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Experimental Research of Drying Characteristics of Red Banana in a Single Slope Solar Dryer Based on Natural and Forced Convection

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SUMMARY

Research background. Traditionally, open sun drying method is used to dry the products for long time preservation. For the same products, solar drying technology is being employed to minimize the drying time for achieving the required moisture content. This solar drying technology, which inherently contains complex heat and mass transfer mechanism, which makes difficult to describe drying kinetics at the micro level.

Experimental approach. In this present paper, research work is carried out to investigate the drying of 5 mm thickness of red banana (*Musa acuminata* “Red Dacca”) in a single slope solar dryer based on natural and forced convection. Based on the experiments, development of new semi-empirical thin layer drying kinetics correlation for red banana is proposed. The proposed correlation is also compared with other existing models. The proposed model is in very good agreement with well-known other models and the correlation coefficient (R^2) of 0.997 is obtained. Based on the model, the moisture diffusivity and activation energy of the red banana are also obtained.

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Results and conclusions. It is found that, the moisture diffusivity of the red banana samples is in the range of $8.74\cdot10^{-10}$-$1.56\cdot10^{-9}$ m^2/s for natural convection solar drying and $8.43\cdot10^{-9}$-$2.61\cdot10^{-8}$ m^2/s for forced convection solar drying. The activation energy of the red banana is varied from 24.58 to 45.20 kJ/mol for passive mode and 22.56 to 35.49 kJ/mol for active mode. Besides, energy and exergy analysis of red banana in a dryer are also carried out. It is found that, the average exergy losses for the forced and natural convections are obtained as 16.1 kJ/kg and 6.63 kJ/kg and the average exergic efficiency for the natural and forced convection dryer was obtained as 57.7 % and 70.9 %, respectively.

Novelty and scientific contribution. A single slope direct type solar dryer was designed and fabricated to maintain the desired temperature for a specified period in both natural and forced convection phenomena. A novel drying kinetics model is proposed to preserve red banana. The proposed model given a superior correlation coefficient (R^2) when compared to other drying kinetics models.

Key words: single slope solar dryer, red banana drying, drying kinetics, moisture ratio correlation, moisture diffusivity, activation energy

NOMENCLATURE

EUR	Energy utilization ratio (No unit)
E_L	Exergy Loss (kJ/kg)
g	Gravitational acceleration (m^2/s)
t	Time (h)
T	Temperature (°C)
I	Global solar radiation (W/m^2)
J	Joule constant (No unit)
$\dot{m}$	Mass flow rate (kg/s)
N	No of observations
n	Constants (No unit)
P	Pressure (Pa)
$\dot{Q}$	Net heat rate (kWh)
S	Specific entropy (J/kg K)
V	Velocity of air (m/s)
x	Specific humidity (g/kg)
MR	Moisture ratio (%)
R	Universal gas constant (J/K mol)
I	Uncertainty analysis (No unit)

GREEK LETTERS

ϕ	Relative Humidity (%)
η_{Ex}	Exergetic efficiency (%)

SUBSCRIPTS

a	Air
c	Constant
ia	Drying air
i	Inlet
o	Outlet
sat	Saturated air
∞	Surrounding air

INTRODUCTION

Banana is one of the most liked fruits around the world. Among all the developing countries, India is one of the largest producers of banana (*1*). The banana is abundantly grown and harvesting in almost all tropical countries. Almost 40 % of its production is lost in the post-harvesting process due to improper handling and unconventional way of storing the banana. There are 1000 varieties of banana are available in and around the world. Among these 1000 varieties, in India, the popularly used varieties are Baby banana, Dwarf cavendish banana, Giant cavendish banana, Red banana, Pisang raja, Manzano banana, Burro banana, Barangan banana, Gold finger banana, Saba banana. Among all these banana, red banana is costly and having good nutritional value. Hence, the author made an attempt to study the drying kinetics of red banana. In this aspect, Arivazhagan and Geeta (*2*) reported that 6.5 % of the bananas are wasted at the wholesale distribution points in Tamil Nadu, India. In one of the studies, it was reported that the lifetime of bananas is 2 to 9 days in a refrigerator, 2 to 3 months in a freezer and 6 to12 months when dried, respectively. Therefore, it is preferred that the drying of bananas is the reliable method to avoid wastage and improve its life. Koua *et al*. (*3*) developed thin layer drying mathematical model for mango, banana and cassava in a passive solar dryer. In order to validate their studies, developed model was tested in seven empirical / semi-empirical models available in literature. It was mentioned that the Henderson and Pabis dehydrating mathematical model was in close agreement with experimental results. Silva *et al*. (*4*) dried whole Brazilian bananas at temperatures varied from 40 to 70 °C in the convective dryer to develop the mathematical model for describing its drying phenomenon. It was concluded that Page and Silva et al. model was in close agreement for the drying kinetics. Gaye *et al*. (*5*) study the drying characteristics of green olives in hot air dryer at varied air temperatures in the range of 40 – 70 °C with a constant air speed of 1 m/s. It was found that the green olives attained equilibrium moisture content with good sensory acceptance in 22 hrs. It was also mentioned that the dried olives products can be stored up to 1 year without any deterioration.

Akbulut and Durmus (*6*) study the energy and exergy analysis of mulberry in a forced convective dryer based on five different mass flow rate ranging from 0.014 to 0.036 kg/s. It was mentioned that, the EUR and exergy loss were decreased with the increase in the mass flow rate. Omolola *et al*. (*7*) modeled a thin layer drying characteristics for Luvhele banana in an oven for calculating the effective diffusivity. Their developed model was compared with six mathematical drying models and it was observed that, two-term model predicted the better results of drying Luvhele banana. Ibrahim Doymaz (*8*) experimentally determined the drying characteristics of banana in a hot air dryer with varied air temperatures from 50 to 80 °C at a rated wind speed of 2.4 m/s. It was mentioned that the Page and Logarithmic models were in comparable, when compared to existing models. The effective diffusivity of banana sample was in the range of $7.374\cdot10^{-11}$ to $2.14\cdot10^{-10}$ m^2/s and its activation energy was obtained as 32.65 kJ/mol. Mierzwa *et al*. (*9*) made comparative analysis between hybrid and microwave dryer by taking the ultrasonically assisted osmotic processed carrot samples. It was observed that the combination of microwave/infrared with hot air dryer allows short period to dry the carrot sample with consumption of little amount of electric power.

