Research Article

Modelling of the Water Absorption Kinetics and Determination of the Water Diffusion Coefficient in the Pith of *Raffia vinifera* of Bandjoun, Cameroon

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The present work focuses on the study of the water absorption phenomenon through the pith of *Raffia vinifera* along the stem. The water absorption kinetics was studied experimentally by the gravimetric method with the discontinuous control of the sampling mass at temperature of 30°C. The samples of 70 mm × 8 mm × 4 mm were taken from twelve sampling zones of the stem of *Raffia vinifera*. The result shows that the percentage of water absorption of the pith of *Raffia vinifera* increases from the periphery to the center in the radial position and from the base to the leaves in the longitudinal position. Fick's second law was adopted for the study of the water diffusion. Eleven models were tested for the modelling of the water absorption kinetics and the model of Sikame Tagne (2014) is the optimal model. The diffusion coefficients of two stages were determined by the solution of the Fick equation in the twelve sampling zones described by Sikame Tagne et al. (2014). The diffusion coefficients decreased from the center to the periphery in the radial position and from the base to the leaves in the longitudinal position.

1. Introduction

The raffia is a plant which is found in the tropical zones particularly in Madagascar and which is generally grown in the swampy zone [1, 2]. In the world, there are about twenty (20) species among which the *Raffia vinifera* is found in the West, the Northwest, the South, the Center and the East Regions of Cameroon. This raffia is constituted with a feather grass bearing stick with stout rachis and large petiole [2, 3].

Raffia is generally used in the realization of arts, crafts, decoration, braces, clothes, baskets, hats, beds, and food (sap/wine) [1, 4]. Raffia is also used in the West Region of Cameroon as a building material specially as ceiling material, but this use is still local. Our main objective is to extend the use of raffia as ceiling material over the world particularly in our country. The pith of raffia will be combined with another material, such as polymer and other vegetal material, to produce a new composite building material suitable for ceiling applications. The physical behavior of our pith of *Raffia vinifera* has to be known because the realization of

the composite material will use the matrix, which is liquid and will be absorbed by our pith of raffia. It is important in our study to know the water diffusion coefficient and the percentage of the water absorption that will help us to predict the behavior of the composite material.

Several works have been carried out on the raffia such as the study of the thermal properties on trunk of *Raffia hookeri* which is used as ceiling material [5]. Some studies are also carried out on the study and the use of raffia and other vegetal products as insulation material in Cameroon [6]. Other works include the use of raffia in the reinforcement of concrete [7]. The use of raffia in the textile industry is equally growing. Studies are also carried out on the study of the microstructure and the physical properties of fibers coming from the leaves of raffia; the drying kinetics of these fibers is carried in view of its use as roofing elements [8, 9]. Mechanical studies have been carried out on the long-term creep behavior of the *Raffia vinifera* stem in compression and flexion tests [10–13]. A study on the long-term mechanical behavior and the mechanical properties of fibers from the

FIGURE 1: Localization of the sampling zone on the stem of raffia. (a) Longitudinal position and (b) radial position corresponding to each longitudinal position [1, 4, 15].

Raffia vinifera has been done [4]. Studies have been equally done on the traction and compression of composite cement matrix reinforcement by the raffia fiber [14].

In the same vein and in the view of improving the scientific knowledge so as to optimize the use of *Raffia vinifera*, this study focuses on the study of the water absorption phenomenon in the *Raffia vinifera* pith. The main objective of this work is to evaluate the percentage of the water absorbed, do the modelling of the water absorption kinetics, and evaluate the diffusion coefficient of water through the pith of *Raffia vinifera*.

In this article, we analyzed the distribution of water absorption rate of our material through the stem of raffia respectively on the sampling zones described by Sikame Tagne et al. [4]. The modelling of the water absorption kinetics is also taken in place. The diffusion coefficient of water through the material was evaluated in the sampling zones and followed by the conclusion.

2. Methods

2.1. Materials. The samples used in this work come from the stem of *Raffia vinifera* originating from Bandjoun in the West Region of Cameroon particularly the Koung-Khi division. In the stem, prismatic samples are cut particularly on the parallelepiped shape with $70 \text{ mm} \times 8 \text{ mm} \times 4 \text{ mm} \pm 1 \text{ mm}$. The largest dimension of the sample is along the length of the stem. The samples were taken from the twelve sampling zones described by Sikame Tagne et al. [4] and presented in Figure 1. In the stem, we distinguished four parts (Figure 1(a)) from the bottom to the top named P1/4 (near the root), P2/4, P3/4, and P4/4 (near the leaves). In the radial position, we distinguished three zones (Figure 1(b)) called center, half-radius, and periphery (near the bark) zones.

