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Mob: +92 300 3008585, Fax: +92 41 8815544
E-mail: editorpjn@gmail.com

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Mathematical Modelling of Microwave Drying of Safou Pulp

Daniel Massamba[1], Excellent Matouba[1], Gentil Elenga[2], Jean Goma Maniongui[2] and Thomas Silou[1]
[1]Equipe Pluridisciplinaire de Recherche en Alimentation et Nutrition (EPRAN),
Pôle d'Excellence Régional AUF, Faculté des Sciences,
Université Marien Ngouabi, BP 69, Brazzaville, Congo
[2]Laboratoire des Matériaux et Energie, Faculté des Sciences,
Université Marien Ngouabi, BP 69, Brazzaville, Congo

Abstract: Microwave drying characteristics of safou pulp (*Dacryodes edulis*) were evaluated in a laboratory scale microwave dryer. The drying experiments were carried out at 0.42, 0.56 and 0.70 kW. Third commonly used mathematical models were evaluated with the experimental data. The results indicated that the Page model was most adequate in predicting moisture transfer for safou pulp, just a falling rate period was observed in the microwave drying processes; the values of effective diffusivity were increased with the increasing of the experimental power levels. The regression equations of drying rate against drying duration or moisture were found to describe very well the drying characteristics for safou pulp; it took nearly 70% of total drying time to remove the latter half of moisture in the microwave drying safou pulp. The above findings can facilitate the design and operation of microwave drying of safou pulp.

Key words: *Dacryodesedulis*, microwave drying characteristics, modelling, diffusivity, drying rate

INTRODUCTION

Safou tree (*Dacryodes edulis* (H.G) H.J. Lam (Burseraceae)) is an oleiferous fruit tree which can reach 8-10 m height with crown diameter of 150 m. This specie is manly found under equatorial and humid tropic climates and originates from central Africa and Golf of Guinea area (Aubreville, 1962; Kengue, 2002; Tchoundjeu *et al*., 2002).

The fruit of safou tree is a valuable alimentary resource. According on the Fig. 1 the structure of this fruit present from exterior to interior the epicarp, the mesocarp, the endocarp and the grain (Fig. 1: fruit structure of *Dacryodes edulis*).

The mesocarp is the edible part of the fruit, containing as a percentage of dry matter 50% oil, 10 to 26% proteins 27% digestible fibres, 14% carbohydrates and %4 mineral. The main fatty acids in the lipid fraction are palmitic acid (16:0), oleic acid (18:1n-9) and linoleic acid (18:2n-6) giving a profile similar to palm oil (*Elaeis guineens*) (Silou *et al*., 2006). Safou pulp oil is rich in unsaponifiables matter 2% approximately (Silou *et al*., 1999; 2000; 2006a; 2006b; Silou *et al*., 2002). This pulp also brings vitamins as ascorbic acid, about 24.5 mg/100 g.

Unfortunately because of its great hygroscopicity the losses post harvest by natural softening of pulp can reach 70% in the various producer countries (Silou *et al*., 1991). In rural medium and to a lesser extent in urban environment one resorts to solar drying with the free air or in traditional attics on the top of the fire of kitchen. The principal disadvantages of air drying free are well-known: they relate to the painfulness of work, its great dependence with the bad weather, the heterogeneity of final moisture and the poor hygienic quality of the product obtained.

Some studies were already devoted to the improvement of the drying of the pulp of safou for purposes of consumption or oil extraction (Silou and Avouompo, 1995; Ali *et al*., 1997).

The principal results obtained indicate that solar drying in structures improved such as the solar tents and drying with the drying oven in electric furnaces last approximately 15 h with kinetics presenting a phase of deceleration of approximately 10 h (Ali *et al*., 1997).

In fact all this problems are due, to the low thermal conductivity of food during this phase at decreasing speed and the transfer of heat in the deep layers of food during the conventional heating is limited (Feng and Tang, 1998; Prabhanjan *et al*., 1995). We propose to study the drying of the safou pulp to the microwawe oven.

