraction rate (MER)

The moisture extraction rate was calculated using Equation (1):

$$MER = \frac{\left(W_i \times \dfrac{M_i - M_f}{100 - M_f}\right)}{t} \qquad (1)$$

Where MER = moisture extraction rate (%/h)., W_i = Initial mass of grains dried (kg), M_i = initial moisture content (% w.b), M_f = final moisture content (% w.b) and t = total time (h).

Drying rate (DR)

The drying rate was calculated using Equation (2):

$$DR = \left(\frac{M_w}{d_t}\right) = \frac{m_i - m_f}{t} \qquad (2)$$

Where, DR = drying rate (kg/h), m_w = change in mass (kg), d_t = change in time (h), m_i = initial mass of maize samples (kg), and m_f = final mass of maize samples (kg).

Table 1 Mathematical models for thin-layer drying curves

Model	Equation	Reference
Newton	$MR = \exp(-kt)$	Mujumdar (2006)
Two-term	$MR = a \times \exp(-k_1t) + b \times \exp(-k_2t)$	Henderson (1974)
Page	$MR = \exp(-kt^n)$	Page (1949)
Henderson and Pabis	$MR = a \times \exp(-kt)$	Zhang and Litchfield (1991)
Logarithmic	$MR = a \times \exp(-kt) + b$	Yagcioglu (1999)
Wang and Singh	$MR = 1 + at + bt^2$	Wang and Singh (1978)
Weibull	$MR = \exp(-t/a)^{b}$	Vega-Gálvez *et al*. (2010)
Two-Term Exponential	$MR = a \times \exp(-kt) + (1-a) \times \exp(-kat)$	Sharaf-Eldeen *et al*. (1980)
Midilli kucuk	$MR = a \times \exp(-kt^n) + bt$	Doymaz, (2008).
Modified Page	$MR = \exp[-(kt)^n]$	White *et al*. (1980)

Drying efficiency (η)

The drying efficiency, η was determined using Equation (3):

$$\eta = \frac{M_{ER} \times L_v}{Mair \times Cp_{air} \times \Delta T} \quad (3)$$

where, η = drying efficiency (%), M_{ER} = rate of moisture evaporation (kg/h), M_{air} = mass flow rate of air (kg/h), Cp_{air} = specific heat capacity of air (kJ/kg. ˚C) Lv = Latent heat of vaporisation of water (kJ/kg), and ΔT = change in temperature between the drying air and ambient (˚C).

.

Thin-layer mathematical modelling

In the simulation of the thin-layer drying process, empirical models are crucial for describing water removal, and heat penetration when heated air is used (Da Silva *et al*., 2014). In this study, the calculated moisture ratio (MR) from Equation (5) was fitted into ten (10) thin-layer drying models to describe the drying kinetics of the biomass-powered inclined bed dryer. The selected ten (10) thin-layer drying models used in the study are shown in Table

The moisture ratio of the drying maize in the dryer was calculated using Equation (4):

$$MR = \frac{M_t - M_e}{M_o - M_e} \quad (4)$$

Where MR = moisture ratio, M_t = moisture content on a dry basis at any drying time (t), M_e = equilibrium moisture content on a dry basis, and M_o = the initial moisture content on a dry basis. For long drying periods, M_e values are relatively small as compared to M_t and Mo (Hussein *et al*., 2016). Hence, Equation (4) is simplified to Equation (5) as:

$$MR = \frac{M_t}{M_o} \quad (5)$$

Mathematical model fitting

To determine the best fit Equation to account for variation in the drying curves of the dried maize samples, the coefficient of determination (R^2), which is the square of the correlation between the experimental and calculated values, and the Root Mean Square Error (RMSE), thus, the deviation between the predicted and experimental values were utilized as major criteria. The equations for the Root Mean Square Error (RMSE) and coefficient of determination (R^2) are shown in Equation (6) and Equation (7), respectively.

$$RMSE = \left[\frac{\Sigma^{N}_{i=1}(MR_{rei} - MR_{ex,I})}{N}\right]^{0.5} \quad (6)$$

$$R^2 = 1 - \frac{residual\ SS}{Corrected\ total\ SS}^{0.5} \quad (7)$$

Where SS = sum of squares, $MR_{pre,i}$ = predicted moisture ratio, $MR_{exp,i}$ = experimental moisture ratio, and N = number of observations.