A microwave of Bosch mark was used as oven for the drying of the sample at a constant temperature until the mass is stabilized. Digital scales of ADAM mark with a maximum weight of 750 g and to the milligram accuracy level are used for the various weighing. A numerical slide caliper with the hundredth of the millimeter accuracy is used for the measurement of the sample dimensions. The distilled water

at the ambient temperature of $30^\circ\text{C} \pm 1^\circ\text{C}$ is used for the immersion of the samples as in the case of the absorption of other types of wood such as *Afra*, *Ojamlesh*, and *Roosi* [1, 16, 17, 28].

2.2. Methods. The section of the stem of raffia has an elliptic form. The large diameter of the raffia stem is about 62 mm on the base, 40 mm on the middle, and 34 mm on the top. The small diameter of the raffia stem is about 51 mm on the base, 36 mm on the middle, and 29 mm on the top. After subdivision of the stem in four parts named P1/4, P2/4, P3/4, and P4/4, we removed the bark of each part. According to each longitudinal position, the remaining diameter was divided into three parts to obtain primary samples following radial position (center, half-radius, and periphery zones). On this primary samples, we extracted the final samples which have a parallelepiped shape with the following dimensions $70 \text{ mm} \times 8 \text{ mm} \times 4 \text{ mm}$. The samples were extracted in the twelve sampling zones on the stem.

The obtained samples are now conditioned in the microwave used as the oven at the constant temperature of 90°C until stabilization of the mass. This gravimetric analysis method is done in order to eliminate residual water found in the samples. The samples were then introduced in plastic bags to avoid reabsorption of moisture from the air during the samples cooling period. Conditioned samples are weighed and labeled before being introduced into the distilled water. After the drying phase, we introduced our samples in the distilled water at the laboratory room temperature estimated at $30^\circ\text{C} \pm 1^\circ\text{C}$. The samples are maintained under water by nuts made of rustproof steel. During the regular time intervals, samples were removed from the water; surface water of the sample was then eliminated with a dry fabric base on cotton and the samples were weighted and reintroduced into the distilled water. This operation was done in very short time so as to enable us to neglect the time that was spent out of the distilled water. At the beginning of the test, immersion time is taken at five minutes. After one hour of test, we changed it to ten minutes. We prolonged the weight time until we arrive at weight one time per day, one time after two days, three days, and eventually one time per week. The process of

weighting is repeated until the constant mass, that is, until samples reach water saturation level [16, 29–32].

In each sampling zone, twenty (20) samples were tested for a total of two hundred and forty (240) samples of *Raffia vinifera* along the stem. These samples were extracted from two dry mature stems of *Raffia vinifera* for each zone. These samples were mixed and tested in the group. The test was stopped when the mass no longer varies.

The statistical analysis of experimental data was done in the Matlab 2009b software environment which enabled drawing experimental curves and doing the modelling with different models as found in Table 4. The best model was the one which has an average correlation coefficient near to the unit, the square root of mean error average near zero, and the sum of square error average near zero. These two last statistical parameters are defined by the following [1, 26]:

$$\begin{aligned} \text{RMSE} &= \sqrt{\frac{\sum_{i=1}^n (m_{ci} - m_{ei})^2}{n}}, \\ \text{SSE} &= \sum_{i=1}^n (m_{ci} - m_{ei}), \end{aligned} \quad (1)$$

where m_{ci} , m_{ei} , and n are the theoretical mass, the predicted mass, and the number of observation, respectively.

2.2.1. Mass Diffusion Theory through Solid. The mass transfer equation of solid result from the second Fick law given by

$$\frac{\partial C}{\partial t} = \text{div} \left(\overrightarrow{D \text{ grad } C} \right), \quad (2)$$

where C is the molar concentration (mol/m^3), D is the diffusion coefficient (m^2/s), and t is the time (s).