In a microwave drying system, the microwave energy has an internal heat generative capacity and can easily penetrate the interior layers to directly absorb the moisture in the sample. The quick energy absorption causes rapid evaporation of water, creating an outward flux of rapidly escaping vapour, thus, both thermal gradient and moisture gradient are in the same direction. Theoretically, the microwave drying technique

Corresponding Author: Excellent Matouba, Equipe Pluridisciplinaire de Recherche en Alimentation et Nutrition (EPRAN), Pôle d'Excellence régional AUF, Faculté des Sciences, Université Marien Ngouabi, BP 69, Brazzaville Congo

can reduce drying time and produce a high quality end-product so as to offer a promising alternative and significant contribution to the safou pulp disposal (Feng and Tang, 1998; Prabhanjan *et al.*, 1995).

Therefore, the overall purpose of this study was to analyze and model microwave drying characteristics of safou pulp. The specific objectives of this study were to: (a) describe the influence of microwave output power on drying kinetics; (b) select optimal thin layer drying models for the purpose of simulation and scaling up of the process; (c) calculate effective diffusivities in the microwave drying process of safou pulp and (d) present the drying rate equations so as to give suggestions.

MATERIALS AND METHODS

Experimental material: Drying tests were carried out on safou fruits collected on only one tree in the district Diata Brazzaville. They are the safou of gauge III, according to Silou classification (Silou *et al.*, 1999). To determine the initial moisture content of safou pulp, amount of 10 g samples were dried using oven at 105°C for 12 h (Silou *et al.*, 1999) in three replications.

Physical properties of safou fruits: One ten safou were randomly selected and the mass (measured with a balance with a precision of 0.001 g), the three linear dimensions, namely length, width and thickness (on a haf safou fruit) were measured using a micrometer with a reading accuracy withing 0.01 mm.

The average moisture content was found to be about 72.4% (w.b).

Experimental apparatus: Drying tests were carried out in the microwawe oven (Geepas, type GMO 185). It is a digital furnace domesticates, its following design features: The microwaves are emitted there at a frequency of 2450MHZ; it makes it possible to operate on 5 different levels of power, namely, 0.7 kW, 0.56 kW and 0.420 kW. Its room of drying measures 135 mm x 458 mm x 380 mm of volume; it has a plate out of glass 280 mms in diameter which can carry out 5 turns per minute and whose direction of rotation to 360° can be reversed while pressing on the button" On/Stop". The duration of the operations is regulated using another button; a watch with digital posting placed in the frontal wall of the furnace makes it possible to control this duration of operation.

Experimental procedure

Fruit preparation: After reception the fruits are removed from their stalk, cleaned manually using a cloth to remove them from dust; they are sorted according to their mass and of their form in order to obtain a homogeneous sample not understanding that safou of gauge III and for the later needs for calculation. Each fruit is cut out in two about equal halves and then stoned, using a stainless blade knife.

Drying: One weighs approximately 100g of pulp (4 to 5 half fruits) and one lays out them on a box of pyrex Petri of 12.0 cm of diameter, the whole is placed on the rotary table inside the furnace. Thus the process of drying can be considered as a drying in thin layer.

After powering of the furnace, one regulates the temperature and time at the selected levels. One starts the furnace. During drying, one carries out successive weighing until stabilization of the mass of the product.

After cooling the fruits are packed out of plastic sachets, labelled and stored on the straw mattress.

Theoretical basis

Modelling of the drying curves: Effectively modelling the drying behaviour is important for investigation of drying characteristics of Safou pulp. In this study, the microwave experimental drying data of Safou pulp at different power levels were fitted to three commonly used thin layer drying models, listed in the Table 1.

Correlation coefficients and error analyses: The goodness of fit of the tested mathematical models to the experimental data was evaluated with the correlation coefficient (R^2), the reduced (Chi^2). The higher the R^2 values and the lower the Chi^2 values, the better is the goodness of fit (Ertekin and Yaldiz, 2004; Ozdemir and

Table 1: Mathematical models given by various authors for drying curves

Name of model	Model	References
Avrami (Page)	$MR = \exp(-kt^n)$	Page (1949); Avrami (1939, 1940)
Peleg	$MR = M_0 - t/a + bt$	Peleg (1988)
Diffusional	$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp(-\frac{(2n+1)^2\pi^2 D_{eff} t}{4L_0^2})$	Crank (1975)

In these models, MR represents the dimensionless moisture ratio, namely:

$$MR = (M - M_e)/(M_0 - M_e)$$

Where M is the moisture content of the product at each moment, M_0 is the initial moisture content of the product and M_e is the equilibrium moisture content.