Pantira *et al*. (*10*) focused to investigate the drying kinetics of cayenne pepper and its effects on drying treatments in both solar dryer and electrical based tray dryer. This work was carried out for whole pods and cut samples of cayenne pepper samples. It was observed that cayenne pepper dried faster in electrical dryer than solar one, due to stable drying temperature. It was also observed that, Midilli-Kucuk model was better agreement for whole pods and Page model for cut samples of cayenne pepper. Akpinar (*11*) fabricate the convective dryer for drying red pepper at different air temperatures from 54 °C to 70 °C with a constant wind speed of 1.5 m/s. It was reported that exergetic efficiency was found to be varied from 67.28 % to 97.92 % for increased drying time. Dandamrongrak *et al*. (*12*) examined the effect of four different pre-treatments such as blanching, chilling, freezing and combined blanching and freezing of banana on the drying kinetics at 50 °C dryer temperature with inlet condition of 3.1 m/s air velocity and 10-35 % relative humidity in a heat pump dryer. It was found that drying rate was enhanced for the pre-treatments of freezing. Also, the Two-term exponential drying model was in close agreement for this drying process of banana and moisture diffusivity of banana was obtained as $4.3\cdot10^{-10}$ to $13.2\cdot10^{-10}$ m^2/s. Using first and second law of thermodynamics energy and exergy analyses of dried of shelled and unshelled pistachio were carried out in a solar cabinet dryer by Midilli and Kucuk (*13*).

Merlin *et al*. (*14*) developed the mathematical model to evaluate the convective and mass transfer coefficients of dried ebony wood in a natural convection indirect solar dryer. The obtained convective heat and mass transfer coefficient during drying process of sample was varied from 0.25 to 5.5 $W/m^2\cdot K$ and 1.0 to $5.5\cdot10^{-8}$ m/s. Komes *et al*. (*15*) studied the quality improvement of dried strawberry by addition of two different sugars such as trehalose and sucrose. It was found that the combination of trehalose with freeze drying dried samples showed superior quality than other sample.

Based on the literature review, very few research works were performed to analyze the energy and exergy efficiencies of the banana. Most researchers concentrated on the drying process of commonly available species of yellow banana. Nonetheless, no research work is carried out on red banana. Hence, in this article, an attempt has been made to study the drying characteristic of red banana and to estimate the moisture diffusivity and activation energy of red banana in a single slope direct solar dryer (SSSD) under passive and active mode. Besides, the results were compared with open drying and new drying moisture ratio correlation was developed and compared with the other existing drying models.

MATERIALS AND METHODS

Experimental set-ups

The experiments were performed in a SSSD. The single slope solar dryer has a trapezoid shape with base dimensions of 1290·850 mm with two different heights of 500 mm and 260 mm, respectively. Sides of the solar dryer were constructed using a dual 1.5 mm thick galvanized sheet with a gap of 50 mm between the inner and outer walls of the sheets, which were filled with coconut husk to reduce the heat losses from the sides of the dryer. Top of the dryer was covered with a flat transparent glass of 5 mm thickness with an inclination of 10.9° (latitude of the place, Karaikal). Outer surfaces were enclosed in an insulation chamber that consists of two layers of thermocol each 25 mm thick with an air gap of 25 mm between them to reduce heat losses significantly. An aluminium mesh of dimension 1190·750 mm was constructed and placed inside the dryer at about 50 mm vertically from the absorber plate of the dryer. This mesh acts as the plate on which the red banana to be dried were placed. The inlet air was supplied to the dryer through a 22 mm diameter mild steel pipe and placed horizontally in the lower side of the drying chamber. A similar outlet pipe was placed vertically on the opposite side end of the dryer (perpendicular to the inlet of the system). The entire drying chamber was placed on a stand of mild steel L-brackets of thickness 25 mm that has dimensions of 1290·1000 mm with a height of 750 mm. Two similar set-ups were developed. One was used for natural convection and other one for forced convection with a blower (Model No: M4000B, Makita, Bangalore and India) of wind speed of 1.5 m/s. In addition to that, open drying method experimental set-up was made and the same quantity of red banana was dried to compare the drying time of forced and natural convection. The photographs of natural convection, forced convection single slope dryer and open sun drying experimental set-ups was shown in Fig. S1. Eight K-type thermocouples (with the accuracy of ±0.1 °C) were attached at different locations to measure the surface, air and atmospheric temperatures continuously. A Hukseflux Pyranometer (SR20-TI, Hukseflux, Delft, Netherlands) (with the accuracy of ±10 W/m^2) was used to measure the intensity of global radiation. The thermocouples and the Pyranometer were connected to a data acquisition unit (Agilent 34972A, Keysight, New Delhi and India) to measure the temperatures and global radiations (*16*,*17*).

Sample preparation

The red bananas (3 kg) were purchased from the local market in Karaikal, Puducherry, India. The samples were peeled off from the skin on the day of the experiment and cut into 5 mm thick cylindrical shaped with a uniform diameter of 50 mm. The samples were then carefully placed in an open sun drying, forced and natural convection dryer to record the drying characteristics such as energy analysis, exergy analysis, effective moisture diffusivity and activation energy of the red banana samples from 9.00 am to 5.00 pm

Exergy and energy analysis

The analyses are carried out for the red banana based on first and second law of thermodynamics. In first and second law analyses of thermodynamics, the solar dehydrating process of red banana is considered as a steady-flow process. The drying of red banana involves heating and humidification in the dryer chamber for effectively removes the moisture from the samples. The conservation of mass and energy in steady-state flow can be used to equate the processes (*5*).The equations that govern the conservation of mass /1/ and energy /2/ are as follows.

$$\sum\left(\dot{m}_{\mathrm{ia}} w_i + \dot{m}_{\mathrm{mp}}\right) = \sum \dot{m}_{\mathrm{ia}} w_{\mathrm{o}} \qquad /1/$$

$$\dot{\mathrm{Q}} - \dot{\mathrm{W}} = \sum \dot{m}_{\mathrm{o}}\left(h_{\mathrm{o}} + \frac{V_o^2}{2}\right) - \sum \dot{m}_{\mathrm{i}}\left(h_{\mathrm{i}} + \frac{V_i^2}{2}\right) \qquad /2/$$

The relative humidity of the solar dryer chamber is an important factor to control the drying samples. The amount of relative humidity inside the solar chamber highly influences the drying rate and time of the samples. The relative humidity of the system can be computed by using the following equation

$$\phi = \frac{\mathrm{xP}}{(0.622+\mathrm{x})P_{\mathrm{sat}}} \qquad /3/$$

where x denotes specific humidity, P denotes pressure in the atmosphere, and P_{sat} denotes the saturated pressure of air.

The enthalpy of the dehydrating air inside the dryer is computed by using the following equation:

$$h = c_{p_{\mathrm{da}}}T + xh_{\mathrm{sat}} \qquad /4/$$

where $c_{p_{da}}$ denotes the drying air specific heat.

