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Solar drying of cowpea bean combined with drying in a heat accumulator dryer

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ABSTRACT: As solar radiation is abundant in Brazil during most of the year and this source of energy is renewable and non-polluting par excellence, solar drying of agricultural products is a promising methodology. The objective of this study was to dry cowpea [*Vigna unguiculata* (L.) Walp.] bean grains using solar energy in different exposure times, adjusting the mathematical models and calculation of the effective diffusivity. Drying was performed during the day with samples exposed to the sun; during the night, half of the samples were put to dry in a heat accumulator dryer for nighttime drying and the other half was left on a laboratory bench as control. Cowpea bean grains had initial and final moisture contents of 65.42 and 6.73% d.b. (after drying in the heat accumulator dryer), respectively. The models Approximation of Diffusion, Page, Verma, Logarithmic and Two Terms were fitted to the drying kinetics and all of them fitted well to the experimental data, with coefficients of determination (R^2) higher than 0.98, mean square deviations (MSD) less than 0.01 and chi-square (χ^2) values lower than 0.0001. The effective diffusivity values were of the order of 10^{-11} m^2 s^{-1} for the cowpea bean samples. The heat accumulator dryer was effective as a complement to the drying by exposure to the sun, maintaining a suitable temperature for nighttime drying.

Key words: *Vigna unguiculata*, renewable energy, mathematical models

Secagem solar de feijão-caupi combinada com secagem em secador acumulador de calor

RESUMO: Como a radiação solar é abundante no Brasil durante quase todo o ano e por ser essa a fonte de energia renovável e não poluente por excelência, a secagem solar dos produtos agrícolas é uma metodologia promissora. Objetivou-se, neste trabalho, secar grãos de feijão-caupi [*Vigna unguiculata* (L.) Walp.] utilizando energia solar em diferentes tempos de exposição, ajustando os modelos matemáticos e calculando a difusividade efetiva. As secagens foram realizadas durante o dia com as amostras expostas ao sol; durante a noite metade das amostras eram postas para secar em secador acumulador de calor de uso noturno e a outra metade era deixada em bancada de laboratório como amostras testemunhas. Os grãos de feijão-caupi apresentaram teor de água inicial e final de 65,42 e 6,73% b.u. (após a secagem no secador acumulador de calor), respectivamente. Os modelos de Aproximação da Difusão, Page, Verma, Logarítmico e Dois Termos foram ajustados às cinéticas de secagem, os quais apresentaram bons ajustes aos dados experimentais, com valores dos coeficientes de determinação (R^2) superiores a 0,98, desvio quadrático médio (DQM) inferiores a 0,01 e valores de qui-quadrado (χ^2) inferiores a 0,0001. Os valores de difusividade efetiva foram da ordem de 10^{-11} m^2 s^{-1} para as amostras de feijão-caupi. O secador acumulador de calor foi eficaz como complemento à secagem por exposição ao sol, mantendo temperatura adequada à secagem no período noturno.

Palavras-chave: *Vigna unguiculata*, energia renovável, modelos matemáticos

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Introduction

Cowpea bean or black-eyed pea [*Vigna unguiculata* (L.) Walp.] is originated from African origin and well adapted to the climatic conditions of Brazil, being cultivated all over its territory, mainly in the North and Northeast regions. Nevertheless, information related to drying using solar energy is scarce in the literature. Such information is essential in the decision-making in order to obtain maximum efficiency in the process and, especially, without affecting the quality of the product to be dried (Gely & Giner, 2007). High prices and the scarcity of fossil fuels have increased the need for using solar energy as an alternative source of energy for drying agricultural products, especially in developing countries (Tripathy & Kumar, 2009).

Doymaz & Ismail (2011) point out the slowness of the process as one of the disadvantages of drying by direct exposure to the sun, which can be attributed to weather conditions and the interruption of the process during the night period. Studies to overcome such inconvenience should consider the accumulation of solar energy during the day in order to maintain the drying during the night, though at a lower rate (Tripathy & Kumar, 2009; Queiroz et al., 2011; Santos et al., 2014). Hence, the use of water to accumulate solar energy during the day has the advantage of allowing the utilization of a relatively small volume of liquid and simple solar collectors.

