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Kinetics of Convective Drying of *Khaya senegalensis* Bark, *Fagara senegalensis* Roots, and *Senna alata* Leaves

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Abstract

Traditional medicine plays a key role in primary health care in Africa. The plant biodiversity used in traditional pharmacopoeia in Burkina Faso is very rich and varied. Medicinal plants such as *Khaya senegalensis*, *Fagara senegalensis*, and *Senna alata* are used to treat several diseases. Unfortunately, the lack of proper conservation of these plants alters the quality of the active ingredients used to treat diseases. Drying, as a method of conservation, makes it possible to have active ingredients available at all times. This study on the kinetics of convective drying of various parts of these plants focuses on the effect of temperature on diffusion coefficients. The results show that the effective diffusion coefficients increase with temperature. They range from 4.76×10^{-10} to 2.17×10^{-9} $m^2 \cdot s^{-1}$ for the bark of *Khaya senegalensis*, from 4.14×10^{-10} to 9.25×10^{-10} $m^2 \cdot s^{-1}$ for the root of *Fagara senegalensis*, and from 3.36×10^{-11} to 3.69×10^{-10} $m^2 \cdot s^{-1}$ for the leaves of *Senna alata*.

Keywords

Medicinal Plants, Kinetics, Diffusion Coefficient, Temperature, Drying Time

1. Introduction

In developing countries, particularly in sub-Saharan Africa, medicinal plants are widely used as a therapeutic alternative. This is justified by the high cost and inaccessibility of modern conventional medicine for certain social groups [1] [2]. These countries boast a rich diversity of medicinal plant biodiversity. Furthermore, in countries like Burkina Faso, traditional pharmacopoeia is deeply rooted

[3]. Among the most prized species, the bark *of Khaya senegalensis*, the roots of *Fagara senegalensis*, and the leaves of *Senna alata* are widely used for their multiple therapeutic properties, including their antimicrobial, anti-inflammatory, and antimalarial activities [4] [5].

However, the harvesting of these plants is seasonal and limited. In addition, they are characterized by a high initial water content. This characteristic makes their long-term preservation almost impossible. Indeed, their biochemical, enzymatic, and microbiological components degrade rapidly after harvesting [6]. The lack of standardized post-harvest preservation methods severely compromises the stability, concentration, and quality of the heat-labile bioactive molecules responsible for their medicinal efficacy [7] [8].

One preservation method is hot-air convective drying. This is one of the most accessible and cost-effective unit operations for extending the shelf life of medicinal biomass. This unit operation involves lowering water activity to levels that inhibit microbial growth and harmful enzymatic pathways [9]. It is important to note that despite these advantages of convective drying, optimizing the process for such diverse structural tissues as roots, bark, and leaves presents significant challenges. Insufficient or poorly controlled drying parameters can lead to surface hardening, severe color degradation, and thermolytic destruction of the active ingredients [10] [11]. Conversely, excessive drying leads to unnecessary energy consumption and processing costs [12].

To design energy-efficient drying systems that preserve the intrinsic quality of the product, a thorough understanding of moisture transfer mechanisms and drying kinetics is essential [13]. Within mass transfer models, the effective diffusion coefficient (D_{eff}) is the key physical property for describing internal water transport during the decreasing rate drying phase [14] [15]. While numerous kinetic studies have focused on common agricultural food products [16], data characterizing mass transport phenomena in specific tropical medicinal tissues remain limited.

2. Materials and Methods

The materials used are samples of medicinal plants, weighing, drying, and cutting equipment. The methodology is based on the laws of kinetics and Fick's second law of mass transfer.

2.1. Sample Preparation

The plant material consisted of *Khaya senegalensis* bark, *Fagara senegalensis* root, and *Senna alata* leaves. The leaves were picked on the grounds of the Accart-ville Mixed High School in Bobo Dioulasso, and the roots were collected in the village of Tien in the commune of Péni. The bark was purchased at a local market in Bobo Dioulasso. The plants were transported to the Laboratory of Materials, Heliophysics, and Environment (LaMHE) at Nazi Boni University in Bobo Dioulasso.

