

Oven and Microwave Drying of Voandzou (*Vigna subterranea* (L.) Verdc) Seeds Harvested at Djambala and Nkamba: Study of Drying Kinetics and Modelling

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Received July 13, 2024; Revised August 15, 2024; Accepted August 22, 2024

Abstract The aim of this study was to model the drying kinetics of *Vigna subterranea* seeds harvested in Djambala and Nkamba. Two drying methods were used: radiation drying (microwave) at 380 W power and conduction drying (oven) at 70 °C. Weighing was carried out every 2 minutes. The choice of the best model was based on a comparison of R^2 , RMSE and χ^2 . The best model is the one with the highest R^2 and the lowest RMSE and χ^2 . The results show that the smaller Voandzou seeds from Nkamba dry faster than the larger Djambala seeds. Microwave drying is faster than oven drying. The modelling data showed that the best model for modelling the drying kinetics of voandzou seeds was the model of Midilli et al. whose R^2 vary between 0.99657 and 0.98503 for the oven-dried and microwave-dried Nkamba variety and between 0.99976 and 0.99998 for the oven-dried and microwave-dried Djambala variety

Keywords: Diffusivity, convection, OriginPro 8, drying curve, humidity

Cite This Article: Reyes Herdenn Gampoula, Michel Gadet Dzondo, Arnaud Wenceslas Geoffroy Tamba Sompila, Nadia Pamela Gladys Pambou-Tobi, Roniche Nguie, and Sylvia Pétronille Ntsossani, "Oven and Microwave Drying of Voandzou (*Vigna subterranea* (L.) Verdc) Seeds Harvested at Djambala and Nkamba: Study of Drying Kinetics and Modelling." *American Journal of Food Science and Technology*, vol. 12, no. 4 (2024): 133-138. doi: 10.12691/ajfst-12-4-4.

1. Introduction

In Africa, Voandzou (*Vigna subterranea* L.Verdc) is the third most important food legume in terms of production and consumption after groundnut (*Arachis hypogaeae* L.) and cowpea (*Vigna unguiculata* L Walp.) [1]. Voandzou (*Vigna subterranea* L.Verdc) is considered a neglected and under-exploited species [2]. According to Diallo et al., [1], Voandzou seeds are rich in protein and contain between 14.61 and 20.74 %. The use of Voandzou seeds in food improves the quality of the diet in terms of protein and antioxidant intake and contributes to the proper functioning of the body [3].

According to the African Post-Harvest Loss Information System, grain losses prior to processing and transformation vary from 10 % to 20 %. In Eastern and Southern Africa, these losses were estimated at 1.6 billion dollars a year, or around 13.5 % of the total value of grain production. Between 2005 and 2007, the total value of

post-harvest losses in sub-Saharan Africa was estimated at 4 billion dollars per year, for a total annual production valued at 27 billion dollars [4]. In order to promote the Voandzou crop, ensure the availability of seeds during non-harvest periods and combat post-harvest perishing, it is imperative to master seed drying techniques in order to effectively control the drying process and thus preserve the quality of the finished product.

Drying is a very old process for preserving agricultural and food products. It is used to convert perishable foodstuffs into stabilised products by lowering the water activity (aw) to a value below 0.5. Most of the time, these products are stored at ordinary temperature, before being rehydrated for use in an industrial process or in a culinary preparation [5]. The aim of drying is to reduce the water content of a wet product so that its water activity is raised to a value that allows it to be stored at ordinary temperature for long periods. Drying can be carried out by three (03) methods: convection drying, conduction drying and radiation drying. As the quality of the finished product depends on the processing conditions, modelling

the drying kinetics makes it possible to predict the evolution of the drying parameters in order to better size and control the drying process [6].

The aim of this work is to study the modelling of the kinetics of drying Voandzou seeds in an oven and in a microwave oven and to evaluate the method that gives a short drying time. This will enable us to understand the influence of microwaves on drying times.

2. Materials and Methods

2.1. Plant Material

The plant material used consists of two strains of voandzou: the Nkamba strain (harvested in the DRC) and the Djambala strain (harvested in the Republic of Congo).

The harvested pods were sorted to remove damaged seeds and then shelled to obtain the seeds.