Effective moisture diffusivity

The mechanism of moisture diffusivity during the falling rate period of drying was estimated using 'Fick's diffusion equation. Consideration was made for a constant moisture diffusivity, infinite slab geometry and uniform initial moisture distribution (Wang *et al*., 2018). Using Fick's second law, effective moisture diffusivity is estimated using the following equations.

$$MR = \frac{8}{\pi^2}\Sigma^{N}_{n=0}\frac{1}{(2n+1)^2}exp\left(-\frac{(2n+1)^2\pi^2}{d_t}D_{eff}t\right) \quad (8)$$

For long drying period, Equation (8) was simplified as:

$$(MR) = \left(\frac{8}{\pi^2}\right)\exp\left(\frac{\pi^2 D_{eff}t}{4L^2}\right) \quad (9)$$

Equation (9) can be linearized as:

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}t}{4L^2}\right) \quad (10)$$

$$k = \left(\frac{\pi^2 D_{eff}t}{4L^2}\right) \quad (11)$$

Where $D_{eff}t$ = effective moisture diffusivity (m^2/s) at drying time (t), K = slope for a plot of In(MR) against drying time (t), and L = half the thickness (meters) of the sample.

Activation energy

Activation energy is the minimal amount of energy needed to initiate the drying process (Aghbashlo and Samimi-Akhijahani, 2008). The Arrhenius type equation which describes the relationship between the effective moisture diffusivity with temperature was used to compute the activation energy. The Arrhenius type equation is shown in Equation (12):