Using a stainless steel serrated knife, the bark was cut manually into parallelepipeds measuring approximately 2 cm × 1.1 cm × 1 cm, while the roots were cut into cylinders with radii between 0.8 cm and 1.38 cm and a thickness of 0.96 cm. The leaves remained whole and flat, with a thickness of approximately 0.91 mm. We used three (03) samples of each type to ensure acceptable reproducibility of the results.

2.2. Drying Techniques

After assessing their initial masses using an electronic scale (SARTORIUS, with an accuracy of ±0.001 g), we place the samples in an oven (AIR concept, temperature ranging from 40 to 250˚C, with digital display) previously set to a specific temperature for drying.

During this process, the samples were removed from the oven every thirty (30) minutes to determine their masses and then quickly returned to the oven so as not to upset the thermodynamic equilibrium. To comply with commonly used temperatures, *Senna alata* leaves are dried at 40 to 70˚C, *Khaya senegalensis* bark at 40˚C to 60˚C, and *Fagara senegalensis* roots at 50 to 80˚C. We then set the temperature to the minimum values for the pretreated samples. The experiment ends when there is no further change in mass.

2.3. Data Processing

2.3.1. Water Content

The initial water content of the plants is determined by the relationship:

$$X_0 = \frac{m_{eau}}{m_s} = \frac{m_0 - m_s}{m_s} \tag{1}$$

where m_{eau} is the total mass of water, m_0 is the initial mass of the sample and m_s is the mass of solid matter obtained after drying the sample with a constant mass for 24 hours at 105˚C.

The water content $X(t)$ at any given moment t during drying is calculated from the mass $m(t)$ of the sample at that moment using the following expression:

$$X(t) = \frac{m(t) - m_s}{m_s} \tag{2}$$

where $m(t)$ is the mass of the sample at time t and m_s is the mass of solid matter.

The equilibrium water content of the plants is determined by the relationship:

$$X_e = \frac{m_e - m_s}{m_s} \tag{3}$$

where m_e is the mass of the sample at equilibrium, m_s is the mass of solid.

2.3.2. Drying Kinetics

Each time value is associated with a corresponding water content value, *i.e.*:

$$X(t) \to t \tag{4}$$

This relationship (4) gives us the curve of the variation in water content over time. For each plant, we use three (03) samples, and each point on the drying kinetics curve corresponds to the arithmetic mean of the water content of these three samples.

To have a common basis for comparison, we normalize the water content at time t by the initial water content X_0 of the product determined according to Equation (1). This gives us the graphs:

$$X/X_0 \rightarrow t \tag{5}$$

2.3.3. Diffusion Coefficient

To determine the diffusion coefficient, the root of the plant is considered to be quasi-cylindrical and the leaves as an infinite plate. As for the bark, it is first assumed to be an infinite plate and then a cylinder. The solution to Fick's second law depends on the shape of the sample [17] [18]. The experimental results are interpreted using Fick's diffusion equation, developed by Crank [19] [20]. Considering that the initial water content in the plant is uniform and that the transfer is unidirectional without contraction of the solid matter, the analytical solutions of Fick's equation, specific to the shape of the sample, are given by Equations (6) and (7) [21]:

Cylindrical shape:

$$MR = \frac{X_t - X_{eq}}{X_0 - X_{eq}} = \frac{4}{\beta^2}\exp\left(-\frac{\beta^2 D_{eff} t}{r_c^2}\right) \tag{6}$$

Infinite plate:

$$MR = \frac{X_t - X_{eq}}{X_0 - X_{eq}} = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2}{4}\frac{D_{eff} t}{L^2}\right) \tag{7}$$

In Equations (6) and (7), MR is the water content rate, X_t ($\text{kg}_\text{e}\cdot\text{kg}_\text{ms}^{-1}$) is the average water content of the product, X_0 ($\text{kg}_\text{e}\cdot\text{kg}_\text{ms}^{-1}$) is the initial water content, X_{eq} ($\text{kg}_\text{e}\cdot\text{kg}_\text{ms}^{-1}$) is the equilibrium water content, D_{eff}($\text{m}^2\cdot\text{s}^{-1}$) is the effective diffusion coefficient, r_c (m) is the radius of the cylinder, L (m) is the characteristic length of the plate, and t (s) is the drying time.

