THIN-LAYER DRYING OF *RAFFIA TEXTILIS* FIBER

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The *Raffia textilis* fiber has interesting specific mechanical properties among other vegetables fibers. But its production remains entirely based on empirical knowledge. The fibers are dried in the open air and in the shade for about 48 hours. This study explores the effect of the drying temperature, from 30° to 70°C, on its drying kinetics. It was found that the drying duration passes from 55 min at 30 °C to 20 min at 70 °C. Among the three models used to simulate the drying kinetics, the Page model yields the best results. The values of the parameters of this model agree with the hypothesis that the water diffusion is one-dimensional. The activation energy of water in the fiber varies from 49 to 71 KJ/mol, depending on the model used. The effective diffusion coefficient is about $3x10^{-14}$ $m^2.s^{-1}$ at 30 °C. This low value justifies the traditional use of the raffia leaves for house roofs.

Keywords: Raffia fiber; Drying; Modeling; Mechanical properties

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INTRODUCTION

Steadily growing environmental awareness throughout the world has generated a renewed interest in vegetable fibers with new applications in several fields such as composites, building materials, and geotextiles (Bledzki and Gassan 1999; Ernest and Young 2005; Ghavami et al. 1999; Reddy and Yang 2005; Youngquist et al. 1994). These fibers are more environmental friendly and have specific properties at least as high as the synthetic or metallic ones (Baley 2009). The application of more protective laws of the environment and the decrease of the oil reserves would increase their uses (Bertucelli 2009).

The tropics, and in particular the Amazon and Congo basins, have the biggest forests to the world. These areas provide a large variety of vegetable fibers, which have several local uses. Paradoxically, none of these fibers is involved in a significant way in international trade (Ernest & Young 2005). In many cases, their physico-chemical properties remain unknown and their production is weak. This lack is particularly striking for plants of the Congo basin. Following the examples in Brazil and India (Rao and Rao 2007; Satyanarayana et al. 2007), a better valorization and a sustainable management of this renewable natural resource would contribute on the one hand to reducing the poverty in this region, and on the other hand to preserving these forests that are essential for biodiversity and the fight against the climate change. According to our knowledge, among these fibers, the raffia fiber is the only one that has been exported. There are about 28 species of raffia fibers in the tropical zone, probably with different properties (Elenga et al. 2009; Sandy and Bacon 2001). A recent study shows that the specific properties of the *Raffia textilis* fiber are among the highest of the vegetable fibers. Furthermore, this fiber presents alveoli on one face and scales on the other one (Elenga et al. 2009). Thus, for example, this fiber is an interesting potential reinforcement for composites.

The raffia fiber is the epidermis of the leaflet of the raffia palm tree. In Europe, it is especially used as ligature for grafting, while in the central Africa area, for example, it is used for making traditional and modern dresses, carpets (Kasai velvet), and objects of art. Despite the various existing applications and the possibility of having new ones of higher added value because of the above-mentioned properties, its production remains entirely based on empirical knowledge. Products so obtained are of variable quality in terms of color and strength. Traditionally, the fiber is processed by extracting the upper leaflet epidermis of young leaves, generally with a knife. After extraction, fibers are dried in the shade during two days. Drying directly in sunlight is faster, but fibers so obtained are often twined, which limits their range of potential applications. In every case, the drying duration is estimated in a subjective way. For a better valorization of this fiber, it is not only important to optimize its production (growing conditions, harvesting period, processing and stored conditions) in quantity but also to understand the relationship between its processing and its properties. Within this framework, the present study focuses firstly on the effect of drying temperature on the drying kinetics of the raffia fiber. Secondly, three models are used to model its drying kinetics.

