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Modeling the Drying Kinetics of Pigeon Pea [*Cajanus cajan* (L.) Millspaugh]

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Abstract

We set out to model the oven-drying kinetics of a legume known as pigeon pea, harvested in the Bouenza department in the south-west of the Republic of Congo. The drying kinetics of pigeon peas was carried out in an oven under experimental conditions using temperatures of: 50˚C, 60˚C and 70˚C. Seven mathematical models were used to describe pigeon pea drying. During drying, water loss was faster and shorter at 70˚C [10.446 g/25 g wet weight (wwb) for 320 min (5.3 h)] compared to 50˚C [10.996 g/25 g wet weight (wwb) for 520 min (8.6 h)] and 60˚C [10.616 g/25 g wet weight (wwb) for 420 min (7.0 h)] where it was slower and longer. With regard to modeling, and based on the principle of choosing the right model focusing on the high value of R^2 and low values of χ^2 and RMSE, two models were selected, the Midili model for temperatures of 50˚C and 60˚C and the Henderson and Pabis model modified for temperature of 70˚C showed better results. The R^2, χ^2 and RMSE values calculated for pigeon pea are 0.99985, 3.93404E−5 and 0.00627; 0.9997, 9.245E−5 and 0.00962; 0.99996, 1.56332E−5 and 0.00395 respectively at 50˚C, 60˚C and 70˚C.

Keywords

Cajanus cajan, Legume, Kinetic Models, Drying

1. Introduction

Pulses, also known as “pulses”, are part of the staple diet in many poor and developing countries. Mainly represented by beans and cowpeas, peas, broad beans and lentils [1], legumes have remarkable nutritional and culinary virtues. They are consumed all over the world in different forms such as stews, flours, purees, side dishes, snacks and desserts [2]. In terms of food, legumes are particularly appreciated for their nutrient-rich products, where these include the seed, and very often, the plant part consisting of leaves and pods [3] cited by S. Napp *et al*., [4].

Legumes therefore provide quality protein, low fat content (for the most part), a wealth of fiber, and a low glycemic index via their starch [5]. In addition, consumption of these could help combat obesity, but also prevent and treat chronic diseases such as diabetes, cardiovascular pathologies and cancer [6]. This is why, in 2016, these legumes received particular attention in their importance for sustainable food production and a balanced diet [2] [6].

Legumes belong to the Fabaceae family, the third largest group of plants in the world [4] [7] in which there are over 20,000 species and 700 genera, of which only some are classified as leguminous plants, in this case the Vicia, Cicer, Lens and *Cajanus* groups [2]. In the *Cajanus* group, we find a legume, pigeon pea (*Cajanus cajan* L. Millspaugh), which is thought to originate from the Indian subcontinent although its origin is sometimes disputed with Africa, the continent where it is known as Congo pea [2].

While legumes can contribute to food security in a number of ways, such as the edibility and germination of seeds stored for several years, they need to be properly dried before storage, as the water content of legumes can be high at harvest time. Drying, an ancestral practice is commonly carried out on sun-exposed areas, on terraces or in open containers, or even today in improved devices such as solar dryers, ovens and kilns. Drying is more efficient if the crop has been shelled. Thus, to meet the requirements of storage with a generally satisfactory moisture content, the moisture content can be lowered to 12% or 13% [8]. It should be noted that not all legumes have the same initial moisture content at harvest, since this depends on the species, variety and climate, which is why drying behavior needs to be monitored.

Drying kinetics is a phenomenon involving the interaction of heat and mass transfers at the interface between the product, the air and transfers within the same product [9]. This phenomenon makes it possible to evaluate the drying behavior of a product by determining the relationship between drying air velocity, temperature, humidity and relative mass as a function of time. The result is an equation that describes two characteristic curves [10]. The modeling of drying kinetics enables us to understand the influence of aerothermal parameters on drying processes, and to obtain the data needed, for example, for the sizing and design of dryers adapted to a given product [11].

