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Thin-layer Drying of Cashew (*Anacardium Occidentale L.*) Bagasse in an Active Solar Dryer: Drying Characteristics and Mathematical Modeling of Drying Kinetics

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ABSTRACT

Cashew apple bagasse is rich in bioactive compounds, vitamins and minerals, but is easily degraded by microorganisms and enzymatic activities due to its high moisture content. Hence, it is essential to reduce the moisture content before storage. Red and yellow species of cashew apples were separately blended at 200 rpm for 2 minutes and filtered through a 150-micron filter to separate the bagasse from the juice. The bagasse was subsequently pressed using a hydraulic press for 5 minutes. After pressing, the bagasse was placed in an air-tight polythene bag and kept in a refrigerator at 3 °C for the drying operations. Both species of bagasse were dried separately in the open sun and a locally fabricated active solar dryer. The drying rates, effective moisture diffusivities, as well as the thin-layer drying model that best describes the drying kinetics of the yellow and red cashew apple bagasse, were determined. Both the red and yellow cashew apple bagasse dried faster in the active solar dryer compared to the open sun. The highest drying rates of the red and yellow bagasse in open sun were 0.0256 and 0.0357 g water/g dry matter. min, respectively, while they were 0.0366 and 0.0709 g water/g dry matter. min, respectively, in the active solar dryer. The effective moisture diffusivities for the open sun and solar drying of the yellow bagasse were 1.332×10^{-9} $m^2\ s^{-1}$ and 1.368×10^{-9} $m^2\ s^{-1}$, while those of the red bagasse were 9.726×10^{-10} $m^2\ s^{-1}$ and 1.368×10^{-9} $m^2\ s^{-1}$, respectively. The Weibull thin-layer drying mathematical model best described the drying kinetics of both the yellow and red cashew apple bagasse in open sun and active solar dryer. The active solar dryer developed in this study can be used to effectively and sustainably reduce the moisture content of cashew apple bagasse using free, abundant, and renewable solar energy.

INTRODUCTION

The cashew fruit (*Anacardium Occidentale L.*) is a native of Brazil that belongs to the Anacardiaceae family (Das and Arora, 2017). The fruit consists essentially of two parts, the nut and the apple. In 2022/2023, the world cashew production was 4.6 million (Zie *et al*., 2023). The tree is commonly planted for the cashew nut and after harvest and removal of the nut, the apple is usually discarded as waste. The key factors limiting the complete utilization of cashew apple are a short shelf life, poor storage and limited information on other uses (Pinho *et al*., 2011). When the juice in cashew is extracted, a residue is obtained, cashew apple bagasse, which is about 20% of the total weight of apples processed (Silva *et al*., 2018). This residue can cause environmental pollution and waste disposal problems. Cashew apple bagasse is an agricultural residue biomass that is rich in bioactive compounds, macro and micro-nutrients, vitamin C, minerals (zinc, iron, manganese, copper, boron, magnesium, calcium, potassium, sodium and phosphorus), pectin, carotenoids, polyphenols, proanthocyanidin, anthocyanins flavonoids and Tannins (Zie *et al*., 2023). It can also serve as a nutritional supplement in animal feeds, cakes, biscuits and pasta, as a source of vitamins, minerals, or bioactive substances (Luka *et al*., 2020). Moreover, natural antioxidants are found in bioactive constituents of cashew apple bagasse (Reina *et al*., 2022). Due to a high level of lignocellulosic compounds, bagasse can be converted to biofuel and bioenergy through thermochemical conversion processes such as combustion, pyrolysis and gasification. It is also a potential feedstock for ethanol manufacture through hydrolysis and fermentation. (Guran, 2018). Other products of cashew apple bagasse include biosorbent and biochar, which can be used as a soil supplement.

