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MODELLING OF THIN LAYER DRYING KINETICS OF COCOA BEANS IN A MICROWAVE OVEN AND SUN

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Abstract: *The purpose of this work was to make a drying experiment of fermented cocoa beans concomitantly in the sunlight (using the experimental tray as a recommended device) and in a microwave oven (MO) to simulate the process by empirical models. The gradient method was used to estimate the coefficient of empirical models used in the study. The experimental data were adjusted from eleven equations published in the literature. The best suitable model was evaluated using the coefficient of determination (R^2), reduced chi square (χ^2), the Root Mean Square Error (RMSE), the Sum Square Error (SSE) and the Mean Relative Deviation (MRD) in percentage (%) between the experimental and predicted values. The diffusion approach model was selected for the solar drying because this model presents the best statistics characteristics (0.991; 2.49 E-04; 0.036; 0.037 and 3.401%). For the microwave oven drying, high R^2 values (higher than 0.95), low values of χ^2, RMSE, SSE and the MRD values below 10% are given by the Page and Newton models proposed: 0.981; 0.002; 0.080; 0.080; 3.718% for the device MO 2400W; 0.974; 0.003; 0.096; 0.067; 7.708% for the MO 2800W and 0.982; 0.002; 0.069; 0.107; 8.496% for MO 3200W.*

Keywords: *drying, microwave, sun, empirical models, gradient method.*

1. Introduction

The cocoa bean is the raw base material of the chocolate industry. It is used to obtain chocolate products [1]. The beans must undergo different processing steps including drying [2]. It is one of the oldest methods of preserving agricultural products [3]. It consists in water evaporation, thus reducing the potential growth of microorganisms and some undesirable chemical reactions such as the enzymatic browning in order to increase the product life [3]. It provides a dry and homogeneous product [4]. At harvest which occurs just after the maturity of the pods, the beans are fermented and dried before any other form of industrial transformations. The fermentation lasts for approximately six days and can be done with banana leaves or wooden crates [5, 6]. After fermentation two drying methods of beans are used. Natural drying in the sunlight and artificial drying by forced convection. The beans are dried until they reach the accepted limit of moisture (8%) and the establsihed limit for free fatty acid (≤1.75%) [2, 7]. Natural drying has a high dependence on weather conditions, which could influence the quality of cocoa beans [8]. Artificial drying meanwhile is carried out with hot air that is forced convection. Several authors report the influence of different crops post-treatment on the quality of agricultural products [8, 9]. Many research studies were conducted in order to provide solutions [7]. Drying is a crucial step. Sunlight drying of cocoa beans is done on tray at free air with a relatively long time (7-21 days) [10]. The recovery of the moisture beans causes the change of the constituents of fat depending on seasons' variability [11]. In industry, the drying of beans is carried out by the forced convection mode in 24 to 48 hours which is a relatively short time in comparison with solar drying [12, 13]. However, this heat transfer mode has the disadvantage of retaining volatile acids in the cotyledons [12-14]. This fact can change the physical and chemical properties, leading to an acid and unstructured cocoa butter [11]. Among other reported disadvantages of hot air drying, one can notice the increase of bitterness, appearance and smell caused by the presence of acrolein and an undesirable flavor of burnt beans [15]. Several studies of artificial drying in electromagnetic environment have shown excellent results on various products and in various fields. Derya and Mehmet showed that the onion drying kinetics by electromagnetic waves has better characteristics than those obtained by sun-drying modes (drive) and the hot air oven (forced convection). This study showed that the mineral constituents (K^+, Ca^{2+}) are higher and have better rectangular coordinates L * a * b *. Concentrations of phenolic compounds are also more important for the electromagnetic wave drying as compared to the others mentioned above [16]. Chekroune showed that the dates are likely to be dried with the aid of electromagnetic waves while maintaining their physicochemical characteristics [17]. Furthermore, the work done by Kone has shown that the tomato could be dried in electromagnetic environment intermittently with a specific power steering [18]. The results of this work showed improved retention rate of the lycopene. Lucchesi demonstrated the efficiency, speed (reduction factor extraction time 9) and selectivity without inertia in the heating mints by using microwave, revolutionizing the vegetable oil extraction process [19]. Their work has been the subject of a study Patent in Europe and the United States. Microwave drying generally has enough benefits including speed, uniformity of the dried material and more effectiveness in terms of energy transfer compared to convection (forced) and infrared. It accelerates moisture loss from the inside to the outside of the material [20]. Microwave technology is quickly growing. Indeed, it is variously used for drying, either directly to dry agricultural products and or as an adjunct to other drying methods (convection hot air) in industry [18, 21, 22, 23]. A good practice and monitoring of the drying process is necessary to obtain good quality of cocoa beans by the formalization of the phenomenon [2]. In this regard, several empirical models (mathematical equations) were exploited and described in the literature [2, 22]. These models establish relations between reduced water content and drying time in order to obtain the characteristic curves and describing the phenomenon [24]. The aims of this work are to describe drying characteristics and to model the cocoa beans drying as an experimental tray device and microwave oven by the empirical models of thin layer.