In this context, this study aimed to evaluate the drying of cowpea bean grains by direct exposure to the sun combined with drying in a heat accumulator dryer for nighttime drying to study the drying kinetics by fitting different models, and determine the effective diffusivity in the drying of the samples.

Material and Methods

The experiment used grains of *Vigna unguiculata* L. Walp. cultivated in the municipality of Campina Grande (7° 13' 11" S, 35° 52' 31" W, and altitude of 551 m), in the PB, Brazil, 2016 season.

The bean grains were transported to the Laboratory of Storage and Processing of Agricultural Products, at the Universidade Federal de Campina Grande, in low-density polyethylene plastic bags and subjected to manual cleaning to remove foreign matter, such as fragments of leaves and stems, and physical injuries. The experiment was performed with three repetitions, in a thin layer, and each replicate consisted of approximately 50 g of sample, fractionated in baskets made with wire mesh (10 × 10 × 3 cm). Moisture losses were monitored by weighing at regular times of 15, 30, 60, 120, 180, 240 and 360 min.

Before the drying began, the initial moisture content of the samples was determined in an oven at 105 ± 3 °C (IAL, 2008). At the beginning of the drying process, the samples had moisture content of 65.42% w.b. (189.2% d.b.). Drying by direct exposure to the sun began approximately at 8h00min and was carried out on a concrete base covered with 0.5-mm-thick black polyethylene tarpaulin, with the samples placed on trays and exposed to the sun. From 16 h 30 min, half of the samples were placed in the heat accumulator dryer for nighttime drying and the other half was kept in the laboratory (control). Nighttime drying ended at 8h00min in the next morning, when the samples from the heat accumulator dryer and the control returned to the direct exposure to the sun. This cycle continued until the samples reached constant weight. The drying process ended when the samples reached a hygroscopic equilibrium moisture content, when the final moisture content was then determined in an oven (IAL, 2008). During the process, temperature with digital meter HM-2030 and relative humidity were monitored with the use of an HT-7050 thermo-hygrometer model inside the drying chamber and in the environment where the control samples were kept. The heat accumulator dryer for nighttime drying (Figure 1) is a device that accumulates heat from solar radiation and allows it to be used in nighttime drying.

It works on the basis of solar collectors with vacuum tube heaters, water reservoir and drying chamber, forming two circuits connected by tubes equipped with valves to control water circulation. During the day, water circulation is restricted to the first circuit (solar collectors/thermal reservoir). In the daytime operation, water circulation between the solar collectors and the reservoir was carried out using a water pump powered by photovoltaic energy. Water heated in the solar collectors moves upward through a pipe, from the upper outlet of the collector to the inlet of the reservoir, located at the highest position of the entire circuit. The water pump powered by photovoltaic energy accelerates the movement of water, allowing faster heating in the solar collectors in open sun events, with shorter residence times and consequent improvement in the utilization. For the drying during the night, the circulation is interrupted in this circuit, while the circulation is released in the second circuit (water reservoir/drying chamber). The heated water is used in the night drying as it passes through a heat exchanger made with a copper tube coil installed in the drying chamber. During the night, water is circulated by pumping, passing through the heat exchanger, located below the tray of samples. As the water passes through the heat exchanger, it is cooled and circulates to the lower part of the circuit (bottom of the reservoir).

During the night, the sample was placed in the nighttime heat accumulator dryer to follow up the daytime drying in the sun, while the control sample was placed on a laboratory bench

Figure 1. Heat accumulator dryer for nighttime drying. Photovoltaic panel (A), solar collectors (B), thermal reservoir (C) and drying chamber (D)

under room conditions, in order to evaluate the efficiency of the nighttime heat accumulator dryer.

The experimental data of drying kinetics were expressed as moisture content ratio (RX), using Eq. 1, as a function of time.

$$RX = \frac{X_t - X_e}{X_o - X_e} \tag{1}$$

where:

RX - moisture content ratio of the product, dimensionless;
X_t - moisture content at time t, d.b.;
X_e - equilibrium moisture content, d.b.; and,
X_0 - initial moisture content, d.b.