The values of M_e are relatively small compared with M or M_0 for long drying time.

Thus, $MR = (M - M_e)/(M_0 - M_e)$ can be simplified as $MR = M/M_0$ (Akgun and Doymaz, 2005; Thakor *et al.*, 1999).

Devres, 1999). The reduced χ^2 can be calculated as follows:

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})}{N - z} \quad (1)$$

Where MRexp, i is the ith experimental moisture ratio, MRprei is the ith predicted moisture ratio, N is the number of observations and z is the number of constants. In this study, the nonlinear or linear regression analysis was performed with statistical software, OriginPro7.5.

Calculation of effective diffusivities: It has been accepted that the drying characteristics of biological products in the falling rate period can be described by using Fick's diffusion equation. The solution to this equation developed by Crank (1975) can be used for various regularly shaped bodies such as rectangular, cylindrical and spherical products and the form of Eq. (3) can be applicable for particles with slab geometry by assuming uniform initial moisture distribution:

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-\frac{(2n+1)^2\pi^2 D_{eff} t}{4L_0^2}\right) \quad (2)$$

Where Deff is the effective diffusivity (m^2/s); L_0 is the half thickness of slab (m). For long drying period, The equation (2) can be further simplified to only the first term of the series (Tutuncu and Labuza, 1996). Then, the equation (2) is written in a logarithmic form as follows:

$$\ln MR = \ln\frac{8}{\pi^2} - \frac{\pi^2 D_{eff} t}{4L_0^2} \quad (3)$$

Diffusivities are typically determined by plotting experimental drying data in terms of lnMR versus drying time t in the equation (3), because the plot gives a straight line with a slope:

$$\left(\pi^2 D_{eff}\right) / \left(4L_0^2\right)$$

RESULTS AND DISCUSSION

Physical properties: The mean, minimum, maximum and standard deviation of the physical properties of safou pulp measured are summarized in Table 2.

The mass of pulp ranged from 52.803 to 57.64 g, length ranged from 6.99 to 8.20 cm, width ranged from 4.40 to 5.72 cm and thickness ranged from 0.61-1.02 cm.

Microwave drying behaviour of fresh safou pulp: Figure 1 present the drying curves of fresh safou pulp at different microwave powers. We note that an increase in the power results in an increase in the loss of moisture content by fresh of safou pulps. There is, consequently, reduction of the time of operation as the power increases.

Table 2: Some physical properties of safou pulp

Parameters	Mean	Minimum	Maximum	SD
Mass (g)	55.22	52.80	57.64	3.42
Length (cm)	7.60	6.99	8.20	0.86
Width (cm)	5.06	4.40	5.72	0.93
Thickness (cm)	0.81	0.61	1.02	0.30

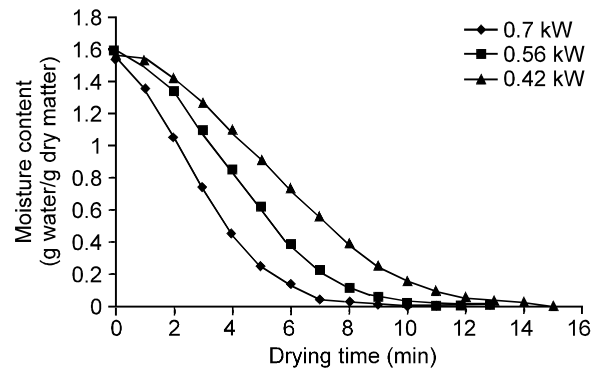

Fig. 1: Drying curves of fresh safou pulp at different microwave powers

During the first two minutes of the operation pulps of safou show a rate of raised drying, follow-up later of a slower drying: it is the phase of relieving. One notes the absence of phase I (phase with increasing pace) and of phase II (with constant pace) and the single presence of phase III (with decreasing pace) in the curves of drying. Similar results were obtained for various crop products (Kouhila, 2001; Belghit *et al*., 2000; Bellagha *et al*., 2002; Kechaou; 2000).

