Comparative Study of Indirect Solar Drying, Electric Tray Drying and Open Sun Drying of Pineapple Slices Using Drying Kinetics and Drying Models

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Abstract: **In this study comparison between electric tray drying, solar cabinet drying and open sun drying was done using drying kinetics of pineapple slices. A laboratory scale solar dryer was designed and fabricated with a capacity of 1kg, for electric tray drying a convective electric drying oven was used and for open sun drying a white tile with pineapple slices was placed in the open sun. Drying temperature, moisture content (MC_{wb}), drying rate, drying ratio (MR) and effective moisture diffusivity (D_{eff}) were the indicators used for comparisons. Four common convective drying mathematical models namely Newton, PAGE, Henderson & Pabis and the Logarithmic model were compared for goodness of fit. The PAGE model showed the highest correlation coefficient (R^2) of 0.940032652. The Henderson & Page model had the lowest root mean square error (RMSE) of 0.018514552. Both models were used to estimate and compare the model constants *a*, *c* and *n* the empirical constants and *k* the drying constant. These values showed very little difference between solar drying and electric tray drying. Effective moisture diffusivity (D_{eff}) was compared. D_{eff} was 19 x 10^{-9} m^2s^{-1}, 1.5x10^{-9} m^2s^{-1} and 1.1x10^{-9} m^2s^{-1} in tray, solar and sun drying respectively.**

***Key words*: Solar dryer, open sun drying, drying rate, thin layer drying, effective moisture diffusivity, mathematical modeling**

I. INTRODUCTION

Most developing countries are battling with food security mainly due to overpopulation, poor rains, underperforming agriculture amongst other reasons. A closer investigation suggests that there are cyclic times of plenty (seasonal glut) and times of scarcity. Use of solar drying technologies can be useful in food preservation such as grains, fruits and vegetables. Preservation by drying will ensure longevity of availability and variety in the diet. Other problems of malnutrition can be addressed as well. Recent years have seen the European market opening up and creating a growing demand for dried fruits and vegetables. Some small scale farmers in developing countries have began to supply dried fruit to Europe. The value addition to the seasonal glut fruits has been reported to be above 50%. This if exploited goes a long way to alleviate poverty and create employment.

Solar drying remains a viable drying and food preservation technology alternative with a potential to reduce post-harvest loses which can be as high as 25-30% in food grains and 30-50% in fruits and vegetables as reported by (Patel et al [1]. Despite the obvious advantages of solar drying technology, which are; cheap, environmentally friendly, hygienic, minimal loss of heat and light sensitive nutrients, it is yet to be commercialized and accepted widely [2],[3]. The reasons of poor acceptance are multifold. It has been argued that the design of solar dryers is largely based on empirical and semi-empirical data. The lack of sound theoretical data upon which to base the designs has resulted in poor performance prototypes[1]. In this regard research is ongoing to generate as much data as possible through experiments and developing mathematical models to predict drying time, rate constants. Popular mathematical models namely the PAGE, Newton, Henderson & Pabis, Logarithmic, Verma et al, Midilli et al and the Two-Term Exponential model have been developed and used to this effect [4],[3],[5],[6].

Another challenge with solar drying has been the fluctuations in drying temperature during drying. Solar dryers efficiency is reduced in times or places of reduced direct solar insolence and they become redundant during the night. This has an impact on final product quality. Work has been done to hybrid solar dryers with supplementary heating and heat reservoirs. This has led to the development of novel dryers such as a mixed mode solar dryer with forced convection [7], drying system with water/ oil/rocks as heat storage fluid, mixed mode dryers, heat storage by irradiation [2]. On the same note, improvements have been made over the years on the solar collector design. A flat –plate and offset plate fin was designed by (Hachemi [8] and a PV-thermal hybrid collector was proposed by Garg [9].

Despite these advances in solar drying through research and development, the technology has not been accepted as expected. High initial cost of installation, need for technical aptitude and competence on personnel to use the technology and lack of awareness about the technology has not helped. Most of all farmers (the intended users of the technology) remain skeptic [10]. There needs to be clear advantages of solar drying over electrical and traditional methods of open sun drying in poor agricultural communities as well as in advanced commercial undertakings.

It is from this background that this research work sought to bring to the fore, the advantages of solar drying by carrying out a comparative study of solar drying and open sun drying and electrical drying of pineapples. The objectives were to determine and compare the drying time, drying rate and drying rate constants and predicting/forecasting behavior of the drying processes based on mathematical models. Thorough knowledge of the drying characteristics of fluctuating temperature drying would aid in quality improvement of dried products, value addition and food preservation.

II. MATERIALS AND METHODS

2.1 Fruit selection and preparation

Mature pineapples *(Ananas comosus)* of green-yellow colour were obtained from the fruit market in Chennai area with an average weight of 150g ±7g, a moisture content of 87% ± 5% [11]. The initial moisture content was determined by gravimetric measurement method where a sample was placed in a hot air oven at 105^{o}C and measuring the moisture until a constant weight was obtained [12]. The fruits were peeled, sliced to an average thickness of 10mm ±3 and cored [13]. They were divided into three lots and the lots were dried in the electric tray dryer, solar dryer and in open sun drying simultaneously.