The models Approximation of Diffusion (Eq. 2), Page (Eq. 3), Verma (Eq. 4), Logarithmic (Eq. 5) and Two Terms (Eq. 6) were fitted to the kinetic curves of cowpea bean drying. The program Statistica 7.0 was used to fit the models by nonlinear regression using the Quasi-Newton estimation method.

$$RX = a\ \exp(-kt) + (1-a)\exp(-kbt) \tag{2}$$

$$RX = \exp\left(-at^b\right) \tag{3}$$

$$RX = a\ \exp(-kt) + (1-a)\exp(-k_1 t) \tag{4}$$

$$RX = a\ \exp(-kt) + c \tag{5}$$

$$RX = a\ \exp(-k_o t) + b\ \exp(-k_1 t) \tag{6}$$

where:

t - drying time, min; and,
a, b, c, k, k_o, k_1 - parameters of the models.

The drying rates were calculated based on the moisture content data of the samples and drying times, according to Eq. 7.

$$TX = \frac{X_{t+dt} - X_t}{dt} \tag{7}$$

where:

TX - drying rate, g g^{-1};
X_{t+dt} - moisture content at t+dt, g g^{-1};
X_t - moisture content at time t, g g^{-1}; and,
t - drying time, min.

The criteria used to evaluate the fits of the models to the experimental data were the coefficient of determination (R^2), chi-square (χ^2) and mean square deviation, calculated by Eqs. 8 and 9, respectively.

$$\chi^2 = \frac{\sum_{i=1}^{n}\left(RX_{Pred} - RX_{exp}\right)^2}{DF} \tag{8}$$

$$MSD = \sqrt{\frac{\sum\left(RX_{Pred} - RX_{exp}\right)^2}{n}} \tag{9}$$

where:

χ^2 - chi-square;
MSD - mean square deviation;
RX_{pred} - moisture content ratio predicted by the model, g g^{-1};
RX_{exp} - experimental moisture content ratio, g g^{-1};
n - number of experimental observations; and,
DF - degrees of freedom of the model.

The effective diffusivity (D_{ef}) was obtained by fitting the mathematical model of liquid diffusion (Eq. 10) to the experimental data of cowpea bean drying using 8 terms (n_t). This equation is the analytical solution of Fick's second law, considering the geometric shape of the product as a sphere, disregarding the volumetric shrinking of the grains, considering the boundary condition of known moisture content on the grain surface and assuming that the water transport mechanism inside the product occurs through the diffusion of vaporized liquid water (Morais et al., 2013; Camicia et al., 2015).

$$RX = \frac{6}{\pi^2}\sum_{n_t=1}^{\infty}\frac{1}{n_t^2}\exp\left[-\frac{n_t^2\pi^2 D_{ef}\,t}{R_e^2}\right] \tag{10}$$

where:

D_{ef} - effective diffusivity, $m^2\ s^{-1}$;
R_e - equivalent radius, m;
n_t - number of terms (8); and,
t - time, s.

To calculate the equivalent sphere radius, the volume of 50 grains was determined by the mass displacement method (Mohsenin, 1986), and the equivalent radius was determined based on the volume of the sphere (Eq. 11).

$$V = \frac{\pi(abc)}{6} = \frac{4\pi r^3}{3} \tag{11}$$

where:

V - volume of the grain, mm^3;
a - longest axis of the grain (length), mm;
b - intermediate axis of the grain (width), mm;
c - shortest axis of the grain (thickness), mm; and,
r - grain radius, mm.

Effective diffusivity was calculated using the computer program Prescribed Adsortion-Desortion 2.2 for Fick's law, with equivalent radius of cowpea bean grain of 0.0036 m.