The EUR is a measurement of the amount of energy used in comparison to the total energy that could be used by the system. The EUR is important to calculate the amount of energy utilized by the dryer to perform its function and to calculate the amount of energy that is unutilized by the system. The equation to compute the EUR for the drying chamber is given as follows:

$$EUR_{dryer} = \frac{m_{\mathrm{da}}\,(h_{\mathrm{dryi}})}{m_{\mathrm{da}}c_{\mathrm{p_{da}}}(T_{\mathrm{dryo}} - T_{\mathrm{dryi}})} \qquad /5/$$

In order to quantify the losses from the dryer, the exergy is also calculated. The calculation of exergy technique is based on the second law of thermodynamics under steady state by balancing the different forms of energy present inside the system using the first law of energy (*18*,*19*). The equation for exergy inside the dryer can be given as follows (*20*):

$$\mathrm{Exergy} = (u - u_\infty) - T_\infty(s - s_\infty) + \frac{P_\infty}{J}(v - v_\infty) + \frac{v^2}{2gJ} + (z - z_\infty)\frac{g}{g_c J} + \cdots \qquad /6/$$

Here, ∞ denotes ambient atmospheric condition of the area. Based on the solar dryer and source terms, the above equation is deduced to

$$\mathrm{Exergy} = \bar{c}_p[\,(T - T_\infty) - T_\infty \ln\frac{T}{T_\infty}] \qquad /7/$$

The amount of exergy in and outflow can be estimated by changing the parameters on the above equation /7/ depending on the inlet or the outlet condition. By applying this method, the amount of exergy inflow and outflow are computed. The exergy loss on the system can be calculated by analyzing the difference between the inflow and outflow of exergy in the system.

$$\mathrm{Exergyloss} = \mathrm{Exergyin\ flow} - \mathrm{Exergyout\ flow}$$

$$\sum E_{X_L} = \sum E_{X_i} - \sum E_{X_o} \qquad /8/$$

The proposed solar dryer exergetic efficiency is calculated by taking the ratio of the difference between exergy inflow and exergy loss of the dryer to the exergy inflow of the dryer (*21*). It is given as:

$$Exergetic\ efficiency = \frac{\mathrm{Exergy\ (inflow - \ loss)}}{\mathrm{Exergy\ inflow}}$$

$$\eta_{Ex} = 1 - \frac{E_{X_\mathrm{L}}}{E_{X_\mathrm{i}}} \qquad /9/$$

Drying model and estimation of its parameters

The drying kinetics of thin layer of red banana is evaluated under active and passive mode in a developed single slope dryer. The moisture ratio of the red banana samples is obtained by considering the initial and instantaneous moisture content for every one hour. Then, the moisture ratio is given as:

$$MR = \frac{\mathrm{M}}{\mathrm{M_i}} \quad /10/$$

Based on the moisture ratio, the drying parameters (moisture diffusivity and activation energy) can be estimated. The procedure for determining the moisture diffusivity is given below:

Effective moisture diffusivity

Moisture diffusivity is the estimate the diffusion of wetness during the dehydrating method. The dehydrating method occurs in three stages - a first stage, a uniform drying time, which is followed by a falling rate dehydrating time. The final stage occurs when the wetness has to move from the center to the surface to be diffused (*22*). Fick's second law of diffusion is widely reported as a suitable technique to predict the activity of wetness during the falling rate dehydrating time. The equation is expressed as

$$\frac{\partial \mathrm{Y}}{\partial \mathrm{t}} = \nabla(Di_{\mathrm{eff}}\nabla \mathrm{X}) \quad /11/$$

where Y represents moisture content (per kg), Di_{eff} represents moisture diffusivity, and t represents the period.

The general solution for the above equation in terms with the parameters given can be given as appropriated by the given boundary conditions (*23*).

$$MR = \frac{X_t - X_e}{X_o - X_e} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\exp(-(2n-1)^2\frac{\pi^2 Di_{\mathrm{eff}}\mathrm{t}}{\mathrm{L}^2}) \quad /12/$$

$$MR = \frac{X_t - X_e}{X_o - X_e} = \sum_{n=1}^{\infty}\frac{1}{\varepsilon_n{}^2}\exp\left(-\frac{\varepsilon_n^2 Di_{\mathrm{eff}}\mathrm{t}}{\mathrm{r_c^2}}\right) \quad /13/$$

The derived equations can be simplified by considering the first terms of the equations to compute moisture diffusivity as applicable in most cases (*24*). The simplified equation is given as:

$$\frac{X_t - X_e}{X_o - X_e} = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 Di_{\mathrm{eff}}\mathrm{t}}{\mathrm{L}^2}\right) \quad /14/$$

$$\frac{X_t - X_e}{X_o - X_e} = \frac{4}{\varepsilon_1^2}\exp\left(-\frac{\varepsilon_1^2 Di_{\mathrm{eff}}\mathrm{t}}{\mathrm{r_c^2}}\right) \quad /15/$$

The equations can be further simplified by taking natural logarithm on both sides to make the equation logarithmic. The equation can be rewritten as:

$$\ln(MR) = \mathrm{A} - \mathrm{C} \cdot \mathrm{t} \quad /16/$$

where constant C is $\frac{\pi^2 \mathrm{Di_{eff}t}}{\mathrm{L}^2}$ for a cube and $\frac{\varepsilon_1^2 \mathrm{Di_{eff}t}}{\mathrm{r_c^2}}$ for a cylinder.

The final equation can be represented as an Arrhenius type equation:

$$Di_{\mathrm{eff}} = Di_{\mathrm{o}} \exp(-\frac{E_a}{RT}) \quad /17/$$

where E_{a} is activation energy, R stands for gas constant, and T is temperature of red banana.

Activation energy

The activation energy of the red banana refers to the minimum of energy at which the dehydrating process occurs. The prediction of activation energy of red banana is an important task for drying to minimise the energy required to be supplied for the method. The activation energy of convective dehydrating can be formed from /17/ by taking a natural log on each sides of the equation /17/ becomes

$$\ln(Di_{\mathrm{eff}}) = \ln(Di_{\mathrm{o}}) - \left(\frac{E_{\mathrm{a}}}{R} . \frac{1}{T}\right) \quad /18/$$

E_a of the banana can be determined by plotting a graph between ln(Di_{eff}) versus $\frac{1}{T}$ having a slope k (*25*). Then, the activation energy can also be calculated as:

$$k = \frac{\mathrm{E_a}}{\mathrm{R}} \quad /19/$$

Statistical and error analysis

Three statistical criteria namely, Root mean square deviation (RMSD), correlation coefficient (R^2) and reduced chi-square test (χ^2) are calculated using Data fit 8.0 software program to validate the goodness of the fit (*26*). The best fit of the drying curve has higher correlation coefficient value and the lower Root mean square deviation value. Statistical analysis is carried out to assess the consistencies between measured and predicted values. The Root mean square deviation (RMSD), correlation coefficient (R^2), reduced chi-square test (χ^2) and standard error (SE) value are calculated by using the following formulae /20-23/ (27).

$$\mathrm{SE} = \frac{\sigma}{\sqrt{\mathrm{n}}} \quad /20/$$

$$\mathrm{R}^2 = \frac{\sum_{\mathrm{i=1}}^{\mathrm{n}} (\mathrm{MR_i} - \mathrm{MR_{pr,i}}) \cdot [(\mathrm{MR_i}) - (\mathrm{MR_{ex,i}})]}{\left[\left[\sum_{\mathrm{i=1}}^{\mathrm{n}} (\mathrm{MR_i} - \mathrm{MR_{pr,i}})^2\right] \cdot \left[\sum_{\mathrm{i=1}}^{\mathrm{n}} (\mathrm{MR_i} - \mathrm{MR_{ex,i}})^2\right] \right]^{\frac{1}{2}}} \quad /21/$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{ex,i}-MR_{pr,i})^2}{N-n} \quad /22/$$

$$RMSD = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pr,i} - MR_{ex,i}\right)^2\right]^{\frac{1}{2}} \quad /23/$$

where $MR_{ex,i}$ represent the experimental value and the $MR_{pr,i}$ stands for the predicted value of the measurement. The values of N and n stand for the number of observations and constants, respectively (*28*).

