Mathematical Modelling of Banana Slices in Natural Convection Indirect Solar Dryer

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Abstract. The energy for drying agricultural products comes from various sources such as electricity, natural gas, biomass and fossil fuels. The practice of solar energy utilization in the agricultural sector has a potential scope to minimize the cost of operation, replace the conventional drying methods and save environment by reducing carbon foot print. In the present study, heat pipe assisted natural convection indirect solar dryer (HNISD) was used to determine the drying behaviour with respect to thickness in banana slices with three different thickness namely 2,4 and 6mm. The drying time taken for 2 and 4 mm thick slices was 12 hours whereas the slices with 6 mm thickness took 13 h of drying time. The experimental data was best fit with the Midilli-kucuk model for HNISD. For open sun drying Two-term model was found to be best model to explain the drying characteristics of banana slices.

Keywords: Solar, banana, heat pipe and drying kinetics

1. Introduction

The majority of the energy required by the food processing sectors is provided by non-renewable energy sources like oil, gas, coal, and fossil fuels, which also increase the atmosphere's carbon footprint. Carbon emissions can be considerably decreased by using renewable energy sources like solar energy. Agricultural products are dried using a variety of solar drying procedures. Solar drying techniques represent a cornerstone of sustainable and energy-efficient drying processes, harnessing the abundant and renewable energy resource of the sun. It hold dominant significance across various industries, notably agriculture, food processing, and material manufacturing. There are different solar drying

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techniques such as direct, indirect and hybrid type solar drying systems. In addition it can be classified into active and passive dryer systems. In direct type, the food products are placed beneath the transparent glass cover for drying and product will be exposed to direct sunlight. It may lead to bleaching of colour of the food products. When operating in mixed mode, heated air would still be supplied together with direct radiation to complete the drying process. Among this indirect type solar dryer retains the active compound in the food and gives a better quality food [1]. Indirect methods offer more control over drying parameters and can be adapted to a wider range of materials. Novel solar drying techniques were designed by many researchers for different food products.

The banana is one of the oldest and most valuable crop plants in the tropics and subtropics. India is the world's largest banana producer, followed by China, Indonesia, and Brazil. Banana has more nutrient and is a great source of energy because of its high starch and sugar content. On the other side, it is a source of potassium, vitamins A and C, fiber, sodium, magnesium, and calcium. At the same time we know it is a perishable product so to enhance the shelf life of the banana, different value added products like chips, banana powder, wine, flour etc. are made. In this context, drying of banana slices using different drying techniques is becoming popular. Nowadays the consumers prefer organic foods rather than treated ones. Therefore solar dried banana products have got high demand in the market and fetch more prices.

Various researchers have developed indirect solar dryers to enhance the performance of the system. Maiti et al., [2] developed ISD with reflectors in solar collector and reported that the collector efficiency can be increased from 40 to 58.5 % during peak sunshine hours. Essalhi et al., [3] developed ISD for drying grapes. It was reported that the drying time taken to reduce the moisture content of grapes from 79.8 %(w.b) to 20.2 (w.b) was 120h. The drying curve showed the best fit with Midilli et al model. Singh and Mall [4] investigated the thermal performance of the ISD with PCM. It was noted that time taken to reduce the moisture content of banana slices to 20 (w.b) was 18 h and Modified Henderson and Pabis model showed the behaviour of drying banana slices. The drying efficiency ranged from 9.8 to 2.9%. Halil [5] reported the useful energy consumption using the solar dryer with packed bed thermal storage materials was 89.89MJ for drying orange slices. One notable variant in the present study is the use of heat pipe-assisted indirect solar dryers, which integrate heat pipes to enhance heat transfer efficiency and facilitate controlled drying conditions. The aim of the study was to determine the effect of the thickness of banana slices with drying time, to fit the experimental data with seven thin-layer mathematical drying models and find the best fit model suitable for drying banana slices both in solar dryer and open sun drying.

2. Materials and Methods

2.1. Raw Material:

Banana fruits that had ripened, belonging to the Musa species, were obtained and sliced into pieces of 2, 4, and 6 mm thickness. 10g of banana slice was weighed and held at 105°C in a hot air oven for roughly 24 hours until it attained a consistent weight in order to determine the banana's initial moisture content. Based on the banana slice's original and final weights, the moisture reduction was calculated. Therefore, it was determined that the initial moisture content for this experiment was 150% d.b.