Results and Discussion

Figure 2 presents the mean values of temperature recorded during the drying of cowpea bean in the external environment and inside the nighttime heat accumulator dryer in the drying chamber. The mean values of temperature and relative humidity

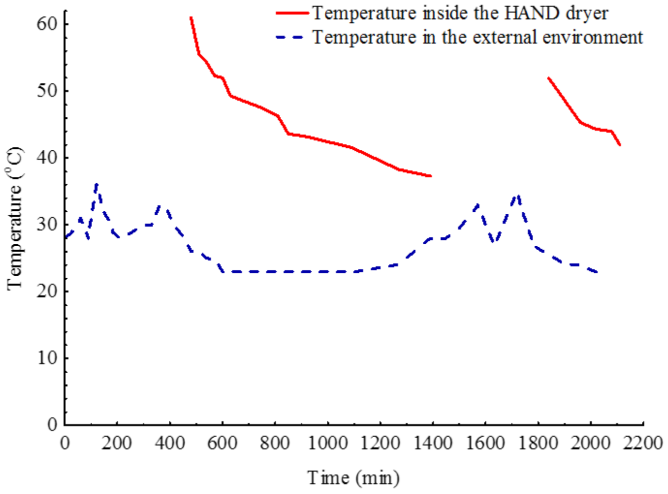

Figure 2. Temperature variation inside the heat accumulator dryer (HAND) and in the external environment during the drying of cowpea bean

inside the heat accumulator dryer were 43.0 ± 3.3 °C and 56.44 ± 12.6%, while for the same period the mean values of these variables in the external environment were 26.92 ± 2.9 °C and 67.87 ± 12.3%, respectively. Although the temperature inside the dryer decreased along the drying period, the average temperature remained above 40 °C, exceeding that of the external environment, reaching a final temperature of 38.55 °C.

Figure 3 presents the experimental points of the drying kinetics of cowpea bean for drying by direct exposure to the sun in the daytime and combined with nighttime drying in the heat accumulator dryer (HAND) and for drying by only exposed to the sun and to the relative humidity of the laboratory environment at nighttime (control). It was found that in the daytime, on the first day of drying, both samples lost water at the same rate, because they were exposed to the same conditions during the drying by direct exposure to the sun. At the end of the first day of drying, 480 min after the drying began, the mean values of moisture content ratio (RX) were around 0.0715 for the samples of drying by exposed to the sun/drying in HAND dryer and for the samples of the control.

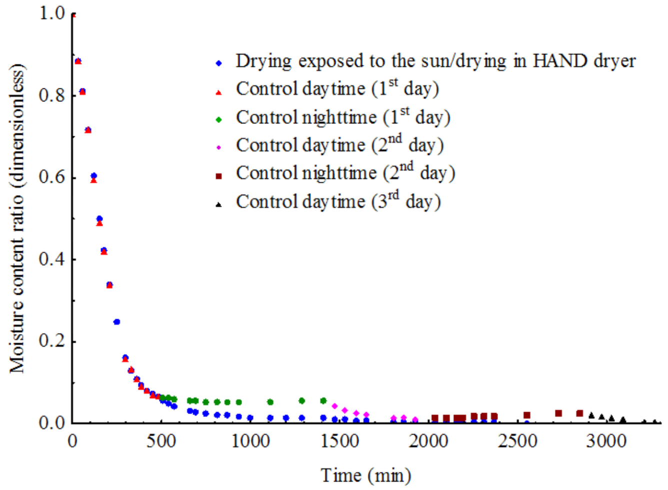

Figure 3. Moisture content ratio - RX in the drying process of cowpea bean by direct exposure to the sun in the daytime and combined with nighttime drying in the heat accumulator dryer (HAND) and drying by only exposed to the sun and to the relative humidity of the laboratory environment at nighttime (control)

According to Figure 3, the samples in the nighttime dryer continued to lose water along the drying time.

The moisture content adsorbed by the control samples exposed to the relative humidity of the laboratory environment of 95.03% demonstrates the reversal in the loss of part of the water during the night period. At the end of the nighttime drying in the heat accumulator dryer (1410 min from the beginning), the mean RX value of the samples was 0.0127, evidencing the continuity of the drying process during the night period, while the control showed a mean RX value of 0.0511. This result demonstrates the efficacy of the nighttime heat accumulator dryer in continuing the drying during the night period, corroborating the results of Queiroz et al. (2011), who dehydrated jack fruit almonds by exposure to the sun combined with drying in a solar energy-accumulator dryer and reported lower moisture content in the samples dried in the solar energy-accumulator dryer. According to Figure 3, for the first night period, water loss also occurred in the control samples.

