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Full Length Research Paper

Drying of waste grains flour of annatto by using solar energy

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This study is aimed at drying annatto seed powders produced from seeds with and without oil used in bixin extraction. Drying was done at night, using a solar energy dryer. The drier consists of a system of solar panels that heat water, which is transferred to a thermal reservoir from where it is used as heat source for drying during the night. The waste grain flour of annatto with initial moisture content of approximately 20% w.b. was dried by approximately 5% w.b. The samples were split into two batches: Exposed to external environment and placed in the drier. The drying kinetic data were fitted by five mathematical models. The drier showed effectiveness in the drying of annatto grains flour at night with difference of more than 10% of moisture content in relation to the samples exposed to external environment. Powders obtained from seeds containing oil took approximately 40% longer to dry than those without oil. The mathematical models assessed satisfactorily represented drying behavior. The highest values of diffusivity were found in dehydrated samples in the drier.

Key words: *Bixa orellana* L., agroindustrial waste, nocturnal drier.

INTRODUCTION

In accordance with Queiroz et al. (2011), products classified as agricultural waste are often valuable material in the nutritional point of view; this material may also be used in order to increase the yield of the main product. Moreover, its disposal in the environment causes economical and environmental costs, proportional to the exploration volume.

The annatto waste grains (*Bixa orellana* L.) are by-product of the pigment extraction in the dye industry, mainly the bixin. Its gain would represent, in mass or volume, one of the largest returns among agricultural products, since the bixin layer that wraps the grains is very thin, in a manner that during the industrial extraction process there is from 94 to 98% of leftovers (Silva et al., 2006). Rêgo et al. (2010) provided the information that approximately 2,500 t of annatto waste grains are annually obtained in Brazil, almost 97% of it is not used.

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Currently, most of this waste is disposed; however there is already demand for it by breeders that use it in the composition of animal feed and scientifical works that evidence its practicability for this purpose (Silva et al., 2006; Harder et al., 2007; Rêgo et al., 2010). By exploring its potentiality, these grains can be used in the human nourishment, with differentiated indication for dietary food, due to its high fiber content. Authors such as Pereira et al. (2010) reported the amount of crude fiber in waste grains of annatto of 13.5% d.b. Tonani et al. (2000) found higher amount of crude fiber, corresponding to 15% d.b.

The literature contains a number of studies on the drying of agribusiness waste: grape seeds (Roberts et al., 2008); pumpkin seeds (Sacilik, 2007; Jittanit, 2011); guava processing subproduct (Konga et al., 2010); pineapple fiber derived from pineapple waste (Waughon and Pena, 2008); olive oil subproduct (Montero et al., 2011; Milczarek et al., 2011); fermented grape bagasse (Ferreira et al., 2012); orange juice subproduct (Garau et al., 2007); tomato processing subproduct (Celma et al., 2009); among others. Despite the wide diversity of research in the area of agro-food wastes, no references on drying annatto grain powder were found, demonstrating the importance of studying this subproduct.

In the case of agricultural waste with low commercial value, as annatto grain, energy expenditure in processing make their use problematic. The drying important operation in order to reduce the amount of moisture content in agricultural products at safe levels (approximately 4 to 13% b.u. of moisture, with low moisture for oleaginous seeds and higher for amylaceous seeds) requires high energy expense. Acquiring this energy tends to migrate, in the medium or long-term, to renewable sources, representing, in the case of agricultural waste, a means of promoting its industrial reuse. Among these sources, the solar energy is shown as the first alternative, for being plenty and direct heat source. The tropical localization of most part of the Brazilian territory places Brazil in privileged position for the use of solar energy. As for the use of this source for drying agricultural products, the study of systems and processes that increase its advantages is responsible for it.