$$D_{eff} = D_o exp\left(-\frac{E_a}{RT}\right) \quad (12)$$

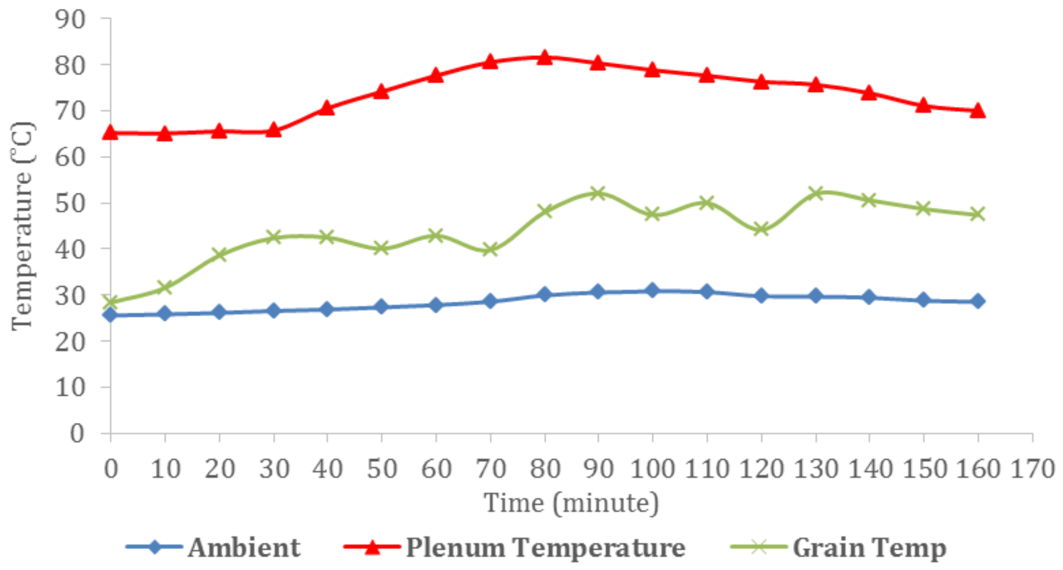

Figure 3 Temperature distribution in the drying system

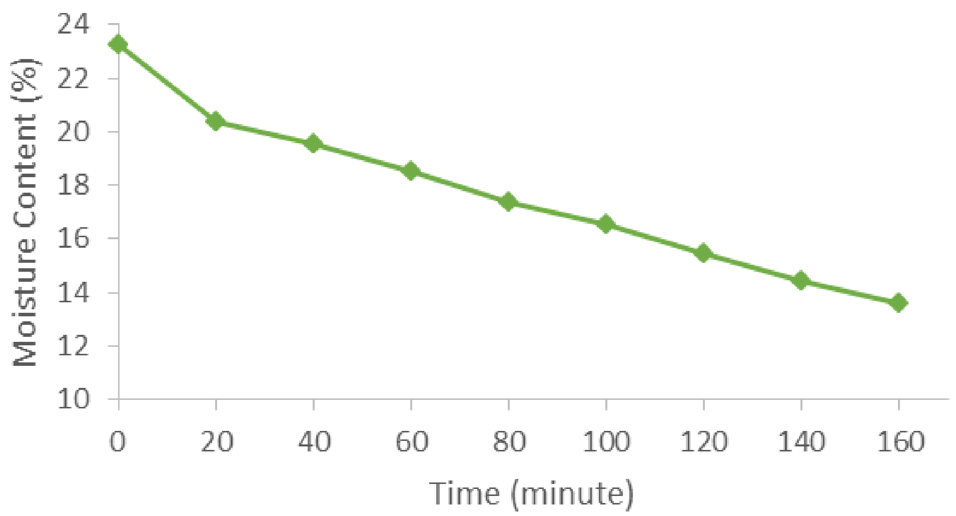

Figure 4 Moisture content versus drying time

Table 2 Results of the mathematical thin-layer drying models

Model Name	Parameters	R^2	RMSE
Newton	k = 0.06948	0.9689	0.02327
Two-term	**a = 0.05839, b = 0.9416** **k_1 = 20.85, k_2 = 0.05774**	**0.9980**	**0.00738**
Page	k = 0.1012 n = 0.7801	0.9923	0.0124
Henderson and Pabis	a = 0.9681 k = 0.06312	0.9846	0.01748
Logarithmic	a = 0.6364 b = 0.3428 k = 0.1152	0.9876	0.01693
Wang and Singh	a = -0.07878 b = 0.003597	0.9795	0.0202
Weibull	a = 47.66 b = 3.314	0.9689	0.02488
Two-term exponential	a = 0.05264 k = 1.128	0.9923	0.01238
Midilli kucuk	a = 0.9923, b = 3.227e-07 k = 0.09477, n = 0.8059	0.9927	0.01426
Modified Page	k = 0.05306 n = 0.7801	0.9923	0.0124