The aim of this work is to study the drying characteristics of pigeon pea (*Cajanus cajan* (L.) Millspaugh) in an oven at three (03) different temperatures.

2. Materials and Methods

2.1. Material

The plant material consisted of a legume, the pigeon pea known by the scientific name *Cajanus cajan* (L.) Millspaugh, illustrated in **Figure 1**, from the Bouenza department and purchased at the Total market in Bacongo, south-west of Brazzaville (Congo).

The ventilated oven [INDERLAB (0˚C - 250˚C)] and a precision balance [OHOUS/Explorer Pro (0 - 210 g)] were the main laboratory equipment used.

2.2. Methods

2.2.1. Preparation of Pigeon Pea Weights *Cajanus cajan* (L.) Millspaugh

After receiving the pigeon peas in the laboratory, those purchased without pods were sorted directly, whereas those purchased with pods were first shelled and then selected before drying.

But before drying, we first calibrated the pigeon peas with and without pods, focusing morphological measurements on length, width and thickness using a caliper. The mass of each pod or grain was also measured using a precision balance OHOUS/Explorer Pro (0 - 210 g).

2.2.2. Drying of Pigeon Pea *Cajanus cajan* (L.) Millspaugh

To carry out drying, 25 g of pigeon pea seeds were spread evenly on a glass dish and placed in a ventilated oven INDERLAB (0˚C - 250˚C) for drying at 50˚C, 60˚C and 70˚C [12]. The mass of the sample was measured every 30 min during oven drying, using a digital balance accurate to 0.001 g OHOUS/Explorer Pro (0 - 210 g). A sample dish was removed from the drying chamber, weighed on the digital balance and immediately returned to the drying chamber. The digital balance was placed very close to the drying apparatus, and the weight measurement process took a very short time (around 10 seconds) to avoid moisture pick-up. The experiments were repeated three times and mean values were used for each experimental condition.

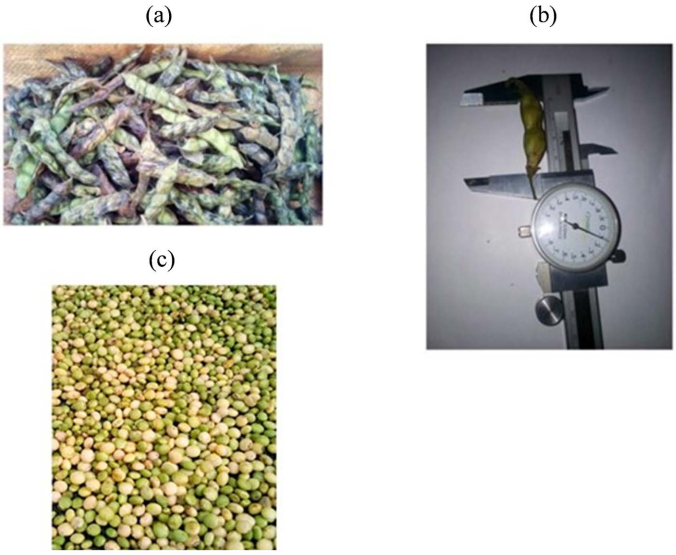


Figure 1. Fresh pods (a), caliper measurement of a fresh pod and seeds (c) of pigeon pea (*Cajanus cajan (L.) Millspaugh*).

2.2.3. Moisture Content

The initial moisture content of pigeon pea seeds was measured by oven-drying at 105˚C for 24 h using the AOAC method [13] and expressed as kg water/kg dry matter.

The change in mass during drying enabled us to determine the variation in water content in the wet base during drying. This is given by the formula below:

$$X = \frac{m - MS}{MS} \tag{1}$$

With:

X: moisture content on wet basis (kg water/kg dry matter);

m: product mass;

DM: dry matter mass (DM = total starting mass − starting water mass (calculated from wet-base water content).

