

Mathematical Modelling of Fermented Chilli Pepper (*Capsicum chinense*) Drying in a Hot Air Oven

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Abstract

Chilli pepper (*Capsicum chinense*) is considered amongst the highly consumed spices in the Republic of Congo, wherein it is available at any time of the season. The product consumption in its raw state gives rise to considerable post-harvest losses, which is a problem that needs to be resolved. To resolve the problem to better the chilli pepper preservation, three (03) samples of chilli peppers were used to be fermented and dried in a FALC hot-air oven at temperatures of 45°C, 60°C and 70°C. Origin pro 18 software was used for mathematical modeling of thin-layer drying. Six (06) mathematical drying models were compared using the linear regression method, the constants, coefficients of the different models and statistical parameters—Coefficient of Determination (R^2)—Chi-Square (X^2)—Root Mean Square Error (RMSE)—were determined. Drying time decreased from 480 min to 150 min with increasing temperature from 45°C to 70°C. From these results, Wang and Singh's model satisfactorily describes the drying curve of fermented chilli pepper under the experimental conditions studied.

Keywords

Capsicum chinense, Fermented Chilli Pepper, Drying Kinetic, Mathematical Modeling

1. Introduction

The *Capsicum* genus comprises 23 species, 5 of which are cultivated: *Capsicum*

annuum, *Capsicum frutescens*, *Capsicum chinense*, *Capsicum baccatum*, and *Capsicum pubescens* [1]-[3] *Capsicum annum* has a wide variety of cultivated forms, including pungent and non-pungent varieties such as *capsicum*, while *Capsicum frutescens* has varieties whose forms are smaller and generally pungent [4].

The pepper is a tropical fruit that originated in South and Central America, then spread to Europe, Africa and Asia [5] [6]. Christophe Colomb introduced the pepper to Europe on his return from his first voyage to America. The Spanish, followed by the Portuguese, would later spread it around the world. Chilli-producing countries in Europe are Türkiye and Spain, and in Africa, Nigeria, Egypt and Ghana. Chilli production in Türkiye, Spain and Nigeria represented respectively 7%, 3.8% and 2.9% of world production in 2006 [7].

Although the consumption of *Capsicum* fruits is probably classified as one of the world's leading spices or food additives, the increase in its production is noticeable. China is the world's biggest pepper producer, producing over 125,000,000 tonnes in 2005. In 2005, Asia produced 65.6% of chilli pepper, followed by America (13.9%) and Africa (8.8%) [8].

Chilli peppers are a basic product that we use in many types of ethnic cooking, such as Thai, Korean, Indian, Hungarian, African, Mexican, etc. [9]. *Capsicum* fruits are popular and highly appreciated all over the world. They are often consumed as a food additive to provide a spicy taste.

To avoid post-harvest losses in developing countries, the most used process they implement is drying. Drying is a process of eliminating water by simultaneous heat and mass transfer (Gögüs, 1994), it is also one of the most widely used methods of preserving agricultural products, and is the most energy-intensive process in the industry [10].

Drying is one of the oldest food preservation techniques, and is a difficult food processing method due to undesirable changes in the quality of dried products [11]. Long shelf-life and product diversity are the reasons for the increasing presence of dried fruit and vegetables, and these could expand as product quality and process applications improve.

Drying food products is a vital technique for developing countries whose food self-sufficiency is mainly based on agriculture. It consists of reducing the water activity of these products to a value that ensures their conservation; this by respecting certain quality criteria linked to them and by guaranteeing, for the production chain, a reasonable rate and cost. Among the drying processes, we find sun drying, solar drying, lyophilization and hot air drying [12].

Sun drying has experienced rapid development in arid or semi-arid areas whose optimal climatic conditions are a dry season with considerable sun, low humidity and very low rainfall, this drying process has disadvantages such as: dried products being soiled with sand, the presence of various debris, dust. The presence of animals and insects in the environment attacks products exposed to the sun. All these disadvantages cause the dry product to be of lower quality because of the significant losses on the product, which damages the product. It is also observed that

the products dry too much or not enough [13].