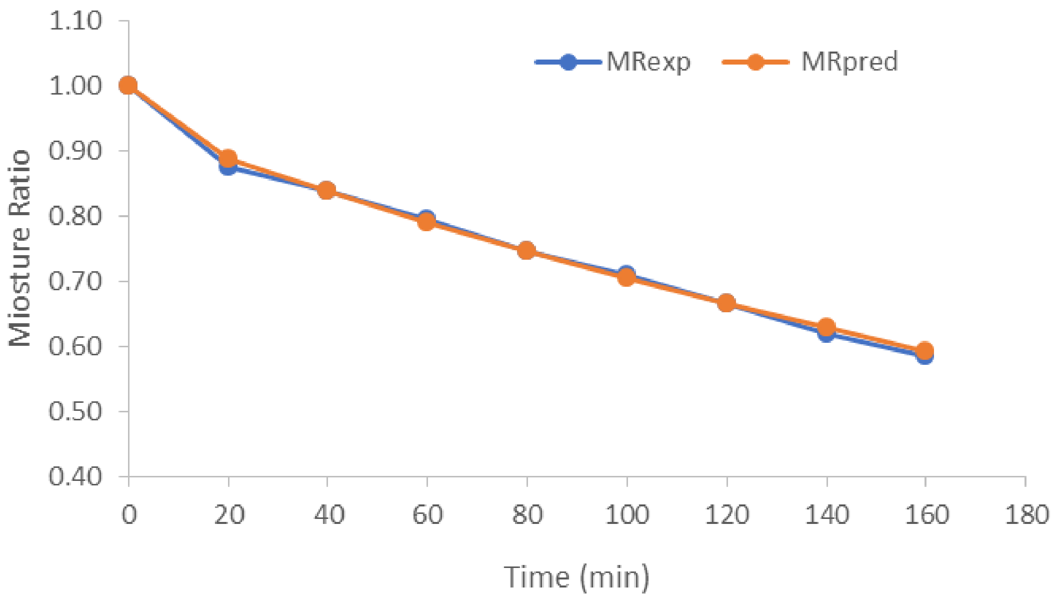

Figure 5 Curves for experimented and predicted moisture ratios

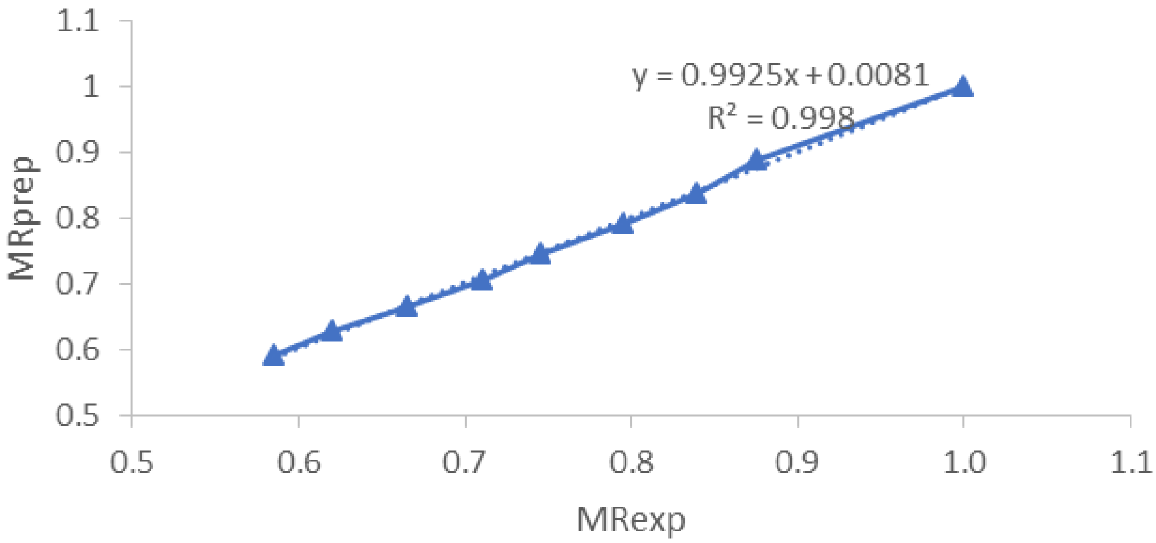

Figure 6 Experimental versus Two-term predicted moisture ratios

Where E_a = activation energy (kJ/mol), R = universal gas constant (8.3143 kJ/mol), T = absolute air temperature (K), and D_o = pre-exponential factor of the equation (m^2/s). After a plot of ln(Deff) against 1/T according to Equation (12), the slope K_1 was used in calculating the activation energy from Equation (13).

$$K_1 = \left(\frac{E_a}{R}\right) \tag{13}$$

Results and Discussion

Temperature variation in the drying system

After 15 minutes of biomass burning in the biomass chamber, the blower was switched on and an average drying air temperature of 65.23 ˚C was recorded in the plenum against 25.58 ˚C ambient temperature as shown in Figure 3. The highest drying air temperature of 81.63 ˚C was recorded at the 80th minute of the experiment. The drying system recorded an average drying air temperature of 73.54 ± 5.74 ˚C compared to an average ambient temperature of 28.42 ± 1.76 ˚C.

It is important to state that for the purpose of drying grains for seed production, the drying temperature should be 50 ˚C or less as reported by Akowuah *et al*. (2022). The grain temperature increased with increased in drying air temperature and vice versa. The grain temperature and drying air temperature were in the range of 28.4 ˚C – 52.1 ˚C and 65.12 ˚C – 81.63 ˚C, respectively. The relatively high temperature variation with time in the plenum compared to the ambient, which resulted in the high grain temperature was due to the timely restocking of the biomass fuel (bamboo) used for combustion to generate heat for the drying process. Similar observation was reported by Akowuah *et al*. (2018) and Obeng-Akrofi *et al*. (2021) on maize drying using biomass heat source.

Moisture variation of maize

The moisture content variation of maize during the drying process over time in the biomass-powered inclined-bed dryer is shown in Figure 4. It was observed that the moisture content of the maize decreased with time during the drying process, which occurred in the falling rate period. The drying of the maize grains resulted in a reduction of moisture content from an MC of 23.25 ± 0.02 % (w.b) to 13.61 ± 0.13 % (w.b) within 2 hours and 40 minutes drying period with a specific energy consumption of 25.70 MJ/kg. The drying time was shorter due to the dryer's capacity relative to the amount of biomass feedstock used for the drying process. Comparatively, the drying time reported in this study was about half what was observed for a similar study on maize drying in a 1-tonne capacity dryer using a biomass heat source by Akowuah *et al*. (2018).