2. Matherials and methods

2.1 Sample preparation

Thirty kilograms of fresh cocoa beans were purchased in the month of October 2013 from growers (3) Yamoussoukro (a town in central Cote d'Ivoire, West Africa) and put into fermentation for six days in banana leaves.

2.2 Drying procedure

The obtained fermented beans were removed from waste before starting the drying process. During this period, a thermo-hygrometer (Auriol IAN 71010, France) was used to raise the ambient temperature. Relative humidity and air velocity were recorded using an anemometer (PCE-81 AM, France). Solar drying operation took place five hours on experimental tray of one square meter raised of one meter in relation to the ground during seven days. For artificial drying device, a microwave oven (Guangzhou Qualiway LTD 510630, China) at three power levels (2400W, 2800W and 3200W) was used. Thirty (30) samples of the same mass (200 g) were spreaded in thin layer of 3 to 4 cm thick in experimental tray [7, 24]. The weight loss was recorded regularly every hour using scales (Sartoruis, A200S, France) until stability thereof ie the difference between three successive weighing not more than 0.001g. For drying oven at MO, three sets of 30 samples of 200 g were dried in the three powers mentioned above. The differential mass loss was regularly recorded every minute (application time) under the same conditions as above [25]. The initial and final water content was performed according to AOAC methods [26].

2.3 Mathematical modelling

The reduced water content and the drying rate were determined using the following equations (1 and 2):

$$X^* = \frac{X_t - X_e}{X_o - X_e} \quad (1)$$

$$\frac{dX}{dt} = \frac{X_{t+dt} - X_t}{dt} \quad (2)$$

Where X_t is the water content at t; Xe is the water content at equilibrium and X_0 is the initial water content [27, 28].

The table 2 below presents eleven models used to model the drying kinetics of cocoa beans in thin layer. They are semi-empirical models used in the literature [22]. These equations contain coefficients that need to be adjusted from experimental data [29]. To do the calculation, a program implemented in MatLab R2014a was developed. It is based on the gradient method to estimate model coefficients and linear regressio to calculate the following statistical criteria: the coefficient of determination (R^2), the reduced chi-square (chi-square), the Root Mean Square Error (RMSE), the Sum Square Error (SSE) and Mean Relative Deviation (MRD) [30]. They have been used for the selection of models that fit best the experimental values and values predicted by the model [23, 29].

Table 1

Nomenclature

Classifications	
a, b, c,	Drying coefficients
RMSE	Root Mean Square Error
MRD	Mean Relative Deviation
SSE	Sum Square Error
k, g, n, h	Constants drying
N	Number of observations
R^2	Coefficient of determination
$X*$	Reduced water content
DM	Dry matter
Greek Symbols	
χ^2	Reduce chi square
Subsrcipts	
i	At time *i*
e	Equilibrium
o	Initial
exp	Experimental
pre	Predicted