The use of the solar energy as direct heat source is likely to have as the great inconvenience the interruption of the process at night. Studies in order to overcome this inconvenient should consider the accumulation of solar energy during the day in order to keep the drying at night, even in lower rate. The use of one water body in order to accumulate solar energy has the advantage of being able to be done in a relatively small volume and by using simple solar collectors. In these collectors, the water temperature may rise at 80°C or more, depending on the construction details, as the thermal isolation (Queiroz et al., 2011). The solar energy accumulated in the water during the day can be used for dryings during the nocturnal period, by heating the air of the drying chamber at temperatures higher than 50°C.

Bixin extraction from the seeds used in this study was performed at ambient temperature, agitating the material in cooking oil, which was used as solvent. Thus, it is expected that samples behave like other seed powders in drying, but the peculiar characteristics of the tegumentary cell matrix and the presence of oil may induce the results obtained. From the industrial viewpoint, one of the most interesting aspects is drying time, due to its associated costs. In the light of the foregoing, the purpose of this study was using an accumulative drier of solar energy in order to dry waste grains flour of annatto in the nocturnal period and studying the drying kinetic through mathematical models.

MATERIAL AND METHODS

Waste grains of annatto given by one local food industry were used; this local food industry performs the bixin extraction in oily medium (soy oil). The grains were received in the laboratory and stored in plastic containers in the chamber with temperature of -18°C until the beginning of the tests. These grains were impregnated of soy oil resulting from the bixin extraction process.

In order to obtain flour, the waste grains were processed in two ways: in the first one, they were conserved with the oil layer from the pigments extraction process, and in the second one, the oil layer was removed by washings using water and neutral detergent. After the washing, the elimination process of the remaining water was done by air exposure in the internal environment.

The grains with and without oil were crushed in shredding mill, by obtaining the grain flours with oil (Treatment 1) and grain flours without oil (Treatment 2), whose moisture content was approximately 20% w.b. (25% d.b.), determined in oven at 105 ± 3°C, according to the AOAC's method (2010).

The drying tests were done with 4 repetitions, being each repetition done with approximately 15 g of sample, put in aluminum containers (diameter of 13.5 cm and height of 1.5 cm). The drying kinetic data was obtained by samples weighing in regular intervals of 15, 30, 60 and 120 min.

The dryings were started at approximately 5 pm and continued until the samples reached the moisture content of approximately 5.0% w.b. (5.26% d.b.), by using one drier built in order to store solar energy in one water body and transfer the accumulated heat for the drying chamber during the night. This drier was built according to Dantas (2007) for drying of jackfruit almonds (*Artocarpus heterophyllus*), and it was modified according to Diógenes (2010), in study of drying of pumpkin seeds (*Cucurbita moschata*). The drier absorbs solar energy by means of solar collectors, in which it heats the water that is later used in the nocturnal drying, when passing through one heat exchanger. During the day, the water is heated and stored in a thermally isolated reservoir, circulating with the help of a pump whose energy is provided by one photovoltaic panel. During the night, the circulation of heated water between the thermal reservoir and the heat exchanger of the drying chamber is done through thermal siphon. In this assembly, when providing heat for the drying chamber the water contained in the heat exchanger has its density increased, by displacing to the lowest part of the reservoir and creating conditions for the occurrence of the thermal siphon, once the entrance and the exit of the reservoir and the coiled descending heat exchanger are placed in proper heights and different between themselves. The principle of thermal siphon also occurs in the collectors/reservoir circuit, however in this case the heated water ascends of the collectors for the upper part of the thermal reservoir, by suctioning the cold water from the bottom of the reservoir; however, the photovoltaic energy driven water pump speeds up the circulation, making possible faster heating in the solar collectors, with lesser times of residence and consequent improvement in the use of events when there is open sky.

In Figure 1, the schematical representation of the drier that uses solar energy at night is shown. During the day, the circulation of the water, controlled by shutoff cocks, is restricted to the thermal collectors/reservoir circuit. In the nocturnal period, the circulation in the collectors/reservoir circuit is interrupted, so cocks are open in order to release the circulation in the reservoir/chamber circuit of drying. Half of the samples were submitted to drying and the other half was sheltered in external environment, exposed to the environmental conditions of temperature and relative humidity.