Several research studies upon mathematical modeling and experimental studies on the thin-layer solar drying process for various vegetables and fruits, such as grapes [14], pistachio [15] and red peppers [11]. The solar dryer improves sun drying on 4 points namely: the speed of drying by reducing the time, the efficiency by reducing the deterioration or contamination of the product, the preservation of nutritional quality and the fact of being cheap [16].

Lyophilization is a process of preservation by vacuum desiccation of frozen products. The loss of water is mainly obtained by sublimating the ice under reduced pressure; there is then a direct passage from the solid state to the gaseous state. Lyophilization has disadvantages including: high cost which results in high investment and operating costs due to energy consumption, use of very tight packaging due to the very hydrophilic nature of the product, the process being limited to powdered or small-piece foods for the drying time and energy consumption are too much.

Hot air oven drying is a process where heated air is brought into contact with the wet material to be dried to facilitate heat and mass transfer. Transfers are essentially convective. Two important aspects of mass transfer are the transfer of water to the surface of the product and the removal of water vapor from the surface. This drying process is the most widely used nowadays due to its simple operating principle and low economic aspect. It is because of these advantages and the availability of the hot air-drying oven that we have retained this type of drying in this study.

Drying in a hot-air oven, contrary to the sun or shade drying, is still the best way to ensure uniform drying of the product, without any deterioration caused by environmental factors such as insects, birds, dust, etc. Work on drying requires simulation methods for large-scale drying. Therefore, a great deal of studies have been directed on how to carry out the drying of various fruits [15] and vegetables such as mushrooms and pollen [17], green bell pepper, green bean and pumpkin [14], red bell pepper [18] [19] and olive pomace [20].

In the Republic of Congo, it is noticeable to say that the more they produce chilli pepper, the lower they consume it. To avoid considerable post-harvest losses. There has been a need to utilize drying fermented chilli pepper process which is a chilli processing product that is free of the enterobacteria responsible for some gastroenteritis [21], making chilli pepper a healthy, non-toxic food product.

Fermented chilli pepper is a food product obtained by a tedious process of uncontrolled traditional fermentation of *Capsicum* fruits. This processing is carried out at family level or by small artisanal units in the Republic of Congo.

In this study, the drying behaviour in a hot-air oven of fermented pepper was investigated and mathematical modeling using thin-layer drying models was performed.

2. Materials and Methods

2.1. Material

The biological material presented in **Figure 1** is *Capsicum chinense* (pepper) fruit.



Figure 1. Fresh *Capsicum chinense* fruit.

2.2. Methods

2.2.1. Sampling

Fresh red chilli peppers of the *Capsicum chinense* variety were collected from markets in the city of Brazzaville in the Republic of Congo, including the Total market (MTO) in the Bacongo arrondissement, the Bourreau market (MBO) in the Makélékélé arrondissement and the Tsiémé market (MTS) in the Ouenzé arrondissement. These three (03) markets were chosen because they represent the key markets for the marketing of chillies in Brazzaville. The geolocation of these markets, determined using Garmin GPS, is shown in **Table 1**.

Table 1. Geolocation of sites.

Sites	Latitude	Longitude
Total Market	4.28829°S	15.25303°E
Bourreau Market	4.233848°S	15.2822°E
Tsiémé Market	4.29859°S	15.24049°E

2.2.2. Fermented Chilli Production

Samples of fresh chilli pepper purchased at the market are transported to the laboratory, the chilli pepper are sorted and the putrified ones are removed. The chilli pepper stems were removed and the chilli peppers were washed three (03) times with tap water, then left to drain. After draining, the chilli peppers were ground using an E-Jeff Moulinex and a quantity of cooking salt equivalent to 5% of the weight of the chilli pepper puree was added to each preparation, then the whole was mixed. For each site, 550 g of the mixture was placed in three (03) glass jars with stoppers, sterilized in an oven at 180°C for 2 hours. The mixture was left to ferment at room temperature for 7 days.