2.2 Laboratory scale solar dryer prototype design

A laboratory scale solar dryer was designed and fabricated for this study. It had a capacity of1kg. The dryer was constructed using sheet metal of thickness 4mm which had an insulated drying cabinet to prevent secondary heating from the walls. The dryer was intended to dry products from an average moisture content of 90% to 10% or less which caters for a wide range of fruits and vegetables. The amount of moisture removed moisture load was determined by equation 1

$$\boldsymbol{Mw} = {}^{\boldsymbol{Mp}(\boldsymbol{Mi} - \boldsymbol{Mf})}\Big/_{(\boldsymbol{100} - \boldsymbol{Mf})} \qquad \text{(equation 1)}$$

Where *Mw* is mass of moisuture, *Mi* is initial moisture content, *Mf* is final moisture content.

The solar collector was a “flow above” flat bed collector with a black metal absorber covered with a 4mm transparent glass as illustrated in Fig 1.

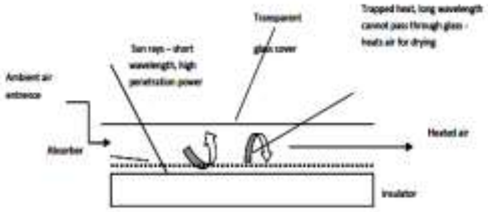


Fig1: Flat bed solar collector

The tilt angle was determined for the Chennai area where the latitude and longitude were determined based on data from NASA Langley Centre for Atmospheric Science [14] as shown in Table 1

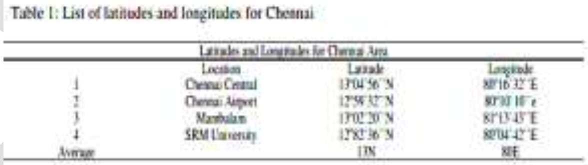


Table 1: List of latitudes and longitudes for Chennai

Latitudes and Longitudes for Chennai Area			
	Location	Latitude	Longitude
1	Chennai Central	13°04'56"N	80°16'32"E
2	Chennai Airport	12°59'32"N	80°10'10"e
3	Mambalam	13°02'20"N	81°13'43"E
4	SRM University	12°82'36"N	80°04'42"E
Average		13N	80E

From the data in Table 1, the tilt angle for the collector was determined to be 13^{o} facing South as illustrated in Fig 2

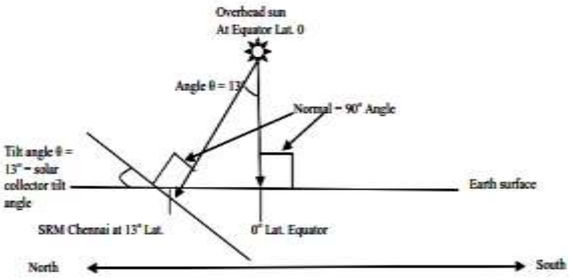


Fig 2: the tilt angle for maximum insolation at noon day sun

Psychrometry of dying air was considered so as to estimate the moisture carrying capacity of the air and the volume required hence the dimensions of the dryer. The Vernmaces HDPbypscych Chart 7.5.6 software was used. From these calculations the dryer dimensions were determined. The dryer was classified as an active, indirect and forced convection cabinet solar dryer. It used heated air as the only heat source and air velocity for mass transfer [2]. A PID temperature controller was incorporated to aid in temperature measurement of the drying air in the solar cabinet. The schematic diagram of the solar dryer is shown in Fig 3

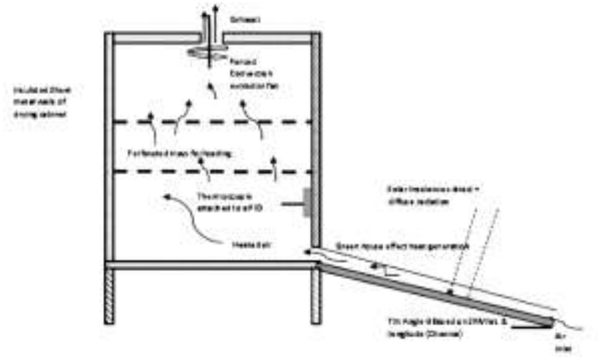


Fig 3: Schematic diagram of the solar dryer

2.3 Electric tray drying

Tray drying was done using a convective electric tray dryer as shown in Fig 4. The samples were placed on a perforated tray and the oven temperature was set at 60^{o}C. This according to Belessiotis & Delyannis [2] is the optimum drying temperature for drying most fruits and vegetables.