Voandzou of Nkamba



Voandzou of Djambala

Photo 1. Seeds of Voandzou (*Vigna subterranea* (L.) Verdc)

2.2. Drying Kinetics

To monitor the loss of product mass during drying, we took weight measurements at different time intervals using a precision balance (OHOUS/Explorer Pro (0 - 210 g)). Drying time is the time required to dry a product to the desired final moisture content at a drying temperature less than or equal to the maximum temperature tolerated by the product.

In the oven (INDERLAB (0 - 250 °C)), drying took place at 70 °C, while in the microwave (Whirpool, EASY tronc, MO 201, two cooking levels) we worked with a power of 280 W.

The change in water content during drying enabled us to determine the variation in water content on a dry basis during drying.

It is given by the following formula [7]:

$$X = \frac{m - MS}{MS} \quad (1)$$

With:

X: water content on a dry basis (kg water/kg dry matter)

M: mass of the product

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

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

$$\frac{dX}{dt} = - \frac{(X(t + \Delta t) - X(t))}{\Delta t} \quad (2)$$

Where:

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

X: water content on a dry basis (kg water/kg dry matter)

Δt : Time difference in seconds.

2.3. Modelling Drying Kinetics

To model the drying kinetics, we used **Origin Pro 8** software, which allows us to determine the R^2 (coefficient used to predict the best equation describing the drying curves), the chi-square χ^2 (used to improve the smoothing accuracy) and the RMSE (mean square root error). The best model is the one with the highest R^2 but the lowest chi-square χ^2 and RMSE.

Drying kinetics are frequently represented by empirical or semi-empirical models (Table 1), for fruit and vegetables for example.

Although this approach is simpler than theoretical models, such as the diffusive model or the capillary transport model, it enables a mathematical representation to be produced quickly, with a view to optimisation [8].

$$X^* = \frac{X(t) - X_{eq}}{X_{cri} - X_{eq}} \quad (3)$$

Where:

X = the average water content of the product (kg water kg^{-1} ms)

X_{eq} = thermodynamic equilibrium water content determined by sorption isotherms diffusion coefficient [—]

X_{cri} = the critical water content marking the transition between the drying phase at constant speed (phase 1) and that at decreasing speed (phase 2)

The equilibrium water content corresponds to the limit value obtained after an infinite time for a product subjected to given temperature and humidity conditions.

Table 1 gives the equations for the four models we used:

Table 1. Models used to model sample drying

Models	Equations
Newton [9]	$X^* = \exp(-kt)$
Page [10]	$X^* = \exp(-kt^n)$
Henderson et al [11]	$X^* = a \times \exp(-kt)$
Midilli et al [12]	$X^* = a \times \exp(-kt^n) + b \times t$

Where: a, k, c and n are drying constants that depend on the air temperature and the nature of the product.

b is an empirical constant (s)⁻¹.

The fit between experimental and predicted data can be determined using the coefficient of determination (R²), the reduced chi-square (χ^2) and the root mean square error (RMSE). The choice of the best model is based on the highest R², lowest χ^2 and RMSE [12].

- The coefficient of determination (R²) is one of the first criteria for predicting the best equation to describe the drying curves.

$$R^2 = \frac{\sum_{i=1}^n (M_{Ri} - M_{Rpre,i})^2}{\sqrt{\left[\sum_{i=1}^n (M_{Ri} - M_{Rpre,i})^2 \right] \cdot \left[\sum_{i=1}^n (M_{Ri} - M_{Rexp,i})^2 \right]}} \quad (4)$$

- The statistical parameter chi-square (χ^2) is used to improve smoothing accuracy. This parameter is calculated using the formula:

$$\chi^2 = 2 \frac{\sum_{i=1}^N (M_{Rexp}(i) - M_{Rpre}(i))^2}{N - n} \quad (5)$$

- The mean square root error (RMSE)

$$RMSE = \sqrt{\frac{1}{N} \times \sum_{i=1}^N (M_{Rexp}(i) - M_{Rpre}(i))^2} \quad (6)$$

With $M_{Rexp}(i)$ the ith experimental reduced water content, $M_{Rpre}(i)$ the ith predicted reduced water content, N the number of experimental points and n_p the number of constants in the model studied.