Table 2

Description of the empirical models in thin layer drying tested in the study

Equation N°.	Model name	Expression of the model	References
I	Newton	$X^* = Exp^{(-kt)}$	[31]
II	Page	$X^* = Exp^{(-kt^n)}$	[32]
III	Page I modified	$X^* = Exp^{((-kt)^n)}$	[24]
IV	Henderson and Pabis	$X^* = aExp^{(-kt)}$	[33]
V	Logarithmic	$X^* = aExp^{(-kt)}+c$	[34]
VI	Two term	$X^* = aExp^{(-k_0 t)}+ bExp^{(-k_1 t)}$	[29]
VII	Two term exponential	$X^* = aExp^{(-kt)}+ (1-a)Exp^{(-kat)}$	[24]
VIII	Wang and Singh	$X^* = 1 + at + bt^2$	[35]
IX	Diffusion approach	$X^* = aExp^{(-kt)}+ (1-a)Exp^{(-kbt)}$	[3]
X	Verma *et al.*,	$X^* = aExp^{(-kt)}+ (1-a)Exp^{(-gt)}$	[36]
XI	Midilli and Kucuk	$X^* = aExp^{(-kt^n)} + bt$	[37]

With a, b, c (coefficients) and g, h, k, k_0, k_1, n (parameters) to be determined.
Statistical criteria for choosing models:

Coefficient of determination $$R^2 = \frac{\sum_{i=1}^{N}(X^*_{exp,i}-X^*_{pre,i})^2}{\sqrt{\left[\sum_{i=1}^{N}(X^*_{exp,i}-X^*_{pre,i})^2\right]*\left[\sum_{i=1}^{N}(X^*_{exp,i}-X^*_{pre,i})^2\right]}} \quad (3)$$

Reduced chi square: $$\chi^2 = \frac{\sum_{i=1}^{N}(X^*_{exp,i}-X^*_{pre,i})^2}{N-z} \quad (4)$$

Root Mean Square Error: $$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(X^*_{exp,i} - X^*_{pre,i})^2\right]^{\frac{1}{2}} \quad (5)$$

Sum Square Error: $$SSE = \frac{100}{n}\sum_{i=1}^{N}(X^*_{exp,i} - X^*_{pre,i})^2 \quad (6)$$

Mean Relative Deviation: $$MDR = \frac{100}{n}\sum_{i=1}^{N}\left|\frac{X^*_{exp,i}-X^*_{pre,i}}{X^*_{exp,i}}\right| \quad (7)$$

3. Results and discussion

3.1 Drying characteristics

The initial water content of the cocoa beans is 53.52 ± 2.93% and is reduced to a value less than 8% at end of the drying [1, 2, 7]. The mean levels of the end of drying beans vary from 5.49 to 5.77%. They are respectively: MO 2400W (5.77 ± 0.17%); MO 2800W (5.63 ± 0.20%); MO 3200W (5.60 ± 0.14%) and 5.49 ± 0.11% at the tray device. The figure 1 shows the evolution of aerodynamic parameters during 35hours of solar drying. These are: the relative humidity which fluctuated between 52-74%, the temperature flucted to 27.4-36.2°C and the velocity air of the drying varied from 0.2-2ms^{-1}.

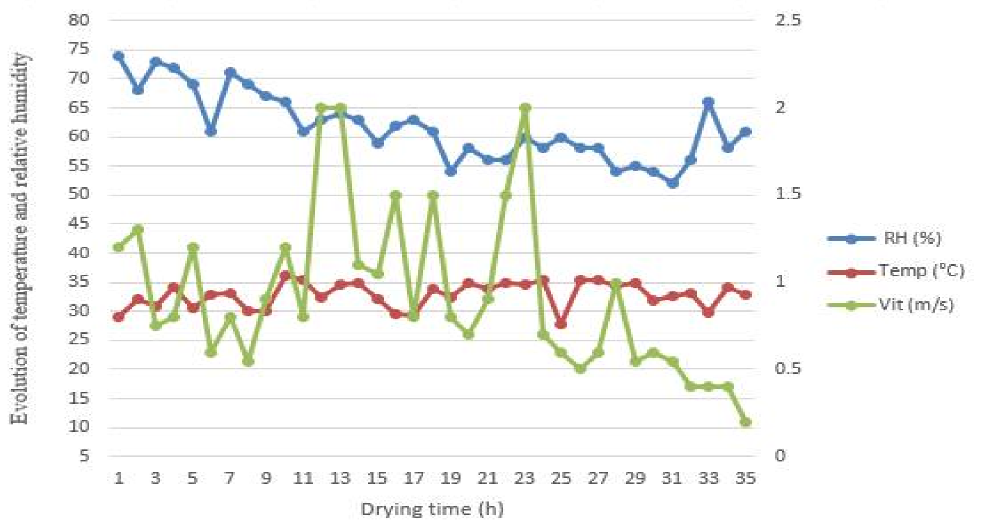

Fig. 1: Evolution of aerodynamic parameters (solar drying)

Similarly, the evolution of the temperatures of dried cocoa beans with different powers in the microwave oven is shown in figure 2.