To simplify the resolution of (2), it is supposed that the diffusion coefficient is independent of the space direction [33, 34]. This hypothesis enables us to write (2) in the following form:

$$\frac{\partial C}{\partial t} = D \left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2} \right). \quad (3)$$

It is assumed that the sample is the plane shape and it is assumed to have a single long direction, the z direction in Figure 2(b), so that the diffusion equation can be solved in one dimension across the shortest dimension of the sample. In our case, the x direction is the one on which diffusion has taken place. Figure 2 presents the samples obtained for the test (Figure 2(a)) and the plan which presents the dimensions of the sample (Figures 2(b) and 2(c)). These hypotheses enabled the reduction of (3) which then gives [29, 33, 34]

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2}. \quad (4)$$

By taking into account the boundary's conditions, we have

$$\begin{aligned} C &= C_0, \\ 0 &< x < L, \\ t &= t_0, \\ C &= C_1, \end{aligned} \quad (5)$$

where L is the thickness of the sample.

The solution of (4) can be given in the following form:

$$\begin{aligned} \frac{C - C_0}{C_1 - C_0} &= 1 - \frac{4}{\pi} \sum_{n=0}^{\infty} \frac{(-1)^n}{2n+1} \exp \left\{ -\frac{D(2n+1)^2 \pi^2 t}{4L^2} \right\} \\ &\cdot \cos \left(\frac{(2n+1) \pi x}{2L} \right). \end{aligned} \quad (6)$$

If we call M_t the total mass of water which diffuses in the material at t instant and M_{∞} , the same quantity at the infinite time, that is to say, when the saturation of the material is reached, then [23, 25, 29, 35] (6) can be written in the following form:

$$\begin{aligned} \frac{M_t}{M_{\infty}} &= 1 \\ &- \sum_{n=0}^{\infty} \frac{8}{(2n+1)^2 \pi^2} \exp \left(-\frac{D_{\text{eff}}(2n+1)^2 \pi^2 t}{4L^2} \right). \end{aligned} \quad (7)$$

2.2.2. Percentage of Water Absorption. The percentage of water absorption of our sample (WA) is given by the following relation, which was also used for the determination of the water absorption by [15, 16, 36]

$$\text{WA} = \frac{m_f - m_i}{m_i} * 100, \quad (8)$$

where m_f and m_i are, respectively, the final and initial mass of the sample.

2.2.3. Study of the Absorption Kinetics. The ratio of the water absorption called $g(t)$ is defined as follows:

$$g(t) = \frac{M_t}{M_{\infty}} = \frac{m_t - m_0}{m_{\infty} - m_0}. \quad (9)$$

The similarity between (7) and (9) enables us to write

$$\begin{aligned} g(t) &= \frac{M_t}{M_{\infty}} = \frac{m_t - m_0}{m_{\infty} - m_0} \\ &= 1 - \sum_{n=0}^{\infty} \frac{8}{(2n+1)^2 \pi^2} \exp \left(-\frac{D_{\text{eff}}(2n+1)^2 \pi^2 t}{4L^2} \right), \end{aligned} \quad (10)$$

where m_0 , m_t , and m_{∞} are, respectively, the anhydrous mass (at the initial instant), at current moment and at the infinite time ($t = \infty$), that is, at saturation.

FIGURE 2: Illustration of the samples used for the test. (a) Picture of the sample, (b) axis orientation of the sample, and (c) extraction zone of the samples in the radial position.

3. Results and Discussions

3.1. Determination of the Percentage of Water Absorption. The percentage of water absorption of our samples for the twelve sampling zones is done by (8). The synthesis result is presented in Table 1.

It is observed that the average percentage of water absorption stands between $392.044\% \pm 36.618\%$ and $1331.956\% \pm 49.144\%$ during the immersion period estimated at 45 days.

A comparative study of the percentage of the water absorption of the *Raffia vinifera* pith and other vegetal products has been done, in Table 2. This study indicates that the *Raffia vinifera* pith absorbs more water than the fibers taken in the same position of the stem [4]. This is probably due to the fact that the samples of pith of *Raffia vinifera* are the natural composites materials comprising fibers and a spongy part that work as a natural binder between the fibers and which in addition absorbs water.

The average of the percentage of water absorption along the stem is presented on Figure 3. Globally the observation of Figure 3 enables us to see that the percentage of water absorption increases from the periphery to the center on the radial position and from the base to the leaves on the longitudinal position along the stem of *Raffia vinifera*.

3.2. Kinetics of Water Absorption. Equation (9) allows us to plot the curve of water absorption ratio according to the time and the obtained curve is presented by Figure 4. This curve presents the results of water absorption test of the pith of *Raffia vinifera* taken from the center of part 4/4.