The graphs of the ln(MR) functions of relations Equations (6) and (7), allow the diffusion coefficients to be determined from the slopes of the straight lines obtained. In fact, Equations (6) and (7) [22] can be simply expressed in the form Equation (8) [23] [24]:

$$\ln(MR) = A - kt \tag{8}$$

For roots, the diffusion coefficient is obtained by Equation (9), [25]:

$$\begin{cases} A = \ln\left(\dfrac{4}{\beta^2}\right) \\ k = \dfrac{\beta^2 D_{eff}}{r_c^2} \end{cases} \Rightarrow \begin{cases} \beta^2 = \dfrac{4}{\exp A} \\ D_{eff} = \dfrac{k \cdot r_c^2}{\beta^2} \end{cases} \tag{9}$$

The parallelepiped shape is assimilated to a cylinder of the same volume, whose radius is obtained by Equation (10):

$$r = \sqrt{\frac{a \cdot b}{\pi}} \tag{10}$$

where r(m) is the radius of the cylinder, and a and b (m) are the length and width of the parallelepiped, respectively.

For sheets, the diffusion coefficient is determined by Equation (11):

$$\begin{cases} A = \ln\left(\frac{8}{\pi^2}\right) \\ k = \frac{\pi^2}{4}\frac{D_{eff}}{L^2} \end{cases} \Rightarrow D_{eff} = k\left(\frac{2L}{\pi}\right)^2 \tag{11}$$

3. Results and Discussions

3.1. *Khaya senegalensis* Bark

Figure 1 illustrates the effect of the three (3) temperatures on *Khaya senegalensis* bark. At 180 minutes, the samples lose 62.81% and 90% of their initial water content at temperatures of 40˚C, 50˚C, and 60˚C, respectively, before the drying kinetics curves tend toward a horizontal asymptote. The curve at 40˚C is the only one to show phase 2 of drying from 450 minutes onwards with a water content of 0.14 $\text{kg}_e \cdot \text{kg}_{ms}^{-1}$.

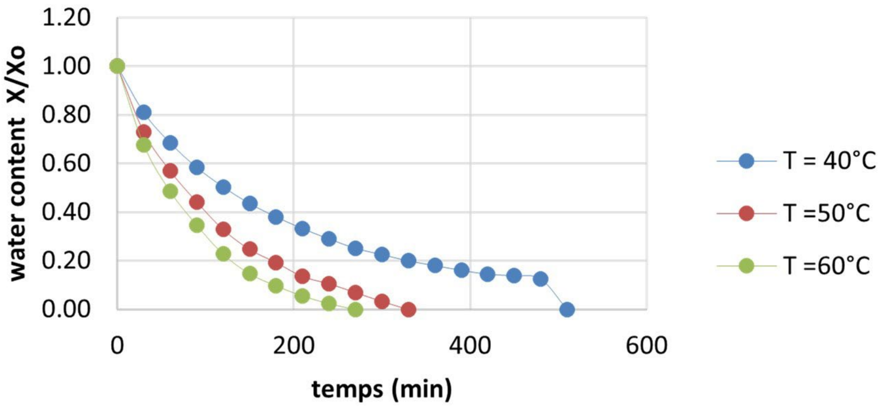

Figure 1. Reduced water content X/X_0 of *Khaya senegalensis* bark samples versus time.