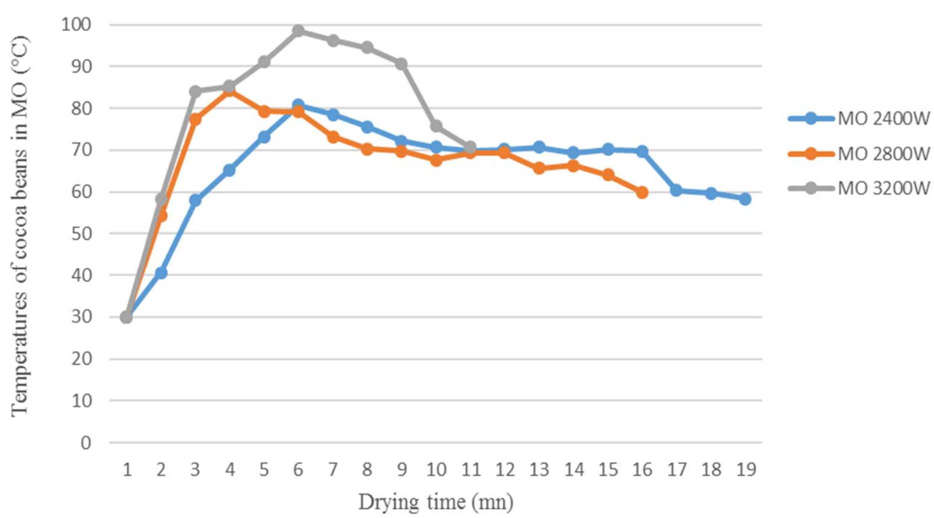

Fig. 2: Evolution of cocoa beans drying temperature in MO

The curves reflecting changes in the temperatures during microwave drying of cocoa beans generally have the same allure. The trend of evolution can be seen in six (6) minutes followed by falling to the tenth (10th) minutes. Then some stabilization thereof is noticed until the end for MO 2400W device. At the drying MO 2800W, the temperature increases during first four (4) minutes, and then decreases until the end of drying with a phase slight increase in the eleventh to twelfth minute. An increasing speed to phase ((3) first three minutes) followed by a lasting stable phase one (1) minute and a decrease thereof to 3200W. Following the determination of the water content of the beans after drying, successive readings of the masses permitted to establish the curves of the differential mass loss of samples of fermented cocoa beans. They are obtained by expressing the reduced water content as a function of drying time [X* = f (t)] and are plotted for triplicates (figure 3 and 4).