Figure 4: Photograph of an electrical convective drying oven

2.4 Open sun drying

Pineapple slices were spread (uni-layer) on a flat wooded surface and exposed to direct solar radiation. The drying process involved heat transfer by convection from the surrounding air and by direct absorption of solar incidence and diffuse radiation on the surface of the pineapples which caused the drying to occur. A dry bulb thermometer was mounted to record the ambient air temperatures as shown in fig 5

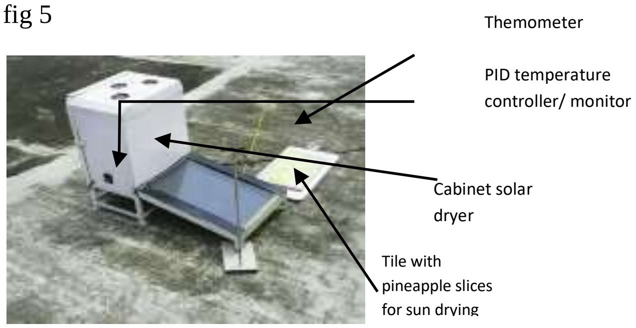


Fig 5: A photograph of the experiment set-up

2.5 Gravimetric analysis

Periodic sampling and weighing was used to record the reducing weights of both the samples in open sun and solar dryer. An electronic weighing balance was used to measure the weights which were taken at half hour intervals. Gravimetric analysis is based on the principle of loss of water due to drying (evaporation) which directly translates to a decrease in the sample weight. The change in weight over time was recorded and the data was analysed [15].

2.6 Modeling drying data

The assumption in thin layer drying (as was the case in this study) is the infinitely large ratio of air volume to the product. Hence the drying rate is assumed to be dependent on material property to be dried, its size, drying air temperature and moisture content [2].

2.6.1 Moisture content determination

The moisture content in wet basis was calculated using the following equation 2 [2].

$$\%MC = \frac{Wo - Wf}{Wo} \times 100 \qquad \text{(equation 2)}$$

Where W_o is initial and W_f is the final weight of the sample in grams [4],[3].

2.6.2 Moisture Ratio

The dimensionless moisture ratio (MR) was calculated using equation 3

$$MR = \frac{M - Me}{Mo - Me} \qquad \text{(equation 3)}$$

Where M is the average moisture content at time t, Mo is the initial moisture content and Me is the equilibrium moisture content [4]. This expression is further simplified by considering that the equilibrium moisture content (Me) is very small compared with (M) and (Mo) hence the error associated with it is negligible [2]. It can be assumed as zero [4],[16], and the expression is modified in equation 4.

$$MR = \frac{M}{Mo} \qquad \text{(equation 4)}$$

2.6.3 Drying rate

Drying rate was calculated based on the weight of water removed per unit time per kilogram of dry matter and modified from Agarry et al and Kemp et al [4],[15] to be expressed in grams per minute [12]. Equation 5 was used to calculate drying rate at various stages during drying [3].

$$dM/_{dT} = Mo - Mt/_{t} \qquad \text{(equation 5)}$$

2.6.4 Mathematical Drying Models

Simulation mathematical models that predict thin layer drying behavior of materials were used. Thin layer drying models (Table 2) sought to describe the drying process in a uniform way by disregarding the controlling mechanisms [4]. The best fit was determined by calculating the regression analysis using Microsoft Excel and IBM SPSS statistics v19 software. The root mean square coefficient (R^2) was determined. The higher the (R^2) value, the better the fit. Another parameter was the root mean square error RMSE where RMSE should be at a minimum for best fit [3]. Upon determination of the best fit, the drying rate constant (k) for both cases was estimated, the k values were compared and the higher the k value, the better the drying process.

Table 2 shows a list of the common mathematical models used to compare the two drying processes in this study [4],[3].

Table 2: List of Common Mathematical Models Used to Predict Convective Drying Processes

	Model name	Model equation
1	Page	$MR = e^{-kt^n}$
2	Henderson & Pabis	$MR = ae^{-kt^n}$
3	Newton	$MR = e^{-kt}$
4	logarithmic	$MR = ae^{-kt} + c$

Where *a*, *c* and *n* are empirical constants, *k* is drying constant, *t* is drying time and *MR* is moisture ratio

2.7 Effective moisture diffusivity

The moisture transfer mechanism during drying as governed by Fick`s second law of diffusion (Fick`s model) was used to determine the effective moisture diffusivity. Fick`s model expresses a linear relationship between MR and effective diffusivity. For long drying processes the relationship is expressed in equation 6

$$\boldsymbol{MR = \frac{8}{\pi^2} e^{\frac{-D_{eff}\ \pi^2 t}{4l^2}}} \qquad \text{(equation 6)}$$

Where *MR* is moisture ratio, D_{eff} is moisture diffusivity (m^2s^{-1}), *t* is drying time in seconds and *l* is thickness (*m*). Linear adjustment was done to fit the experimental data to equation 5 and R^2 calculated by linear regression [16],[4],[6].