In the calculations of the moisture ratio of samples the Equation 1 was used:

$$MR = \frac{X - X_e}{X_i - X_e} \qquad (1)$$

where: MR = moisture ratio (dimensionless); X = moisture content; X_i = initial moisture content; X_e = equilibrium moisture content. The mathematical models of Two Term, Midilli, Page and Thompson (Table 1) were fitted to the experimental data of the dryings, by

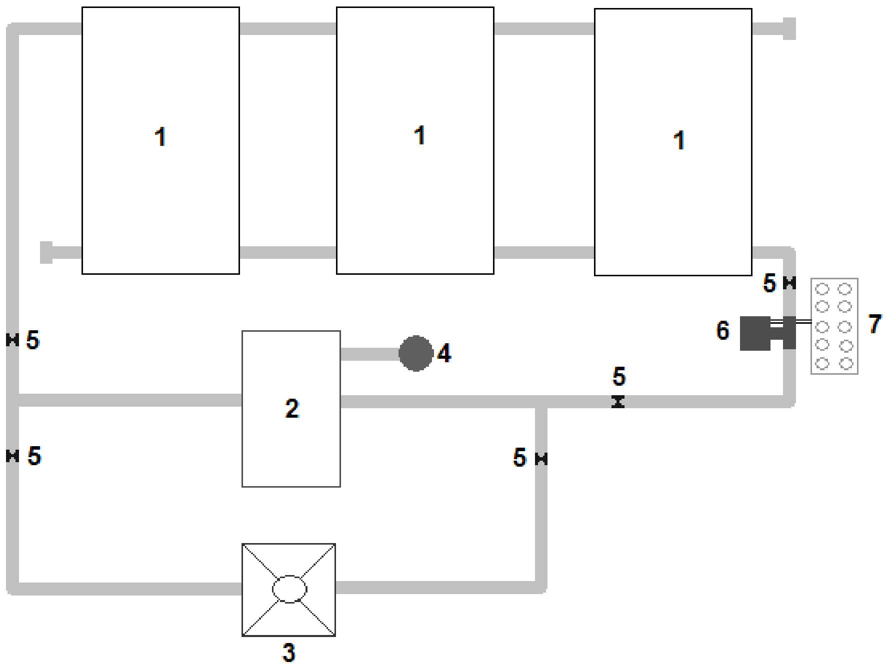

Figure 1. Schematical representation of the solar energy accumulative drier: 1-solar collector, 2-thermal reservoir, 3-drying chamber, 4-reservoir for water supply lost by evaporation, 5-shutoff cock, 6-water pump and 7-photovoltaic panel. Source: Modified of Diógenes (2010).

using the computational *Statistica*® program 5.0 by means of non-linear regression analysis, through the Quasi-Newton method. In the evaluation of the quality of the models fitment there were used as criteria the determination coefficient (R^2) and the mean-square deviation (MSD), in accordance with Equation 2:

$$MSD = \sqrt{\frac{\sum(MR_{pred} - MR_{exp})^2}{n}} \quad (2)$$

where: MSD = mean-square deviation; MR_{pred} = moisture ratio predicted by the model;MR_{exp} = experimental moisture ratio; n = number of comments.

To determine the coefficient of diffusion, based on the Diffusional Theory (Fick's second law), powder drying data were fit to the mathematical model of liquid diffusion for an infinite flat plate shape, thus considered because the powder was dried in the shape of a disk, 13.5 cm in diameter and 0.3 cm thick. The model was applied with approximately nine terms (Equation 3), considering uniform initial moisture distribution and absence of thermal resistance.

$$MR = \frac{X - X_e}{X_i - X_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-(2n+1)^2\pi^2 D\frac{t}{4L^2}\right] \quad (3)$$

where: MR = moisture ratio, dimensionless; D = coefficient of diffusion, $m^2\ s^{-1}$; n = amount of terms;L = characteristic dimension, m (half thickness of the plate); t = time, s.