EXPERIMENTAL

Materials

The fibers were collected from leaves that were harvested from wild raffia palm trees. Their extraction process is described above. They are about 0.5 cm wide, 30 to 40 cm long, and 0.15 µm thick. Their color varies from yellow to yellow green. To determine their moisture content, three samples of 6 g each were placed in an oven (Termosi SR 3000) at 105°C during 24 hours. The mean value of the moisture content so obtained was of 0.66g / g, dry basis

Drying

Immediately after their extraction, fibers were dried by convective drying in a preheated laboratory-scale oven at 30, 40, 50, 60, or 70 °C. The air velocity was 1m/s, and the humidity was about 60%. For each experiment, 6 g of fibers are put in the dryer, and the mass of the sample is regularly measured until it becomes constant. At every drying temperature, three replications of experiment were performed. The variability is about 8 %. The moisture ratio at time *t*, $M_r(t)$, is defined as follows,

$$M_r(t) = \frac{M(t)-M_f}{M(0)-M_f} \quad (1)$$

where $M(t)$ and M_f represent the mass of the sample at time t and at the end of drying, respectively.

Modeling of the Drying Kinetics

In most cases, during the drying of a plant the structure and composition of the plant vary, in addition to exchange of heat and mass that occur with air. These variations of structure and composition are difficult to predict. Nevertheless, empirical and semi-empirical models generally describe fairly well the evolution of the water content of the product during drying. In the present study, three models were selected because their constants have physical meaning.

The Page model has the same expression as the Avrami's law (Karathanos and Belessiotis 1999; Piorkowska et al. 2006), as given by:

$$M_r(t) = \exp(-kt^n) \tag{2}$$

The constant n is an integer or half-integer whose value depends on the nucleation and the growth of the new phase. The coefficient k depends on the nucleation. This model is used to simulate various phase transformations, including crystallization kinetics of polymers and drying kinetics (Demir et al. 2004; Karathanos and Belessiotis 1999; Piorkowska et al. 2006; Simal et al. 2005).

The diffusionnal model is a simplified solution of Fick's second law for an infinite plate (Crank 1975). It is described by the following formula,

$$M_r(t) = A\exp(-\frac{\pi^2 D_e t}{4L^2}) \tag{3}$$

where A is a constant, D_e is the effective diffusivity coefficient, and L is the half-thickness of the fibre. This model is widely used for drying curves that have no constant rate phase (Ghazanfari et al. 2006a; Simal et al. 2005).

From Peleg's model (Peleg 1988),

$$M(t) = M(0) - \frac{t}{a+bt} \tag{4}$$

where the meaning of constants are deduced as $a^{-1} = -\left(\frac{dM}{dt}\right)_{t=0}$ and $b^{-1} = M(0) - M_e$

This model was used to simulate the sorption and desorption of mint leaves, pulp of papaya, peas, etc. (Palou et al. 1994; Turhan et al. 2002). To be able to compare the Peleg's model to the two others models, the following expression of $M_r(t)$ was deduced,

$$M_r(t) = 1 - \frac{t}{c+dt} \tag{5}$$

where c is the inverse of the initial drying rate $c^{-1} = -\left(\frac{dM_r}{dt}\right)_{t=0}$

Statistical Analysis

The statistical analysis of the models was performed with the software Origin Pro version 8.0. The agreement between the model and experimental results was judged in terms of the reduced coefficient of determination (R^2) and the reduced chi-square (χ^2).

RESULTS AND DISCUSSION

Effect of Temperature on Drying Kinetics

The evolution of the moisture ratio of fibers during the drying at different drying temperatures is reported in Fig. 1. The constant rate period was more marked at 30 °C than above 40°C, where it seems to have disappeared. The drying time of fibers decreased from about 55 min at 30 °C to 20 min at 70 °C. Thus, even taking into account the fact that with more fibers the drying time will increase as shown by Ghazanfari et al. (2006c) for flax fibers, the duration of 48 hours observed by the producers is probably exaggerated. However, these durations are still relatively short compared to those reported for the drying of hemp and flax fibers (Bruce et al. 2005; Ghazanfari et al. 2006a). Moreover the final moisture content of the fiber decreases when the drying temperature increases. The risk of attack by pests is reduced.