The water content decreases significantly with temperature. Thus, the bark of *Khaya senegalensis* dries faster at 60˚C than at 50˚C, while drying at 40˚C is slower. Drying times are 510, 330, and 270 minutes at 40˚C, 50˚C, and 60˚C, respectively. However, it should be noted that as the drying temperature increases, the brown color of the bark becomes darker and darker, resulting in the destruction of certain active components.

Figure 2 shows the evolution of ln(MR) over time. These curves have a linear downward trend. The slopes are 7.10^{-5}, 2.10^{-4}, and 2.10^{-4} at temperatures of 40˚C, 50˚C, and 60˚C, respectively.

The slope becomes steeper as the temperature rises. From Equation (9), the diffusion coefficient values obtained are 4.76×10^{-10}, 1.82×10^{-9} and 2.17×10^{-9} $m^2 \cdot s^{-1}$

for temperatures of 40˚C, 50˚C, and 60˚C, respectively. These values are consistent with the ranges recommended in the literature for food products [12]. The value of D_{eff} therefore increases with temperature.

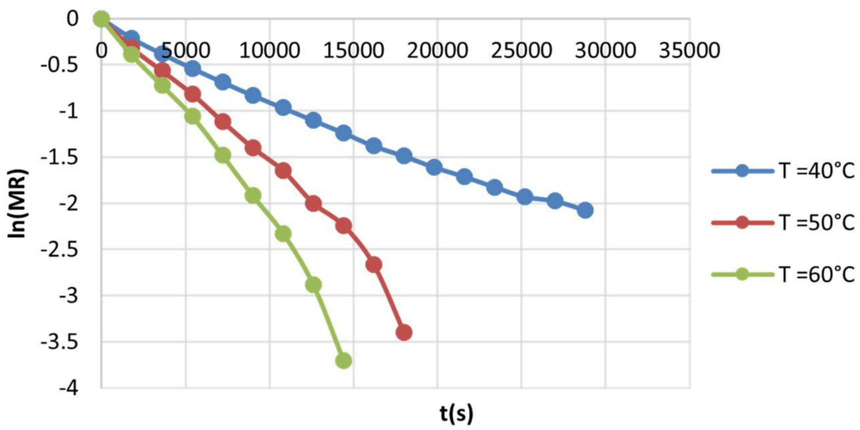

Figure 2. ln(*MR*) as a function of temperature for *Khaya senegalensis* bark.

3.2. *Fagara Senegalensis* Root

The drying curves for *Fagara senegalensis* root at temperatures of 50˚C, 60˚C, 70˚C, and 80˚C are shown in **Figure 3**.

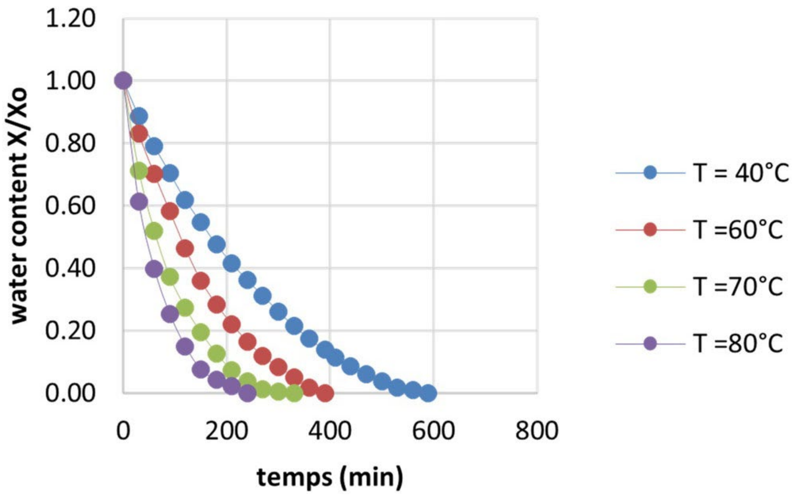

Figure 3. Reduced water content X/X_0 of *Fagara senegalensis* root samples versus time.