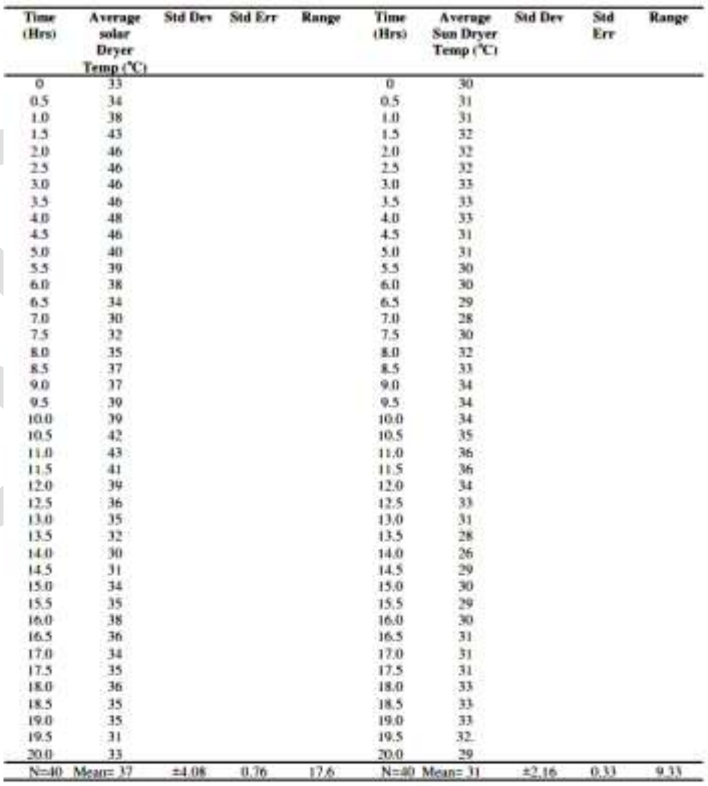
By plotting natural log of MR (*lnMR*) versus time, a straight line is obtained and its gradient (k_o) is determined (equation 7).

$$\boldsymbol{k_o = \frac{\pi^2 D_{eff}}{4l^2}} \qquad \text{(equation 7)}$$

III. RESULTS AND DISCUSSION

Table 3 shows the average temperatures recorded of three experimental runs. The aim of the experiment was to compare the drying kinetics of pineapple under fluctuating temperatures experiences in sun and solar drying. The range of temperature in the solar dryer was 17.6 °C which indicated a difference between the lowest and highest recorded temperature of 30 and 47°C respectively. Sun drying recorded lower temperatures compared with solar dyer temperatures. The range was 9.33 which showed a difference between the lowest temperature of 26.67°C and the highest of 36°C. The mean temperature for solar drying was 37°C while that of sun drying was 31°C. The apparent gain in temperature was attributed to the green house effect described by Belessiotis & Delyannis [2]. Temperatures up to 40°C higher than ambient temperature have been reported on solar dryers subject to collector efficiency [2]. Tray dryer temperatures were not considered since the drying temperature was constant.

Table 3: Average recorded temperatures for solar and sun dryers



Time (Hrs)	Average solar Dryer Temp (°C)	Std Dev	Std Err	Range	Time (Hrs)	Average Sun Dryer Temp (°C)	Std Dev	Std Err	Range
0	33				0	30			
0.5	34				0.5	31			
1.0	38				1.0	31			
1.5	43				1.5	32			
2.0	46				2.0	32			
2.5	46				2.5	32			
3.0	46				3.0	33			
3.5	46				3.5	33			
4.0	48				4.0	33			
4.5	46				4.5	31			
5.0	40				5.0	31			
5.5	39				5.5	30			
6.0	38				6.0	30			
6.5	34				6.5	29			
7.0	30				7.0	28			
7.5	32				7.5	30			
8.0	35				8.0	32			
8.5	37				8.5	33			
9.0	37				9.0	34			
9.5	39				9.5	34			
10.0	39				10.0	34			
10.5	42				10.5	35			
11.0	43				11.0	36			
11.5	41				11.5	36			
12.0	39				12.0	34			
12.5	36				12.5	33			
13.0	35				13.0	31			
13.5	32				13.5	28			
14.0	30				14.0	26			
14.5	31				14.5	29			
15.0	34				15.0	30			
15.5	35				15.5	29			
16.0	38				16.0	30			
16.5	36				16.5	31			
17.0	34				17.0	31			
17.5	35				17.5	31			
18.0	36				18.0	33			
18.5	35				18.5	33			
19.0	35				19.0	33			
19.5	31				19.5	32			
20.0	33				20.0	29			
N=40	Mean= 37	±4.08	0.76	17.6	N=40	Mean= 31	±2.16	0.33	9.33

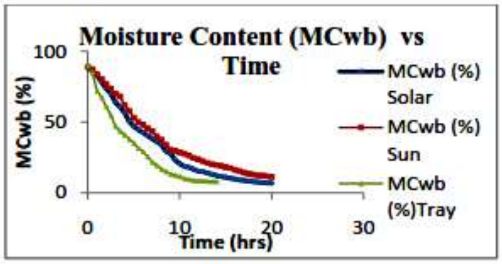


Fig 6: Moisture Content Comparison in wet basis for Tray, Sun and Solar Dryers

From the graph in Fig 6, the moisture content of the pineapple slices in the tray solar and sun dryers is shown. After 14 hours of drying, the moisture content of the tray dried samples was in the region of 8%. It took an extra 6 hours for both the solar dried and the sun dried samples to attain a similar moisture content with that of tray drying. According to Belessiotis & Delyannis, [2], the expected drying time for solar dried foods is 15-30 hours. Typically the drying occurred over three days with 20 hours of active drying. This was within the range of 2-3 days given by the El-Paso Solar Energy Association [17].