Figure 2 shows the characteristic drying curve of the raffia fiber. This curve represents the normalized drying rate ($f = V(t) / V(0)$) according to the moisture ratio $M_r(t)$. This curve is supposed to depend only on the product that is being dried and not on the drying conditions. It is noticeable that, except for the curve at 30 °C, curves for the other drying temperatures overlap. This difference may be justified by the absence of the constant rate period for drying temperatures above 40 °C. Under these drying temperatures, the characteristic curve of the raffia fiber is almost linear,
$f = 0.015 + 0.99\, M_r$ with a coefficient of determination $R^2 = 0.99$.

Although the quantity of fiber used here was small, the shape of the characteristic drying curve was more like that reported for thick than for thin-layers vegetable fibers (concave downwards shape) (Langrish 2008). This could be explained by the low diffusion coefficient of water in the raffia fiber.

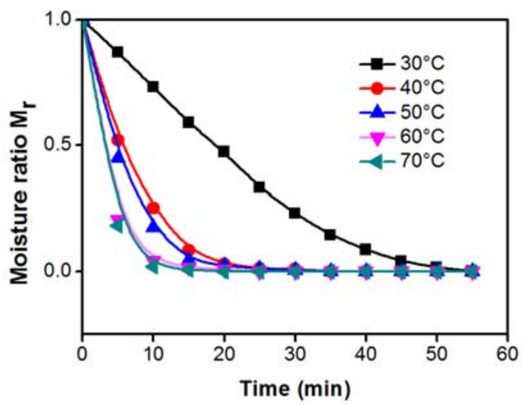

Fig. 1. Effect of air temperature on the drying kinetics of *Raffia textilis* fibers. Air velocity: 1 m.s^{-1}

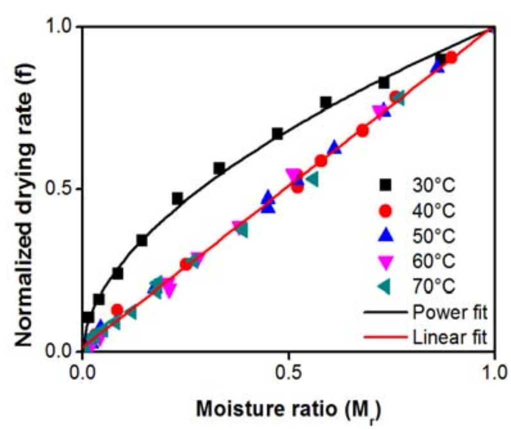

Fig. 2. Relationship between normalized drying rates and the moisture content at various temperatures: the characteristic drying curve

Evaluation of the Models

The drying curves, with the three theoretical models, are reported in Fig. 3. Except for the curve at 30 °C where the diffusional and Peleg's models differed slightly from the experimental data, there was a good agreement between models and experiment. As for the flax fiber (Ghazanfari et al. 2006b), the page-Avrami model was the best for the raffia fiber in this temperature range (Table 1). The diffusional and Peleg models underestimated the moisture content at the beginning of drying, but overestimated it at the end. The agreement between experimental data and models was even better when the drying temperature was high.