In the statistical analysis the summary provided for in the factorial scheme 2 × 2 × 4 was used; 2 types of drying (in the dryer and in the external environment), 2 types of samples (Treatments 1 and 2) and four repetitions. The data were submitted to variance analysis and comparison of averages was carried out by the Tukey test ($p<0.05$), by using the computational program *Assistat*®.

RESULTS AND DISCUSSION

In Figures 2 and 3, the variations of temperature and relative humidity observed during the dryings of samples grain flours with oil and grain flours without oil in the dryer and external environment are shown. One can verify that in both dryings (Treatments 1 and 2) the temperature reached in the solar dryer was higher than that recorded external environment. Although the reduction in the temperature of the solar drier over the drying time, caused by the loss of energy of the heated water mass during the night, we can verify that this temperature remained above 40°C. The recorded average temperature in the drier was 44.81°C, for the drying of samples grain flours with oil samples and of 43.56°C, for the drying of grain flours without oil samples. Some oscillations in the relative humidity along the dryings were verified, however, this thermodynamic parameter remained lower in the drier, compared to that one recorded in the external environment. For the dryings of samples grain flours with oil and grain flours without oil, the average relative humidity recorded in the solar drier was approximately 67%, whereas the external environment showed average relative humidity of approximately 88%.

In Figures 4A and B, the experimental values of the drying curves of waste grain flours of annatto with or without oil were shown. It was observed that the samples put in the drier, as well as those samples that were

Table 1. Mathematical models used for fitment of the drying of annatto waste grain flour with or without oil.

Model designation	Equation	Reference
Two Term	MR = a.exp(-k.t) + b.exp(–q.t)	Santos et al. (2011)
Midilli	MR = a.exp(-k.t^n) + b.t	Midilli et al. (2002)
Page	MR = exp(-k.t^n)	Doymaz (2005)
Thompson	MR = exp((-a-(a^2 + 4.b.t)^{0,5})/2.b)	Sousa et al. (2011)

t = Drying time (min); k = constant of drying (min^{-1}); a, b, n, q = models coefficients.