The obtained curves on the twelve sampling zones have the same profile as that presented in Figure 4.

FIGURE 3: Distribution of the water absorption rate percentage of the pith of *Raffia vinifera*.

An observation of the curve presented in Figure 4 shows that, during the first 5000 minutes, approximately 50% of the sample masses reached saturation level.

The curve presented in Figure 4 is similar to the curve obtained by other authors who have studied water absorption kinetics in natural materials [4, 16, 26, 27, 34, 37]. It was noticed that the water absorption kinetics of the pith of *Raffia vinifera* takes place in two phases: the first phase rapidly takes place and enables reaching approximately 50% of the mass at saturation. This is done in the first 5000 minutes and the second phase that is relatively slow and is represented by the second part of the curve. This brings out two diffusion

TABLE 1: Average rate of water absorption and standard deviation of the *Raffia vinifera* pith.

	Center	Half-radius	Periphery
Part 1/4	1141.509 $\pm$ 156.063	847.525 $\pm$ 95.568	392.044 $\pm$ 36.618
Part 2/4	1256.696 $\pm$ 87.415	1156.705 $\pm$ 79.810	565.967 $\pm$ 100.128
Part 3/4	1331.956 $\pm$ 49.144	1207.133 $\pm$ 107.053	612.198 $\pm$ 132.146
Part 4/4	1308.677 $\pm$ 53.766	1137.932 $\pm$ 61.979	705.018 $\pm$ 113.600

TABLE 2: Comparison of the percentage of water absorption of the pith of *Raffia vinifera* with other natural materials.

Types	Percentage of water absorbed (%)	Absorption duration	Temperature (°C)	References
Afra wood	102	25 Days	25	[16]
Ojamlesh Wood	54			
Roosi Wood	120			
Hemp	62	13 Days	27–67	[17]
Okra	64			
Betel nut	38			
Fibers of <i>Raffia vinifera</i>	303–662	25 Days	23	[4]
Pith of the <i>Raffia vinifera</i>	392–1331	45 Days	30 $\pm$ 1	Studied case

FIGURE 4: Average of the water absorption kinetics of the pith of *Raffia vinifera* from the center and at the base of the stem (1/4).

coefficients which indicate the velocity of the water diffusion in the pith of *Raffia vinifera* samples.

3.3. Modelling of the Water Absorption Kinetics. The water absorption kinetics in the pith of *Raffia vinifera* is done by using the mathematical models found in the literature. In this fact, we found eleven models which are in Table 3.

The experimental data of the pith of *Raffia vinifera* of the center from the base of the stem and the eleven models found in the literature are represented in the Figure 5.

Table 4 provides a summary of the parameters of the various models previously cited concerning samples of the pith coming from part 1/4 of the *Raffia vinifera* stem.

FIGURE 5: Experimental curve of the pith of *Raffia vinifera* and curves of models.

The variations presented by some models such as those by Singh and Kulshrestha (1987) and Pilosof et al. (1987) can be interpreted by the fact that these models are not ideal to describe the kinetics of water absorption of the pith of *Raffia vinifera*.

According to Table 4, it can be seen that the models used in this work have the coefficients of correlation higher than 0.93. In the case of this work the model of Weibull has the lowest correlation coefficient. The better model is the model of Sikame Tagne et al. which has the correlation coefficient

TABLE 3: Utilized models summary for the modelling of the absorption kinetics.

Number	Model's name	Model's equation	References
1	Pilosofo	$g(t) = a + \frac{b * t}{c + t}$	[18]
2	Mohsenin	$g(t) = a * [1 - \exp(-k * t)] + c + d * t$	[16, 19]
3	Singh	$g(t) = a + \frac{b * t}{c * t + 1}$	[20]
4	Peleg	$g(t) = a + \frac{t}{b * t + c}$	[21, 22]
5	García-Pascual	$g(t) = 1 - \exp\left[-\left(\frac{t}{a}\right)^b\right]$	[23]
6	Gowen	$g(t) = (a - b) * \exp(-k * t) + b$	[24]
7	Czel and Czigany	$g(t) = a * t^m$	[25]
8	Vega-Gálvez	$g(t) = a * \exp\left(-\frac{b}{(1 + t)^\alpha}\right)$	[26]
9	Gornicki	$g(t) = a * (b - \exp(-k * t))$	[27]
10	Gornicki	$g(t) = a + b * \left(1 - \frac{1}{1 + b * c * t}\right)$	[27]
11	Sikame Tagne	$g(t) = c - a * \exp(-k * t) - b * \exp(-m * t)$	[4]

close to the unit. In this particular work, the correlation coefficient is 0.99 for the Sikame Tagne et al. model.