The error analysis (I) from the experiment depends on the various factor such as environmental conditions (x_1), instrument error (x_2) and observation (x_3). The moisture content, solar radiation and temperatures are measured using mass balance, pyranometer and thermocouple for open dehydrating and solar dehydrating of red banana. The error values are presented in Table S1. It is calculated by using the following equation (*29*,*30*):

$$w = [(x_a)^2 + (x_b)^2 + (x_c)^2 + \cdots + (x_\infty)^2]^{1/2} \quad /24/$$

The measured uncertainty for temperature and solar radiation is ±0.05 °C and ±5.7 W/m^2, respectively. Considering the above parameters, the uncertainty of drying rate and kinetic parameter of drying red banana in a SSSD is about ±0.08 kg/s and ±0.42 m^2/s, ±0.18 kJ/mol respectively.

RESULTS AND DISCUSSION

Extensive experiments were carried out to estimate the moisture ratio of the red banana under open drying, active and passive mode. On 10th May 2020, three experiments were performed to compare the red banana dehydrating rates. The same quantity (one kg) of the samples was placed in each mode of experiments. The investigations were carried out from 09:00 am to 5.00 pm under clear weather. The global radiation, surface and air temperature were recorded continuously from 9.00 am to 5.00 pm. The rate of dehydrating curve was obtained. The variation of moisture ratio of the red banana with dehydrating period under forced convection, natural convection and open sun drying were given in Fig. 1.

From Fig. 1, it was determined that, the reduction in moisture ratio was higher for active solar dryer than the passive solar dryer and sun dehydrating processes. The effectiveness of moisture removal from the samples was also enhanced with the use of forced solar dryer. It was noted that, to achieve the same moisture ratio percentage of 18.75 %, forced convection dryer took 28.5 % faster drying time with respect to natural convection dryer and 71.4 % faster compared to open sun drying. The maximum average absorber and air temperature developed in the forced solar dryer was found to be 83 °C and 79.1 °C. It was also evident from the Fig. 1, that the rate of moisture removal was higher for the active solar dryer than the passive solar dryer and open dehydrating method. This is primarily due to the movement of the forced convection currents over the entire surface of the red banana samples in forced convection and the hot air penetrates throughout entire surface of the samples. This movement of convection currents and hot air penetration in to the samples were very slow in natural convection and open sun drying process. This obviously led to slow down the reduction rate of moisture content. This is evident by observing the variation of the plate, air and ambient temperature for different global radiations. The variations of the plate, air and ambient temperature for different global radiations for both natural and forced convection dryer were shown in Fig. S2a and Fig. S2b).

It was observed that, for the maximum global radiation of 1029 W m^{-2} and ambient temperature of 34.3 °C, under natural convection mode, the maximum of the average plate temperature and maximum of the average inside air temperature were in the range of 71.3 °C - 63.8 °C respectively. Similarly, for the forced convection mode, the maximum of the maximum average plate temperature and inside air temperature were found to be 83 °C and 79.1 °C. It was evident that, in active dryer, due to the presence of air currents with 1.5 m/s, the plate and air temperature were higher than natural convection one.

Comparison with other existing moisture ratio models

In the literature review, most of the researchers developed drying kinetics thin layer of the yellow banana and separate moisture ratio models also developed. The list of mathematical models for moisture ratio is given in Table 1.

Based on this present study of active and passive dryer from the Fig. 2, a new moisture ratio model was developed. The proposed mathematical model was based on the Fick's law of diffusion. The proposed semi-empirical moisture ratio correlations for red banana based on active and passive mode were:

Natural Convection Moisture Ratio Correlation based on 53°C drying air temperature

$$MR = A \exp[-(kt)^n] + Bt + C \qquad /25/$$

where A = 3.02225, B = 0.07711, C = - 2.03566, k = 0.07685, n = 1.02043, t is in hrs.

Forced Convection Moisture Ratio Correlation based on 64°C drying air temperature

$$MR = A \exp[-(kt)^n] + Bt + C \qquad /25/$$

where A = 1.23559, B = - 0.05846, C = -0.23589, k = 0.02300, n = 0.48056, t is in hrs.

The same form of correlation for both natural and forced convection was used and constants were different for both the cases. Based on the existing mathematical moisture ratio models and constants, the moisture ratio was predicted for the red banana for different drying time (h) for both passive and active dryer. The comparison of the mathematical moisture ratio model with present study of the experimental moisture ratio for both passive and active dryer is shown in Fig. 2a and Fig. 2b.

In order to compare the proposed model with other existing mathematical models, correlation coefficient (R^2) is predicted. The correlation coefficient (R^2) was considered as the primary parameter to check the compatibility of the experiments to the developed model (*37*-*39*). The values of the correlation coefficient (R^2), root mean square deviation (RMSD) and the chi-square test were calculated for the present experimental study of both natural and forced convection is given in Table 2 and Table 3. It was noted that, the developed model is in good agreement with other existing mathematical models. The maximum value of R^2, RMSD and the chi-square test is 0.985;0.997, 0.003;0.009, and 0.0640;0.0873 for both natural and forced convection. Many researchers have been reported similar results, where: Correlation coefficient R^2 for plantain banana slices (*3*), Cavendish banana slices (*4*), banana cv. Luvhele slices (*7*), papaya slices (*40*), Cardaba banana slices (*41*) were found to be 0.99. Therefore, it was observed that the newly proposed semi-empirical thin layer drying kinetics model is a relatively good model for predicting of drying kinetics of red banana slices. Thus, similar to other existing moisture ratio models, the present model can also be used effectively to determine the moisture ratio for red banana. In addition to that, parity plot was plotted for experimental moisture ratio and correlated moisture ratio for both natural and forced convection drying process of red banana. The parity plot for natural and forced convection is given in Fig. S3a and Fig. S3b). The correlation coefficient and standard deviation error for the parity plot of natural and forced convection is 0.985; 0.997, 0.046; 0.0199.