Cashew apple bagasse is a byproduct of cashew apple fruit juice extraction with high moisture content (Akubor, 2016). This high moisture must be reduced as soon as possible to avoid microbial growth and reduce biochemical reactions, which lead to deterioration (Akubor, 2016). Besides, the effectiveness of some of the thermochemical conversion processes (direct combustion, pyrolysis, and gasification) can be reduced by the high moisture content of cashew bagasse, so the moisture content of the bagasse should be reduced before these processes (Agbede, *et al*., 2020). Hence, it is essential to reduce the high moisture content of cashew bagasse through a drying operation. Drying is a technique applied to reduce the moisture content, thereby limiting enzyme and microbial activities, to preserve agricultural produce or residue. It is a simultaneous heat and mass transfer process (Verma and Srivastav, 2020). Heat is provided to the biomass either directly or indirectly, which results in to escape of water from the surface of the biomass and later, the internal water moves to the surface of the product (Mahanti, et al., 2021). There are several advantages of drying, including an increase in shelf-life of the products as well as a reduction in packaging and transportation costs (Agbede *et al*., 2021, thus ensuring the accessibility of seasonal products all through the year (Verma and Srivastav, 2020).

The drying performance of biological materials can be illustrated by thin-layer drying mathematical models (Kucuk *et al*., 2014). Thin-layer drying refers to the process of drying materials as one layer of sample particles or slices, so that the material has a thin structure (Akpinar, 2006). These mathematical models are used to forecast and describe the drying kinetics of agricultural residue biomass of agricultural products. (Nukulwar & Tungikar, 2020.). Solar dryers are equipment that utilize solar energy for the removal of moisture from agricultural produce and residues (Agbede *et al*., 2023). A passive solar dryer operates by natural convection, whereas an active solar dryer operates by forced convection and requires a fan or blower (Belessiotis and Delyannis, 2011). Since solar drying uses the free, abundant and renewable energy from the sun radiation, it is considered a sustainable and cheaper method of drying agro-products and byproducts (Agbede *et al*., 2023).

Thin-layer drying of cashew (*Anacardium Occidentale L*.) apple bagasse in an active solar dryer has not been previously reported. Therefore, this study aimed to dry cashew apple bagasse in an active solar dryer and compare it with open sun drying. The objectives of this study were to illustrate the drying characteristics (including the drying rate and effective moisture diffusivity) of cashew bagasse in open sun and active solar dryer and define the drying kinetics by fitting thin-layer drying models to the drying data.

MATERIALS AND METHODS

Sample Collection and Preparation

Firm-ripened cashew apple fruits (both yellow and red species) were plucked from cashew trees, the nuts were removed and the apples were washed with distilled water. The apples were fed into a fruit blender and blended at 200 rpm for 2 minutes. The paste was filtered through a 150-micron filter to extract the juice, while the remaining pomace/bagasse was pressed between two plates of a hydraulic press for 5 minutes. The bagasse was then placed in an air-tight polythene bag and kept in a refrigerator at 3 °C for the drying operations. Cashew bagasse for each of the red and yellow cashew apples was prepared in this way (Rajasekar *et al*., 2012; Mushtaq, 2018; Ghinea *et al*., 2022).

Experimental Procedure

Drying of Cashew Bagasse in Open Sun and Active Solar Dryer

Ten grams (10 g) of the cashew bagasse were spread in pre-weighed aluminium drying pans and then separately placed in open sun and a forced air convection (active) solar dryer depicted in the schematic of Figure 1. The mass of the cashew bagasse in the pan was determined, using a digital weighing balance, at the beginning of the drying operation and 30 minutes afterwards until it remained constant. The experiment was carried out in triplicate. The ambient and solar dryer temperatures were monitored during drying experiments.