2.2 Details of experimental setup

The flat plate collector, three cylinder-shaped heat pipes, a wooden drying chamber, and a temperature control system make up the heat pipe-assisted solar drier. The flat plate solar collector has measurements of 100 x 50 x 10 cm. Fig 1 shows the experimental setup of the developed indirect solar dryer. It comprises of a heat pipe with a 16mm outer diameter and a wall thickness of 0.5mm, a double-layer glass aperture that is 4mm thick, an absorber plate that is 1mm thick and painted black. Double-layer glass is used to maximize solar radiation absorption. The evaporator portion of the heat pipe is placed at the top of the absorber plate. To reduce heat loss from the absorber plate to the environment, the bottom surface of the absorber plate is insulated with glass wool. Following that, the condenser part of the heat pipe is fitted into the dryer assembly. Over the condenser portion of the heat pipe, three trays were positioned in the drying chamber. The first, second, and third trays are each 260mm, 180mm, and 100mm apart from the condenser portion, respectively. On top of the drying chamber, a 20mm air vent hole was constructed to ensure the exit of moist air.

Fig 1. Experimental setup of heat pipe assisted indirect solar dryer

2.3 Experimental technique

The experimental setup was located at 10°56'03.439" N and 76°44'41.648" E latitude and longitude, with a maximum temperature of 38°C and a minimum temperature of 24°C. Slices of nandren banana were obtained and measured at 2, 4, and 6 mm thick. After that, three trays had one kilogram of 2mm thick banana slices. Every hour during the day, banana slices weight loss and temperature reaction were observed from 9.30 am to 5:00 pm, when it was sunny.

2.4 Moisture Content

The amount of moisture in a product is given on the basis of the weight of water present in the product and is usually expressed in per cent. Moisture Content (MC)is expressed in dry basis (%). The formula is given by the equation (1) [6]

$$MC_{db,t} = \frac{m_b - m_d}{m_d} \times 100 \quad (1)$$

Where, m_d is the mass of dry matter and m_b is the mass of banana

Table 1. Drying models used in the present study

SI.No.	Drying Models	Models	References
1	Exponential model	$MR = exp(-kt)$	[7]
2	Generalized exponential model	$MR = a\ exp(-kt)$	[8]
3	Weibull	$MR = exp\left[-\left(\frac{t}{\beta}\right)^{\alpha}\right]$	[9]
4	Page	$MR = exp\left(-(kt^n)\right)$	[10]
5	Two-terms	$MR = a\ exp(-k_1 t) + b\ exp(-k_2 t)$	[11]
6	Modified Henderson & Pabis	$MR = a\ exp(-kt) + b\ exp(-gt) + c\ exp(-ht)$	[12]
7	Midilli-Kucuk	$MR = a\ exp(-kt^{n_1}) + bt$	[13]

2.5 Drying Kinetics

Moisture ratio is the ratio of the moisture content at any time, t to that of the initial moisture content of the sample. Moisture Ratio is nondimensionalized value.

The formula to find out Moisture Ratio is expressed as eq (2):

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

Where M_t is the moisture content at any time t, M_e is the equilibrium moisture content, M_i is the initial moisture content of the sample. The equation can be reduced to M_t/M_i as value of M_e was negligible and also due the fluctuation of the relative humidity [4]. The selected models for studying the drying kinetics of banana slices are presented in the Table 1. Using 'R' Software the model parameters was determined using the non-linear regression analysis and the experimental data was fitted with drying model. To find out the quality of fit the statistical parameters such as correlation coefficient (R^2), reduced chi square, and root mean square error (RSME) values were used. The main criterion to find the best fit is to have highest R^2 value and least chi-square and RMSE values. These values were calculated using the eq (3)(4):

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{ex,i} - MR_{pr,i}\right)^2}{N-n} \quad (3)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{ex,i} - MR_{pr,i}\right)^2}{N}} \quad (4)$$

Where $MR_{ex,i}$ − calculated i th moisture ratio, $MR_{pr,i}$ −predicted i th moisture ratio using models, N − number of observations, n −number of constants in the drying models.

3. Results and discussions

3.1 Moisture content determination

It was known from the literature that for the safe storage of food products the moisture content should be less than 12%. So the experiment was conducted till the moisture content of banana slices reached 12% dry basis (d.b). From the Fig 2 it was found that the time taken for reducing the moisture content from the 150 % (d.b) to 12% (d.b) was 12 hours for the banana slices with 2 and 4 mm thickness. The drying time of banana slices with 6mm thickness was 13 hours. It can also be noted that the banana slices with 2 mm thickness the moisture removal rate was faster when compared to 4 and 6 mm thickness.