In addition to the above experimental analyses of passive and active dryer, EUR, exergy loss and the exergic efficiency were predicted from experimental data based on the Eq. 5. The EUR is predicted for both passive and active dryer. The variation of EUR with dehydrating period for passive and active dryer is shown in Fig. 3a. It was found that, maximum EUR reached at the time of high insolation. The maximum obtained EUR for natural and forced convection is 0.428 and 0.65 respectively. From the magnitude of the values, it was understood that, the forced convection dryer is efficiently sustained the EUR than the natural convection solar dryer due to constant airflow and effective moisture removal from the system.

Apart from that, the exergy loss was also predicted to examine the wastage of energy that could have been utilized for drying the red banana samples. The variation of exergy loss with dehydrating Period for natural and forced convection dryer is shown in Fig. 3b.

From the Fig. 3b, it was noted that, exergy loss is more in forced convection dryer than natural convection dryer. For passive and active dryer, the maximum exergy loss was about 11.11 kJ/kg, 25.42 kJ/kg respectively. This is due to that, in natural convection dryer, the air was not admitted with uniform velocity, this allowed longer retention time of humid air before ventilated from the dryer, which led to lower exergy loss than the forced convection dryer. Also using second law of thermodynamics, the exegetic efficiency was predicted for passive and active dryer as per Eq. 9. The variation of the exergetic efficiency for the samples of red banana under passive and active dryer dehydrating process is shown in Fig. 4. The maximum efficiency exergetic efficiency for natural and forced convection dryer is 67.97 % and 77.97 %. This is due to the retainment of moisture content of the samples in the dehydrating chamber for a lesser period than the natural convection drying process. Hence, the exergetic efficiency for forced convection is higher than natural convection dryer. Based on the exergetic efficiency, one can understand the thermodynamic characteristics of solar drying process both in large- and small-scale drying chamber. However, the problem of process-scale up of the solar dryer; is achieving the high temperature which deteriorate the color parameters of the sample. This is one of the major problems in scaling up of the dryer.

The important parameters such as moisture diffusivity and activation energy were also predicted based on the experimental drying data of red banana using Eq. 17 and Eq. 19. The moisture diffusivity of the red banana depicts the rate of removal of moisture from the red banana. The least energy required for drying the sample is known as activation energy. Based on the Eq. 17 and Eq. 19, the range of effective moisture diffusivity for the sun dehydrating, passive and active dehydrating method was predicted as: open sun drying from $3.86 \cdot 10^{-11}$ to $1.10 \cdot 10^{-10}$ m^2/s; natural convection from $8.74 \cdot 10^{-10}$ to $1.56 \cdot 10^{-09}$ m^2/s; forced convection from $8.43 \cdot 10^{-09}$ to $2.61 \cdot 10^{-08}$ m^2/s. In general, the value of moisture diffusivity falls in the range of 10^{-9} to 10^{-11} m^2/s for fruits, vegetables and grains (*42*,*43*). The D_{eff} value obtained for mushroom samples ($9.619 \cdot 10^{-10}$ to $1.556 \cdot 10^{-9}$ m^2/s), pomegranate seeds ($0.74 \cdot 10^{-10}$ to $52.5 \cdot 10^{-10}$ m^2/s) and sweet potato ($9.32 \cdot 10^{-11}$ to $1.76 \cdot 10^{-10}$ m^2 /s) were similar to previous research works (*44*,*45*,*46*). Besides, our research group earlier reported that the moisture diffusivity of pre-treated ivy gourd ($7.94 \cdot 10^{-8}$ to $3.37 \cdot 10^{-10}$ m^2/s) (*47*).

The variation of natural logarithm of effective moisture diffusivity with temperature is shown in Fig. 5. It was mentioned that, variation of moisture diffusivity is almost linear. Similarly, the range of activation energy for the sun dehydrating, passive and active dehydrating method was found to be 29.05 to 56.53 kJ/mol for sun dehydrating, 24.58 to 45.20 kJ/mol for passive mode and 22.56 to 35.49 kJ/mol for active mode. The range of moisture diffusivity and activation energy for red banana is in close agreement with other fruits reported in the literature (*48*).

CONCLUSIONS

The experimental analysis of red banana was carried out to develop the semi- empirical thin layer drying kinetics moisture ratio correlation based on passive and active solar dryer. The results of drying time were compared with sun dehydrating method. In order to achieve the same equilibrium moisture ratio percentage of 18.75 %, forced convection dryer took 28.5 % faster drying time with respect to natural convection dryer and 71.4 % faster compared to open sun drying. The proposed semi-empirical thin layer drying kinetics moisture ratio correlation was in very close agreement with other existing models with natural convection correlation coefficient of 0.9846 and forced convection of 0.9977. Based on the uncertainty of the temperature (±0.05 °C) and solar radiation (±5.7 W/m^2), the uncertainly of drying rate and kinetic parameter for the SSSD is found to be ±0.08 kg/s and ±0.42 m^2/s, ±0.18 kJ/mol respectively. Besides, the moisture diffusivity, activation energy was found for the red banana. The obtained values of the moisture diffusivity and activation energy are within range of the fruit’s values. In addition to the above, energy and exergy analyses were carried out to predict the losses from the system. In order to compare the dehydrating characteristics of the red banana with other fruits, the experimental results have been compared with other well-known models for broader scientific analysis. It is observed that, the present drying characteristics of red banana are in good agreement other well - known models. Thus, the developed SSSD can be effectively used for drying the agricultural products and the proposed semi-empirical moisture ratio correlation for forced and natural convection can also be used for analyzing the thin layer drying kinetics of food products of fruits and vegetables. Further, above study will be extended to analyze the drying rate of red banana for different dipping solutions.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

AUTHORS' CONTRIBUTION

Elavarasan Elangovan: Data Curation, Conceptualization, Investigation, Formal analysis, Writing Orginal Draft preparation. Sendhil Kumar Natarajan: Resources, Validation, Project administration, Writing-Review and Editing, Conceptualization, Supervision.