The model of Sikame Tagne et al. (2014) is the one which has better statistical parameters for the sampling zones. This model is used for the modelling of the absorption kinetics in the twelve sampling zones of the stem of *Raffia vinifera*. The average parameters of this model are provided in Table 5, the coefficient of linear correlation, the square root of the mean error, and the squared sum of errors of the *Raffia vinifera* stem.

It can be noticed from Table 5 that the correlation coefficient is always more than 0.98 and remains higher than the obtained values for the other models in Table 4. Then, we can say that the model of Sikame Tagne [4] is the one which enables the modelling of the experimental data and is illustrated by Figure 6.

It can be concluded that the mathematical equation which enables the description of the water absorption kinetics of the pith of *Raffia vinifera* from the stem is given by

$$g(t) = c - a * \exp(-k * t) - b * \exp(-m * t), \quad (11)$$

where a , b , and c are constants and k and m are the diffusion parameters expressed per minutes.

3.4. Determination of the Effective Diffusion Coefficient. The determination of the water diffusion coefficient through the pith of *Raffia vinifera* is done by using Fick's dual stage law. It was used in the prediction and interpretation of mass transfer through natural fibers [4, 36]. This method is based on Fick's law and introduces two effective diffusion coefficients $D_{1\text{eff}}$ and $D_{2\text{eff}}$ and two water saturation levels corresponding to the two diffusion coefficients. The use of this method on water absorption kinetics for the pith of *Raffia vinifera* is done by (12) which described two phases of diffusion, that is, an initial and a final stage. The sum of the two saturation levels of the two phases gave the total absorption rate of the pith of *Raffia*

FIGURE 6: Experimental points and model of Sikame Tagne [4] of the pith of *Raffia vinifera* from the center of the base.

vinifera. The effective diffusion coefficient will be determined by using (12):

$$M_t = M_{\infty 1} \left[1 - \sum_{n=0}^{+\infty} \frac{8}{(2n+1)^2 \pi^2} \exp\left(-\frac{D_{1\text{eff}} (2n+1)^2 \pi^2}{4e^2} t\right) \right] + M_{\infty 2} \left[1 - \sum_{n=0}^{+\infty} \frac{8}{(2n+1)^2 \pi^2} \exp\left(-\frac{D_{2\text{eff}} (2n+1)^2 \pi^2}{4e^2} t\right) \right], \quad (12)$$

$$M_{\infty} = M_{\infty 1} + M_{\infty 2}. \quad (13)$$

TABLE 4: Distribution of the average parameters models of the pith of *Raffia vinifera* at the base of the stem (1/4).