2.2.3. Drying Kinetics

Mass loss was carried out at temperatures of 45°C, 60°C and 70°C using a FALC hot-air oven with temperature 250°C ± 0.1°C. Continuous measurement of pepper mass loss through water elimination over time was carried out using a JA500-3N balance with a precision of 500 g ± 0.001 g.

To do this, 15 g of fermented chilli peppers were placed in previously dried and

weighed cups, then the whole was placed in a hot-air oven at drying temperature. Drying kinetics were monitored by taking weights every 30 min, and were stopped when the samples had a wet-base water content of at least 10% to 12% which corresponds to equilibrium humidity [11]. Each sample was analyzed in 3 trials. For drying kinetics, water content and reduced water content in dry basis were calculated and given by Equations (1) and (2)

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

where X : water content at time t ; m : mass at time t and m_s : equilibrium dry mass

$$MR = \frac{M - M_e}{M_0 - M_e} \quad (2)$$

where MR is the reduced moisture, M is the moisture content at time t , M_0 the initial moisture content and M_e the equilibrium moisture [11].

2.2.4. Mathematical Modeling

As shown in Table 2, six (06) semi-empirical and empirical models were used to select the best model to describe hot-air oven drying of fermented red chilli pepper. The different mathematical models examined are fitted to the experimental data by applying the linear regression method. Origin Pro 2018 software is used for mathematical modeling of drying.

Table 2. Mathematical models.

Model name	Model	References
Wang and singh	$MR = 1 + at + bt^2$	[22]
Newton	$MR = \exp(-kt)$	[14]
Page	$MR = \exp(-ktn)$	[23]
Page modified	$MR = \exp[-(ktn)]$	[24]
Approach of diffusion	$MR = a \exp(-kt) + (1 - a) \exp(-kbt)$	[25]
Verna <i>et al.</i>	$MR = a \exp(-kt) + (1 - a) \exp(-gt)$	[26]

In these equations, MR represents the reduced water content.

In these equations, MR represents the reduced water content calculated according to the relationship in Equation (2).

The criteria for assessing the smoothing quality of the experimental results are the coefficient of determination (R^2), the chi-square (X^2) and the root mean square error (RMSE).

These parameters are calculated using Equations (3), (4) and (5) [11].

$$R^2 = 1 - \frac{\sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})^2}{\sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})^2} \quad (3)$$

$$X^2 = \frac{\sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2}{N - z} \quad (4)$$

$$\text{RMSE} = \left[\frac{1}{N} \sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})^2 \right]^{\frac{1}{2}} \quad (5)$$

The coefficient of determination R^2 is the first criterion for assessing the smoothing quality of experimental results. The model that best describes drying kinetics is the one with the highest R^2 value and the lowest RMSE and X^2 values [11] [27] [28].

3. Results-Discussion

The kinetics curves of drying in a hot-air oven, showing the reduction in water content to a constant mass according to the time, at temperatures of 45°C, 60°C and 70°C, for samples from Total, Bourreau and Tsiémé markets are shown in **Figures 2-4**.