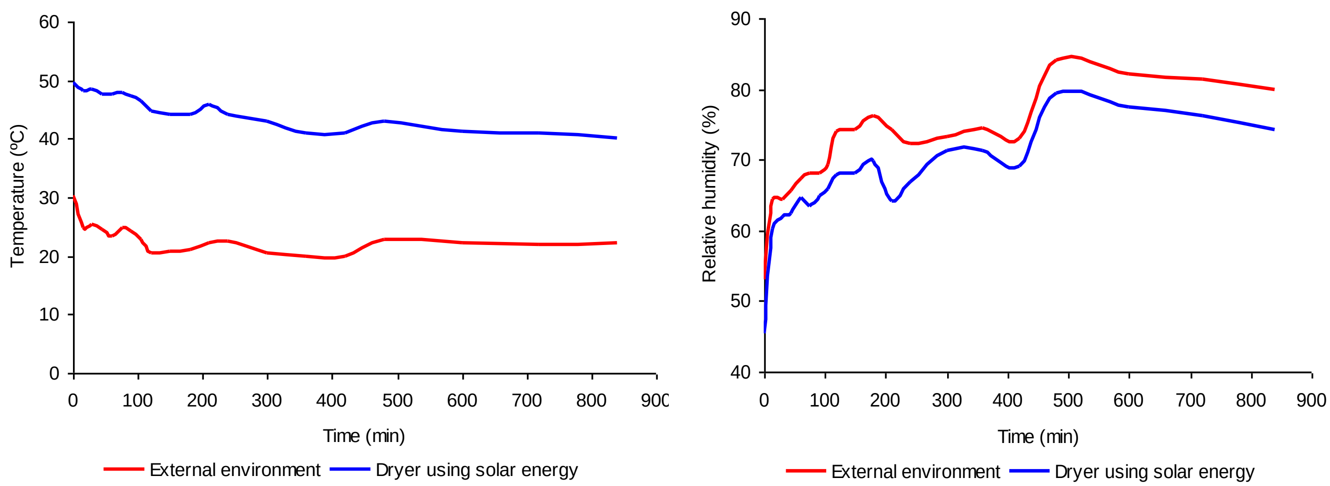

Figure 2. Variation of temperature and relative humidity in the solar energy accumulative drier and external environment during dryings of Treatment 1 samples.

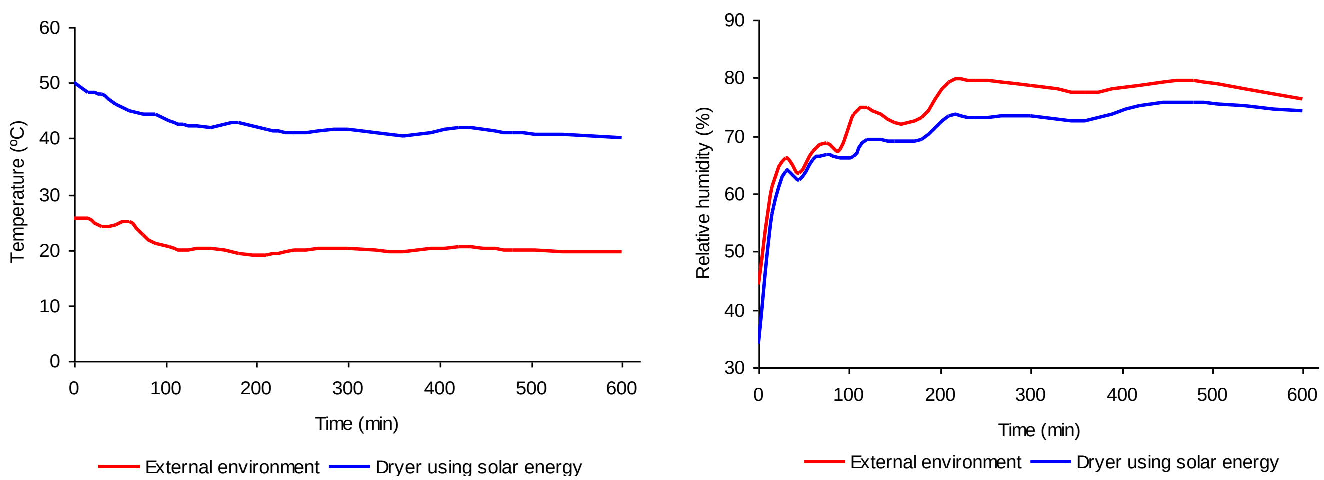

Figure 3. Variation of temperature and relative humidity in the solar energy accumulative drier and external environment during dryings in Treatment 2 samples.

external environment (control sample) lost moisture content during the nocturnal period, however the samples in the drier lost moisture content at the highest rate. The drying time so that Treatment 1 samples reached the desired moisture content was 14.0 h (840 min), however, the moisture ration in 420 min was already near 0.02 and the moisture content was 5.24% w.b. (5.55% d.b.), whereas the control sample, in equivalent time, showed