The maize was dried at average drying rate and drying efficiency of 9.50 kg/h and 71.37%, respectively. The high drying rate could be attributed to the moderately high drying air temperature from the plenum of the dryer (Figure 3). The moisture extraction rate of grains dried was recorded as 6.70 kg/h.

Kinetic modelling of maize grain in the biomass-powered inclined bed dryer

The Moisture Ratios (MR) calculated from the drying experiment were fitted to 10 thin-layer drying models. The R^2 and the RMSE values were used to evaluate the model that best described the drying characteristics of maize in the biomass-powered inclined bed dryer as illustrated in Table 2. The analysis results showed that the Two-term model recorded the highest R^2 value of 0.9980, while Newton and Weibull recorded the lowest (0.9689). The RMSE values ranged from 0.02488 (Weibull) to 0.00738 (Two-term). The highest R^2 value of the Two-term model indicate that the observations of the MR of the experiment were much closer to the Two-term model prediction (line of best fit). This implies that the Two-term model gives a better goodness fit for the drying kinetics of maize in the dryer and could be used to predict the MR of maize in the dryer much better than the other models considered.

Again, the RMSE value (0.00738) recorded by the Two-term model was closer to zero than the RMSE value of the other models. This indicates that the Two-term model deviated less from the experimented MR as compared to the other models. This justifies the Two-term model as the best to describe the drying kinetics of maize in the dryer

Model verification

The representation of the experimental and predicted moisture ratios of maize in the dryer is shown in Figures 5 and 6. Analysis of the results showed that the experimental and predicted moisture ratios were closely banded around the linear trend line with R^2 value of 0.998.

The results indicate a satisfactory uniformity between the experimental and the predicted moisture ratios. The results confirm the credibility of the two-term model to predict the drying time, and the moisture ratio of maize at any time in the inclined bed dryer for maize drying.

Effective moisture diffusivity and activation energy

The effective moisture diffusivity and activation energy are key factors in moisture movement in grains. The study recorded a high average effective moisture diffusivity of 4.65×10^{-9} m^2/s and a low activation energy of 21.31 kJ/mol compared to respective effective moisture diffusivity and activation energy of 1.768×10^{-10} m^2/s and 29.56 kJ/mol, reported by Doymaz and Pala (2003); 3.10×10^{-11} m^2/s and 96.83 kJ/mol by Akowuah *et al*. (2021) for maize drying using a similar drying system. The activation energy and effective moisture diffusivity are inversely related, with low activation energy indicating less energy required to break the binding moisture particles and accelerate the movement of moisture, thus, higher effective moisture diffusivity value (Anuar *et al*., 2003). The high effective moisture diffusivity recorded could be attributed to the high drying air temperature of 73.54 ˚C used for the drying of maize grains in the dryer. This is corroborated by Doymaz and Pala (2003) who reported of a similar trend of an increase in effective moisture diffusivity value due to an increase in the drying air temperature.

Conclusion

The biomass-powered inclined bed dryer recorded a relatively high average drying air temperature of 73.54 ± 5.74 ˚C, which was enough to initiate a shorter drying time as compared to the average ambient temperature of 28.42 ± 1.76 ˚C. Maize with an initial average moisture content of 23.25 ± 0.02 % (w.b) was dried to 13.61 ± 0.13 % within a period of 2 hours and 40 minutes. Thus, the 200-kg capacity dryer could dry 1 tonne of maize in a day which is suitable enough to dry maize produced by a smallholder farmer in Ghana. The drying system recorded an average drying rate and drying efficiency of 6.70 kg/h and 71.37 %, respectively. The use of the drying system provided an efficient and reliable maize drying technique that would help reduce post-harvest losses and consequently ensure food security in Ghana.