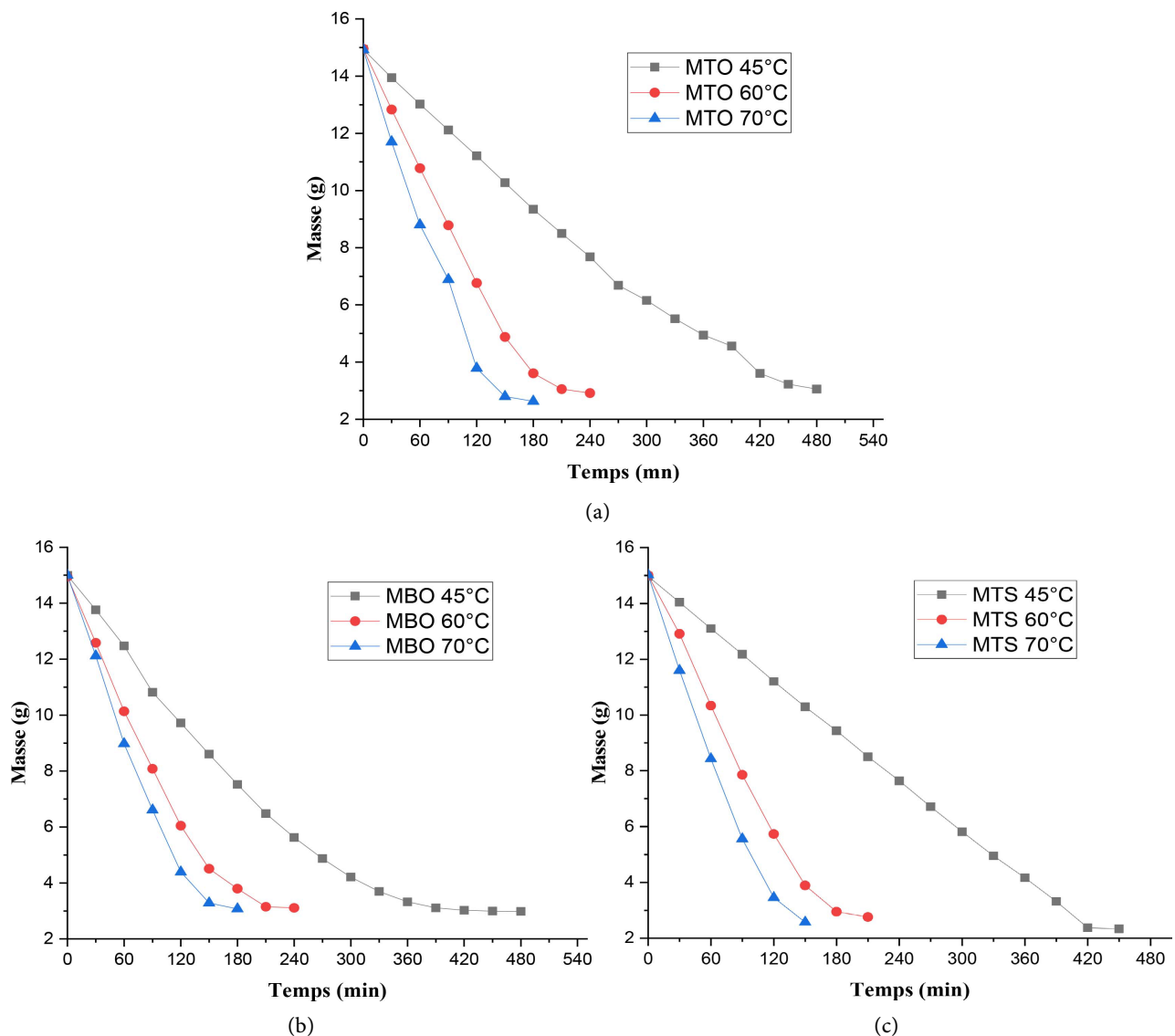


Figure 2. Mass evolution during drying kinetics, Total market (a), Bourreau market (b) and Tsiémé market (c).