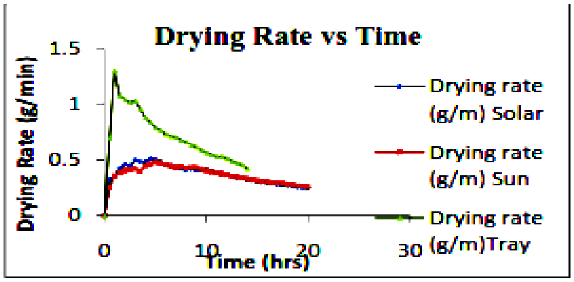


Fig 7: Comparison of Drying Rates for Tray, Sun and Solar Drying

Fig 7 showed the drying rates in the three experimental conditions. It was difficult to compare the curves based on drying rate alone. Further analysis of the drying processes was done using equations 2 and 3.

Equations 2 and 3 were used to determine ***MR*** from the experimental data in tr solar, tray and sun drying experiments. *MR* was the dimensionless ratio used to unify the comparison platform [3],[16]). Thin layer models were fitted into the ***MR vs Drying time*** graphs for both solar and sun drying. Goodness of fit was determined by regression analysis using IMB SPSS statistics v19 software. Figs 8 to 11 show the graphs of ***MR vs Drying time*** for the four thin layer drying models on both solar and sun drying. From the models with the best fit to the experimental data, more accurate comparisons were made between solar and open sun drying.