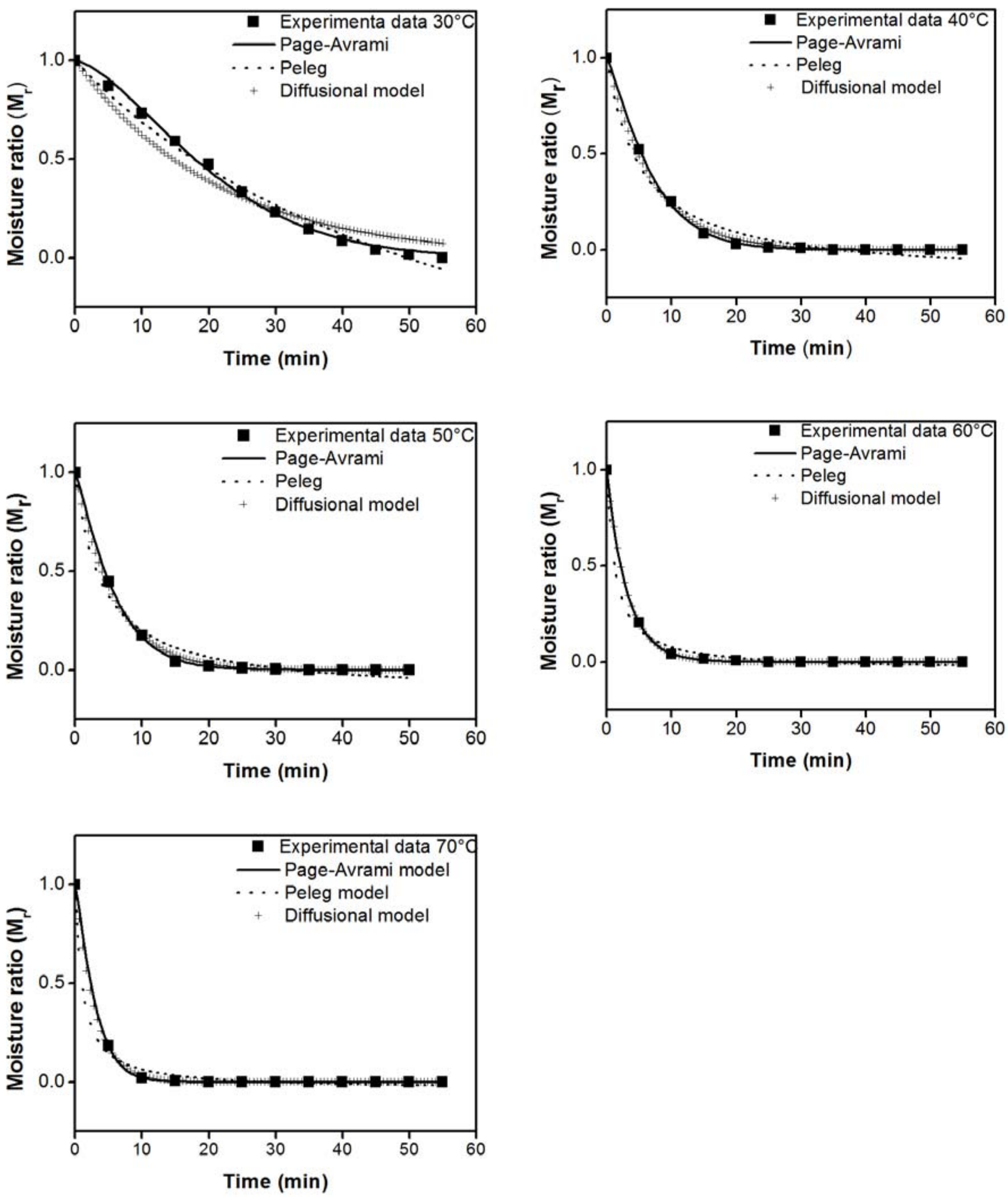

Fig. 3. Modeling drying kinetics of raffia fiber at various drying temperatures

Table 1. Statistical Comparison of the Three Models by the Means of the Coefficient of Determination and the Reduced Chi-square

Temperature (°C)	Model	Coefficient of Determination (R^2)	Reduced Chi-square (χ^2)
30	Page-Avrami	0.996	0.000450
	Peleg	0.989	0.001330
	Diffusional	0.951	0.006070
40	Page-Avrami	0.999	0.000055
	Peleg	0.977	0.002140
	Diffusional	0.996	0.000350
50	Page-Avrami	0.999	0.000033
	Peleg	0.981	0.00180
	Diffusional	0.997	0.000200
60	Page-Avrami	0.999	0.000007
	Peleg	0.994	0.000420
	Diffusional	0.999	0.000008
70	Page-Avrami	0.999	0.000002
	Peleg	0.994	0.000490
	Diffusional	0.999	0.000015