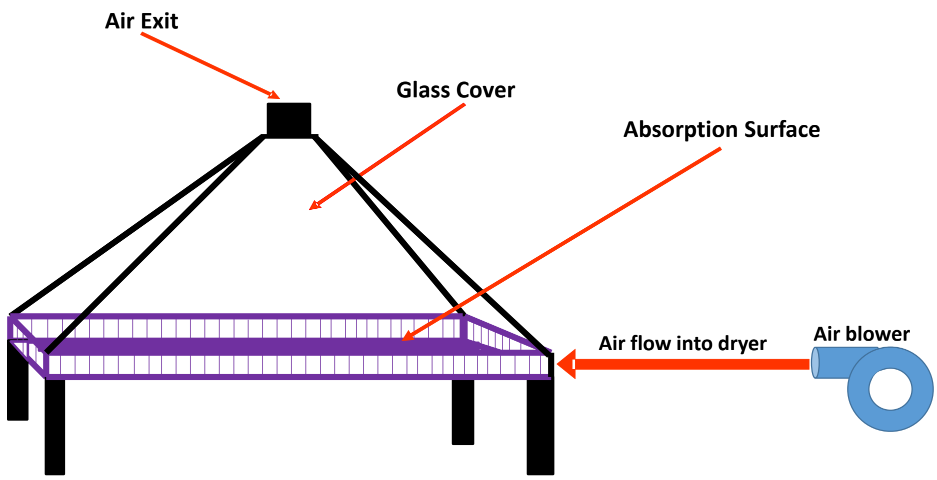

Figure 1: Schematic of an Active (forced convection) Solar Dryer

Determination of Moisture Ratio and Drying Rate

The mass-time data obtained from each set of experiments was changed to moisture content-drying time data. The moisture content of cashew bagasse at time t, X_t (g water, g dry matter^{-1}) is defined as:

$$X_t = \frac{M_t - M_d}{M_d} \quad (1)$$

Where M_t and M_d are mass (g) of cashew apple bagasse at any time, t, and the dried sample, respectively.

The drying rate of cashew apple bagasse was estimated by:

$$D_R = \frac{X_{t+dt} - X_e}{dt} \quad (2)$$

D_R is the drying rate (g water/g dry matter, min)

X_{t+dt} is the moisture content at time t+dt (g water/g dry matter)

The moisture content can be expressed as a dimensionless moisture ratio (M_R)

$$M_R = \frac{X_t - X_e}{X_i - X_e} \quad (3)$$

For long drying time, the moisture ratio can be simplified to:

$$M_{R=}\frac{x_t}{x_i} \quad (4)$$

Determination of Effective Moisture Diffusivity

The diffusion from the internal part of the cashew bagasse to the surface can be illustrated by Fick's second law of diffusion during the falling rate drying period when internal mass transfer is the controlling mechanism (Agbede *et al*., 2024). Fick's law in terms of M_R is stated as:

$$\frac{dM_R}{dt} = D_{eff}\frac{d^2M_R}{dt^2} \quad (5)$$

Assuming a one-dimensional transport of moisture in an infinite slab, negligible shrinkage, constant initial moisture distribution, negligible external resistance and uniform diffusivity, the mathematical solution of Equation (5) according to (Crank, 1975) is:

$$M_R = \frac{8}{\pi^2}\sum_{i=o}^{\infty}\frac{1}{2i+1}exp[-\frac{(2i+1)^2D_{eff}\pi^2 t}{4L^2}] \quad (6)$$

The first term in the sequence expansion of Equation (6) gives a good estimation of the resolution for a satisfactorily long drying time (Di Scala & Crapiste, 2008):

$$M_R = \frac{8}{\pi^2}exp\left[\frac{D_{eff}\pi^2 t}{4L^2}\right] \quad (7)$$

where *L* is half of the thickness of the slab (m) when drying occurs in two directions, but the thickness of the slab when drying occurs in one direction, and *t is* the time of drying (min). Equation (7) can be written in a linear form as:

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

A graph of $\ln(M_R)$ versus t produced a straight line with a slope from which D_{eff} was estimated:

$$\text{Slope} = \frac{D_{eff}\pi^2}{4L^2} \quad (9)$$

Thin-layer Mathematical Modeling of Drying Kinetics

Experimental data of Moisture Ratio (*MR*) versus drying time were fitted to the thin-layer drying models, shown in Table 1, by nonlinear regression analysis using the Microsoft Excel package. The twelve models in Table 1 have been accounted as those that most regularly fit drying data of agricultural products (Kucuk *et al*., 2014). The coefficient of determination (R^2), Sum of Squares Error (SSE), Root Mean Square Error (RMSE) and Chi-square ($\chi 2$) were the statistical parameters used as criteria to determine the model that best fit the moisture ratio–time data. The model that had the highest value of R^2 and the lowest values of SSE, RMSE and $\chi 2$ best described the experimental drying data (Kucuk *et al*., 2014). The values of SSE, RMSE and $\chi 2$ were calculated from Equations 10, 11 and 12, respectively, using Microsoft Excel Spreadsheet, while R^2 values were computed using Excel RSQ function.