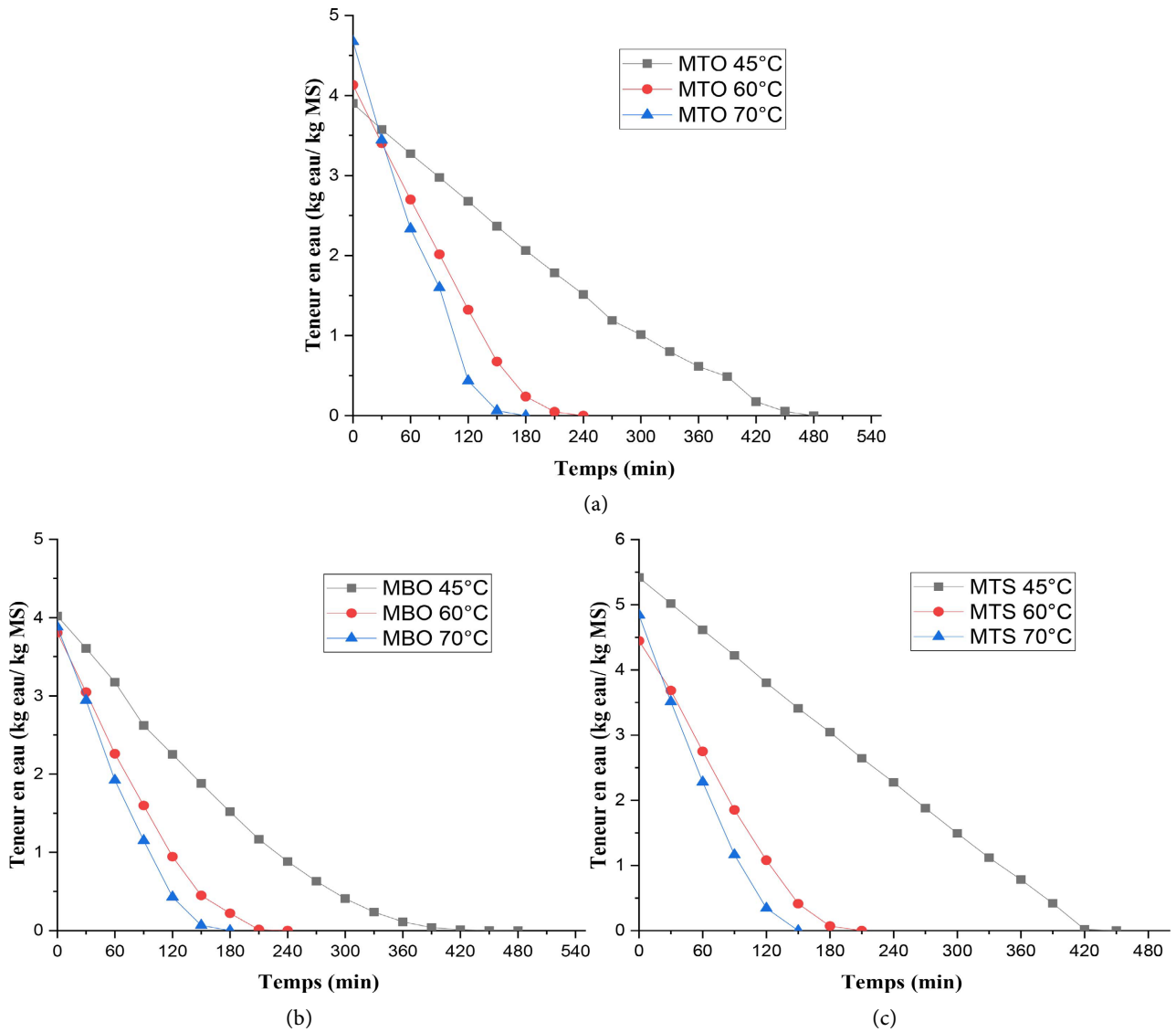
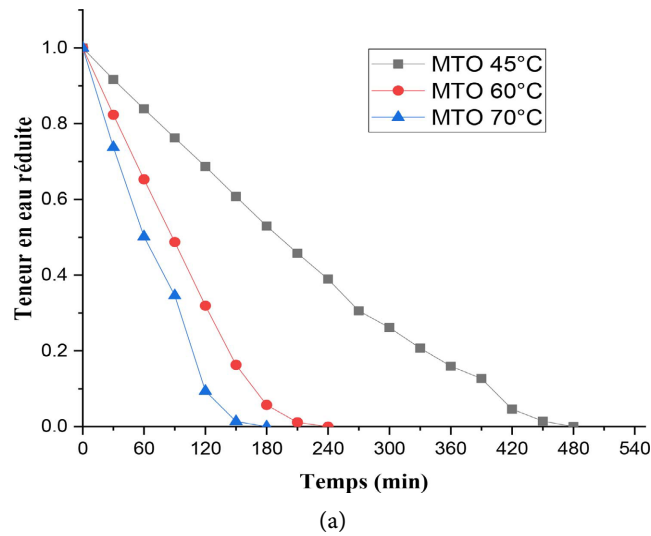


Figure 3. Evolution of water content during drying kinetics, Total market (a), Bourreau market (b) and Tsieme market (c).