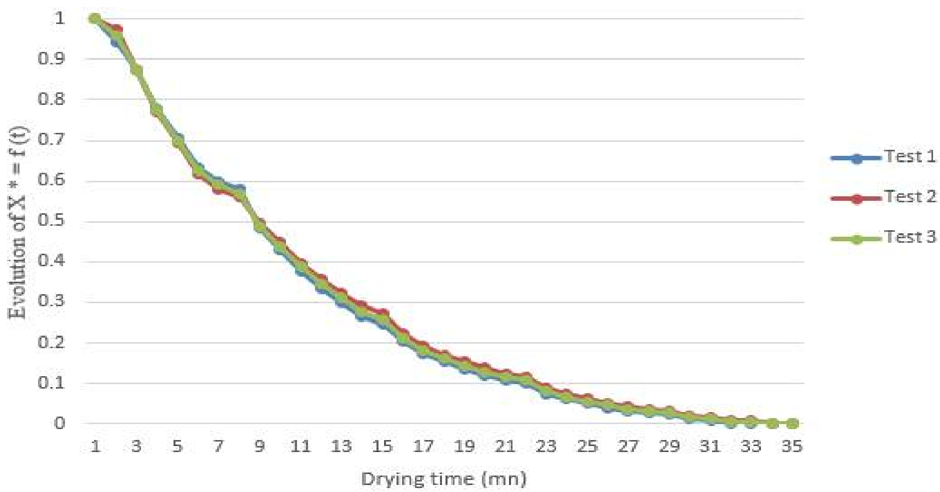

Fig. 3: Curve of cocoa beans drying in tray

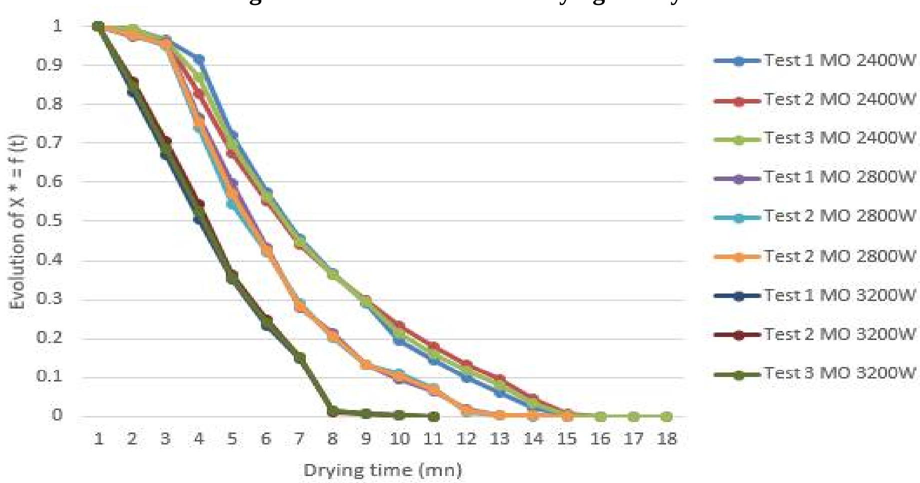

Fig. 4: Curve of cocoa beans drying in the microwave oven

The end of the experiment is reached after thirty-five hours (35) on drying experimental tray, 16, 12 and 8 minutes in the microwave oven as shown in figures 3 and 4. All drying curves have the same shape. Three (3) drying periods are observed: the heating period, the constant rate period and the falling rate; except that obtained at the 3200W power that has almost no heating temperature. The heating period observed during the first 2 hours of drying on tray, 4th and 3rd minute respectively for the MO 2400W and MO 2800W devices. That operates at a constant rate of 2-25 hours of sunshine cumulated on tray, between 4-13th minute for the device MO 2400W; 3-10th minute at MO 2800W and for MO 3200W device during 1-7th minute. The third period is observed during 25-35 hours in the sun, 13-16th minute at 2400W; the 10-12th minute at 2800W and of 7-8th minute at 3200W. Thus, the maximum rate reached during drying of cocoa beans in the microwave oven is 7.59 Kg of H_2O/Kg DM/minute to 2400W; 9.19 Kg of H_2O/Kg DM/minute to 2800W; 13.12 Kg of H_2O/ Kg DM/minute to 3200W and 6.24 Kg of H_2O/Kg DM/hour at sun (tray).

The drying characteristics curves fitting allow to obtain the equations of drying rate in the form of polynomial of degree 3 with the determination coefficients higher than 0.95 (0.982 for sun drying; 0.993 at 2400W; 0.984 at 2800W and 0.982 at 3200W) [24,38]. Mathematical expressions of drying rates of cocoa beans of two devices are:

$1.078X^{*3} - 1.753X^{*2} + 1.631X^*$; (claie)
$0.665X^{*3} - 0.516X^{*2} + 0.825X^*$; (2400W)
$2.454X^{*3} - 2.995X^{*2} + 1.508X^*$; (2800W)
$2.367X^{*3} - 3.003X^{*2} + 1.563X^*$; (3200W)