$$\text{SSE} = \frac{1}{N}\sum_{i=1}^{N}(M_{Rpredi} - M_{Rexperi})^2 \quad (10)$$

$$\text{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}(M_{Rpredi} - M_{Rexperi})^2\right]^{\frac{1}{2}} \quad (11)$$

$$\chi 2 = \frac{\sum_{i=1}^{N}(M_{Rpredi}-M_{Rexperi})^2}{N-Z} \quad (12)$$

Table 1: Thin-layer Drying Models Fitted to Drying Data

No	Model name	Model equation	References
1	Midilli-Kucuk	$M_R = aexp(kt^n) + bt$	Midilli *et al*. (2002)
2	Page	$M_R = exp(kt^n)$	Page (1949)
3	Logarithmic	$M_R = aexp(kt) + c$	Chandra and Singh (1995)
4	Two-term	$M_R = aexp(k_o t) + bexp(k_1 t)$	Henderson (1974), Glenn (1978)
5	Wang and Singh	$M_R = 1 + at + bt^2$	Wang and Singh (1978)
6	Approximation of diffusion	$M_R = aexp(kt) + (1 - a)$exp(-kbt)	Kaseem (1998)
7	Modified Henderson and Pabis	$M_R = aexp(kt) + bexp(-gt) + cexp(-ht)$	Karathanos (1999)
8	Modified Page	$M_R = exp(-kt)^n)$	White *et al*. (1978)
9	Henderson and Pabis	$M_R = aexp(kt)$	Henderson and Pabis (1961)
10	Two-term exponential	$M_R = aexp(kt) + (1 - a)$exp(-kat)	Sharaf-Eldeen *et al*. (1980)
11	Verma	$M_R = aexp(kt) + (1 - a)$exp(-gt)	Verma *et al*. (1985)
12	Weibull	$M_R = a - bexp(kt^n)$	Weibull (1951)

RESULTS AND DISCUSSION

Drying Characteristics

Figures 2a and 2b show the moisture ratio versus drying time for the open sun and active solar drying of yellow and red cashew apple bagasse. Throughout the drying operations, the moisture ratio decreased gradually for all the drying processes until the moisture was removed from both species of bagasse. This means that moisture was successfully removed from the wet yellow and red cashew apple bagasse using the energy from the sun's radiation. Drying times of 300 and 270 min were required for the open sun and active solar drying, respectively. Figure 3 shows the ambient and solar dryer temperatures observed during the drying operation; the solar dryer temperature reached a maximum value of about 58 °C compared to the highest ambient temperature of 48 °C. The active solar dryer had larger heat energy for vaporization of moisture from the bagasse than that of the ambient environment, resulting in a higher drying rate compared to open sun drying.

Figures 4a and 4b show the plot of drying rate versus drying time for the open sun and solar drying of the red and yellow cashew apple bagasse. For the open sun drying, the highest drying rates for red and yellow cashew apple bagasse were 0.0256 and 0.0357 g water/g dry matter. min while those of the active solar dryer were 0.0366 and 0.0709 g water / g dry matter. min, respectively. The effective moisture diffusivities for the open sun and active solar dryer of the yellow bagasse were 1.332×10^{-9} m^2 s^{-1} and 1.368×10^{-9} m^2 s^{-1}, while those of the red bagasse were 9.726×10^{-10} m^2 s^{-1} and 1.368×10^{-9} m^2 s^{-1}, respectively. The higher effective moisture diffusivity of the active solar drying of both species was as result of the higher temperatures obtained in the solar dryer over the ambient sun drying temperature. The measured moisture diffusivities for the open sun and active drying of the cashew apple bagasse in this study are within the range $10^{-12} – 10^{-6}$ m^2 s^{-1} for the drying of agricultural products (Erbay and Icier, 2010). They are close 0.89×10^{-9} to 1.56×10^{-9} m^2 s^{-1} and 3.32×10^{-9} to 6.31×10^{-9} m^2 s^{-1} for sun drying, and active solar drying of red banana (Slices) (Elangovan *et al.,* 2021) and sweet potato (Gasa *et al*., 2022), respectively, but much lower than 1.33×10^{-6} to 5.11×10^{-6} m^2 s^{-1} reported for natural solar dryer of tomato slices (Dianda *et al.,* 2015).