Moisture transport in the food product depends on both the pore structure and the interactions of the moisture with the food matrix. Many models of simultaneous heat and mass transfer have been developed for drying. They are based either on moisture transfer for an effective diffusivity or on the separation of liquid and vapour diffusion [13].

3. Results and Discussion

The results of the drying kinetics for Voandzou (*Vigna subterranea*) are shown in Figure 1 below.

Analysis of Figure 1 shows that in Figure 1-a, mass loss is significant during the first 30 min for the Nkamba Voandzou. This is reflected in a steep slope of the curve, while the rapid loss in mass for the Djambala Voandzou is observed up to the first 180 minutes and then stabilises.

Analysis of Figure 1-b shows rapid water loss at the Voandzou de Nkamba. Minimum moisture content is reached in 10 min, compared with 40 min for steaming. The two curves show similar patterns, but microwave drying is faster than oven drying, because it takes less

time. These results are similar to those obtained for blood orange drying [14].

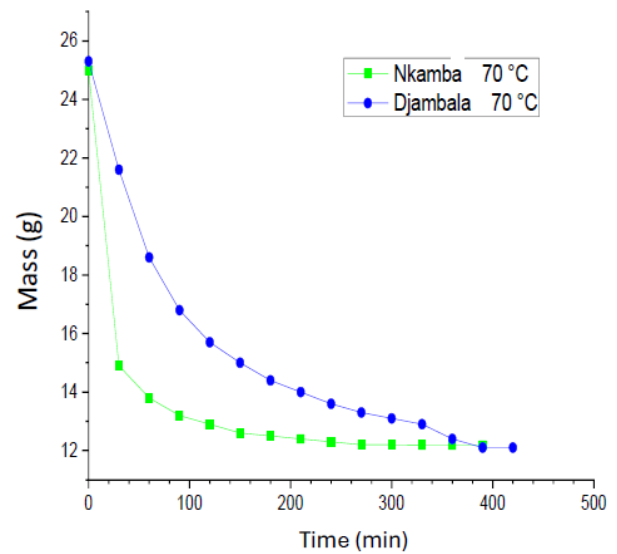
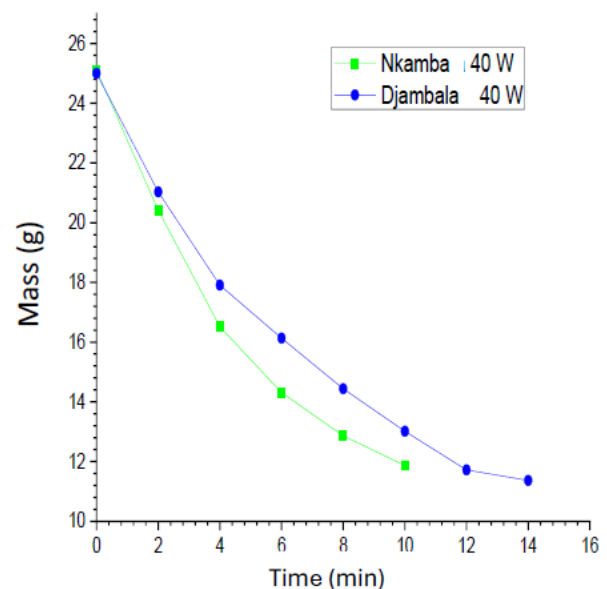
**(a)****(b)**

Figure 1. (a) - Variation in mass of Voandzou during oven drying at 70 °C (b) - Variation in the mass of Voandzou during microwave drying at 280 W

The variation in the mass of the seed provides information on the variation in the moisture content of the product, as shown in figure 2.

Figure 2-c shows a steep decline in moisture content during the first 30 minutes of drying for Voandzou from Nkamba. Overall, the reduction in moisture content is rapid for the Nkamba species.