Among the ten thin-layer models, the Two-term model best described the thin-layer drying kinetics of maize in the biomass -powered inclined bed dryer at R^2 and RSME values of 0.9980 and 0.00738, respectively. The Two-term model exhibited satisfactory conformity between the predicted and experimental moisture ratios, thus, the model was able to reproduce the behaviour of the drying process of maize in the biomass-powered inclined bed dryer. The ability to predict the drying process is crucial for farmers and agro-processors. For possible scale-up of the drying system, the Two-term model would be able to predict the drying time for varied maize moisture contents, allowing the farmer to prepare a drying schedule. The drying processes occurred under a falling rate period with an effective moisture diffusivity of 4.65×10^{-9} m^2/s and an activation energy of 21.31 kJ/mol. Studies on the kinetic modelling of other cereals and crops using the biomass-powered inclined bed dryer are encouraged.

Acknowledgement

The authors express appreciation to The Rockefeller Foundation (grant 2018 FOD 004) and the Foundation for Food and Agriculture Research (grant DFs-18-0000000008) for funding this study. The authors are grateful to the Department of Agricultural and Biosystems Engineering workshop staff, Kwame Nkrumah University of Science and Technology, for their assistance with the fabrication of the biomass-powered inclined bed dryer.

Conflicts of Interest Declarations

The authors declare no conflict of interest.

References

Afriyie, J. K., Rajakaruna, H., Nazha, M. A., and Forson, F. K. (2013). Mathematical modelling and validation of the drying process in a Chimney-Dependent Solar Crop Dryer. Energy Conversion and Management, 67, pp. 103-116. https://doi.org/10.1016/j.enconman.2012.11.007

Aghbashlo, M., and Samimi-Akhijahani, H. (2008). Influence of drying conditions on the effective moisture diffusivity, energy of activation and energy consumption during the thin-layer drying of berberis fruit (Berberidaceae). Energy Conversion and Management, 49(10), pp. 2865-2871. https://doi.org/10.1016/j.enconman.2008.03.009

Akowuah, J. O., Bart-Plange, A., and Dzisi, K. A. (2021). Thin layer mathematical modelling of white maize in a mobile solar-biomass hybrid dryer. Research in Agricultural Engineering, 67(2), pp. 74-83. https://doi.org/10.17221/56/2020-RAE.

Joseph, O. A., Lena, D. M., Chian, C., and Anthony, R. (2015). Effects of practices of maize farmers and traders in Ghana on contamination of maize by aflatoxins: Case study of Ejura-Sekyeredumase Municipality. African Journal of Microbiology Research, 9(25), pp. 1658-1666. https://doi.org/10.5897/AJMR2014.7293

Akowuah, J., Maier, D., Opit, G., McNeill, S., Amstrong, P., Campabadal, C., Ambrose, K. and Obeng-Akrofi, G. (2018). Drying Temperature Effect on Kernel Damage and Viability of Maize Dried in a Solar Biomass Hybrid Dryer. Open Journal of Applied Sciences, 8, pp. 506-517. https://doi.org/10.4236/ojapps.2018.811041

Alhassan, N. F., and Kumah, P. (2018). Determination of post-harvest losses in maize production in the upper West region of Ghana. American Scientific Research Journal for Engineering, Technology, and Sciences, 44(1), pp. 1-18.

Anuar, M. S., Taip, F. S., Shamsudin, R., and AM, S. R. (2017). Effective moisture diffusivity and activation energy of rambutan seed under different drying methods to promote storage stability. In IOP Conference Series: Materials Science and Engineering, 203 (1), pp. 25. https://doi.org/10.1088/1757-899X/203/1/012025

Da Silva, W. P., e Silva, C. M., Gama, F. J., and Gomes, J. P. (2014). Mathematical models to describe thin-layer drying and to determine drying rate of whole bananas. Journal of the Saudi Society of Agricultural Sciences, 13(1), pp. 67-74. https://doi.org/10.1016/j.jssas.2013.01.003

Darfour, B., and Rosentrater, K. A. (2016). Maize in Ghana: an overview of cultivation to processing. In 2016 ASABE Annual International Meeting. American Society of Agricultural and Biological Engineers, pp. 1. https://doi.org/10.13031/aim.20162460492

Doymaz, I. (2008). Convective drying kinetics of strawberry. Chemical Engineering and Processing: Process Intensification, 47(5), pp. 914-919. https://doi.org/10.1016/j.cep.2007.02.003