(a) **(b)**

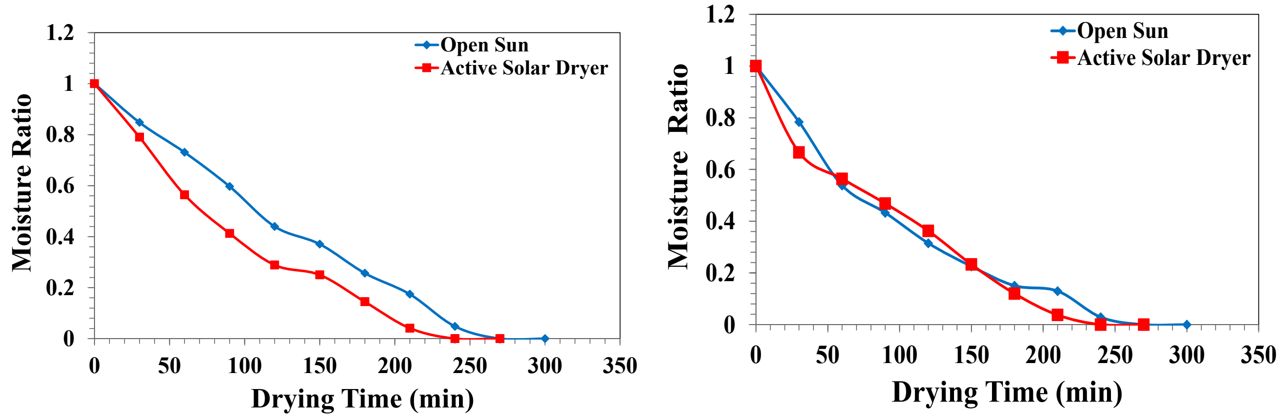

Figure 2: The Plot of the Moisture Ratio against Drying Time for the drying of cashew apple bagasse in open sun and active solar dryer (a) red species, (b) yellow species

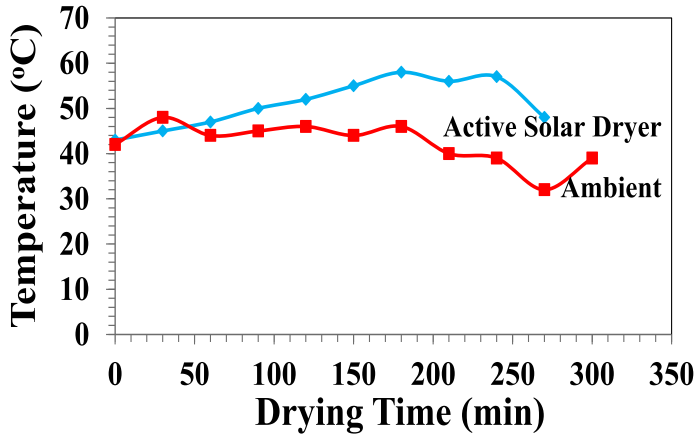

Figure 3: Plot of ambient and solar dryer temperatures versus drying time

(a) **(b)**

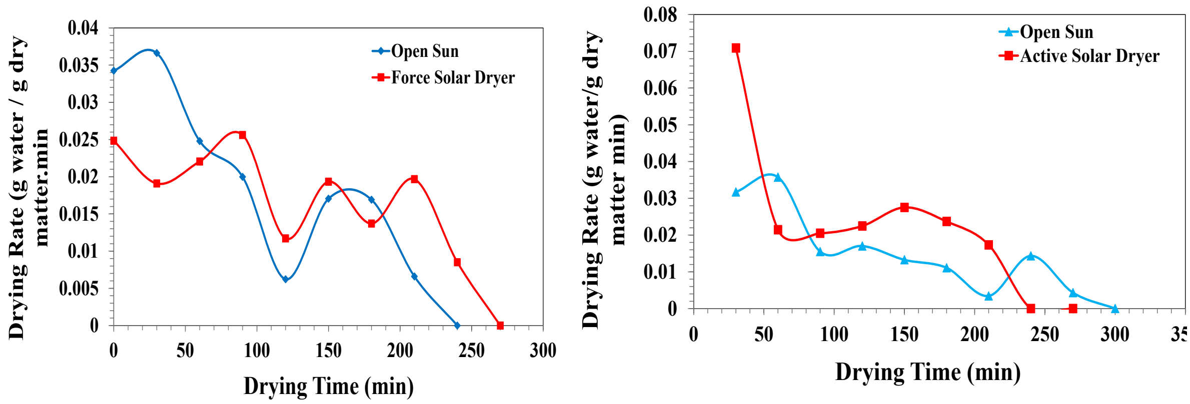

Figure 4: The plot of drying rate against drying time for the open sun and solar drying of (a) red, (b) yellow cashew apple bagasse