At one hour of drying, this graph shows a sharp drop between 30% and 75% of the initial water content for different temperatures ranging from 50˚C to 80˚C before the curves tend towards horizontal. The higher the temperature, the faster the drying rate. The time taken to reduce the water content from 1 $kg_e \cdot kg_{ms}^{-1}$ to a final water content close to 0 $kg_e \cdot kg_{ms}^{-1}$ is 590, 390, 330, and 240 minutes for 50˚C, 60˚C, 70˚C, and 80˚C, respectively. Initially yellow at 50˚C, the color of the roots becomes darker at 60˚C, before turning brown at temperatures of 70˚C and 80˚C.

The ln(*MR*) curves as a function of time shown in Figure 4 show that for all temperatures, drying follows first-order kinetics.

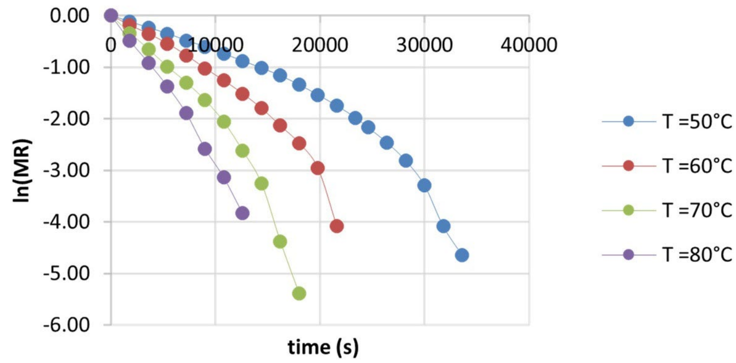

Figure 4. ln(*MR*) as a function of temperature for samples of *Fagara senegalensis* root.

The slopes of the curves range from 8.10^{-5} to 3.10^{-4} for temperatures between 50˚C and 80˚C. The diffusion coefficient at 50˚C for the root of *Fagara senegalensis* is 4.14×10^{-9} $m^2 \cdot s^{-1}$. At 60˚C, 70˚C, and 80˚C, it increases to 6.29×10^{-9}, 7.27×10^{-9}, and 9.25×10^{-9} $m^2 \cdot s^{-1}$, respectively. These values are consistent with those reported in the literature for agri-food products [12].

3.3. *Senna alata* Leaves

The drying kinetics curves for *Senna alata* leaves at four (4) temperatures are shown in Figure 5. Note that the first phase of drying is absent from this graph. At 70˚C, the curve shows a rapid decrease in water content compared to temperatures of 60˚C, 50˚C, and 40˚C. This proves that increasing the temperature significantly accelerates the drying process. Reducing the water content of the leaves to a final water content close to equilibrium requires 450, 330, 210, and 150 minutes at 40˚C, 50˚C, 60˚C, and 70˚C, respectively. The leaves retain their green color at temperatures of 40˚C and 50˚C. They take on a yellowish tint at 60˚C, while at 70˚C they turn brown.

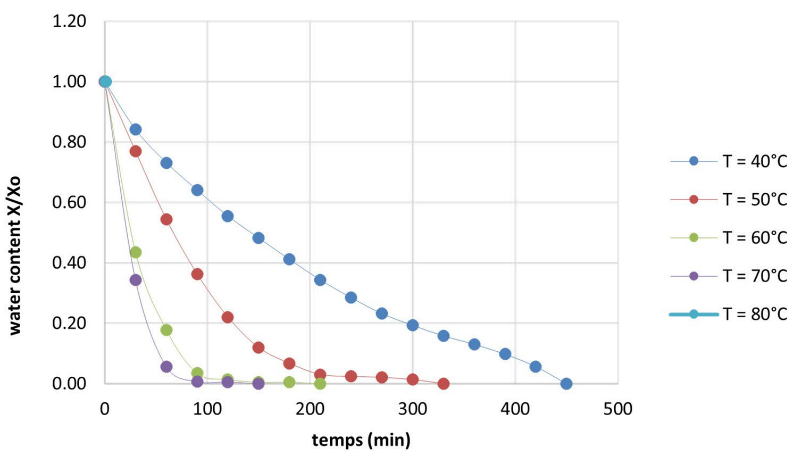

Figure 5. Reduced water content X/X_0 of *Senna alata* leaf samples versus time.