Model's name	Radial position	a	b	c	k (min^{-1})	m (min^{-1})	R^2	RMSE	SSE
Peleg	Center	0.239 ± 0.034	9312.150 ± 2044.966	1.176 ± 0.090			0.972	0.039	0.135
	Half-radius	0.245 ± 0.033	9256.250 ± 2090.859	1.183 ± 0.109			0.971	0.040	0.143
	Periphery	0.216 ± 0.030	4763.550 ± 1040.602	1.252 ± 0.071			0.966	0.047	0.194
Pilosofo	Center	0.230 ± 0.042	0.817 ± 0.045	6492.5 ± 549.047			0.968	0.042	0.152
	Half-radius	0.234 ± 0.041	0.810 ± 0.049	6315.350 ± 879.532			0.967	0.043	0.160
	Periphery	0.215 ± 0.029	0.802 ± 0.044	3762.600 ± 923.578			0.966	0.046	0.193
Singh	Center	0.240 ± 0.033	0.157 ± 0.321	6861.700 ± 4310.801			0.973	0.054	0.135
	Half-radius	0.245 ± 0.033	0.161 ± 0.331	6806.700 ± 4230.220			0.971	0.058	0.143
	Periphery	0.217 ± 0.031	0.168 ± 0.344	2885.300 ± 1656.826			0.966	0.046	0.193
Witrowa	Center	0.228 ± 0.057	0.858 ± 0.068	$1.563 \times 10^{-4} \pm 5.405 \times 10^{-5}$			0.974	0.039	0.139
	Half-radius	0.245 ± 0.033	0.854 ± 0.078	$1.652 \times 10^{-4} \pm 6.949 \times 10^{-5}$			0.960	0.0432	0.101
	Periphery	0.216 ± 0.030	0.801 ± 0.044	$3.489 \times 10^{-4} \pm 1.023 \times 10^{-4}$			0.966	0.047	0.194
Gowen	Center	0.262 ± 0.036	0.972 ± 0.019		$1.910 \times 10^{-4} \pm 2.567 \times 10^{-5}$		0.963	0.046	0.184
	Half-radius	0.268 ± 0.038	0.974 ± 0.022		$1.076 \times 10^{-4} \pm 2.358 \times 10^{-5}$		0.961	0.067	0.198
	Periphery	0.251 ± 0.036	0.932 ± 0.022		$1.856 \times 10^{-4} \pm 3.828 \times 10^{-5}$		0.942	0.060	0.324
Wesolowski	Center	0.710 ± 0.053	1.374 ± 0.080		$1.045 \times 10^{-4} \pm 2.504 \times 10^{-5}$		0.963	0.067	0.184
	Half-radius	0.706 ± 0.058	1.386 ± 0.087		$1.465 \times 10^{-4} \pm 1.662 \times 10^{-5}$		0.961	0.067	0.198
	Periphery	0.681 ± 0.037	1.371 ± 0.070		$1.827 \times 10^{-4} \pm 6.106 \times 10^{-5}$		0.942	0.060	0.323
Mohsenin	Center	0.571 ± 0.110	$3.025 \times 10^{-6} \pm 2.261 \times 10^{-6}$	0.265 ± 0.080	$1.629 \times 10^{-4} \pm 5.107 \times 10^{-5}$		0.963	0.043	0.164
	Half-radius	0.568 ± 0.080	$2.429 \times 10^{-5} \pm 6.555 \times 10^{-5}$	0.255 ± 0.036	$1.638 \times 10^{-4} \pm 5.019 \times 10^{-5}$		0.967	0.044	0.175
	Periphery	0.557 ± 0.046	$3.894 \times 10^{-6} \pm 1.356 \times 10^{-6}$	0.222 ± 0.036	$3.505 \times 10^{-4} \pm 1.351 \times 10^{-4}$		0.958	0.074	0.241
Weibull	Center	6207.600 ± 2386.766	0.379 ± 0.042				0.939	0.058	0.293
	Half-radius	5938.200 ± 2202.506	0.373 ± 0.038				0.938	0.058	0.293
	Periphery	3756.650 ± 933.131	0.388 ± 0.029				0.978	0.037	0.131
Czel and Czigan	Center	0.085 ± 0.026				0.231 ± 0.028	0.973	0.039	0.135
	Half-radius	0.089 ± 0.030				0.226 ± 0.028	0.978	0.057	0.129
	Periphery	0.105 ± 0.023				0.214 ± 0.020	0.978	0.037	0.131
Vega-Gálvez	Center	7.871 ± 2.119	5.471 ± 0.727				0.958	0.048	0.198
	Half-radius	7.734 ± 2.295	5.402 ± 0.791				0.958	0.047	0.182
	Periphery	6.899 ± 1.268	5.028 ± 0.493				0.986	0.029	0.085

TABLE 4: Continued.

Model's name	Radial position	a	b	c	$k \text{ (min}^{-1}\text{)}$	$m \text{ (min}^{-1}\text{)}$	R^2	RMSE	SSE
Sikame Tagne	Center	0.241 ± 0.043	0.686 ± 0.062	0.985 ± 0.079	$3.662 \times 10^{-2} \pm 2.291 \times 10^{-2}$	$8.682 \times 10^{-5} \pm 1.918 \times 10^{-5}$	0.992	0.022	0.041
	Half-radius	0.252 ± 0.042	0.679 ± 0.075	1.001 ± 0.016	$3.917 \times 10^{-2} \pm 2.024 \times 10^{-2}$	$8.563 \times 10^{-5} \pm 1.445 \times 10^{-5}$	0.992	0.022	0.040
	Periphery	0.298 ± 0.047	0.600 ± 0.051	0.991 ± 0.013	$1.035 \times 10^{-2} \pm 1.078 \times 10^{-2}$	$1.053 \times 10^{-4} \pm 2.123 \times 10^{-5}$	0.993	0.021	0.037

TABLE 5: Average parameters of the model of Sikame Tagne [4] on the twelve sampling zones of the stem of *Raffia vinifera*.