Modeling of Drying Kinetics

The statistical parameters obtained when the twelve thin-layer mathematical models listed in Table 1 were fitted to the open sun and active solar drying data are shown in Tables 2 – 5. In all cases considered, the Weibull model had the highest R^2 values along with the lowest values of the SSE, RMSE and x^2values. This implies that the Weibull thin-layer drying mathematical model best described the drying kinetics of both yellow and red cashew apple bagasse in open sun and active solar dryer considered. The Weibull model has been previously reported to also best describe the open sun drying of pretreated banana stalk biomass (Agbede *et al*., 2023) as well as the solar drying of banana peel (Agbede *et al*., 2022) and banana stalk biomass (Agbede *et al*., 2023).

Table 2: Constants and Statistical Parameters of Models Fitted to Drying Data for the Open Sun Drying of Red Cashew Apple Bagasse

Model	Model Constant	R^2	SSE	RMSE	x^2
Midilli-Kucuk	a=0.991, b= -0.000587, k=0.001711, n=1.2324	0.995969	0.000449	0.021193	0.000705
Page	K=0.0006083, n=1.5038	0.988005	0.001454	0.038137	0.001777
Logarithmic	a=1.6649, c=0.6532, k=0.003349	0.995128	0.000542	0.023299	0.000746
Two-term	a=-0.2043, b=1.2043, K0= 0.4665, K1=0.009069	0.970755	0.003671	0.060592	0.005769
Wang and Singh	a= -0.005185752, b= 5.78539E-06	0.996066	0.000447	0.021151	0.000546
Approximation of diffusion	a=1, b=1, k=0.007586	0.967412	0.005920	0.076945	0.008140
Modified Henderson and Pabis	a= -0.1023, b= -0.1020,c= 1.2044,g=0.4086,h=0.009069 ,k=0.4086	0.970755	0.003671	0.060592	0.008077
Modified Page	K=0.007270, n=1.5038	0.988005	0.001454	0.038137	0.001777
Henderson and Pabis	a= 1.0756,k=0.008135	0.960447	0.005047	0.071045	0.006169
Two-term exponential	a=0.0009724,k=7.7779	0.967501	0.005943	0.077095	0.007264
Verma *et al*	a=0.5,g=0.00740, k=0.007404	0.969580	0.005978	0.077318	0.008219
Weibull	**a = -0.2994, b= --1.2915, k= 0.001798, n = 1.1877**	**0.996098**	**0.000434**	**0.020850**	**0.000683**

Table 3: Constants and Statistical Parameters of Models Fitted to Drying Data for the Active Solar Drying of Red Cashew Apple Bagasse

Model	Model Constant	R^2	SSE	RMSE	x^2
Midilli-Kucuk	a=1.003769,b= -0.0003814, k=0.006997, n=1.0482	0.043304	0.000460	0.021448	0.000766
Page	K=0.003393,n=1.2365	0.991306	0.000978	0.031283	0.001223

Logarithmic	A = 1.1802,c= -0.1738 ,k=0.007525	0.995605	0.000466	0.021604	0.000666
Two-term	a= 0.5533, b=0.4871, K0= 0.01083, K1=0.01083	0.984492	0.001944	0.044096	0.003240
Wang and Singh	a= -0.01809,b=7.82901E-05	0.040388	0.558877	0.747581	0.698596
Approximation of diffusion	a= 1,b= 1,k=0.0104451	0.040388	0.558877	0.046671	0.003111
Modified Henderson and Pabis	a= -0.3502, b= -0.3502, c= -0.3400, g=0.01083 ,h=0.01083,k=0.01083	0.986849	0.002178	0.046671	0.003111
Modified Page	K=0.01007, n=1.2365	0.984492	0.001944	0.044096	0.004861
Henderson and Pabis	a= 1.0405,k=0.01083	0.991306	0.000978	0.031283	0.001223
Two-term exponential	a=0.0009322,k=11.194023	0.984491	0.001944	0.044096	0.002430
Verma *et al*	a=0.5,g=0.02998, k=0.02998	0.771352	0.995668	0.239056	0.081640
Weibull	**a = -0.1544, b= -1.1583, k= 0.006868, n = 1.02488**	**0.995638**	**0.000463**	**0.021522**	**0.000772**