Table 2 presents the different model parameters depending on the drying temperature. The values of the Avrami's constant *n* were around 1. They were half way between those obtained with hemp (0.73-0.98) (Bruce et al. 2005) and flax (1.3-1.6) (Ghazanfari et al. 2006b). These values are consistent with the generally accepted idea of a one-dimensional diffusion for such flat materials. However, the value of *n* at 30 ° C was 1.5. It could be explained by the fact that at low temperatures the nucleation of steam is more sporadic. The values of the Peleg's constant C (inverse of initial velocity) decrease with temperature according to experimental results.

Table 2. Evolution of the Model Paramaters with the Drying Temperature

Temperatrure (°C)	Page-Avrami		Peleg		Diffusional	
	n	*k*	*c*	*d*	*A*	$^*\beta$
30	1.52 ± 0.06	0.009 ± 0.002	27.64 ± 1.97	0.44 ± 0.05	1.00 ± 0.06	0.047 ± 0.005
40	1.19 ± 0.03	0.094 ± 0.006	4.56 ± 0.62	0.87 ± 0.03	1.00 ± 0.02	0.144 ± 0.005
50	1.17 ± 0.03	0.122 ± 0.007	3.56 ± 0.50	0.89 ± 0.02	1.00 ± 0.01	0.172 ± 0.005
60	0.97 ± 0.03	0.334 ± 0.016	1.23 ± 0.16	0.96 ± 0.01	1.000 ± 0.003	0.316 ± 0.003
70	1.18 ± 0.02	0.256 ± 0.010	1.03 ± 0.16	0.96 ± 0.01	1.000 ± 0.004	0.345 ± 0.004