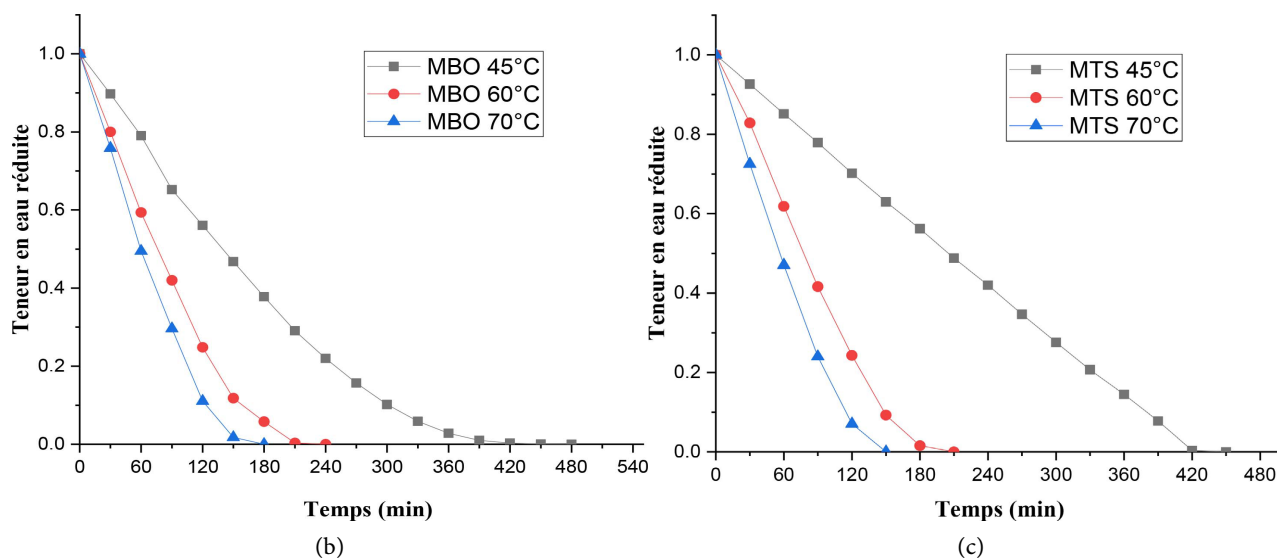


Figure 4. Evolution of reduced water content during drying, Total market (a), Bourreau market (b) and Tsieme market (c).

Figure 2 shows respectively mass evolution for the Total, Bourreau and Tsiémé markets.

Figure 3 shows respectively changes in water content on a dry basis for the Total, Bourreau and Tsiémé markets.

Figure 4 shows respectively the evolution in reduced water content on a dry basis for the Total, Bourreau and Tsiémé markets.

3.1. Analysis of Drying Curves

The drying kinetics of fermented chilli peppers began with an initial dry-base moisture content of $3.90\% \pm 0.25\%$ to $4.68\% \pm 0.14\%$; $3.81\% \pm 0.09\%$ to $4.02\% \pm 0.007\%$ and $4.45\% \pm 0.13\%$ to $5.42\% \pm 0.15\%$ respectively for Total, Bourreau and Tsiémé markets.

For the different sites, drying follows a more or less identical pattern, with drying times of 480 min at 45°C, 240 min at 60°C and 180 min at 70°C in the case of the Total market, of 480 min at 45°C, 240 min at 60°C and 180 min at 70°C for the Bourreau market and of 450 min at 45°C, 210 min at 60°C and 150 min at 70°C for Tsiémé market.

3.2. Modeling

The calculated values of the statistical parameters used are shown in **Tables 3-5** for the Total, Bourreau and Tsiémé markets respectively. The different models are compared on the basis of R^2 , X^2 and RMSE values. These values range respectively from 0.94531 to 0.99861, 1.59×10^{-4} to 7.53×10^{-3} , 2.38×10^{-3} to 9.107×10^{-2} for Total market, from 0.92376 to 0.99867, 1.55×10^{-4} to $8, 47 \times 10^{-3}$, 1.65×10^{-3} to 1.250×10^{-1} for Tsiémé market and from 0.96134 to 0.99822, 2.20×10^{-4} to 5.15×10^{-3} , 1.77×10^{-3} to 6.872×10^{-2} for Bourreau market.