Table 4: Constants and Statistical Parameters of Models Fitted to Drying Data for the Open Sun Drying of Yellow Cashew Apple Bagasse

Model	Model Constant	R^2	SSE	RMSE	x^2
MidilliKucuk	a=1.0028,b= -0.0002630, k=0.007965, n=1.0265	0.996464	0.028597	0.015373	0.000371
Page	K=0.0048945,n=1.1525	0.993168	0.000723	0.026893	0.000883
Logarithmic	a= 0.7395,c= 0.2604,k=1	0.451753	0.054853	0.234207	0.075423
Two-term	a= 1.0997, b=-0.09976 , K0=0.0111 , K1=0.45035	0.992058	0.000887	0.029796	0.001395
Wang and Singh	a= -0.007226,b=1.32425E-05	0.990708	0.001086	0.032968	0.001328
Approximation of diffusion	a=-0.09977,b=0.02628 ,k=0.4232706	0.992058	0.000887	0.029796	0.001220
Modified Henderson and Pabis	a= 0.4412, b= 0.6435, c= -0.08478, g= 0.01086,h=0.3977 ,k=0.01086	0.993755	0.000601	0.024534	0.001324
Modified Page	K=0.00989, n=1.1525	0.993168	0.000723	0.026893	0.000883
Henderson and Pabis	a= 1.0282,k=0.01043	0.995905	0.001139	0.033756	0.001392
Two-term exponential	a=0.0004475,k=22.7090	0.996291	0.001246	0.035311	0.001523
Verma *et al*	a=0.5,g=0.009733 , k=0.0097335	0.993412	0.001391	0.037303	0.001913
Weibull	**a = -0.1190, b= -1.1234, k= 0.008857, n = 0.9778**	**0.996449**	**0.000355**	**0.018846**	**0.000558**

Table 5: Constants and Statistical Parameters of Models Fitted to Drying Data for the Active Solar Drying of Yellow Cashew Apple Bagasse

Model	Model Constant	R^2	SSE	RMSE	x^2
Midilli-Kucuk	a=0.9957,b= -0.00130, k=0.03426, n=0.6348	0.989280	0.001062	0.032600	0.001771
Page	K= 0.00594, n= 1.1161	0.970033	0.003145	0.056086	0.003932
Logarithmic	a= 1.1990, c= -0.2427, k= 0.006360	0.984889	0.001498	0.038705	0.002140
Two-term	a= 0.5337, b=0.4871, K0=0.01083, K1= 0.01036	0.968744	0.003439	0.058644	0.005731
Wang and Singh	a= -0.007317, b= 1.33656E-05	0.982485	0.002202	0.046930	0.002753
Approximation of diffusion	a= 1, b= 1, k= 0.0103817	0.968744	0.003439	0.058647	0.004913
Modified Henderson and Pabis	a= 0.3362, b= 0.3362, c= 0.3258, g= 0.01036, h=0.01036, k= 0.01036	0.968744	0.003439	0.058644	0.008597
Modified Page	K= 0.03003, n= 0.9948	0.755215	0.056221	0.237110	0.070276
Henderson and Pabis	a= 0.9984, k= 0.010366	0.968744	0.003439	0.058644	0.004298
Two-term exponential	a= 0.0009266, k= 11.193928	0.968660	0.003439	0.058643	0.004298
Verma *et al*	a=0.5,g= 0.010381, k=0.01038	0.968628	0.003439	0.058647	0.004913
Weibull	**a = -1.4913, b= -2.4836, k= 0.01212, n = 0.6786**	**0.989601**	**0.001031**	**0.032110**	**0.001718**

CONCLUSION

Yellow and red species of cashew apple bagasse were dried in the open sun and an active solar dryer. The bagasse dried faster in the solar dryer than in open sun with effective moisture diffusivities of 1.368×10^{-9} m^2 s^{-1} and 9.726×10^{-10} - 1.332×10^{-9} m^2 s^{-1}, respectively. The Weibull thin-layer drying mathematical model best described the drying kinetics of both yellow and red cashew apple bagasse in open sun and active solar dryer. The active solar dryer investigated can be adopted by the cashew processing industry for the sustainable drying of cashew apple bagasse.

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