Time necessary to reduce the water content initial of 78.42±0.6% (dried basis) with the water content final of 5.4±0.4% (bases dries) are approximately 8, 11, 13 mn respectively with 0.7, 0.56, 0.42 kW In fact, more generally, necessary time to reduce the water content to any level depends only on the drying conditions.

Drying during the phase with decreasing pace is governed by the water diffusion in the solid. It is a complex mechanism implying liquid water in two states and vapour, which is often characterized by the effective diffusion. This property depends on the temperature, the pressure and the water content of the product (Boudhrioua, 2004; Moyne *et al*., 1992).

Finally these curves show clearly that towards the end of drying the variable conditions of power do not have any effect on the water content of the products. This is in perfect agreement with the theory.

Figure 2 shows relations of drying rate and time in drying of fresh safou pulp. We observe a short period of acceleration, then a fast phase of decrease before, in the third time, the slopes of the curves tend to soften; the speed of drying decrease until reaching a stage.

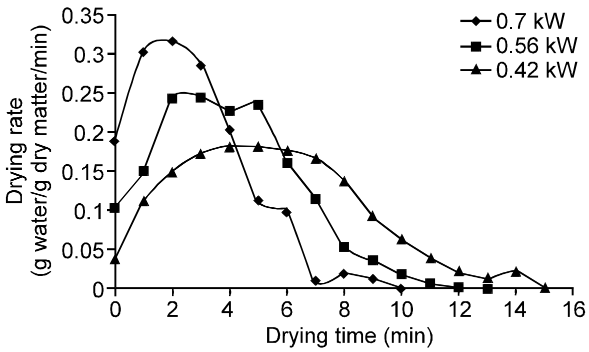

Fig. 2: The relations of drying rate and time in drying of fresh samples

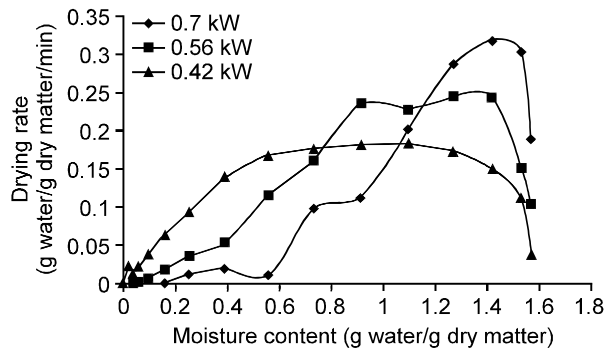

Fig. 3: Drying rate of safou pulp at different microwave powers

This phenomenon makes it possible to observe the increasing difficulty to extract increasingly inaccessible water: dependent water. The shape of these curves is characteristic of the drying of the biological products. Indeed Zhengfu Wang *et al.* (2007) indicates that several authors obtained similar curves during the drying of several varieties of plants the such carrots (Prabhanjan *et al.*, 1995), the garlic (Madamba *et al.*, 1995) and eggplant (Ertekin and Yaldiz, 2004).

The curves present a linear part of significant slope at the beginning of drying, which corresponds to a fast water loss: the pulp of safou loses nondependent water, there is surface evaporation of interstitial water in the product and consequently.

It is also noted that the speed of drying increases more especially as the power increases.

As one could envisage it, one did not observe a phase at constant speed of drying during the drying of the pulp of safou under irradiation microwave. Similar paces were observed by Zhengfu Wang *et al.* (2007) with the oven drying microwaves of the apple plates.

Curves of the process of drying (Fig. 2 and 3) present one period of typical fall the speed of drying with one period of very short acceleration at the beginning. The speed of drying of the pulp of safou is faster with the preceding phase than that of the following phase. This observation is in agreement with previous reports on thin-layer drying of biological products by Diamante and Munro (1991) and Doymaz and Pala (2003), etc.

According to Bimbenet cited by Maskan (2000), the period with constant pace is not observed in many cases of crop products.

During this period remainder apart from the hygroscopic field produces it.

At the end of this period one defines the water content criticizes X_{Cr} of the product.