The wet-base water content also enabled us to determine the drying rate over time according to the formula:

$$-\frac{\mathrm{d}X}{\mathrm{d}t} = \frac{-\left[X\left(t+\Delta t\right) - X\left(t\right)\right]}{\Delta t} \tag{2}$$

With:

-dX/dt: drying rate in kg water/kg DM/sec;

X: moisture content in wet basis (kg water/kg wet matter);

Δt: time difference in seconds.

Three drying curves were thus obtained: the mass vs. time curve, the wet-base water content vs. time curve, and the speed vs. time curve.

2.2.4. Mathematical Model of Drying Kinetics

To carry out the modeling in this specific case, the equations presented in **Table 1** were chosen and tested in order to select the best model that could describe the equation of the pigeon pea drying curve, during oven drying at 50˚C, 60˚C and 70˚C.

Table 1. Mathematical models used to model sample drying.

Model names	Equation N˚	Equations	References
Newton	7	$X^* = \exp\left(-kt\right)$	**Arslan et Musa Özcan, 2010; Lahmari *et al.*, (2012)**
Page	8	$X^* = \exp\left(-kt^n\right)$	**Arslan et Musa Özcan, 2010; Lahmari *et al.*, (2012)**
Henderson *et al.*	9	$X^* = a \times \exp\left(-kt\right)$	**Lahmari *et al.*, (2012)**
Midilli *et al.*	10	$X^* = a \times \exp\left(-kt^n\right) + b \times t$	**Lahmari *et al.*, (2012)**
Henderson et Pabis modifié	11	$X^* = a \times \exp\left(-kt\right) + b \times \exp\left(-k't\right) + c \times \exp\left(-k''t\right)$	**Meziane S. (2013)**
Verna *et al.*	12	$X^* = a \times \exp\left(-kt\right) + b \times \exp\left(-k't\right)$	**Meziane S. (2013)**
Logarithmique	13	$X^* = a \times \exp\left(-kt\right) + c$	**Arslan et Musa Özcan, 2010**

a, b, c, coefficients and n, specific exponent of each drying equation; k specific coefficients of each drying equation, t is the drying time.

Origin Pro 8 mathematical software (for Windows) was used to estimate the quality of model predictions by determining the correlation or regression coefficient (R^2). The latter was used to predict the best equation, taking into account the variation in the drying curves of the dehydrated sample. In addition to R^2, the reduced chi-square (X^2), the root mean square error (RMSE) between the experimental data (Rexp) and the predicted data (Rpre) of X with a 95% confidence level was used to determine the goodness of fit. Thus the choice of the best model will be based on the higher R^2, lower χ^2 and RMSE [14] [15].

R^2, reduced chi-square (X^2), root mean square error (*RMSE*) can be calculated from equations (3), (4) and (5) respectively described as follows:

$$R^2 = \frac{\sum_{i=1}^{n}\left(M_{Ri} - M_{Rpre(i)}\right)^2}{\sqrt{\left[\sum_{i=1}^{n}\left(M_{Ri} - M_{Rpre(i)}\right)\right]\cdot\left[\sum_{i=1}^{n}\left(M_{Ri} - M_{Rexp(i)}\right)\right]}} \quad (3)\ [16]$$

$$X^2 = \frac{\sum_{i=1}^{N}\left(M_{Rexp(i)} - M_{Rpre(i)}\right)^2}{N-n} \quad (4)\ [17]$$

$$RMSE = \sqrt{\frac{1}{N}\times\sum_{i=1}^{N}\left(M_{Rexp(i)} - M_{Rpre(i)}\right)^2} \quad (5)\ [18]$$

With:

$M_{Rexp(i)}$ the experimental reduced water content;

$M_{Rpre(i)}$ the predicted reduced water content;

N the number of experimental points and np the number of model constants studied.

The reduced water content data were obtained by calculation according to the formula defined as follows:

$$X^* = \frac{X}{X_{initiale}} \quad (6)\ [19]$$

where:

X^* is the reduced water content;

X is the water content on a dry basis (kg water/kg dry matter) at a given time t;

$X_{initial}$ is the initial water content of the product.