The drying time in the microwave oven has an incomparable application time to the sun. The drying of cocoa beans by microwave oven shows a fast decrease of the mass with the increased level of power. Dried beans in the microwave oven have higher drying rates than those dried in the sun in the descending order of power level. Dried beans in the microwave oven have higher drying rates than those dried in the sun in descending order of power level. This fast loss of mass of the different samples (beans) can be explained by the large amount of dipolar molecule such as water (53.59 ± 2.93%, initial water content). Their polarization then allows them to orient themselves in the alternating electromagnetic field creating a rotational movement and resulting in the conversion of kinetic energy into heat energy dissipation [39, 40, 41]. To this end, a fast gradual rise of the temperature is observed. They evolve from: 30 to 80.2°C; 30 to 84.4°C and 30-98,5C° respectively for the MO 2400W, MO 2800W and MO 3200W (Fig. 2). The beans become source of energy for the simple reason that the heating system is in volume. In fact, the difference vapor pressure between the inside and outside of the beans is high [21]. Thus, the matter and energy spread from the inside to the outside of the product subject to radiation [18, 27, 39]. Thus, from the standpoint of speed, the microwave drying mode can be a good alternative to solar drying in experimental tray mode which moreover is strongly influenced by the weather [11].

3.2 Mathematical modelling

The table 3 below presents the estimated coefficients of the eleven (11) thin layer drying models of the experimental data used, and the accuracy of the models by comparing the settings: the R^2, the reduced χ^2, RMSE, the SSE and MRD (%).The analysis of the above table (2) shows that the values of the parameter R^2 fluctuate from 0.855 to 0.991; from 0.903 to 0.981; from 0.883 to 0.974; from 0.895 to 0.982, respectively, for the tray, MO 2400W, MO 2800W and MO 3200W. Those (values) of the reduced χ^2 fluctuate from 2.49E-04 to 0.017 for the tray; from 0.002 to 0.065 at MO 2400W; from 0.002 to 2.717 at MO 2800W and from 0.002 to 0.034 at MO 3200W. While it is recorded RMSE of 0.036 to 0.370 for drying on tray; 0.080 to 0.497 at 2400W; 0.096 to 2.760 at 2800W and 0.069 to 0.932 for the MO 3200W drying. As for the SSE, they fluctuate from 0.037 to 13.529 for solar drying; 0.004 to 7.807 at 2400W; 0.001 to 5.672 at

2800W and 0.011 to 8.247 at 3200W. Finally, the MRD fluctuate from 3.401 to 15.200 for the tray device; from 3.718 to 18.309; from 0.249 to 13.628 and from 3.070 to 13.974 in ascending order of powers in microwave oven. Based on what the model that best describes the drying kinetics thin layer is the one with the highest value of the determination coefficient (R^2), low values of reduced χ^2, RMSE, SSE and a lower MRD 10% [23, 29]. The model of the approach of diffusion is retained for solar drying (experimental tray). Those Page and Newton are retained respectively for levels of 2400W, 3200W and 2800W in microwave oven. Other models which have been selected are reported in the literature during solar drying and would be the result of the influence of experimental conditions [8, 9, 42, 43]. Indeed, Akmel *et al*, retained the logarithmic model while Hii *et al*, a new model that is similar to Page model at two terms. This difference in selected models is due to the influence of the following parameters such as temperature, relative humidity, wind speed and initial water content of the cocoa beans [2, 24].