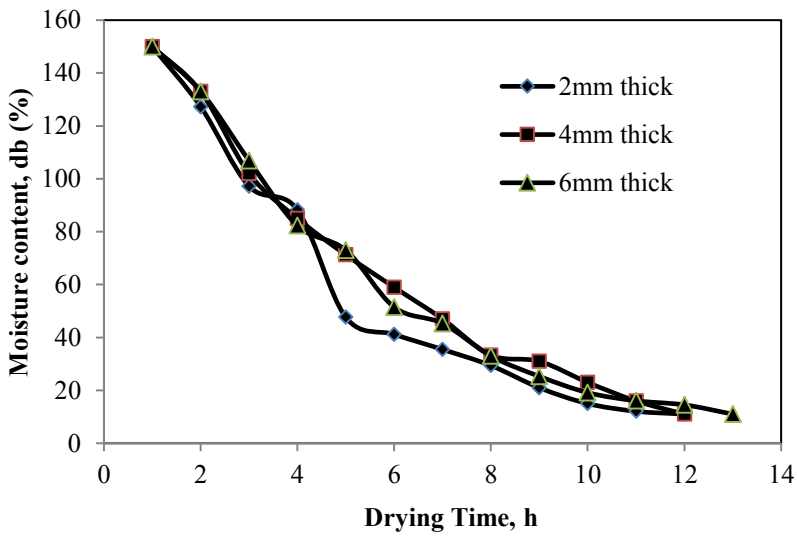

Fig 2. Moisture content of banana slices

3.2 Fitting drying kinetics models

The regression analysis was carried out to relate dimensionless moisture ratio and drying time using different thin layer models for heat pipe assisted solar dryer and open sun drying. The results of the mathematical modelling are presented in the Table 2 and 3. It can be noted that all the thin layer models that are selected had a good agreement with the experimental values. Generalized exponential model, two-terms, Modified Henderson & Pabis and Midilli-kucuk have the highest R^2 values and lowest χ^2 and RMSE values which indicates a good fit. Among this, Midilli-Kucuk showed the best representation of thin layer drying of banana slices because it has a maximum R^2 values (0.9973) and least RMSE values (0.01558) among the other models that are selected for the present study. Cüneyt and Ibrahim [14] studied the drying kinetics with 3mm thick banana slices using the heat pump drying and noted that Midilli-Kucuk model was best fit.The literature also reveals that this model is also suitable for modelling of other food products like bitterguard [15].

The mathematical equation using the model constants can be expressed as:

$$MR = 1.1130\, exp(-0.1007t^{1.37}) + 0.003t \quad (5)$$

Table 2. Results of mathematical modelling on moisture ratio and drying time for HNISD

Drying Models	Model constants	R2	χ^2	RMSE
Exponential model	k= 0.1637	0.9935067	0.006893228	0.07976829
Generalized exponential model	a=1.2983 k=0.2135	0.9930523	0.0007783718	0.02566364
Weibull	β =6.1509 α =1.5167	0.9906402	0.001144715	0.03112242
Page	k= 0.0635 n=1.5167	0.9906402	0.001144715	0.03112242
Two-terms	a =1.26725956 k_1 =0.21350394 b =0.03112769 k_2 =0.21350392	0.9930523	0.0009513433	0.02566364
Modified Henderson & Pabis	a =0.02206635 k =0.21350385 b =0.02206617 g =0.21350394 c =1.25425473 h =0.21350394	0.9930523	0.001223156	0.02566364
Midilli-Kucuk	**a =1.113091025** **k =0.100798867** **n_1 =1.370104541** **b =0.003007872**	**0.9973256**	**0.0003508176**	**0.01558441**

The selected thin layer models also showed a good fit for open sun drying. All the models have R^2 value nearing to 1 and have less RMSE. However, Two –term showed the best representation of thin layer drying of banana in open sun drying since it had a highest R^2 value (0.9969) and lowest RMSE values (0.01517).