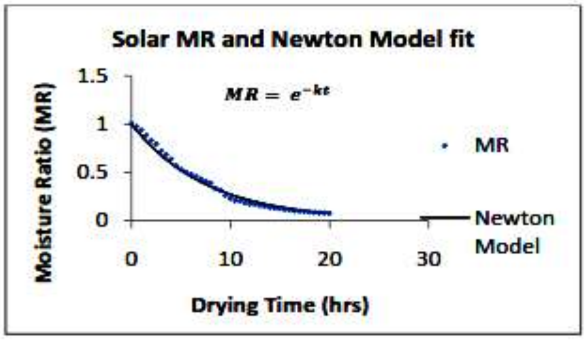


Fig 8 a: Graph of the Newton Model Fit for Solar Drying Kinetics

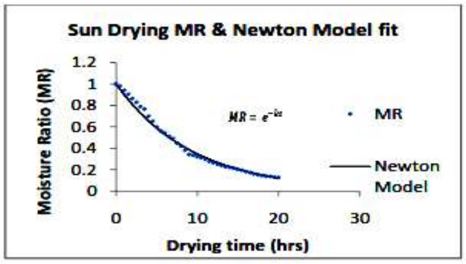


Fig 8 b: Graph of the Newton Model Fit for Sun Drying Kinetics

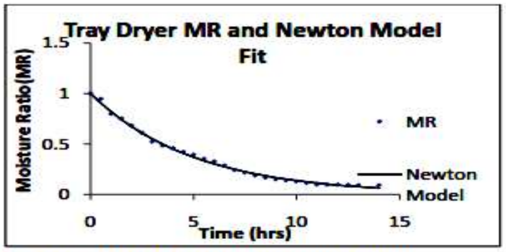


Fig 8 c: Graph of the Newton Model Fit for Tray Drying Kinetics

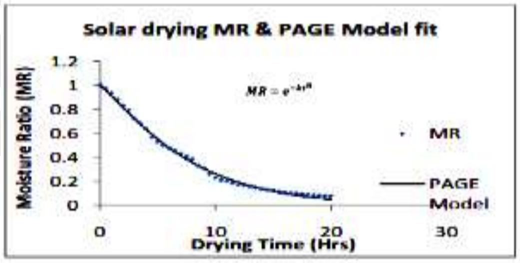


Fig 9 a: Graph of PAGE Model Fit for Solar Dryer Kinetics

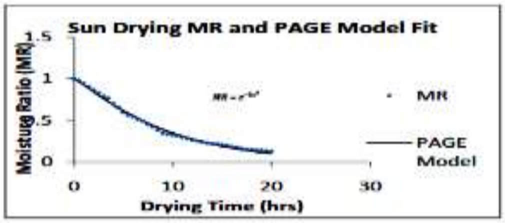


Fig 9 b: Graph of PAGE Model Fit for Sun Dryer Kinetics

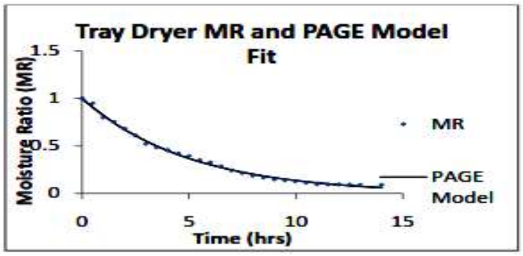


Fig 9 c: Graph of PAGE Model Fit for Tray Dryer Kinetics

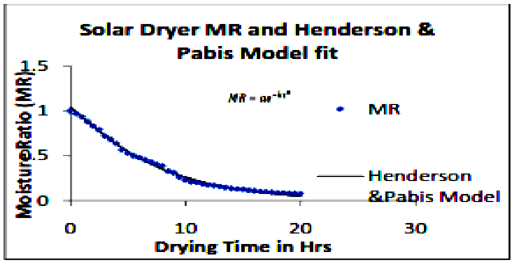


Fig 10 a: Graph of Henderson & Pabis Model Fit for Solar Dryer Kinetics

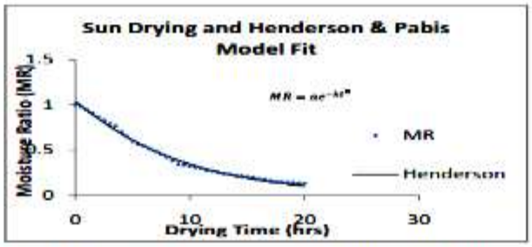


Fig 10 b: Graph of Henderson & Pabis Model Fit for Sun Dryer Kinetics

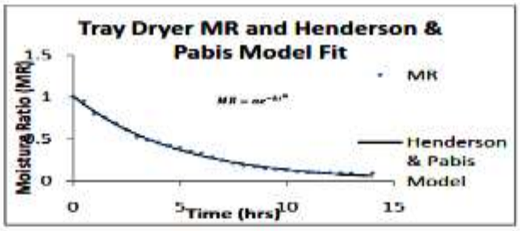


Fig 10 c: Graph of Henderson & Pabis Model Fit for Tray Dryer Kinetics

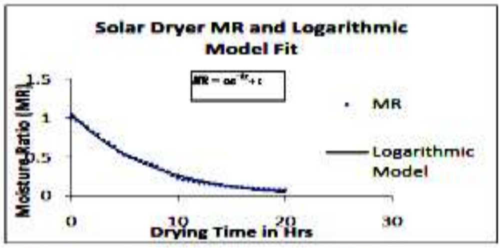


Fig 11 a: Graph of Logarithmic Model Fit for Solar Dryer Kinetics

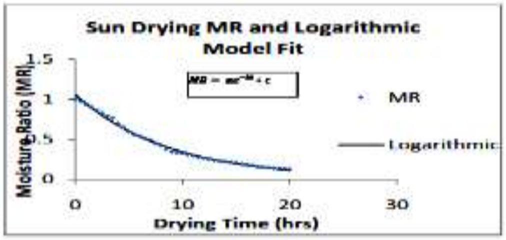


Fig 11 b : Graph of Logarithmic Model Fit for Sun Dryer Kinetics

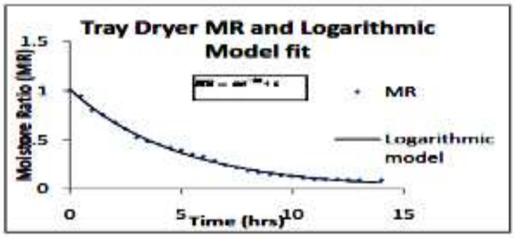


Fig 11 c: Graph of Logarithmic model Fit for Tray dryer Kinetics

The model parameters ***a***, ***c***, and ***n*** which are the empirical constants and ***k*** the drying rate constant were determined and their combinations optimised to suit the requirements of the minimal value of sum of square deviation on the expected data values (model values). The Excel Solver data tool was used for the optimisation and the final values of these constants are listed in Table 4.

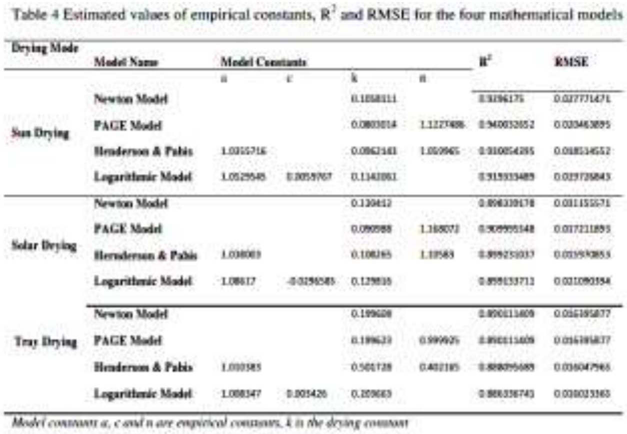


Table 4 Estimated values of empirical constants, R^2 and RMSE for the four mathematical models

Drying Mode	Model Name	Model Constants				R^2	RMSE
		a	c	k	n		
Sun Drying	Newton Model			0.1058111		0.9196175	0.027771471
	PAGE Model			0.0803014	1.1227486	0.940032052	0.020463895
	Henderson & Pabis	1.0315716		0.0962161	1.059965	0.910054295	0.018514552
	Logarithmic Model	1.0529545	0.0059767	0.1142061		0.915933489	0.029726843
Solar Drying	Newton Model			0.120412		0.898330178	0.031155571
	PAGE Model			0.090988	1.168072	0.909995148	0.017211895
	Henderson & Pabis	1.038003		0.108265	1.10583	0.899251037	0.015930853
	Logarithmic Model	1.08617	-0.0296585	0.129816		0.898133712	0.021090354
Tray Drying	Newton Model			0.199608		0.890011409	0.016195877
	PAGE Model			0.199623	0.999925	0.890011409	0.016195877
	Henderson & Pabis	1.010385		0.501728	0.402185	0.888095685	0.016047965
	Logarithmic Model	1.008347	0.003426	0.209683		0.888336743	0.030023363

Model constants a, c and n are empirical constants, k is the drying constant

From Table 4, From Table **4.5**, the PAGE model had the highest values for (***R***^{2}) of 0.89, 0.94 and 0.90 for tray, sun and solar drying respectively. This implies the best fit to describe and predict the drying behavior of all drying processes [16]. It was noted however that the RMSE was lowest in the Henderson & Pabis model with values of 0.0160, 0.0185 and 0.0159 for tray, sun drying and solar drying respectively. The PAGE model was also found to have the best goodness of fit in work done by Agarry & Aworanti [16] and Pereira da Silva *et al* [18] in low temperature convective drying.