Longitudinal position	Radial Position	a	b	c	k (min^{-1})	m (min^{-1})	R^2	RMSE	SSE
1/4	Center	0.241 ± 0.043	0.688 ± 0.062	0.985 ± 0.079	$3.662 \times 10^{-2} \pm 2.291 \times 10^{-2}$	$8.689 \times 10^{-5} \pm 1.918 \times 10^{-5}$	0.992	0.022	0.042
	Half-radius	0.252 ± 0.042	0.679 ± 0.075	1.002 ± 0.016	$3.917 \times 10^{-2} \pm 2.024 \times 10^{-2}$	$8.563 \times 10^{-5} \pm 1.445 \times 10^{-5}$	0.999	0.022	0.040
	Periphery	0.298 ± 0.048	0.599 ± 0.051	0.9913 ± 0.013	$1.035 \times 10^{-2} \pm 1.078 \times 10^{-2}$	$1.053 \times 10^{-4} \pm 2.123 \times 10^{-5}$	0.993	0.021	0.037
2/4	Center	0.2003 ± 0.0219	0.721 ± 0.033	1.026 ± 0.031	$1.120 \times 10^{-2} \pm 1.280 \times 10^{-3}$	$6.530 \times 10^{-5} \pm 1.550 \times 10^{-5}$	0.992	0.022	0.039
	Half-radius	0.2133 ± 0.0446	0.713 ± 0.049	1.019 ± 0.029	$2.840 \times 10^{-2} \pm 3.221 \times 10^{-3}$	$7.390 \times 10^{-5} \pm 2.520 \times 10^{-5}$	0.990	0.027	0.043
	Periphery	0.2975 ± 0.0469	0.599 ± 0.051	0.991 ± 0.013	$1.041 \times 10^{-2} \pm 1.080 \times 10^{-3}$	$1.050 \times 10^{-4} \pm 2.120 \times 10^{-5}$	0.993	0.021	0.037
3/4	Center	0.1877 ± 0.0410	0.711 ± 0.055	1.029 ± 0.024	$8.220 \times 10^{-3} \pm 1.520 \times 10^{-3}$	$5.571 \times 10^{-5} \pm 1.280 \times 10^{-5}$	0.994	0.021	0.056
	Half-radius	0.2009 ± 0.0627	0.694 ± 0.076	1.032 ± 0.017	$1.370 \times 10^{-2} \pm 2.820 \times 10^{-3}$	$5.530 \times 10^{-5} \pm 1.130 \times 10^{-5}$	0.993	0.022	0.055
	Periphery	0.2319 ± 0.0267	0.64 ± 0.075	1.022 ± 0.011	$1.410 \times 10^{-2} \pm 1.730 \times 10^{-3}$	$5.870 \times 10^{-5} \pm 1.040 \times 10^{-5}$	0.990	0.024	0.066
4/4	Center	0.2492 ± 0.0334	0.640 ± 0.092	1.021 ± 0.042	$4.260 \times 10^{-2} \pm 5.600 \times 10^{-3}$	$5.210 \times 10^{-5} \pm 2.520 \times 10^{-5}$	0.988	0.028	0.056
	Half-radius	0.2409 ± 0.0470	0.664 ± 0.090	1.031 ± 0.051	$1.740 \times 10^{-2} \pm 2.701 \times 10^{-3}$	$4.820 \times 10^{-5} \pm 1.790 \times 10^{-5}$	0.992	0.025	0.046
	Periphery	0.2421 ± 0.0548	0.671 ± 0.092	1.023 ± 0.034	$9.700 \times 10^{-3} \pm 1.500 \times 10^{-3}$	$5.681 \times 10^{-5} \pm 2.333 \times 10^{-5}$	0.995	0.021	0.039

FIGURE 7: Curves of the water absorption rate and the two-phase diffusion model in part 3/4 in the half-radius zone.

FIGURE 8: Distribution of the effective diffusion coefficient in the pith of *Raffia vinifera* in twelve sampling zones during the initial stage.

The parameters of this equation are determined in the software environment Matlab 2009b by using experimental data of water absorption M_t depending on the time. $D_{1\text{eff}}$ and $D_{2\text{eff}}$ are the respective values of the diffusion coefficient, respectively, at the initial and final phases. $M_{\infty 1}$ and $M_{\infty 2}$ are the respective water saturation levels at the initial and final stages.