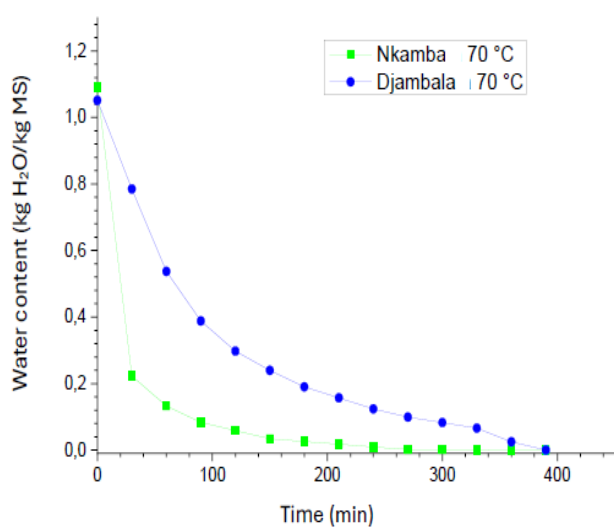
If we analyse the two curves shown in Figure 2 above, we can see that:

- the curve has two parts, the first part where the loss of water content is rapid and linear. During this phase, the quantity of water transported to the interface is greater than the quantity of water evaporated, leading to an accumulation of water.

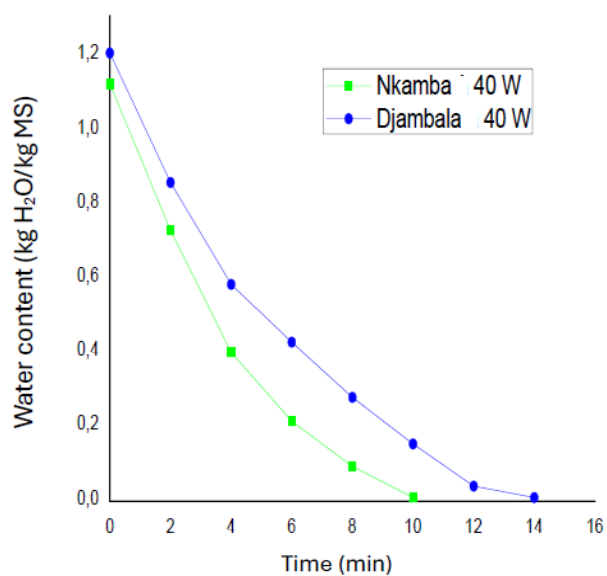
The second part is characterised by slower drying (low water loss). During this phase, there is significant evaporation of water to the surrounding environment [15].

- the drying time is shorter for Voandzou from Nkamba than for Voandzou from Djambala. Nkamba seeds dry more quickly than Djambala seeds. Nkamba seeds are smaller than Djambala seeds and therefore have a larger exchange surface area than Djambala seeds.

The stability of the seed mass can be explained by the fact that the temperature at the surface of the product has reached that of the drying air, which would be due to the low migration of water molecules from the inside to the surface of the product. The humidity at the surface of the product is equal to that of the drying medium. The product has lost almost all its free water [16].



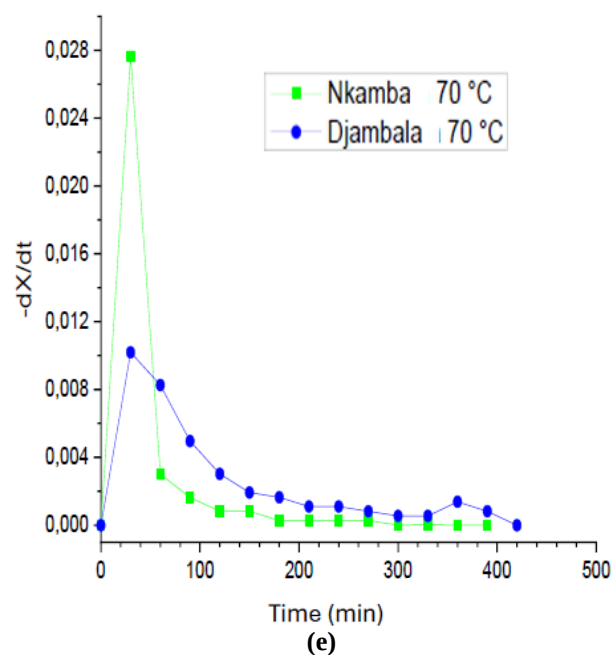
(c)