2.2.5. Statistical Analysis

Minitab (version 2017) for windows was used to calculate the mean, the standard deviation and to perform the controlled one-factor analysis of variance following Tukey's comparison test with a significance level of 0.05.

Origin Pro 8 mathematical software (for windows) was used to perform modelling by determining the correlation coefficient (R^2), the reduced chi-square (X^2), the *RMSE* with a 95% confidence level.

3. Results and Discussion

3.1. Physico-Morphological Analysis of Pigeon Peas (*Cajanus cajan* (L.) Millspaugh)

On a given Cajanus species, there is a diversity of pods. We note pods with 2, 3, 4, 5 and 6 peas. The results of the grading of different fresh pigeon pea pods are shown in **Table 2**. From a sample of 10 for each category of pigeon pea with a defined number of pods ranging from 2 to 6, we note that fresh pigeon pea pods with 6 seeds have a higher average length (7.540 ± 0.346 cm), compared with the averages obtained for other pods with a lower number, and/or with two seeds being the smallest (3.340 ± 0.291 cm). Significant differences were observed between samples ($p < 0.05$), where statically they shared no letters.

Thickness ranged from 0.910 ± 0.032 to 1.100 ± 0.133 cm. There were significant differences ($p < 0.05$) between samples of pods not sharing the same letter. This is the case for 2-grain pods, which are significantly different from 4 and 6-grain pigeon pea pods. No significant difference ($p > 0.05$) between pods for width parameters, where data varied from 0.280 ± 0.155 to 0.380 ± 0.132 cm.

Measurements were also taken on the pea kernel itself, namely: mass, length and thickness. A random selection of 10 samples was used for the experiment. Pigeon peas vary in length from 0.700 to 1 cm, with an average of 0.840 ± 0.084 cm; thickness from 0.400 to 0.600 cm, with an average of 0.530 ± 0.078 cm; and mass from 0.2 to 0.5 g, with an average of 0.38 ± 0.097 g.

3.2. Drying Kinetics of Pigeon Pea (*Cajanus cajan*)

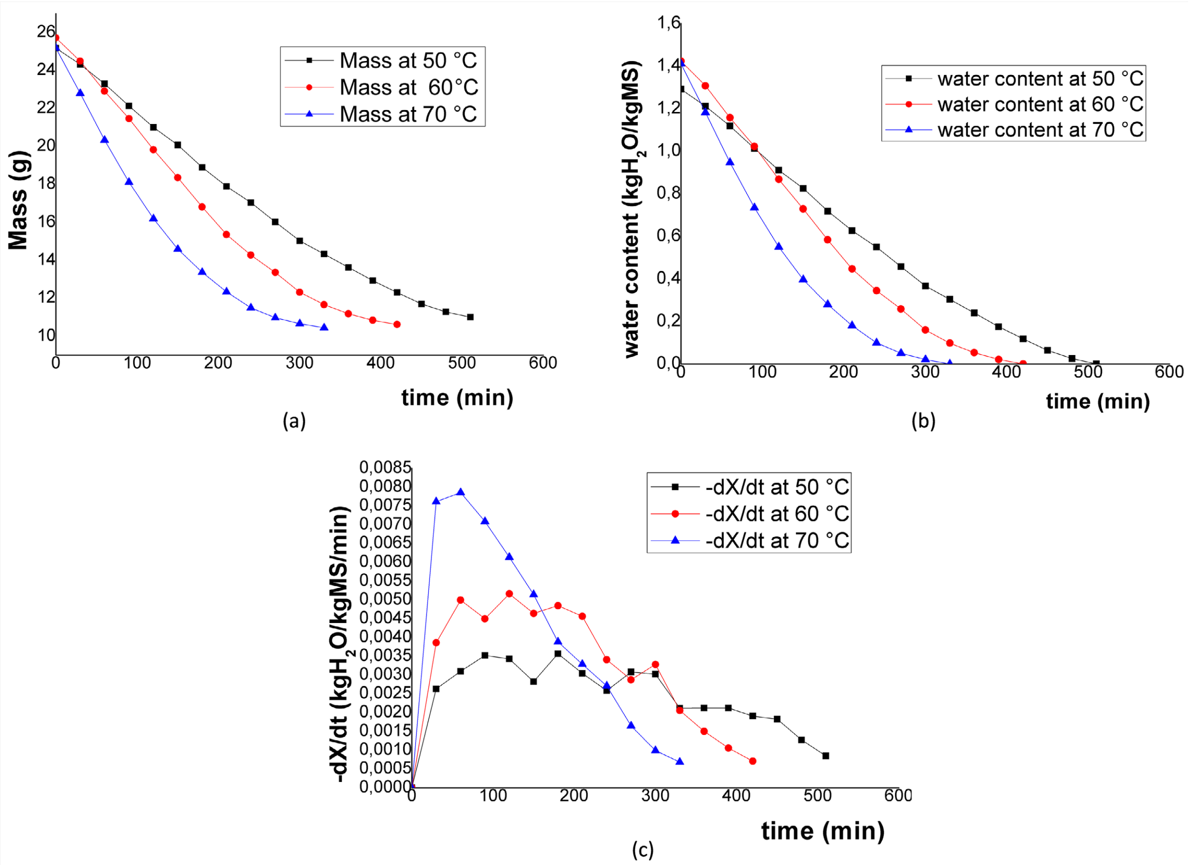
Plots of moisture content (by mass and water loss) versus time are shown in **Figure 2(a)** and **Figure 2(b)**, which represent experimental curves of drying characteristics for oven-dried pigeon peas at three distinct temperatures (50˚C, 60˚C and 70˚C).