$^*\beta = \frac{\pi^2 D_e}{4L^2}$

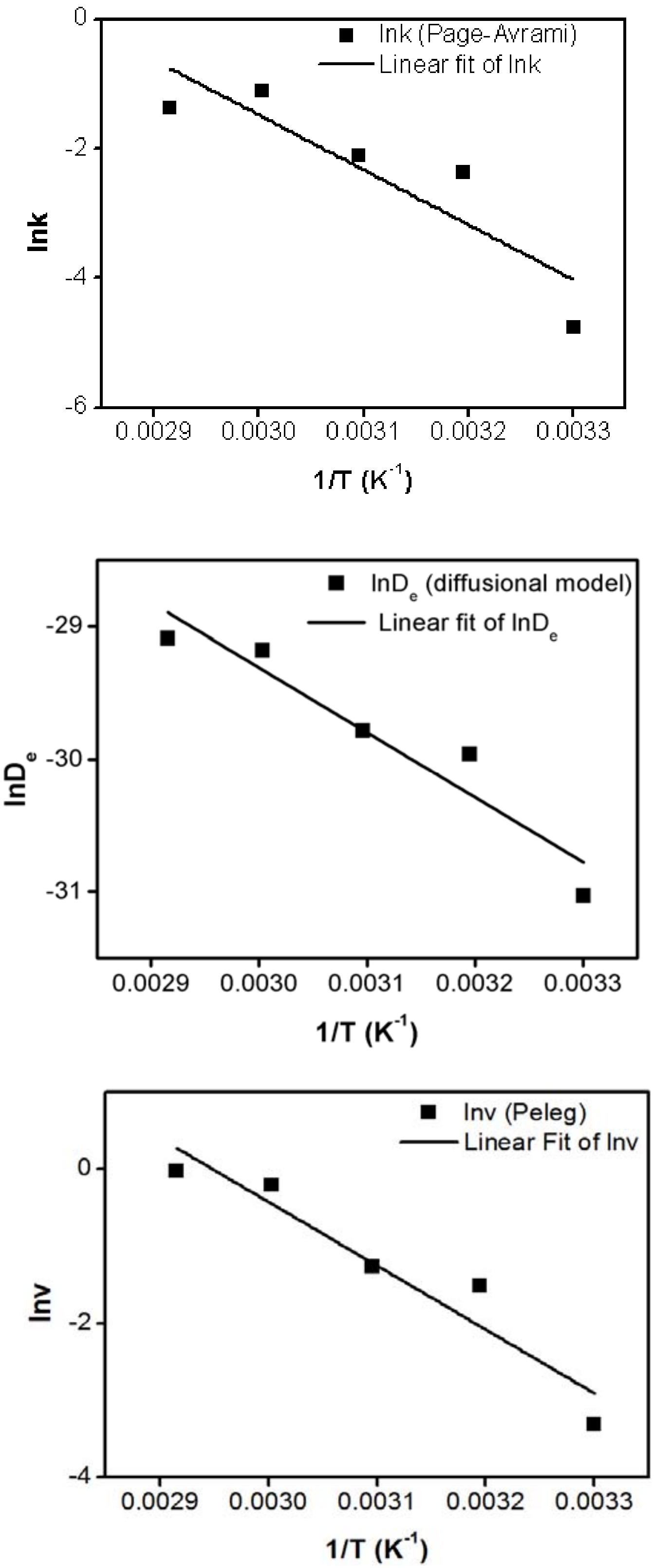

Fig. 4. Deduction of the activation energy from the three models. The values obtained are 71 ± 20, 68 ± 10, and 49 ± 7 kJ/mol, respectively

From the values of the constant *β,* those of the effective diffusivity coefficient were deduced at the different drying temperatures. These values were between 3.34x10^{-14} $m^2.s^{-1}$ (30 ° C) and 2.32x10^{-13} $m^2.s^{-1}$ (70 ° C). They were lower than those of flax (≈ 10^{-8} $m^2.s^{-1}$) (Ghazanfari et al. 2006a) and those of most vegetables (Doymaz 2006; Simal et al. 2000). This low value of the effective diffusion coefficient justifies, as least in part, the traditional use of raffia leaves for house roofs. Besides, it could explain the fact the characteristic curve of this fiber is linear, while such a shape is generally found for thick products. The activation energy of water in the raffia fiber can be deduced assuming that the Avrami coefficient *k*, the drying rate deduced from the Peleg's model and the effective diffusion coefficient follows the Arrhenius law (Fig.4). The values found are respectively, 71 ± 20, 68 ± 10, and 49 ± 7 kJ/mol. These values are relatively close to each other and are of the same order of magnitude as those found for many other vegetables (Doymaz 2006; Jin Park et al. 2002).

CONCLUSIONS

The main objective of this study was to investigate the effect of the drying temperature on drying kinetics and to evaluate three models applied to its drying kinetics. The results can be summarized as follows:

1. At all drying temperatures studied, the drying time was less than 90 min. This duration was reduced to 20 minutes for drying at 70 °C. Thus, the duration of 48 hours observed by the artisans is overestimated.
2. All models simulated fairly well the drying curves. Nevertheless, the Page-Avrami model was the best in this temperature range. The Avrami's coefficient *n* was consistent with the generally accepted hypothesis of diffusion in one dimension for such flat materials. The value of the activation energy deduced from the three models was of the same order of magnitude as those of other plants.
3. The value of effective diffusion coefficient obtained varied between 3.34x10^{-14} ms^{-2} (30 ° C) and 2.32x10^{-13} ms^{-2} (70 °C). This relatively low value compared to those of other plants, coupled with the structure scale of the upper surface of the fiber explain, at least in part, the traditional use of palm leaves as covering for roofs of houses.

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