By comparing the values of ***k***, the drying rate constant as given by the PAGE model, it was 0.199, 0.0803 for tray, sun drying and 0.0909 for solar drying. The ***n*** value also showed the same trend, it was higher in solar drying at a value of 1.168, 1.12 in sun drying and 0.99 in tray drying. The value of ***k*** was also higher in the Henderson & Pabis Model with a value of 0.501in tray drying 0.108 in solar drying and 0.096 in sun drying. The n value followed the same trend and was also higher in solar drying with a value of 1.105 in solar drying and 1.059 in sun drying. It was least in tray drying. The

a value was more or less similar in both cases in the Henderson & Pabis model.

The PAGE model had the highest values for (R^2) of 0.94 and 0.90 for sun and solar drying respectively. This implies the best fit to describe and predict the drying behavior of both drying processes [16]. It was noted however that the RMSE was lowest in the Henderson & Pabis model with values of 0.0185 and 0.0159 for sun drying and solar drying respectively. The PAGE model was also found to have the best goodness of fit in work done by Agarry & Aworanti [16] and Pereira da Silva et al [18] in low temperature convective drying.

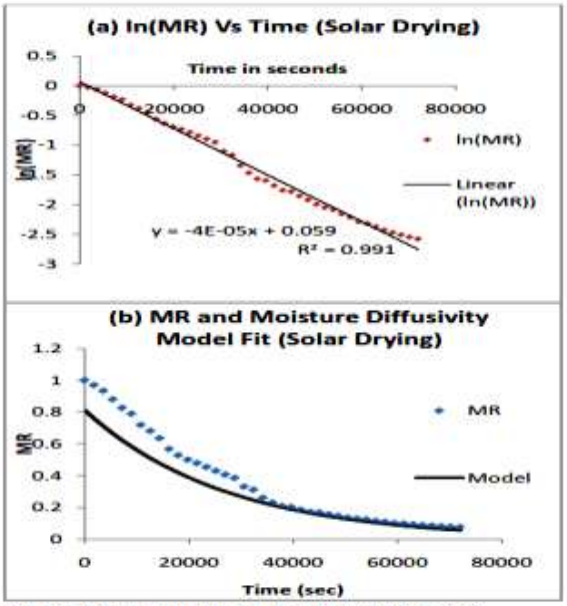


Fig 12: (a) Linear Graph of lnMr vs Time and (b) Moisture Diffusivity Model for Solar Dryer

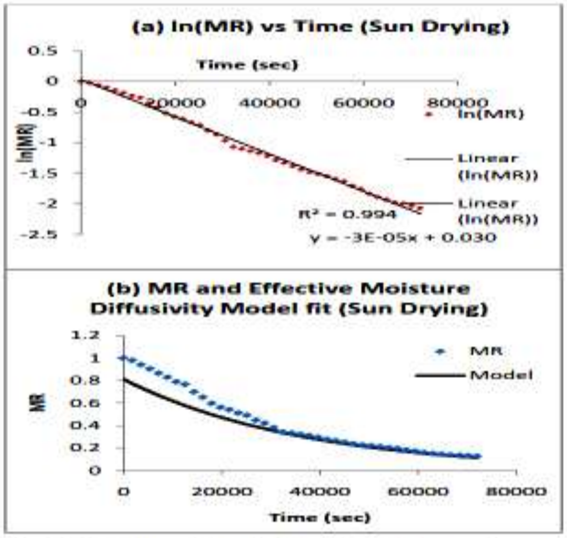


Fig 13: (a) Linear Graph of ln Mr vs Time and (b) Moisture Diffusivity Model for Sun Dryer

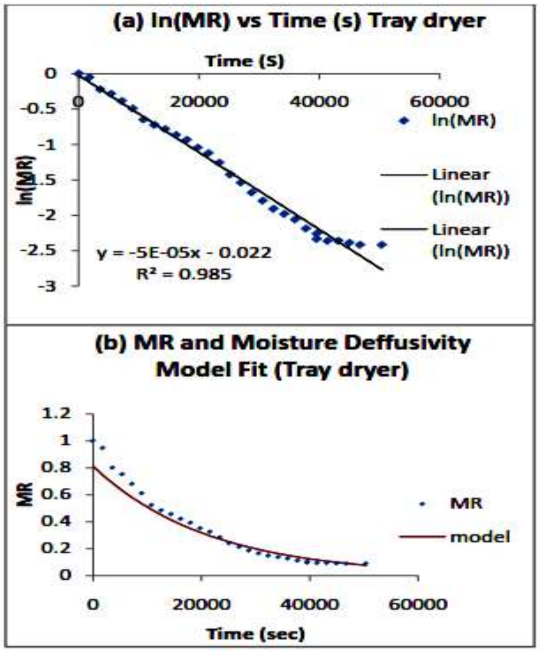


Fig 14: (a) Linear Graph of ln Mr vs Time and (b) Moisture Diffusivity Model for Tray Dryer