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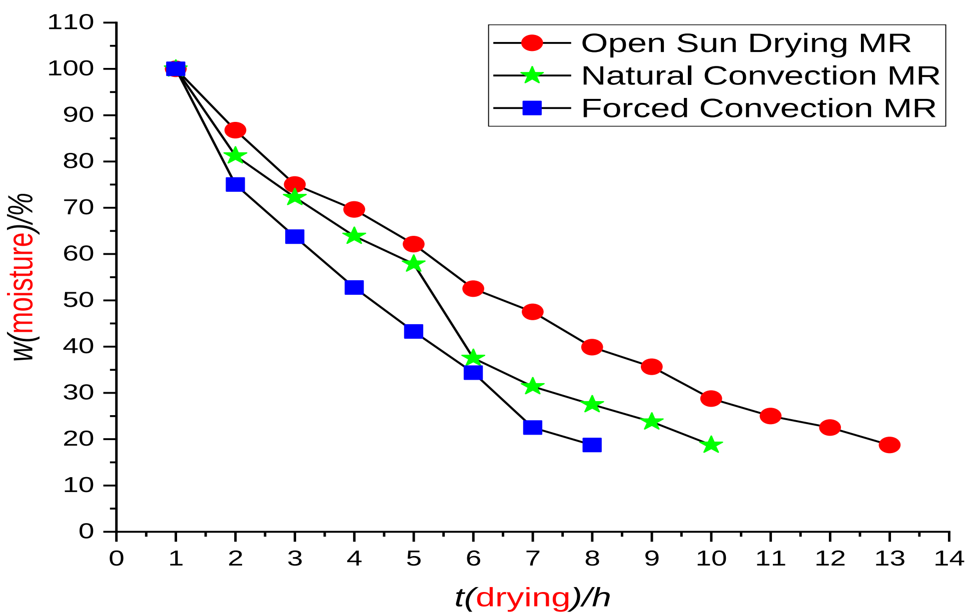
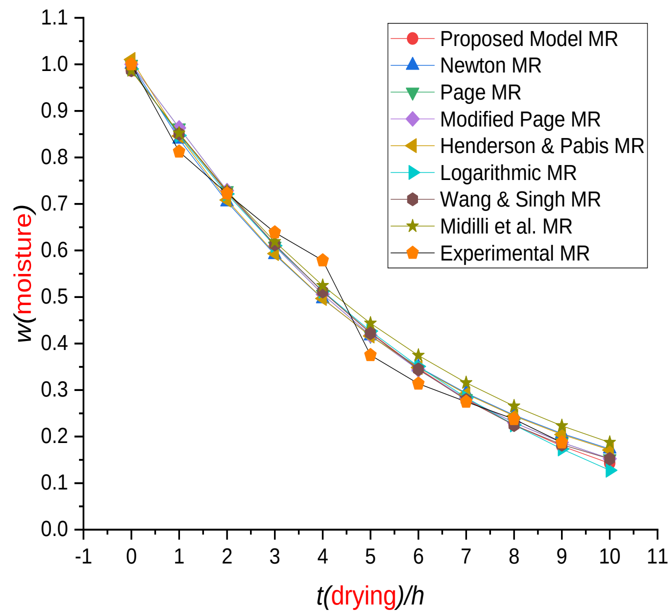


Fig. 1. Variation of moisture ratio of the samples with the drying time for open, natural and forced solar drying

a)


Proposed Model MR
Newton MR
Page MR
Modified Page MR
Henderson & Pabis MR
Logarithmic MR
Wang & Singh MR
Midilli et al. MR
Experimental MR
w(moisture)
t(drying)/h

b)

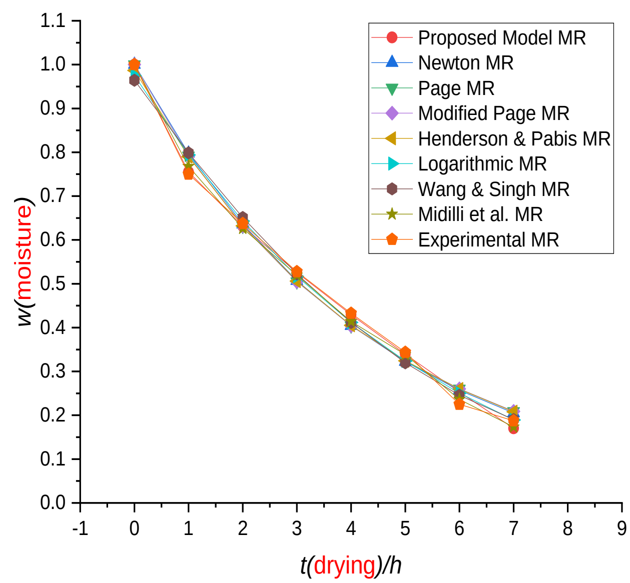

Proposed Model MR
Newton MR
Page MR
Modified Page MR
Henderson & Pabis MR
Logarithmic MR
Wang & Singh MR
Midilli et al. MR
Experimental MR
w(moisture)
t(drying)/h

Fig. 2. Comparison of proposed model with other different drying models from the literature for: a) natural convection dryer, and b) forced convection dryer

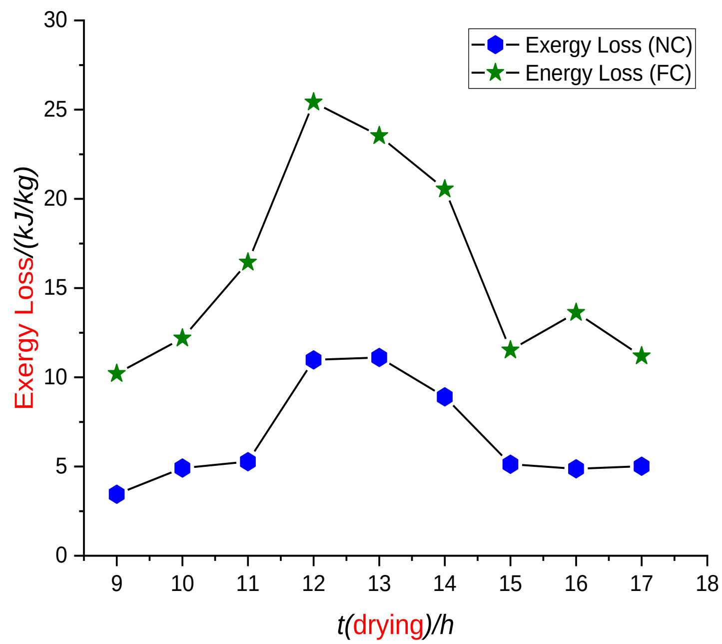


Fig. 3. Variation in drying time of the red banana samples: a) energy utilization ratio, and b) exergy loss