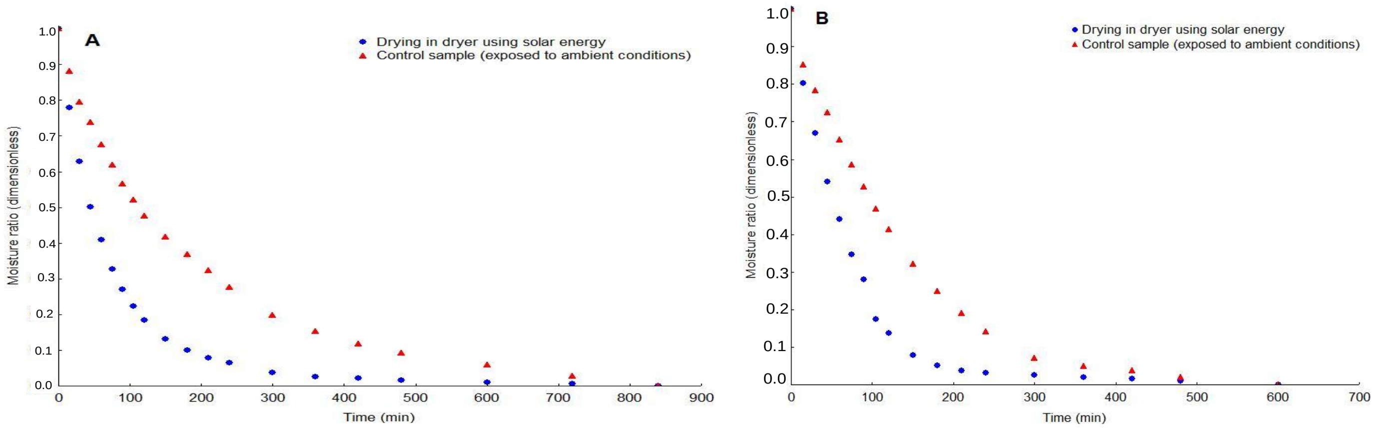

Figure 4. Curves of drying of the waste grain flour of annatto with oil (A) and flour without oil (B) in solar energy accumulative drier and external environment (control samples).

Table 2. The parameters of the drying models and respective determination coefficients (R^2) and the mean-square deviation (MSD).

Model	Sample	Parameters						
		a	b	k	n	q	R^2	MSD
Two term	T1	0.1751	0.8213	0.0052	-	0.0182	0.9999	0.0000
	T1 (C)	0.1482	0.8475	0.0268	-	0.0047	0.9995	0.0018
	T2	0.5084	0.5084	0.0150	-	0.0149	0.9959	0.0000
	T2 (C)	0.4984	0.4984	0.0075	-	0.0075	0.9967	0.0150
Midilli	T1	1.0053	0.000015	0.0238	0.8875	-	0.9992	0.0046
	T1 (C)	1.0000	-0.000022	0.0127	0.8414	-	0.9996	0.0001
	T2	0.9870	0.000023	0.0081	1.1365	-	0.9977	0.0014
	T2 (C)	0.9721	-0.000013	0.0048	1.0843	-	0.9980	0.0001
Page	T1	-	-	0.0240	0.8828	-	0.9989	0.0175
	T1 (C)	-	-	0.0117	0.8616	-	0.9994	0.0061
	T2	-	-	0.0094	1.1022	-	0.9973	0.0098
	T2 (C)	-	-	0.0061	1.0448	-	0.9972	0.0163
Thompson	T1	-13.8849	0.4873	-	-	-	0.9996	0.0075
	T1 (C)	-16.2726	0.3358	-	-	-	0.9982	0.0157
	T2	- 4,358.7000	7.9993	-	-	-	0.9956	0.0046
	T2 (C)	- 4,652.8400	5.9394	-	-	-	0.9967	0.0156

T1 - Treatment 1; T2 - Treatment 2; C - control sample.

moisture ratio higher than 0.10 and the moisture content of 14.08% w.b. (16.39% d.b.).

In equal manner, the Treatment 2 samples in the drier lost moisture at higher speed than the control sample; the drying time for Treatment 2 to reach the desired moisture content was 10.0 h (600 min). Comparing the drying times of Treatments 1 and 2, samples dried in the solar drier, it was verified that Treatment 1 sample needed more time to reach the desired moisture content, which can be attributed to the soy oil in the flour, by creating a physical barrier to the moisture movement in the interstitial spaces. The difference in the drying time of powders with and without oil was approximately 200 min, that is, around 40% higher in samples containing oil. Despite representing a substantial difference in absolute terms, its commercial application in a drying unit is based on a thorough study of its economic feasibility.