The time required to reach a moisture content of 10.996 g/25 g wet weight; 10.616 g/25 g wet weight (wwb: gww) and 10.446 g/25 g wet weight (wwb) was 520 min (8.6 h), 420 min (7.0 h) and 320 min (5.3 h) respectively for oven drying at 50˚C, 60˚C and 70˚C respectively. Observation of the curves revealed a slowdown in mass loss, reflected in the depletion of free water in the product from 200 min for drying at 70˚C, to 300 min for drying at 60˚C and after 400 min for drying at 50˚C. After the time indicated above, there was no significant reduction in the moisture content of the samples (see **Figure 2(b)**). We also found that the drying time at 70˚C was shorter and faster, as drying at a higher temperature and higher energy output would imply a greater driving force for heat transfer. Drying curves at 50˚C and 60˚C were rather linear, reflecting less extraction of moisture from the peas.

Table 2. Calibration of pigeon pea (*Cajanus cajan* (L.) Millspaugh).

Samples of pods with number of grains	Length (cm)	Width (cm)	Thickness (cm)
2	3.340 ± 0.291E	0.280 ± 0.155A	0.910 ± 0.032B
3	4.480 ± 0.278D	0.320 ± 0.132A	1.040 ± 0.151AB
4	5.200 ± 0.194C	0.290 ± 0.088A	1.100 ± 0.133A
5	6.300 ± 0.350B	0.380 ± 0.132A	1.040 ± 0.052AB
6	7.540 ± 0.366A	0.320 ± 0.103A	1.090 ± 0.120A

Mean ± standard deviation. Means with different upper cases in a column (comparison between pigeon pea pod) are statistically significant at 5% probability level.



(a) (b) (c)

Figure 2. Variation in mass (a), water content (b) and velocity (c) of pigeon pea (*Cajanus cajan*) during drying.