The mathematical equation using the model constants can be expressed as:

$$MR = 1.176\, exp(-0.184t) + 0.115\, exp(-1.670t) \quad (6)$$

Table 3. Results of mathematical modelling on moisture ratio and drying time for open sun drying

Drying Models	Model constants	R^2	χ^2	RMSE
Exponential model	k= 0.15	0.9953271	0.003173795	0.05412631
Generalized exponential model	a=1.196 k=0.187	0.9967789	0.000285941	0.01555475
Weibull	β= 6.504 α=1.289	0.9889971	0.001078612	0.03021046
Page	k= 0.089 n=1.289	0.9889971	0.001078612	0.03021046
Two-terms	a= 1.176 k_1=0.184 b= 0.115 k_2=1.670	0.9969563	0.0003327643	0.01517812
Modified Henderson & Pabis	a = 0.1153137 k =1.6727041 b =1.1766091 g =0.1842928 c =2.7346598 h =10.1063	0.9969562	0.0004278506	0.01517831
Midilli-Kucuk	a =1.1948144 k =0.1874727 n_1 =0.9966437 b =0.0000000	0.9968122	0.0003513065	0.01559526

The Fig 3 shows the moisture ratio with respect to time plotted for banana slices dried in HISD fitted along with selected Midilli-Kucuk model. The predicted values using the model were validated with the experimental results. It can be seen that the selected model precisely describes the drying behaviour of the banana slices of 6mm thickness. Likewise Fig 4 shows moisture ratio with the function of time for the banana slices dried in open sun drying along with Two-term predicted model. Clearly a good agreement was found between the predicted and experimental values.

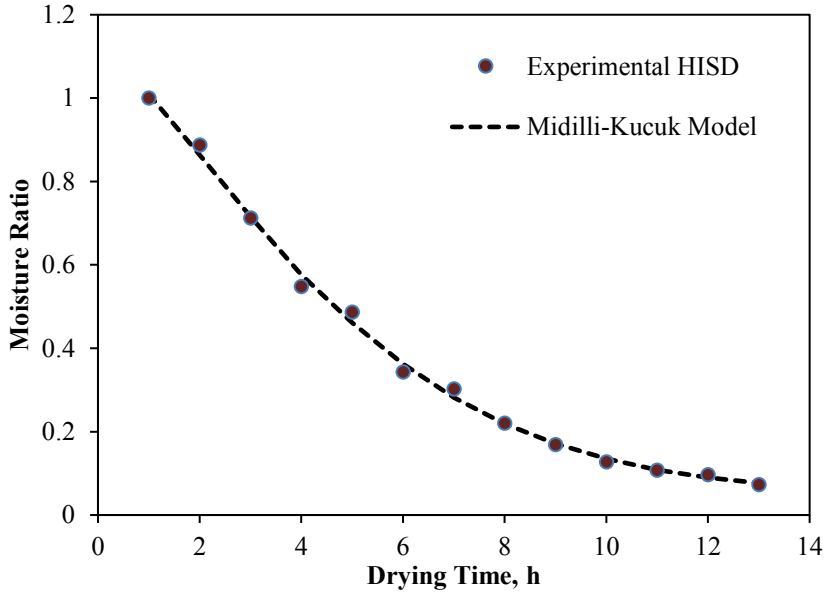

Fig 3. Experimental Vs predicted values of moisture ratio by Midilli-Kucuk Model for HISD

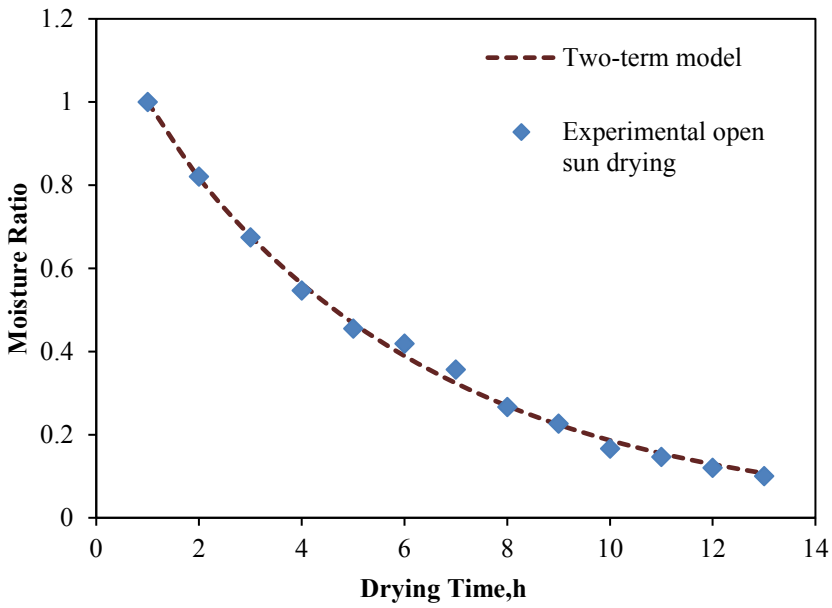

Fig 4. Experimental Vs predicted values of moisture ratio by Two-Term Model for open sun drying

4. Conclusion

The drying characteristics on banana slices were investigated for three different thicknesses in the heat pipe assisted natural convection indirect type solar dryer. Results showed that with increase in thickness of banana slices the drying time increases. To explain the drying kinetics seven thin layer drying models were selected. Midilli-kucuk model found be the

best fit with the experimental data for HNISD and the drying behaviour of banana slices dried in open sun drying was best fit with Two-term model.