In experiments one can observe on the curves of Fig. 3:

- Xcr = 1.544 g water/g dry matter at 0.7 kW
- Xcr = 1.595 g water/g dry matter at 0.56 kW
- Xcr = 1.564 g water/g dry matter at 0.42 kW

These values read directly on the curve comprise significant uncertainties (manual weighings), one can affirm overall that Xcr for pulps is located near to 1.6.

Fitting of the microwave drying curves: Figure 4-6 present the drying curves of fresh safou pulp based on Avrami model, diffusional model and Peleg model at 0.42, 0.56 and 0.7 kW microwave powers.

The moisture content data observed at the drying experiment of safou pulp were converted into the Moisture Ratio (MR) and fitted to the 3 models listed in Table 1. The statistical regression results of the different models, including the drying model coefficients and the comparison criteria used to evaluate goodness of fit, i.e. R^2 and χ^2 are listed in Table 3.

With the reading of this table we note that for all the tests the model of Avrami gives R^2 values higher than 0.99. Indeed the values of R^2 and Chi^2 of this model vary respectively between 0.99511 and 0.99805 and 0.00029 and 0.00075. Consequently the model of Avrami could validly represent behaviour with the drying of safou pulp. The previous Figures show the comparison between the experimental data and the predicted values from Page model at the output power of 0.43 kW; similar results could be also obtained at others output powers. It can be seen that the model presents a little over or under estimation in comparison with the experimental data at different stages of drying process, but they are all very close to the experimental data. Therefore, the Page model was all very satisfactory in fitting to the experimental data of safou pulp.

In addition, we bought to take into account the effect of the level of power on the constants of the model of Avrami, k and n in particular. To this end, we used an analysis of the regression to establish a relation between these parameters and the level of power of the microwaves brought into play.

Table 3: Statistical results of different drying models for safou pulp

Model	Power (kW)	Models constants k	n	a	b	R^2	χ^2
Avrami	0.7	0.08723	0.6754			0.99511	0.00075
	0.56	0.0425	1.552			0.99704	0.00047
	0.42	0.02073	1.97287			0.99805	0.00029
Peleg	0.7			4.79248	0.382828	0.963142	0.006406
	0.56			6.280701	0.421947	0.951838	0.007646
	0.42			9.505581	0.23901	0.962438	0.00075
Diffusional	0.7			1.128163	0.32398	0.935534	0.01115
	0.56			1.151564	0.247138	0.932542	0.010788
	0.42			1.17489	0.183402	0.9266762	0.011386