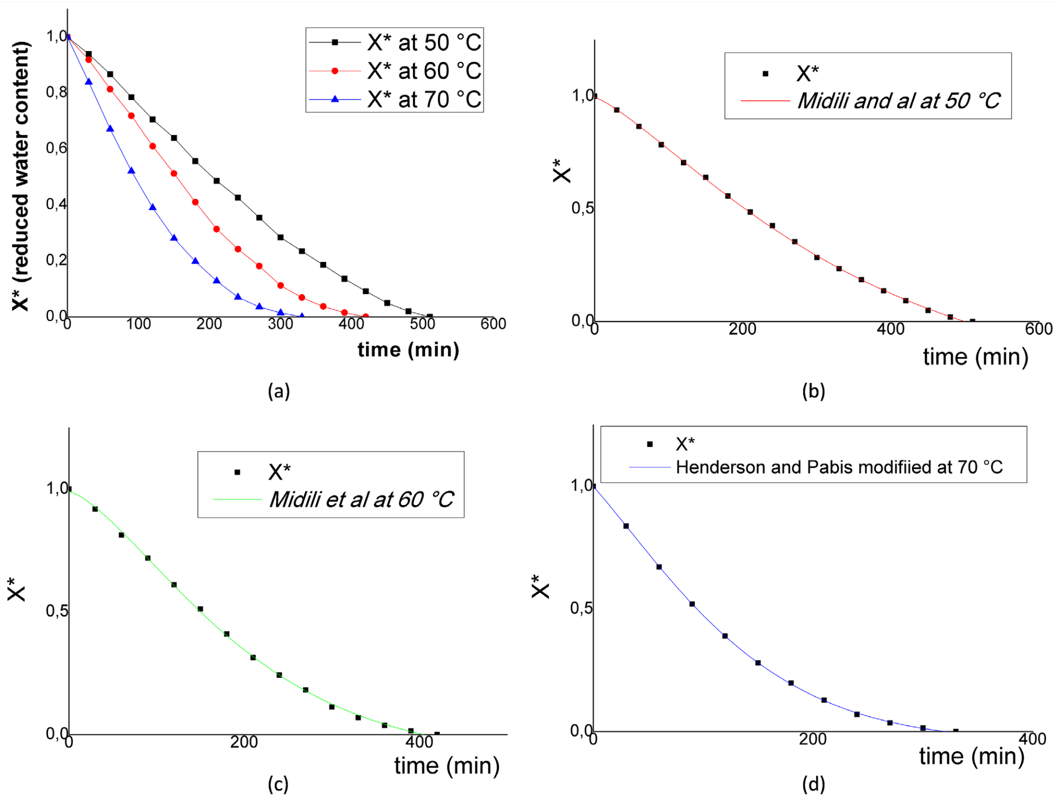
Pigeon pea drying rates shown in **Figure 2(c)** were highest at the start of the drying process, where they increased from 0.26 to 0.35 kg water/kg DM/min, from 0.386 to 0.499 kg water/kg DM/min and from 0.0076 to 0.0079 kg water/kg DM/min for temperatures of 50˚C, 60˚C and 70˚C respectively. In all three cases, a phase of gradual decrease followed, until a value of almost zero was reached at the end of the drying process. This is due to the fact that more energy is initially absorbed by the water on the product surface, resulting in faster drying, and with subsequent drying of the product surface, heat penetration through the dried layer decreased, thus retarding drying rates [20].

The drying process of samples dried at 50˚C and 60˚C revealed velocity curves with a fluctuating trend describing the instability of the product during drying, expressing the partial elimination or low diffusion of free water.

3.3. Modeling Kinetics

3.3.1. Reduced Water Content

The curves in **Figure 3(a)** show the variation in reduced water content as a function of time. Analysis of these curves shows that they follow a similar pattern to the dry-base water content curves. Pea drying times also remain unchanged at 8.5 h, 7 h and 5.5 h respectively at temperatures of 50˚C, 60˚C and 70˚C.



(a) (b)

(c) (d)

Figure 3. Variations in reduced water content (a) as a function of time during oven drying of pigeon pea at 50˚C, 60˚C and 70˚C; modeling curves for reduced water content of pigeon pea at (b) 50˚C and 60˚C using the model of Midili *et al.*; and at (c) 70˚C using the modified Henderson and Pabis model.