In the daytime, referring to the second day of drying by direct exposure to the sun (1920 min after the drying began), cowpea bean grains continued to lose water along the drying time; the same happened to the control, which had absorbed water during the night period, also lost water as the dehydration continued. The mean RX values were 0.0041 and 0.0774 for the samples of the nighttime heat accumulator dryer and the control, respectively. In the night period referring to the second day, the sample was taken to the nighttime heat accumulator dryer and, at the end of the drying process, showed a final RX of 0.0000 at 2550 min, while the control, kept in the laboratory, reached RX of 0.0204 at 2859 min. In the daytime, referring to the third day of drying by exposure to the sun, the control, which had absorbed water during the night period, ended the drying with RX of 0.0000 at 3270 min (Figure 3).

The time required for cowpea bean grains to reach the equilibrium moisture content for the sun/HAND drying was 42.5 h (2550 min) and the time required for the control to reach equilibrium was 54.5 h (3270 min).

Figure 4 shows the drying rates of the samples exposed directly to the sun combined with drying in the HAND dryer and to the control. Initially, the drying rate indicated a phase of adaptation of the material to the drying air temperature, with a gradual elevation of sample temperature and water vapor pressure, with no loss of moisture. In addition, the highest drying rates occurred at the beginning of the drying, decreasing as the process continued. At the end of the process, the water was strongly bound to the material, requiring greater energy for its evaporation, which resulted in lower drying rates. It was observed that the drying rates for the control showed a slight increase within the same time interval. In all samples, more pronounced drying rates were observed in the first 400 min, which correspond to larger losses of water, corroborating results that associate greater energy demand with final stages of drying (Sacilik, 2007; Nuthong et al., 2011; Jittanit, 2011; Santos, 2012; Santos et al., 2013).

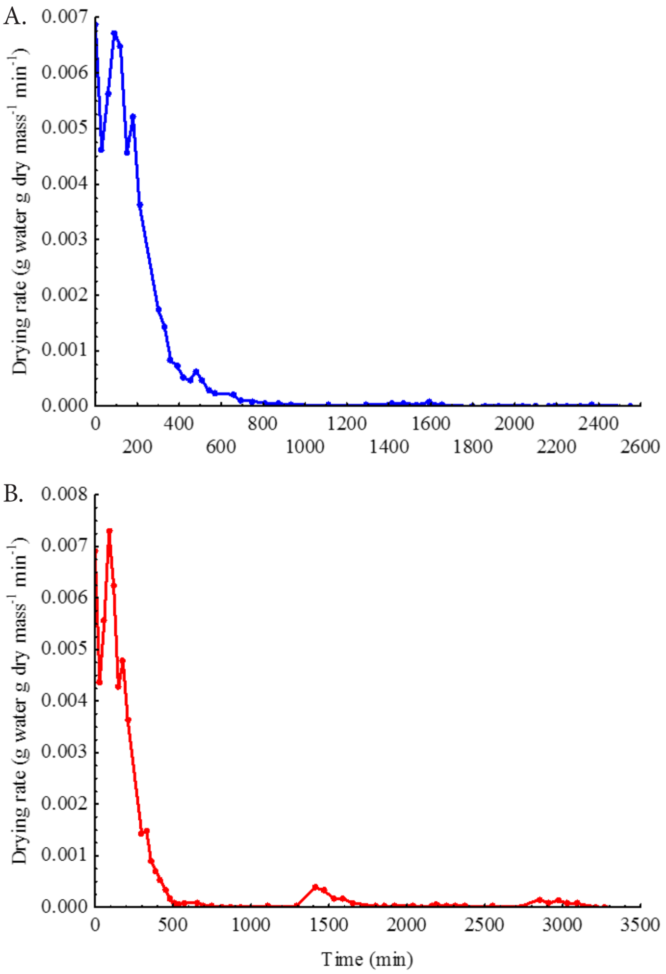

Figure 4. Drying rate of cowpea bean samples dried by direct exposure to the sun combined with nighttime drying in the heat accumulator dryer (A) and drying by only exposed to the sun and to the relative humidity of the laboratory environment at nighttime (control) (B)

The initial and final moisture contents of cowpea bean samples dried by direct exposure to the sun combined with drying in the nighttime heat accumulator dryer and by the control, with the losses of moisture in the five stages of drying, can be observed in Table 1.