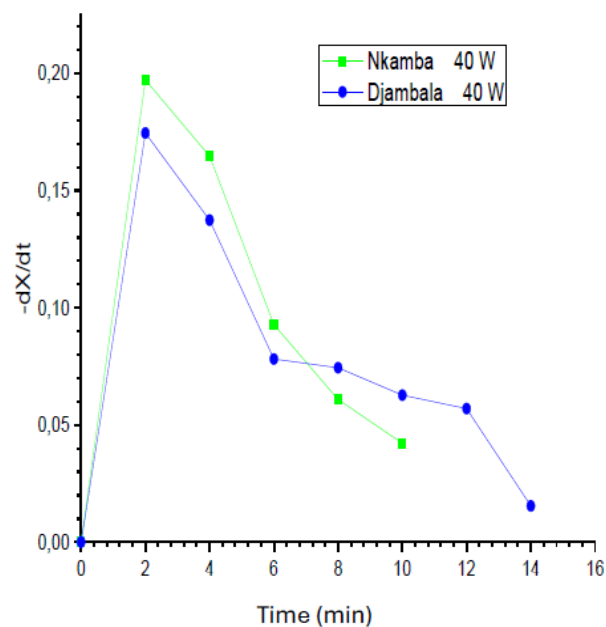
(d)

Figure 2. (c) - Variation in the water content of Voandzou seeds during oven drying at 70 °C (d) - Variation in the water content of Voandzou seeds during microwave drying at 280 W

Figure 3 below provides an overview:



(e)



(f)

Figure 3. (e) - Variation in the drying speed of Voandzou during oven drying at 70 °C (f) - Variation in the drying speed of Voandzou during microwave drying at 280 W

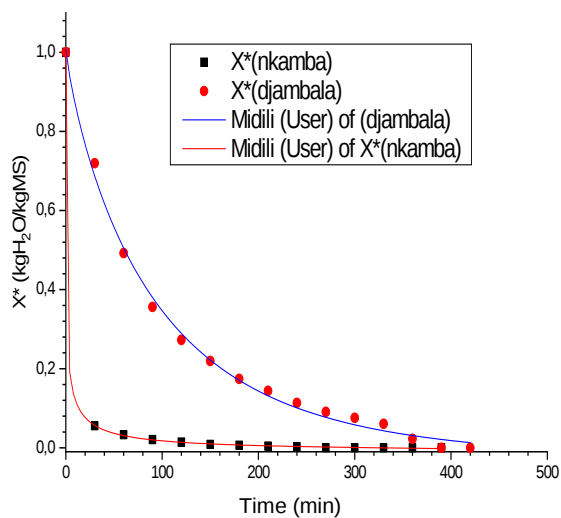
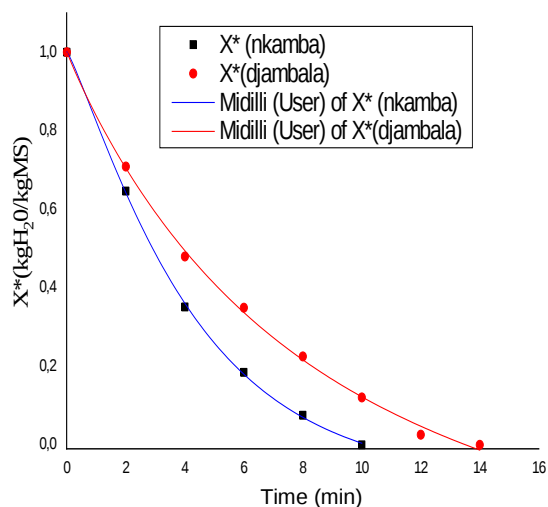
Nkamba seeds dry faster than Djambala seeds. The speed at the start of drying is higher in Nkamba seeds at the start of drying and slows down more quickly. If we analyse these figures, we can see that all four curves have a similar appearance. Microwave drying is faster than oven drying.

The drying process occurred during the period of falling rates when higher temperatures led to a reduction in moisture levels to a greater extent which can be correlated to higher temperatures causing more heat and mass transfer [17].