Table 3

Coefficients of models and statistical parameters of models choice

Model number	Devices	Coefficients & models parameters				R²	χ²	RMSE	SSE	MRD (%)
I	claie	k=0.070				0.991	2.91E-04	0.046	0.022	8.834
	2400W	k=0.078				0.975	0.003	0.112	0.274	8.544
	2800W	k=0.115				0.974	0.003	0.096	0.067	7.708
	3200W	k=0.072				0.966	0.014	0.161	1.135	11.346
II	claie	k=0.078	n=0.091			0.982	0.014	0.315	13.523	13.782
	2400W	k=0.171	n=0.901			0.981	0.002	0.080	0.080	3.718
	2800W	k=0.219	n=0.598			0.970	0.006	0.137	0.206	7.670
	3200W	k=0.148	n=1.029			0.982	0.002	0.069	0.107	8.496
III	claie	k=0.093	n=0.148			0.978	0.002	0.119	0.174	5.702
	2400W	k=0.013	n=0.521			0.970	0.013	0.211	2.071	10.248
	2800W	k=0.112	n=0.052			0.955	0.011	0.169	0.001	0.249
	3200W	k=0.104	n=0.080			0.948	0.010	0.141	0.021	3.070
IV	claie	a=1.040	k=0.009			0.881	0.012	0.304	12.903	14.128
	2400W	a=0.966	k=0.009			0.915	0.022	0.267	4.330	11.495
	2800W	a=0.906	k=0.010			0.894	0.025	0.263	3.094	11.208
	3200W	a=0.958	k=0.009			0.936	0.041	0.281	3.471	12.609
V	claie	a=-0.654	c=0.338	k=0.135		0.977	0.014	0.232	7.533	4.906
	2400W	a=-0.324	c=0.286	k=0.157		0.980	0.031	0.263	4.980	6.157
	2800W	a=1.421	c=0.069	k=0.060		0.943	0.027	0.296	5.239	13.628
	3200W	a=-1.391	c=0.420	k=0.064		0.963	0.370	0.909	6.358	13.974
VI	claie	a=0.928	b=0.452	ko=0.009	k1=0.043	0.931	0.017	0.370	9.174	15.200
	2400W	a=1.444	b=0.150	ko=0.005	k1=0.443	0.954	0.065	0.497	7.807	14.556
	2800W	a=0.839	b=0.003	ko=0.010	k1=0.514	0.899	0.021	0.246	2.332	10.526
	3200W	a=1.363	b=1.585	ko=0.006	k1=0.105	0.974	0.348	0.932	8.247	7.237
VII	claie	a=0.942	k=0.009			0.881	0.011	0.289	11.578	13.907
	2400W	a=0.870	k=0.009			0.915	0.024	0.279	4.947	11.799
	2800W	a=0.809	k=0.010			0.894	0.301	0.291	4.431	12.044
	3200W	a=0.862	k=0.009			0.936	0.046	0.301	3.996	12.926

VIII	claie	a=-7.49E-6	b=2.39E-11			0.855	0.018	0.359	7.961	14.327
	2400W	a=-1.27E-3	b=7.49E-6			0.903	0.031	0.319	6.619	12.128
	2800W	a=-1.52E-2	b=2.45E-5			0.883	0.039	0.325	5.673	12.319
	3200W	a=-6.96E-2	b=4.56E-3			0.922	0.055	0.33	4.799	13.138
IX	claie	a=0.271	b=0.27	k=0.305		0.991	2.49E-04	0.036	0.037	3.401
	2400W	a=0.613	b=0.162	k=0.261		0.962	0.003	0.098	0.004	4.441
	2800W	a=0.401	b=0.208	k=0.174		0.971	0.007	0.148	0.602	9.477
	3200W	a=0.747	b=0.132	k=0.253		0.971	0.003	0.077	0.081	7.726
X	claie	a=0.668	g=0.288	k=0.023		0.981	0.002	0.114	1.417	10.688
	2400W	a=0.591	g=0.289	k=0.025		0.966	0.005	0.139	0.376	7.981
	2800W	a=0.472	g=0.105	k=0.066		0.962	0.005	0.127	0.377	9.199
	3200W	a=0.565	g=0.377	k=-0.003		0.895	0.017	0.171	1.104	10.552
XI	claie	a=1.425	b=-0.301	k=0.119	n=0.992	0.976	0.011	0.267	9.245	13.264
	2400W	a=1.308	b=-0.047	k=0.145	n=1.067	0.976	0.014	0.23	3.814	18.309
	2800W	a=0.815	b=-0.698	k=0.162	n=0.671	0.887	2.717	2.760	5.016	13.001
	3200W	a=1.540	b=-0.109	k=0.159	n=1.401	0.981	0.054	0.326	3.954	4.944

4. Conclusion

The water content of the cocoa beans is less than 8% after 35 hours in sunshine. For the MO, we have respectively 16 min at 2400W, 12 min at 2800W and 8 min at 3200W. The estimated coefficients models and the statistical parameters determined describe well the cocoa beans drying kinetics showed that the model of the diffusion approach is retained for the solar drying. On the other hand, the models Page and Newton have been retained to describe the kinetics of drying thin layer of cocoa beans in electromagnetic environment with high R^2 values (greater than 0.95); low values of χ^2 ; RMSE; SSE and less than 10% for MRD.

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