3.3.2. Model Evaluation

The seven models listed in **Table 1** were used to predict moisture content as a function of drying time. Based on these, the R^2, χ^2, *RMSE* responses as well as statistical constant values obtained under drying conditions at specific temperatures for these models are presented in **Table 3**.

Model comparison was based on R^2, χ^2 and *RMSE*. The results in **Table 2** show that, for drying pigeonpea in an oven, the R^2, χ^2 and *RMSE* values range respectively from 0.97093 to 0.99985, from 3.93404E−5 to 0.99476 and from 0.00627 to 0.99494 for drying at 50˚C; from 0.97281 to 0.9997, from 9.245E−5 to 0.0064 and from 0.00962 to 0.99638 for drying at 60˚C; finally from 0.98815 to 0.99996, from 1.56332E−5 to 0.00275 and from 0.00395 to 0.05242 for drying at 70˚C.

Comparing the 7 models used, two models give the highest R^2 coefficient of determination values and the lowest χ^2 and *RMSE* values. These are the Midili *et al.* model and the modified Henderson and Pabis model.

For pigeonpea oven-drying at 50˚C, the best R^2, χ^2 and *RMSE* values are 0.99985, 3.93404E−5 and 0.00627 respectively (for the Midili *et al.* model). For drying at 60˚C, they are 0.9997, 9.245E−5 and 0.00962 (for the Midili *et al* model); while for drying at 70˚C they are 0.99996, 1.56332E−5 and 0.00395 respectively for R^2, χ^2 and *RMSE* (for the modified Henderson and Pabis model).

Table 3. Results of statistical analyses on the modeling of water content and drying time of pigeon pea grains.

Temperatures	Models	Parameters	R	χ^2	$RMSE$
50˚C	Newton	$K = 0.00407$	0.97093	0.00628	0.07925
	Page	$K = 1.88399\mathrm{E}{-4}$; $n = 1.55161$	0.99681	7.41406E−4	0.02723
	Henderson *et al.*	$a = 0.00451$; $k = 1.10708$	0.97877	0.00489	0.06995
	Midilli *et al.*	$a = 5.32495\mathrm{E}{-4}$; $k = -3.13651\mathrm{E}{-4}$; $n = 1.31235$; $b = 0.99539$	0.99985	3.93404E−5	0.00627
	Henderson et Pabis modified	$a = 0.00802$; $k = 2.8265$; $b = -5.76309$; $k' = 0.00798$; $c = 0.00941$; $k'' = 3.91081$	0.99494	0.00157	0.99494
	Verna *et al.*	$a = 0.00857$; $k = -77.88834$; $b = 0.00847$; $k' = 0.00451$	0.99476	0.99476	0.03602
	Logarithmique	$a = 0.00166$; $k = -0.8233$; $c = 1.85195$	0.99907	2.3123E−4	0.01521
60˚C	Newton	$K = 0.00556$	0.97281	0.0064	0.08
	Page	$K = 2.63149\mathrm{E}{-4}$; $n = 1.57515$	0.99831	4.34232E−4	0.02084
	Henderson *et al.*	$a = 0.00613$; $k = 1.10683$	0.97995	0.0051	0.07143
	Midilli *et al.*	$a = 4.26574\mathrm{E}{-4}$; $k = -1.67507\mathrm{E}{-4}$; $n = 1.45726$; $b = 0.98942$	0.9997	9.245E−5	0.00962
	Henderson et Pabis modified	$a = 0.01723$; $k = 1102.85897$; $b = -2152.58119$; $k' = 0.01646$; $c = 0.01685$; $k'' = 1050.72747$	0.99883	4.33975E−4	0.02083
	Verna *et al.*	$a = 0.01175$; $k = -60.81122$; $b = 0.01156$; $k' = 0.00612$	0.99638	0.00101	0.99638
	Logarithmique	$a = 0.00301$; $k = -0.47032$; $c = 1.5129$	0.99718	7.84033E−4	0.028
70˚C	Newton	$K = 0.00856$	0.98815	0.00275	0.05242
	Page	$K = 0.00154$; $n = 1.34755$	0.99901	2.5484E−4	0.01596
	Henderson *et al.*	$a = 0.00906$; $k = 1.06312$	0.99064	0.00239	0.04891
	Midilli *et al.*	$a = 0.00228$; $k = -1.4909\mathrm{E}{-4}$; $n = 1.25003$; $b = 0.99658$	0.99987	4.01614E−5	0.00634
	Henderson et Pabis modified	$a = 0.0098$; $k = 130.48333$; $b = -62.54088$; $k' = 0.0092$; $c = 0.00862$; $k'' = -66.94271$	0.99996	1.56332E−5	0.00395
	Verna *et al.*	$a = 0.01605$; $k = -55.73766$; $b = 0.01582$; $k'=0.00905$	0.99867	3.77967E−4	0.01944
	Logarithmique	$a = 0.00626$; $k = -0.1794$; $c = 1.20502$	0.99865	3.86E−4	0.01965