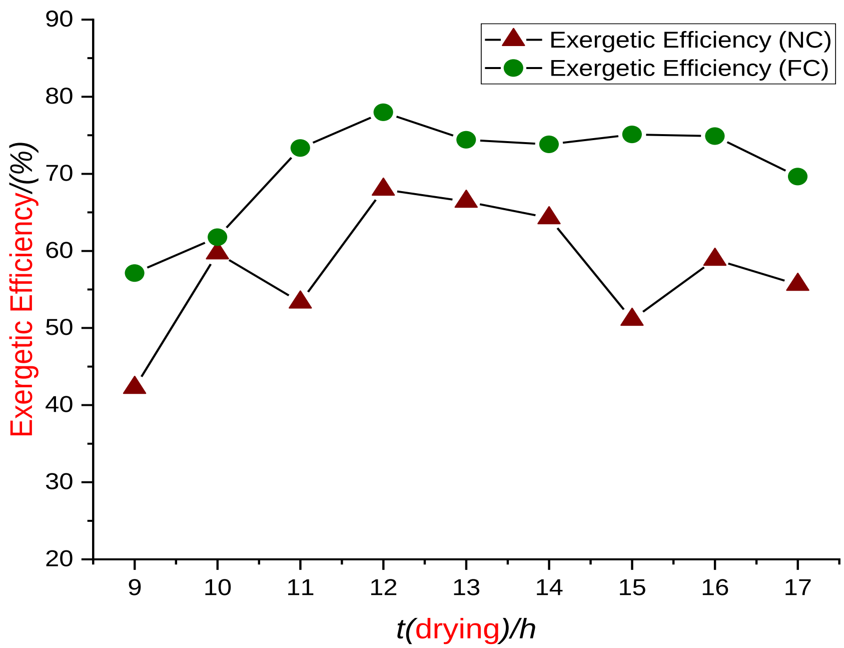


Fig. 4. Variation of exergic efficiency with the drying time of the samples

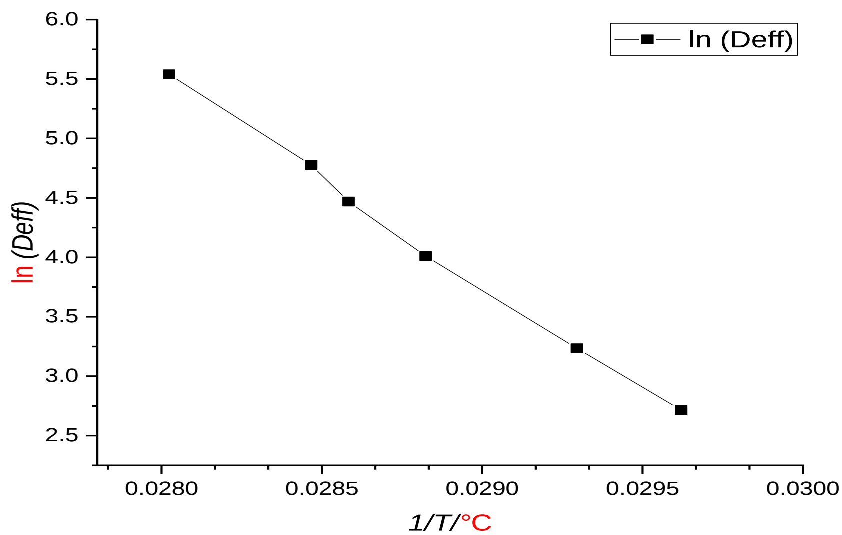


Fig. 5. Variation of ln(D_{eff}) with temperature

Table 1. List of mathematical models

Sl no	Model Name	Model	Reference
1	Newton	*MR= exp(-kt)*	Akoy (*31*)
2	Page	$MR= exp(-kt^n)$	Vega et al. (*32*)
3	Modified Page	$MR= exp[-(kt)^n]$	Akoy (*31*)
4	Henderson and Pabis	*MR= a exp(-kt)*	Radhika et al. (*33*)
5	Logarithmic	*MR= a exp(-kt)+c*	Kaur and Singh (*34*)
6	Midilli et al.	$MR=a exp(-kt^n)+bt$	Ayadi et al. (*35*)
7	Wang and Singh	$MR= M_0+at+bt^2$	Ozdemir and Devres (*36*)

Table 2. Model constants with their R^2, χ2 and RMSE values for natural convection

Model	Temperature/°C	Constants for Natural Convection	R^2 for Natural Convection	χ^2	RMSE
Newton	53	k=0.17518	0.9798	0.0003	0.0640
Page	53	k=0.14681 n=1.10768	0.9830	0.0000	0.0592
Modified Page	53	k=0.17691 n=1.10768	0.9830	0.0000	0.0592
Hernderson and Pabis	53	k=0.17744 a=1.01024	0.9800	0.0001	0.0658
Midilli et al.	53	a=0.98631 b= -0.00687 k=0.13946 n=1.05740	0.9839	0.0000	0.0536
Logarithmic	53	k=0.12678 a=1.20046 c=-0.210228	0.9840	0.0000	0.0495
Wang and Singh	53	M_0=0.98718 a=-0.14244 b=0.00589	0.9851	0.0000	0.0547
Proposed Model	53	a=3.02225 b=0.07711 c=-2.03566 k=0.07685 n= 1.02043	**0.9846**	0.0001	0.0528

Table 3. Model constants with their R^2, χ2 and RMSE values for forced convection

Model	Temperature/°C	Constants for Forced Convection	R^2 for Forced Convection	χ^2	RMSE
Newton	64	k=0.22633	0.9901	0.0009	0.0868
Page	64	k=0.23324 n=0.97855	0.9902	0.0000	0.0873
Modified Page	64	k=0.22592 n=0.97855	0.9902	0.0000	0.0873
Hernderson and Pabis	64	k=0.22252 a=0.98668	0.9906	0.0000	0.0840
Midilli et al.	64	a=0.99971 b= -0.06038 k=0.20362 n=0.48450	0.9977	0.0000	0.0696
Logarithmic	64	k=0.18057 a=1.09485 c= -0.12004	0.9921	0.0000	0.0726
Wang and Singh	64	M_0=0.96432 a=-0.17490 b=0.00919	0.9900	0.0000	0.0851
Proposed Model – Solar Dryer	64	a=1.23559 b=-0.05846 c=-0.23589 k=0.02300 n= 0.48056	**0.9977**	0.0000	0.0562

Supplementary Material

Fig. S1. Photograph of experimental setup of banana drying: a) natural convection, b) forced convection single slope solar dryer and c) open sun drying