It was noted that the samples of cowpea bean started drying with an initial moisture content of 65.42% w.b. (1.8920 d.b.) and, at the end of the dehydration on the first day, showed moisture content of 16.12% w.b. (0.1922 d.b.) under direct exposure to the sun and 16.02% w.b. (0.1909 d.b.) for the control. In this first stage of drying, both samples were dried by direct exposure to the sun, which justifies the similar final moisture contents.

Since the cowpea bean samples of the sun/HAND drying and of the control drying had not reached the desired equilibrium moisture content in the first stage of drying (direct exposure to the sun), the dehydration process was continued at night, when the sun/HAND samples were taken to the nighttime heat accumulator dryer and remained overnight, while the control samples were placed on the laboratory bench (second stage). Samples in the heat accumulator dryer continued to lose water during the night, reaching a value of 8.69% w.b. (0.0952 d.b.), while the control samples reached only 14.64% of moisture content.

As the samples of the nighttime heat accumulator dryer and of the control had not reached the equilibrium moisture content at the end of the drying, a third stage of drying was carried out, in which the samples of the sun/HAND drying and of the control drying were dehydrated again in the sun, reaching the final values of 7.37% w.b. (0.0796 d.b.) and 8.55% w.b. (0.0936 d.b.), respectively.

Since the samples of the nighttime heat accumulator dryer and of the control had not reached the desired equilibrium moisture content in the third stage of drying (exposed to the sun), the dehydration process was continued at night in the heat accumulator dryer, where these samples reached the final moisture content of 6.72% w.b. (0.072 d.b.), completing the drying, with moisture loss of 8.82%, while the samples of the control absorbed water, reaching moisture content of 10.45% w.b. (0.1167 d.b.), with water gain of 22.22%.

As the moisture content in the samples of the control did not reach equilibrium, it was exposed to the sun in the fifth stage of drying and ended with moisture content of 7.44% w.b. (0.0804 d.b.) and moisture loss of 28.80%. At the end of the drying process, the samples of the sun/HAND drying and of the controls had moisture losses corresponding to 89.73 and 88.57%, respectively, which are close to the result found by Doymaz (2011), who reported moisture loss of 83.24% in green bean grains using solar dryer.

Table 2 shows the parameters of the models fitted to the experimental data of cowpea bean drying by direct exposure to

Table 1. Initial and final moisture contents of cowpea bean samples dried by direct exposure to the sun combined with drying in nighttime in the heat accumulator dryer (sun/HAND) and dried by only exposed to the sun and to the relative humidity of the laboratory environment at nighttime (control), in five stages

Drying stage	Treatments	Drying in daytime			Drying in nighttime		
		Moisture content (% w.b.)		Moisture loss (%)	Moisture content (% w.b.)		Moisture loss (%)
		Initial	Final		Initial	Final	
First day	Sun/HAND	65.42	16.12	75.36	-	-	
	Control	65.08	16.02	75.38	-	-	
Second night	Sun/HAND	-	-		16.12	8.69	46.09
	Control	-	-		16.02	14.64	8.61
Third day	Sun/HAND	8.69	7.37	15.19	-	-	
	Control	14.64	8.55	41.60	-	-	
Fourth night	Sun/HAND	-	-		7.37	6.72	8.82
	Control	-	-		8.55	10.45	-
Fifth day	Sun/HAND	-	-		-	-	
	Control	10.45	7.44	28.80	-	-	

Table 2. Parameters of the mathematical models fitted to the data of cowpea bean drying by direct exposure to the sun combined with drying in nighttime in the heat accumulator dryer (Sun/HAND) and dried by only exposed to the sun and to the relative humidity of the laboratory environment at nighttime (control), and respective coefficients of determination (R^2), chi-square (χ^2) and mean square deviations (MSD)