In Table 2, the parameters of the mathematical models of Two Term, Midilli, Page and Thompson were presented to the drying kinetic data of Treatments 1 and 2 samples, with respective determination coefficients (R^2) and the mean-square deviation (MSD).

It was verified that Midilli and Two Term models were those that fitted better to the experimental data, with

Table 3. Initial and final moisture contents of Treatment 1 (T1) and Treatment 2 (T2) samples dried in solar energy accumulative drier and in external environment (control samples).

Sample	Drying in solar dryer			Control sample		
	Initial	Final	Water loss (%)	Initial	Final	Water loss (%)
T1	24.89	5.18	79.19	24.89	15.33	38.41
T2	26.73	5.21	80.60	26.73	18.01	32.62

Table 4. Average values of the effective diffusivity ($m^2\ s^{-1}$) for the diffusion model, without the shrinking effect.

Type of drying	Sample	
	Treatment 1	Treatment 2
Solar dryer	1.90×10^{-10} aB	1.94×10^{-10} aA
control sample	1.38×10^{-12} bB	1.14×10^{-11} bA

Averages with equivalent letter, lower case in the column and capital letter in the line, do not statistically differ at 5% of probability, by the Tukey's test.

values of R^2 above 0.99 and lower values of MSD; however, given that it represented coefficients of determination (R2) above 0.99 and low MSD values, all the models can be used to predict the drying kinetics of samples in a dryer, under ambient conditions, with good results.

The results correspond to those achieved by Diógenes (2010), when studying the drying of pumpkin grains flour in the equivalent drier that accumulates solar energy combined with dehydration for direct exposition to the sun, in which achieved fitments with determination coefficient higher than 0.99 for the Page model. Queiroz et al. (2011) studying the jackfruit almonds drying, verified for the Logarithmic model, fitments with R^2 higher than 0.99 for the dehydration for exposure to the sun combined with drying in drier accumulated with solar energy, and R^2 above 0.98 for drying in solar energy during the day combined with drying in drier that accumulates solar energy. Sacilik (2007) achieved R^2 above 0.99 for Two Term model and higher than 0.98 for Page model when dehydrating pumpkin seeds in solar drier. Saeed (2010) verified values of R^2 above 0.99 when fitting models of Midilli and Page to the drying data of *Hibiscus sabdariffa* L. in solar drier.

In Table 3, the initial and final moisture contents were shown for Treatments 1 and 2 samples regarding the drying in drier and control sample. It was observed that the solar drier caused a greater reduction in the moisture contents at the end of the drying of the Treatments 1 and 2 samples in relation to the control sample, with difference between the samples of 10.15 and 12.80% d.b., respectively. These results are in accordance with those achieved by Dantas (2007) and Diógenes (2010) that also experimentally proved the efficiency of the drier that accumulates solar energy when dehydrating jackfruit almonds flour and pumpkin grains flour, respectively.

Comparing the final moisture contents of Treatment 2 samples and its control sample, it was observed greater difference between the Treatment 1 samples and its control sample, which reflects greater easiness of drying the samples without oil. Diógenes (2010) verified reduction in the moisture content of 87.91% upon drying pumpkin grains flour in solar energy accumulative drier, which is close to that achieved in this study for dehydration of waste grains flour of annatto with and without oil. According to the author, the pumpkin grains flour started the drying with moisture content of 39.77% d.b. and by the end of the process, at the first night, showed moisture content of 4.81% d.b.