Table 2 below shows the results of modelling Voandzou (*Vigna subterranea*) seeds in the oven and microwave:

Table 2. Modelling parameters for drying Voandzou seeds (*Vigna subterranea*)

	Sample	Model	$K(s)^{-1}$	a	b	n	R^2	χ^2	RMSE
Oven at 70 °C	<i>Vigna subterranea</i> (Nkamba)	Newton	0,01042	-	-	-	0,99172	$6,5591.10^{-4}$	0,02637
		Page	0,01893	-	-	0,87515	0,99652	$3,16271.10^{-4}$	0,01778
		Henderson	0,01014	0,97474	-	-	0,99251	$6,81371.10^{-4}$	0,0261
		Midilli et al	0,02139	1,00695	$-3,71733.10^{-5}$	0,84661	0,99657	$3,61109.10^{-4}$	0,019
	<i>Vigna subterranea</i> (Djambala)	Newton	0,04499	-	-	-	0,98434	0,00108	0,03291
		Page	0,2806	-	-	0,49635	0,99945	$4,09579.10^{-5}$	0,0064
		Henderson	0,04473	0,99291	-	-	0,98439	0,00117	0,03419
		Midilli et al	1,13818	1	$-1,30101.10^{-5}$	0,27105	0,99998	$1,986210^{-6}$	0,00141
280 W microwave	<i>Vigna subterranea</i> (Nkamba)	Newton	0,1945	-	-	-	0,98503	0,00184	0,04295
		Page	0,13597	-	-	1,19532	0,99244	0,00109	0,03296
		Henderson	0,19884	1,02409	-	-	0,98589	0,00203	0,04503
		Midilli et al	0,1945	-	-	-	0,98503	0,00184	0,04295
	<i>Vigna subterranea</i> (Djambala)	Newton	0,27119	-	-	-	0,98572	0,00209	0,04571
		Page	0,17333	-	-	1,29944	0,99823	$3,22845.10^{-4}$	0,01797
		Henderson	0,27755	1,02709	-	-	0,98687	0,0024	0,049
		Midilli et al	0,18968	1,00077	-0,00561	1,1703	0,99976	$8,83673.10^{-5}$	0,0094

**a. Oven at 70°C****b. Microwave at 280 W****Figure 4.** Modelling the drying of Voandzou (*Vigna subterranea* (L.) Verdc.)

The models used were compared using the R^2 , the χ^2 and the **RMSE**. The results in this table show that these values range from 0.99172 to 0.99657, $3.16271.10^{-4}$ to $6.81371.10^{-4}$ and 0.01778 to 0.02637 for *Vigna subterranea* from Djambala, from 0.98434 to 0.99998, 1.986210^{-6} to 0.00117 and 0.00141 to 0.03291 for *Vigna subterranea* from Nkamba for oven kinetics; while for microwave kinetics, these values vary respectively from 0.98572 to 0.99976, $8.83673.10^{-5}$ to 0.0024 and 0.0094 to 0.049 for *Vigna subterranea* from Nkamba, and from 0.98503 to 0.9987, $2.79311.10^{-4}$ to 0.00109 and 0.01671 to 0.03296 for *Vigna subterranea* from Djambala.

From the results obtained (oven and microwave drying cases), the model of Midilli et al., is considered the best to describe the drying behaviour of *Vigna subterranea* and *Dioscorea cayenensis*. For tomato drying, similar results were found by Lahmari et al. [18] who showed that the best models for tomato drying are the models of Midilli et al. and Page. Kone et al, [19] showed that for microwave drying of sodium alginate gel, the best model is the model of Midilli et al.

Figure 4 describes the drying behaviour of the products used according to the model of Midilli et al.

$$a \times \exp(-kt^n) + b \times t$$

These results make it possible to optimise product drying, since the quality of the drying process determines the quality of the final products. Modelling also provides the data needed to design dryers adapted to drying tropical products [6].

4. Conclusion

The aim of this study was to model the drying kinetics of Voandzou seeds in a forced convection oven and in a microwave oven. The results showed that drying was faster in the microwave oven than in the oven. The best model to represent the drying kinetics of Voandzou seeds in an oven and a microwave oven is the model of Midilli et al.

These results are of great importance because they provide the data needed to design dryers specific to a type of product. In order to ensure the nutritional quality of the seeds dried by these two methods, further work could be carried out to assess the impact of the drying methods applied on the biochemical composition of the seeds, since the final state of the dried product depends on the quality of the drying.

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