Based on the results obtained, the model of Midili *et al.* is considered to be the best model to describe the drying behavior of pigeon pea (*Cajanus cajan*) in an oven at 50˚C and 60˚C. Similar results were found in the work of Gampoula *et al.*, [12], on modeling the drying of Gamboma yam pulp (*Dioscorea cayenensis*) in an oven at 70˚C; Kone *et al.*, [21] on sodium alginate gel in the microwave and the work of Lahmari *et al.*, [22] on tomato respectively. The best model for drying pigeon pea in an oven at 70˚C is that of Henderson and Pabis, modified.

Figure 3(b) and Figure 3(c) illustrate the drying curves obtained with the Midili *et al.* model at 50˚C and 60˚C, while Figure 3(d) shows the Henderson and Pabis model modified at 70˚C.

4. Conclusions

In this work, we studied the drying kinetics of pigeon peas (*Cajanus cajan*) in an oven at three (03) temperatures set at 50˚C, 60˚C and 70˚C. This study showed that: during the drying of pigeon pea at these three temperatures, the curves were similar. When examining the drying behavior of pigeon peas in the oven, it was found that of the three temperatures, the shortest drying time was obtained at 70˚C. It turns out that the increase in speed correlates with the increase in temperature. The higher the temperature, the shorter the drying time. With regard to the drying speed curves, the curves obtained show the presence of the phases of product temperature setting (phase 0), drying at a constant rate (phase 1) and the sole presence of phase 2. This phase, known as drying at decreasing speed, during which the drop in water evaporation flow is due to the surface passing into the hygroscopic domain, is partially offset by a rise in the temperature of the pigeon peas. Modelling data obtained from 07 models revealed that: the model by Midili *et al.* is considered the best model for describing the drying kinetics of *Cajanus cajan* in ovens at temperatures of 50˚C and 60˚C, and the model by Henderson and Pabis modified for the drying kinetics in ovens at 70˚C.

Further study may be required to assess the impact of these three (03) temperatures on the quantity and quality of heat-sensitive compounds such as vitamins and aromatic compounds.

In the future, this study will help us to optimize future work, in particular on the dehydration conditions of the species studied, by determining their drying kinetics using the most suitable means, *i.e.* oven drying at well-defined temperatures.

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Conflicts of Interest

No conflicts of interest for this article.

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Nomenclature

X: moisture content in wet basis (kg water/kg fresh matter) at a given time t;
m: product mass;
DM: mass of dry matter (DM = total starting mass − starting water mass (calculated from water content in wet basis);
$-\mathrm{d}X/\mathrm{d}t$: drying rate in kg water/kg DM/sec;
Δt: time difference in seconds;
$M_{Rexp(i)}$: the ith experimental reduced water content;
$M_{Rpre(i)}$: the ith predicted reduced water content;
N: number of experimental points;
n_p: number of constants in the model studied;
X^*: reduced water content;
$X_{initial}$: initial product water content (kg water/kg fresh matter).