References

1. Abhay Lingayat, V.P. Chandramohan, V.R.K. Raju, Design, Development and Performance of Indirect Type Solar Dryer for Banana Drying, Energy Procedia, Volume 109, 2017, Pages 409-416, ISSN 1876-6102, https://doi.org/10.1016/j.egypro.2017.03.041.
2. Maiti S, Patel P, Vyas K, Eswaran K, Ghosh PK. Performance evaluation of a small scale indirect solar dryer with static reflectors during non-summer months in the Saurashtra region of western India. Sol Energy 2011;85:2686–96. https://doi.org/ 10.1016/j.solener.2011.08.007.
3. Essalhi H, Benchrifa M, Tadili R, Bargach MN. Experimental and theoretical analysis of drying grapes under an indirect solar dryer and in open sun. Innov Food Sci Emerg Technol 2018;49:58–64. https://doi.org/10.1016/j.ifset.2018.08.002.
4. Singh, D., Mall, P. (2020). Experimental investigation of thermal performance of indirect mode solar dryer with phase change material for banana slices, *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*. DOI: 10.1080/15567036.2020.1810825.
5. Halil Atalay, Performance analysis of a solar dryer integrated with the packed bed thermal energy storage (TES) system, Energy, Volume 172, 2019, Pages 1037-1052, https://doi.org/10.1016/j.energy.2019.02.023.
6. Tarik Hadibi, Abdelghani Boubekri, Djamel Mennouche, Abderrahmane Benhamza, Naji Abdenouri, 3E analysis and mathematical modelling of garlic drying process in a hybrid solar-electric dryer, Renewable Energy, Volume 170, 2021, Pages 1052-1069, https://doi.org/10.1016/j.renene.2021.02.029.
7. El-Beltagy A, Gamea GR, Amer Essa AH (2007) Solar drying characteristics of strawberry. J Food Eng 78:456–464.
8. Shittu, T.A., Raji, A.O. Thin Layer Drying of African Breadfruit (*Treculia africana*) Seeds: Modeling and Rehydration Capacity. *Food Bioprocess Technol* **4**, 224–231 (2011). https://doi.org/10.1007/s11947-008-0161-z
9. Kamenan Blaise Koua, Wanignon Ferdinand Fassinou, Prosper Gbaha, Siaka Toure, Mathematical modelling of the thin layer solar drying of banana, mango and cassava, Energy, Volume 34, Issue 10, 2009, Pages 1594-1602, https://doi.org/10.1016/j.energy.2009.07.005.
10. Page, G. E. (1949). *Factors Influencing the Maximum Rates of Air Drying Shelled Corn in Thin layers*. Purdue University.
11. Madamba, P,S., Robert H. Driscoll, Ken A. Buckle, The thin-layer drying characteristics of garlic slices, Journal of Food Engineering, Volume 29, Issue 1, 1996, Pages 75-97, https://doi.org/10.1016/0260-8774(95)00062-3.
12. İnci Türk Toğrul, Dursun Pehlivan, Modelling of drying kinetics of single apricot, Journal of Food Engineering, Volume 58, Issue 1, 2003, Pages 23-32, https://doi.org/10.1016/S0260-8774(02)00329-1.
13. Midilli A, Kucuk H, Yapar Z. A new model for single layer drying. Dry Technology 2002; 20: 1503-13.
14. Cüneyt Tunckal, İbrahim Doymaz, Performance analysis and mathematical modelling of banana slices in a heat pump drying system, Renewable Energy, Volume 150, 2020, Pages 918-923, https://doi.org/10.1016/j.renene.2020.01.040

15. Vijayan, S., Arjunana, T.V., Anil, K. (2016). Mathematical modeling and performance analysis of thin layer drying of bitter gourd in sensible storage based indirect solar dryer. *Innovative Food Science and Emerging Technologies*, 36, 59–67.