Doymaz, I., and Pala, M. (2003). The thin-layer drying characteristics of corn. Journal of food engineering, 60(2), pp. 125-130. https://doi.org/10.1016/S0260-8774(03)00025-6

Ghana Statistical Service. (GSS). (2014). District Analytical Report, Kumasi Metropolitan Assembly (PDF). Accra Ghana: Ghana Statistical Service. [ONLINE]. Available at: https://www.statsghana.gov.gh/docfiles/2010_District_Report/Ashanti/KMA.pdf [Accessed 12 September 2021]

Henderson, S. M. (1974). Progress in developing the thin layer drying equation. Transactions of the ASAE, 17(6), pp. 1167-1168.

Hussein, J. B., Filli, K. B., and Oke, M. O. (2016). Thin layer modelling of hybrid, solar and open sun drying of tomato slices. Research Journal of Food Science and Nutrition, 1 (1), pp. 15-27. https://doi.org/10.1088/1757-899X/203/1/012025

Inyang, U. E., Oboh, I. O., and Etuk, B. R. (2018). Kinetic models for drying techniques—food materials. Advances in Chemical Engineering and Science, 8(2), pp. 27. https://doi.org/10.4236/aces.2018.82003

Kaaya, A. N., and Kyamuhangire, W. (2010). Drying maize using biomass-heated natural convection dryer improves grain quality during storage. Journal of Applied Sciences, 11, pp. 967-974. https://doi.org/10.3923/jas.2010.967.974

Ministry of Food and Agriculture (MoFA). (2020). Agriculture in Ghana: Facts and Figures. Statistics, Research and Information Directorate (SRID). Available at: https://srid.mofa.gov.gh/sites/default/files/Agriculture%20In%20Ghana%20Facts%20%26%20Figures_%202020%20FINAL.pdf [Accessed 5 February 2022].

Mujumdar, A. S. (2006). Handbook of industrial drying. CRC press.

Obeng-Akrofi, G., Akowuah, J. O., Maier, D. E., and Addo, A. (2021). Techno-economic analysis of a crossflow column dryer for maize drying in Ghana. Agriculture, 11(6), pp. 568. https://doi.org/10.3390/agriculture11060568

Page, G. E. (1949). Factors Influencing the Maximum Rates of Air-Drying Shelled Corn in Thin layers. Purdue University.

Sharaf-Eldeen, Y., Blaisdell, J. and Hamdy, M. (1980). A Model for Ear Corn Drying. Transactions of the ASAE. 23, pp. 1261-1265. https://doi.org/10.13031/2013.34757

Tweneboah, C. K. (2000). Modern agriculture in the tropics with special reference to Ghana. Co-Wood Publishers, Accra, pp. 37-40.

Vega-Gálvez, A., Miranda, M., Díaz, L. P., Lopez, L., Rodriguez, K., and Di Scala, K. (2010). Effective moisture diffusivity determination and mathematical modelling of the drying curves of the olive-waste cake. Bioresource Technology, 101(19), pp. 7265-7270. https://doi.org/10.1016/j.biortech.2010.04.040

Wang, C. Y., and Singh, R. P. (1978). A single layer drying equation for rough rice. ASAE paper. Available at: http://www.sciepub.com/reference/161016 [Accessed 5 March 2022].

Wang, W., Li, M., Hassanien, R. H. E., Wang, Y., and Yang, L. (2018). Thermal performance of indirect forced convection solar dryer and kinetics analysis of mango. Applied Thermal Engineering, 134, pp. 310-321. https://doi.org/10.1016/j.applthermaleng.2018.01.115

White, G. M., Bridges, T. C., Loewer, O. J., and Ross, I. J. (1980). Seed coat damage in thin-layer drying of soybeans. Transactions of the ASAE, 23(1), pp. 224-0227. https://doi.org/10.13031/2013.34559

Yagcioglu, A. D. A. C. F. (1999). Drying characteristic of laurel leaves under different conditions. In Proceedings of the 7th international congress on agricultural mechanization and energy, Faculty of Agriculture, Cukurova University, pp. 565-569.

Zhang, Q., and Litchfield, J. B. (1991). An optimization of intermittent corn drying in a laboratory scale thin layer dryer. Drying technology, 9(2), pp. 383-395. https://doi.org/10.1080/07373939108916672