Figs 12 to 14 showed the linear slope of ***ln(MR)*** against Time which was used to determine the effective moisture diffusivity values for both solar and sun drying. The gradient of the slope in solar drying was $4x10^{-5}$ while that of sun drying was $3x10^{-5}$ this indicated slightly better moisture removal in solar drying over sun drying. From equations 20 and 21, knowing the $\boldsymbol{k_o}$ values, the $\boldsymbol{D_{eff}}$ values were determined. Solar drying had a $\boldsymbol{D_{eff}}$ value of $1.62x10^{-9}$ m^2s^{-1} and sun drying had a $\boldsymbol{D_{eff}}$ value of $1.1x10^{-9}$. m^2s^{-1}. Tray dryer had a $\boldsymbol{D_{eff}}$ value of $1.9x10^{-9}$. These values were found to be within the range recorded of most food materials which is between 10^{-9} and 10^{-11} m^2s^{-1} [3],[19],[20]. A predictive model based on equation 21 (Fick`s diffusion model) was fit onto the *MR* versus Time graph for both solar and sun drying using the estimated $\boldsymbol{D_{eff}}$ values and the optimized values for tray, solar and sun drying for best fit were $1.9x10^{-9}$, $1.5x10^{-9}$ m^2s^{-1} and 1.1 $x10^{-9}$ m^2s^{-1} respectively. It was noted that the $\boldsymbol{D_{eff}}$ value for solar drying reduced from the calculated value of $1.62x10^{-9}$ to $1.5x10^{-9}$ on the model prediction at a correlation coefficient of 89% The k_o and D_{eff} values are summarized in Table 5. The D_{eff} value for solar drying was higher than that of sun drying. This implies a better mass transfer in solar dying compared with sun drying [3].

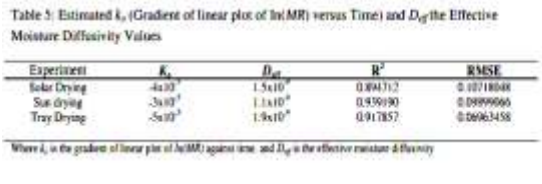


Table 5: Estimated k_o (Gradient of linear plot of ln(*MR*) versus Time) and D_{eff} the Effective Moisture Diffusivity Values

Experiment	K_o	D_{eff}	R^2	RMSE
Solar Drying	$-4x10^{-5}$	$1.5x10^{-9}$	0.894712	0.10718048
Sun drying	$-3x10^{-5}$	$1.1x10^{-9}$	0.939190	0.09999066
Tray Drying	$-5x10^{-5}$	$1.9x10^{-9}$	0.917857	0.06963458

Where k_o is the gradient of linear plot of *ln(MR)* against time and D_{eff} is the effective moisture diffusivity

For the three model predictions it was noted that the **Fick`s model** was not able to predict the effective moisture diffusivity when t is equal to zero as shown in Figs **11 (b), 12 (b)** and **13 (b)**. Furthermore there was an incongruence noted in the first 10 hours of drying between the predictive model and experimental data in all solar and sun drying experiments. This coincides with an irregular fluctuating drying rate displayed in Fig 6 where Drying Rate is plotted against Time. This phenomenon was attributed to fluctuations in solar radiation intensities as the day progresses [3].

IV. CONCLUSION

From the four mathematical models used in convective drying process predictions used in this study, the PAGE Model had the best goodness of fit with the Highest R^2 value of 0.940032652 in sun drying and 0.909995548 in solar drying. For the least RMSE value, the Henderson & Pabis Model had the least values of 0.018514552 in sun drying and 0.015970853 in solar drying. Both models were used to compare the model constants a, c and n the empirical constants and k is the drying constant. In both models these values were higher in solar drying.

Considering the graphs of ln(MR) plotted for sun and solar against time, the linear gradients (k_o), k_o for solar drying was $4x10^{-5}$ and $3x10^{-5}$ for sun drying. The linear relationship was steeper in solar drying than sun drying. Again the solar drying had a slight advantage in moisture removal during the drying process.

Furthermore, effective moisture diffusivity was compared in both experiments. This denotes the effectiveness of mass transfer in the drying process. D_{eff} in solar drying was $1.5x10^{-9}$ m^2s^{-1} and $1.1x10^{-9}$ m^2s^{-1} in sun drying.

The findings in this study suggest that solar drying is more effective in both heat and mass transfer the two critical factors affecting the drying process than sun drying. With further research on improvement of solar thermal energy collection and mechanisms to store the heat energy for periods of reduced solar radiation, this technology can go a long way in assuring food security. Losses experienced during seasonal glut can be minimized. The drying time was shortest in tray drying where the moisture content was reduced from an average of 90% MC_{wb} to an average of 7% MC_{wb} in 14 hours of active drying. It took 20 hours for both the solar and sun drying to achieve the same. Mathematical models such as the **PAGE** model were effective in predicting the drying behaviour in all the three drying treatments. In conclusion the laboratory scale solar dryer has been successful in conduction of drying experiments and in the general understanding of factors that affect the drying process The tray dryer was superior in heat transfer but weaker in mass transfer hence the little difference in drying time in comparison with solar and sun drying. The evidence was suggested by drying models, drying constants and the effective moisture diffusivity model,

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