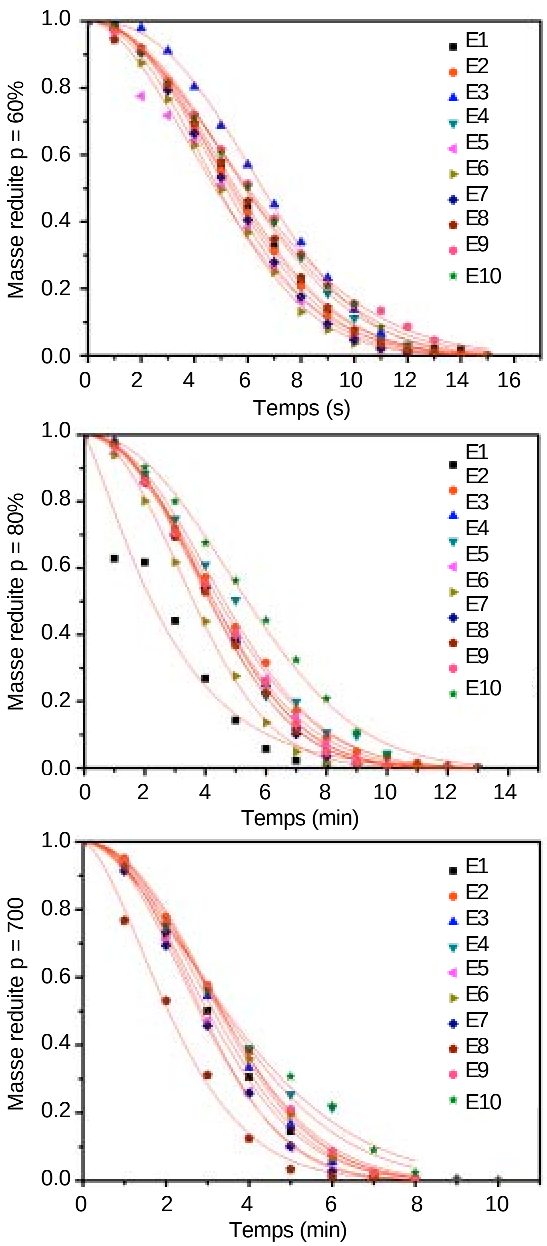

Fig. 4: Microwave drying curves of fresh safou pulp based on Avrami model

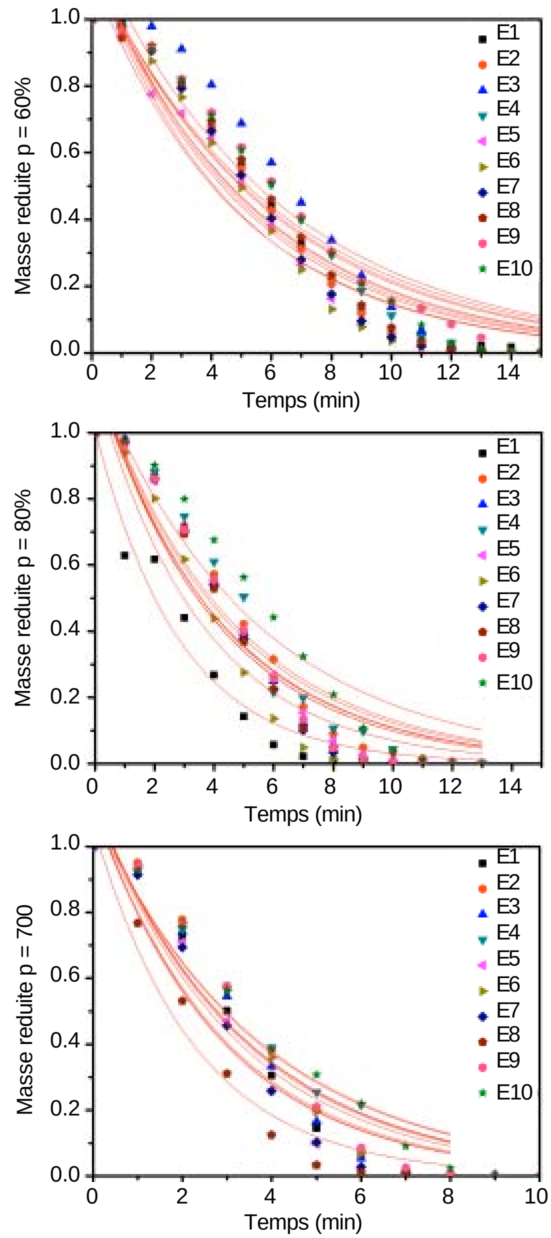

Fig. 5: Microwave drying curves of fresh safou pulp based on diffusional model

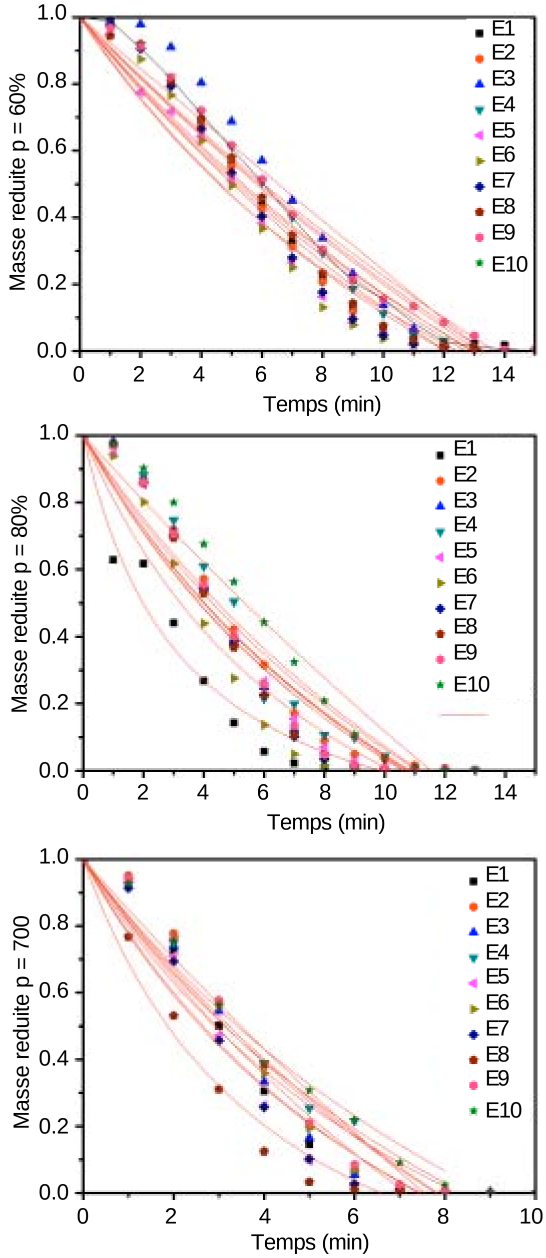

Fig. 6: Microwave drying curves of fresh safou pulp based on Peleg model

Thus the regression equations of these parameters against microwaves powers level P (kW) and the accepted model is as follows:

$$M_R(k,t) = \frac{M}{M_0} = \exp(-kt^n)$$

k = 0.2375P - 0.0828 R^2 = 0.9618
n = -4.6338P + 3.995 R^2 = 0.9605
Where P is the microwave power level (kW).

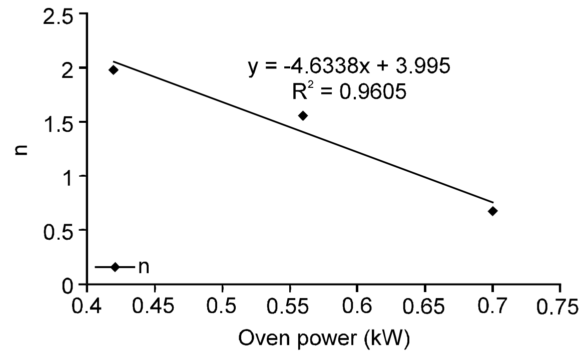

Fig. 7: Relation between the level of Power and the coefficient n of Page Model

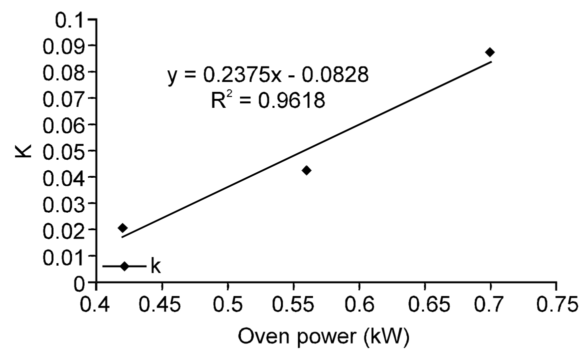

Fig. 8: Relation between the level of power and the coefficient k of Page model

Table 4: Effective diffusivities of safou pulp dried at different microwave output powers

Oven power	Deff x 10^{-5} (m^2/s)	R^2
0.42 kW	0.854	0.8702
0.56kW	1.119	0.9029
0.7 kW	1.285	0.9343

When the power of microwave furnace varies from 0.42 to 0.7 kW, the safou pulp effective diffusivity lies between 0.854 and 1.285 10^{-5} m^2 / s. The values thus obtained are higher than those of potato (Zhengfu *et al*., 2007). Effective diffusivity increases with the power of the furnace and one obtains a more reliable value with 0.7 kW

These relations between the level of power and the coefficients of the model of Page are consistent in comparison of the coefficients of determination and the khi two reduced obtained; in other words, the reduced content water of safou pulps on any level of power and any time of the process of drying can be estimated effectively by using these expressions.

Conclusion: One plotted the curves characteristic of drying of the pulp of safou. One noted in particular the absence of phase I and II and influences it power on the pace of drying.
This study indicated that Avrami model gave excellent fitting to the drying experimental data of pulp safou and

we obtain correlations afterwards: k = 0.2375P - 0.0828 (R^2 = 0.9618) and n = -4.6338P + 3.995 (R^2 = 0.9605). The models and parameters found in this study can be applied to industrial design and operational guide for the microwave drying of safou pulp.

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