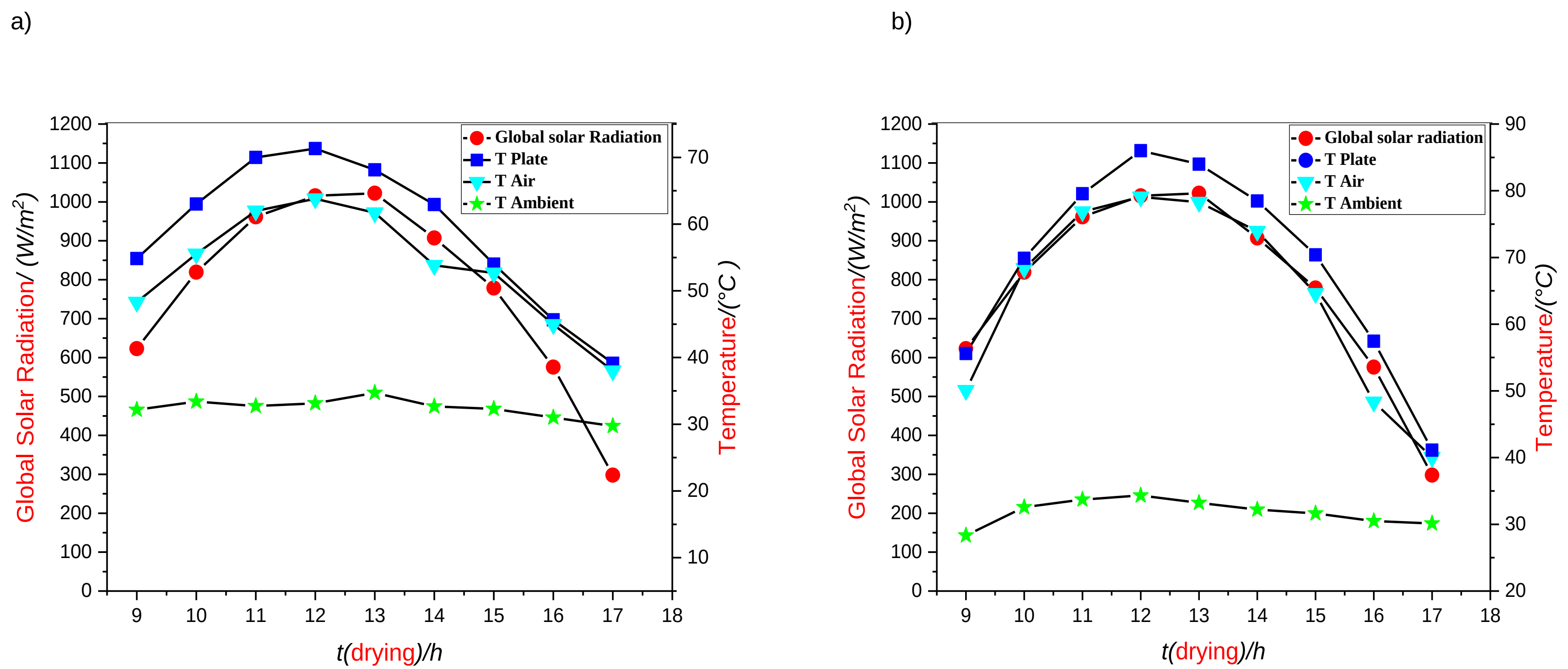


Fig. S2. Variation of solar radiation, ambient temperature, drying air temperature, absorber plate temperature with the drying time of the samples: a) natural convection dryer, b) forced convection dryer

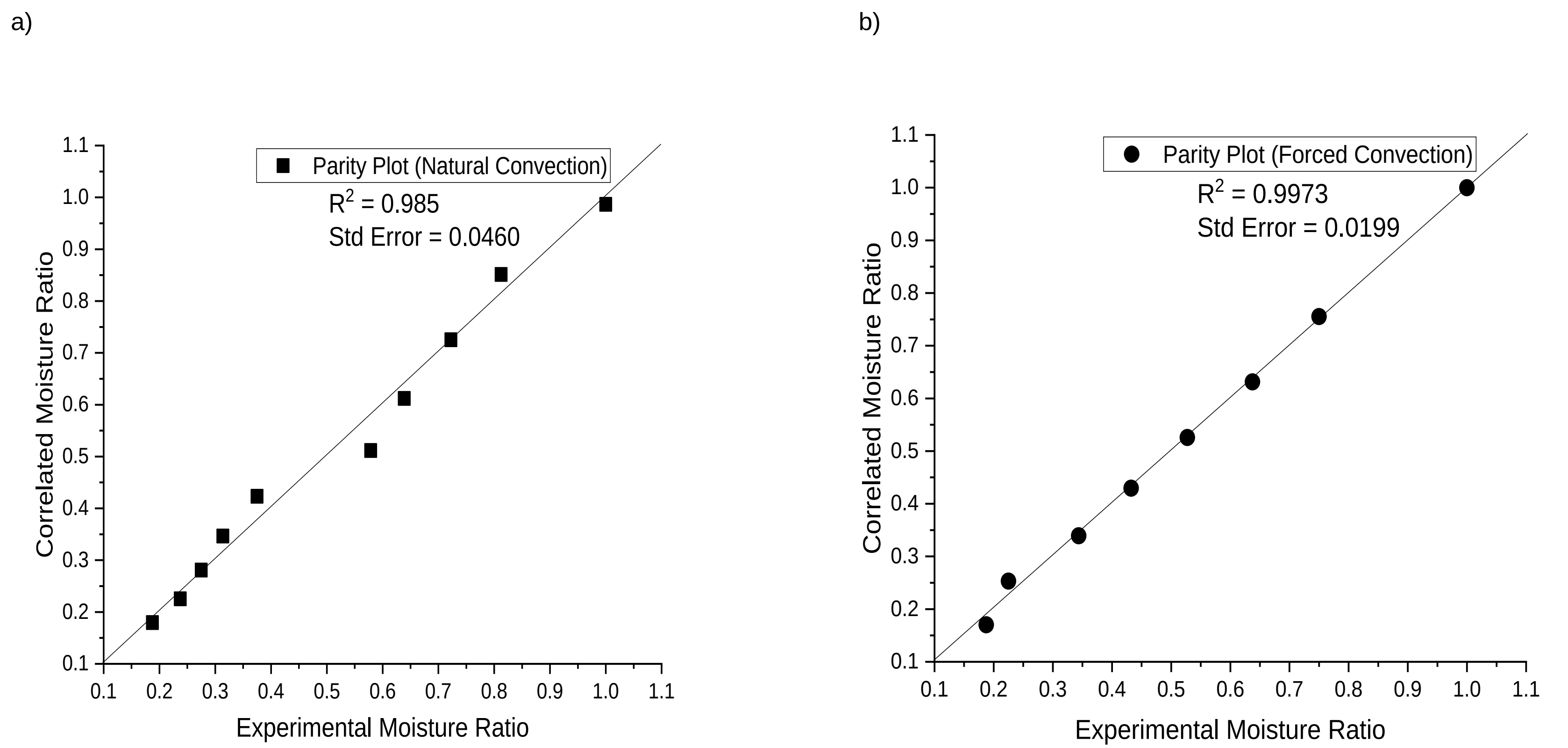


Fig. S3. Parity plot for experimental moisture ratio vs correlated moisture ratio: a) natural convection dryer, b) forced convection dryer

Table S1. Uncertainty analysis during drying experiment of red banana

Sl no	Parameter	Unit	Range	Uncertainty Value
1	K Type thermocouple	°C	-270 °C to 1250 °C	±0.05
2	J Type thermocouple	°C	0 °C to 750 °C	±0.03
3	Air velocity	m/s	0 m/s to 5 m/s	±0.14
4	Relative humidity of air	%	0 % to 100 %	±0.14
5	Moisture quantity	g	0 g to 1000 g	±0.001
6	Global solar radiation	W/m^2	0 W/m^2 to 1650 W/m^2	±5.77
7	Kinetics parameters	m^2/s	-0.0 to 3.02	±0.42
8	Drying rate	kg/s	0.002 to 0.24	±0.08