In Table 4, it was observed the average values of effective diffusion and coefficient determined for dryings of waste grains flour of annatto with or without oil, in the solar drier and external environment (control sample). It was verified that there was significant effect at 1% of probability by F test, for different types of samples (Treatments 1 and 2) and for the different types of drying (in the drier and external environment), as well as the interaction type of sample and type of drying. All diffusivity values showed difference among themselves by the Tukey's test ($p<0.05$).

It was verified that during the drying, the diffusion coefficients showed higher values for the drier samples. For these samples, the diffusivity showed about $10^{-10}\ m^2\ s^{-1}$, thus, being in the range of 10^{-9} to $10^{-11}\ m^2\ s^{-1}$ reported by Madamba et al. (1996), for the drying of agricultural products. Similar results were achieved by Corrêa et al. (2006), during the drying of beans grains (*Phaseolus vulgaris* L.), Markowski et al. (2010), in the drying study of Mauritia cultivating barley, Minaei et al. (2011), in the drying of pomegranate aril (*Punica granatum* L.) and by Abano et al. (2011), in research of the drying of tomato slices. Both authors also found values of the diffusion coefficient about $10^{-10}\ m^2\ s^{-1}$.

As for the control sample, it was verified effective diffusivity coefficient dimensions about $10^{-11}\ m^2\ s^{-1}$, for the sample without oil, and of $10^{-12}\ m^2\ s^{-1}$, for the product with oil. Several authors have found diffusivity values at the same order of magnitude for different plant parts: Sacilik (2007) found dimensions of 8.53×10^{-11} to $17.52 \times 10^{-11}\ m^2\ s^{-1}$ for the effective diffusivity coefficient when studying the drying of pumpkin seeds (*Cucurbita pepo* L.), Reis et al. (2011) reported values of effective diffusivity coefficients ranging between 2,29 10^{-11} and 2.57 $10^{-11}\ m^2\ s^{-1}$ in drying Cumari pepper of Pará (*Capsicum chinense*

Jacqui), Gazor and Mohsenimanesh (2010) found effective diffusion coefficients ranging from 3.76×10^{-11} to 8.46×10^{-11} m^2 s^{-1}, for the drying of seeds of canola and Chayjan et al. (2012) reported the minimum diffusivity for pomegranate seeds (*P. granatum* L.) cultivating Alak of 9.27×10^{-11} m^2 s^{-1}. These results are close to those verified for Treatment 2 control samples. Martinazzo et al. (2007) verified the effective diffusivity of 4×10^{-12} m^2 s^{-1}, when dehydrating Cymbopogon citratus leaves (*Cymbopogon citratus*) at the temperature of 30°C. Akpinar (2006) found diffusion values about 10^{-12} m^2 s^{-1} when drying mint (*Mentha* sp.), parsley (*Petroselinum crispum*) and basil (*Ocimum basilicum*) and Gorjian et al. (2011), when studying the drying of fruits of *Berberis vulgaris* L., reported the effective diffusivity ranging from 2.57×10^{-13} to 9.67×10^{-12} m^2 s^{-1}.

The presented results are in accordance with Goneli et al. (2007), stated that with the rise of temperature, the water viscosity diminishes and, since the viscosity is one overflow resistance measure of the fluid, variations of this property imply changes in the water diffusion in the sample interstices in a way that favors the fluid movement in the product. For the dryings of waste grain flours of annatto with or without oil, it was observed that the temperature affected the diffusivity, where the samples were dehydrated in the drier, whose the average temperature was higher than 40°C, revealed more diffusivity values in comparison to control samples which were at temperature lower than 30°C.

Conclusion

The drier that accumulates solar energy showed efficiency for drying annatto waste grain flour in nocturnal period, reaching the safe moisture content in one drying night. All evaluated mathematical models satisfactorily represented the drying of the waste grains flour of annatto with or without oil. Annatto seed flower with oil required around 40% more drying time than samples without oil. The highest values of effective diffusion coefficient were found in the dehydrated samples in the solar energy accumulator drier.

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