The curves in **Figure 6** show the trend of ln(*MR*) as a function of time. The results show that as the temperature increases, the slopes of the curves become steeper. At temperatures of 40˚C, 50˚C, 60˚C, and 70˚C, the slope values of the different lines are 1×10^{-4}; 3×10^{-4}; 7×10^{-4} and 11×10^{-4}, respectively. Using Equations (9) and (11), the effective diffusion coefficients calculated for the same temperatures are $3.36.10^{-11}$; 10.1×10^{-11}; 23.5×10^{-11} and 36.9×10^{-11} $m^2 \cdot s^{-1}$. Thus, water diffusion increases with temperature. The diffusion coefficient values found fall within the range predicted in the literature for agri-food products [26].

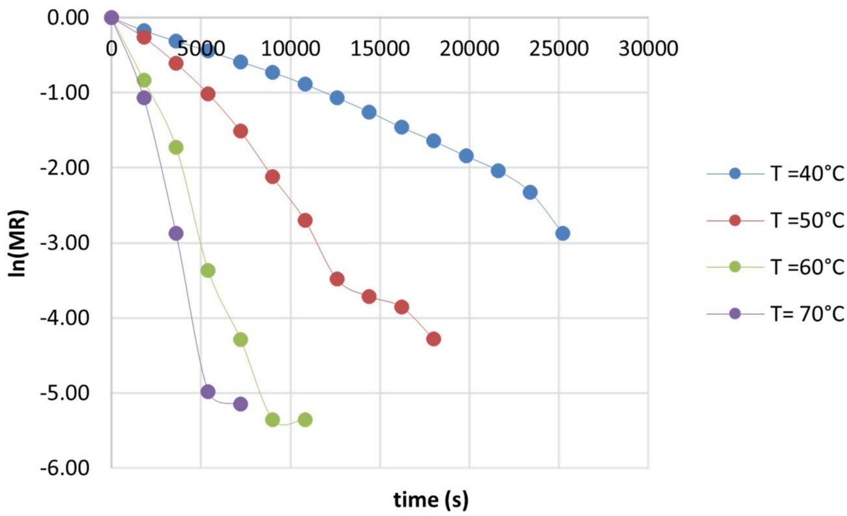

Figure 6. ln(*MR*) as a function of temperature for *Senna alata* leaf samples.

4. Conclusion and Outlook

This study highlighted the impact of temperature on the convective drying of *Khaya senegalensis* bark, *Fagara senegalensis* root, and *Senna alata* leaves. Analysis of drying kinetics shows that temperature plays an important role in the drying process. The drying time decreases with temperature for each of the plants studied. Higher temperatures accelerate moisture removal but must be controlled to avoid altering the bioactive constituents of the plants. The temperature range between 40˚C and 50˚C proved to be the most suitable for convective drying of these plants. The results show that there is no linear correlation between the initial water content and the diffusion coefficient. The diffusion coefficients are in the order of 10^{-10} $m^2 \cdot s^{-1}$ for all samples. However, there is a slight increase in these coefficients with temperature. In the future, the effect of the drying method will be studied to improve the quality of the dried plants and to determine the most appropriate empirical model for each plant. In addition, the temperature ranges will be expanded to better control the drying kinetics and assess the impact of temperature on the bioactive compounds in these plants.

Author Contributions

Conceptualization, K.H.O. and S.H.; methodology, K.H.O. and S.H.; software,

A.K.S.; validation, K.H.O. and S.H.; formal analysis, A.K.S.; investigation, A.K.S.; data curation, A.K.S.; writing—original draft preparation, A.K.S.; writing—review and editing, S.H.; visualization, A.K.S; supervision, K.H.O; funding acquisition, S.H. and A.K.S.

All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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