Experimental data and the curve corresponding to the Fick dual stage formula are presented in Figure 7. An observation of this figure shows that the dual stage saturation method that experimented with Fick's law equation result is the better approach of experimental data.

This work has been done on twelve sampling zones and permits us to obtain the distribution of the effective diffusion coefficient of water in the pith of *Raffia vinifera*. Those distributions are presented in Figures 8 and 9.

FIGURE 9: Distribution of the effective diffusion coefficient in the pith of *Raffia vinifera* in twelve sampling zone during the final stage.

Table 6 provides the effective diffusion coefficient, the water absorption rate, and the correlation coefficient in the twelve sampling zones.

The analysis of Table 6 enables us to see that the correlation coefficient of the pith of *Raffia vinifera* resulting from the modelling of the dual stage of the second law of Fick is higher than 0.98. This table also shows that the effective diffusion coefficient in the pith of *Raffia vinifera* increase from 1.063×10^{-9} to $8.746 \times 10^{-9} \text{ m}^2/\text{s}$ in the initial stage and from 7.668×10^{-11} to $1.615 \times 10^{-10} \text{ m}^2/\text{s}$ in the second or final stage. Globally, the effective diffusion coefficient decreases from the periphery to the center in the radial position and from part 1/4 to part 4/4 in the longitudinal position in the first part or initial stage. In the second stage, the effective diffusion coefficient has the same trend such as the initial stage. The values of the effective diffusion coefficient obtained in this work are in the same greatness order of certain vegetal species such as the sisal fiber, the jute fiber, the flax fiber, the hemp fiber [36], and the raffia fiber [4].

4. Conclusion

This work whose objective is the study of water absorption phenomenon through the pith of *Raffia vinifera* consisted of the determination of the rate of water absorption. The modelling of the water absorption kinetics and the determination of the effective diffusion coefficient in the twelve sampling zones of the pith of *Raffia vinifera* were also the objective of this work. The procedure consisted of the immersion of the sample in the distilled water at the constant and room temperature of $30^\circ\text{C} \pm 1^\circ\text{C}$ and weighing the samples in the regular time intervals. This water absorption rate has values between $392.044\% \pm 36.618\%$ and $1331.956\% \pm 49.144\%$. We have noticed that the percentage of water absorption of the pith of *Raffia vinifera* increases from the periphery to the center in the radial position and from the base (part 1/4) to the leaves (part 4/4) in the longitudinal position. The modelling of the water absorption kinetics was done by eleven models and the model of Sikame Tagne et al. (2014) gives better statistical parameters with the experimental data. The determination of the diffusion coefficient is done by Fick's second law in the dual stage. The values of the diffusion coefficient increase from 1.063×10^{-9} to $8.746 \times 10^{-9} \text{ m}^2/\text{s}$

TABLE 6: Effective diffusion coefficient of water of the pith of *Raffia vinifera* during the initial and final stage.

Longitudinal position	Radial position	$D_{1\text{eff}}$ (m^2/s) $\times 10^{-9}$	$D_{2\text{eff}}$ (m^2/s) $\times 10^{-11}$	M_{∞}	R^2
Part 1/4	Center	8.746	14.00	1148.800	0.988
	Half-radius	5.337	13.55	790.455	0.987
	Periphery	4.808	16.16	367.719	0.985
Part 2/4	Center	2.415	10.48	1304.794	0.985
	Half-radius	2.260	11.83	1163.629	0.986
	Periphery	2.242	14.78	585.027	0.986
Part 3/4	Center	1.493	8.130	1477.300	0.990
	Half-radius	1.163	8.234	1219.823	0.991
	Periphery	1.966	7.792	557.978	0.991
Part 4/4	Center	1.063	8.438	1414.600	0.990
	Half-radius	1.150	7.668	1149.307	0.989
	Periphery	1.149	9.159	646.913	0.988

in the initial stage and from 7.668×10^{-11} to $1.615 \times 10^{-10} \text{ m}^2/\text{s}$. Globally, the diffusion coefficient decreases from the periphery to the center in the radial position and from part 1/4 to part 4/4 in the longitudinal position. This is done in the initial stage and final stage.

Competing Interests

The authors declare that they do not have any competing interests in this manuscript.

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