Samples	Model parameters						χ^2	R^2	MSD
	a	B	c	n	k	k_1			
Approximation of Diffusion									
Sun/HAND	-0.6164	0.4593	-	-	0.0154	-	0.01×10^{-15}	0.9976	0.33×10^{-8}
Control	-0.3273	0.3150	-	-	0.0203	-	4.5×10^{-7}	0.9879	0.0006
Page									
Sun/HAND	-	-	-	1.2631	0.0012	-	4.9×10^{-24}	0.9971	0.02×10^{-15}
Control	-	-	-	1.2193	0.0015	-	4.4×10^{-7}	0.9868	0.0006
Verma									
Sun/HAND	0.5000	-	-	-	0.0051	0.0051	10×10^{-14}	0.9882	3.1×10^{-7}
Control	-0.3290	-	-	-	0.0202	0.0064	5.0×10^{-7}	0.9879	0.0006
Logarithmic									
Sun/HAND	1.0671	-	0.0018	-	0.0055	-	0.0001	0.9916	0.0102
Control	1.0485	-	0.0204	-	0.0057	-	0.0001	0.9882	0.0100
Two Terms									
Sun/HAND	0.5340	0.5340	-	-	0.0054	0.0054	0.0001	0.9915	0.0101
Control	0.5295	0.5295	-	-	0.0054	0.0054	7.6×10^{-5}	0.9836	0.0083

the sun combined with nighttime heat accumulator dryer and by the control, with their respective coefficients of determination (R^2), chi-square (χ^2) and mean square deviations (MSD).

The model Approximation of Diffusion was one of the best fitted to the experimental data of drying of the cowpea bean samples by direct exposure to the sun during the daytime, combined with drying in nighttime heat accumulator dryer. This model showed R^2 higher than 0.990 and low values of MSD and χ^2. For the control samples, the Verma model was the one that best fitted to the experimental data.

All mathematical models evaluated had R^2 values higher than 0.90 and can be used to predict satisfactorily the drying kinetics of the samples of the two drying processes, of cowpea bean. Santos et al. (2014) studied the drying of residues of 'urucum' (*Bixa orellana*) grains by direct exposure to the sun combined with drying in heat accumulator dryer and obtained good results in the fitting of the models. Doymaz (2011) studied sun drying of okra and also obtained good fits using the models employed in the present study. Clement et al. (2009) investigated the sun drying of fermented cocoa seeds and obtained fits with R^2 higher than 0.94 for the Two Terms, Page and Thompson models.

The values of effective diffusivity (D_{ef}) with their respective coefficients of determination (R^2) were $D_{ef} = 6.98 \times 10^{-11}$ m^2 s^{-1} and $R^2 = 0.9451$ for the cowpea bean sample dried by direct exposure to the sun combined with drying in night time heat accumulator dryer and $D_{ef} = 6.84 \times 10^{-11}$ m^2 s^{-1} and $R^2 = 0.9370$ for the samples of the control. The effective diffusivity indicates the speed at which water can be transferred from the interior to the surface of the product (Jittanit, 2011). It can be observed that the D_{ef} of the drying combined with the nighttime heat accumulator dryer was higher than that of the control drying. Several agricultural products have effective diffusivity on the order of 10^{-9} to 10^{-11} m^2 s^{-1}, such as soybean (Niamnuy et al., 2012) and cowpea bean seeds (Morais et al., 2013; Camicia et al., 2015).

CONCLUSIONS

1. The use of the heat accumulator dryer promotes the drying of the samples during the night period, avoiding water absorption by cowpea bean grains, being effective as a complement to the drying by exposure to the sun, maintaining a suitable temperature for nighttime drying.

2. The models Approximation of Diffusion, Page, Verma, Logarithmic and Two Terms fitted well to the drying kinetics of cowpea bean samples.

3. The mathematical model Approximation of Diffusion gave the best fit to the experimental data of the drying of cowpea bean by direct exposure to the sun combined with drying in nighttime in the heat accumulator dryer (sun/HAND) and the Verma model is the one that fitted best to the data of the drying by only exposed to the sun and to the relative humidity of the laboratory environment at nighttime (control).

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