The pattern of high R^2 values and low X^2 and RMSE values indicates the good fit of all models to the experimental results.

Table 3. Statistical parameter values for Total Market.

Model	T°	R ²	X ²	RMSE	Constant
Wang et singh	45 °C	0.99861	1.59E-04	0.00238	a = -0.00294; b = 1.70601E-6
	60 °C	0.99345	0.00103	0.00721	a = -0.00706; b = 1.1408E-5
	70 °C	0.99221	0.00139	0.00693	a = -0.00985; b = 2.29718E-5
Newton	45 °C	0.94683	0.00569	0.09107	k = 0.00432
	60 °C	0.94531	0.00753	0.06024	k = 0.01014
	70 °C	0.95252	0.00703	0.04219	k = 0.01407
Page	45 °C	0.99096	0.00103	0.01548	k = 3.00926E-4; n = 1.48339
	60 °C	0.99306	0.00109	0.00764	k = 6.10368E-4 ; n = 1.59275
	70 °C	0.98677	0.00235	0.01175	k:0.00151; n = 1.5016
Page modified	45 °C	0.99101	0.00103	0.01541	k = 0.00422; n = 1.50165
	60 °C	0.99309	0.00109	0.00761	k = 0.00958; n = 1.61263
	70 °C	0.9868	0.00235	0.01173	k = 0.01322; n = 1.51846
Approach of the diffusion	45 °C	0.99825	2.14E-04	0.00299	a = -9582.25309; k = 8.37189E-4; b = 1.00027
	60 °C	0.99066	0.00171	0.01028	a = -48.82034; k = 0.00267; b = 1.03491
	70 °C	0.98933	0.00237	0.00948	a = -10901.10145; k = 0.00429; b = 1.00013
Verna <i>et al.</i>	45 °C	0.99825	2.14E-04	0.00299	a = -32.08737; k = 8.03963E-4; g = 8.70366E-4
	60 °C	0.99066	0.00171	0.01028	a = -50.70952; k = 0.00267; g = 0.00276
	70 °C	0.98933	0.00237	0.00948	a = -47.60989; k = 0.00423; g = 0.00435

Table 4. Statistical parameter values for Bourreau Market.

Model	T°	R ²	X ²	RMSE	Constant
Wang et singh	45 °C	0.99822	2.20E-04	0.0033	a = -0.00434; b = 4.65703E-6
	60 °C	0.9977	3.58E-04	0.00215	a = -0.00791; b = 1.47892E-5
	70 °C	0.9964	5.64E-04	0.00339	a = -0.00932; b = 2.18977E-5
Newton	45 °C	0.96282	0.0043	0.06872	0.00608
	60 °C	0.96134	0.00516	0.03614	0.01116
	70 °C	0.97247	0.0037	0.02592	0.01279
Page	45 °C	0.99606	4.8577E-04	0.00729	k = 5.97462E-4. n = 1.43873
	60 °C	0.99617	5.9731E-04	0.00358	k = 0.00123. n = 1.47619
	70 °C	0.99812	2.9459E-04	0.00177	k = 0.00193. n = 1.41894
Page modified	45 °C	0.99608	4.8358E-04	0.00725	k = 0.00574. n = 1.45102
	60 °C	0.99618	5.9525E-04	0.00357	k = 0.01069. n = 1.48737
	70 °C	0.99812	2.9443E-04	0.00177	k = 0.01221. n = 1.42204
Approach of the diffusion	45 °C	0.99296	9.2888E-04	0.013	a = -3264.55886; k = 0.00237; b = 1.00031
	60 °C	0.9959	7.6689E-04	0.00383	a = -10811.39793; k = 0.00331; b = 1.00014
	70 °C	0.99291	1.3400E-03	0.00668	a = -48.96302; k = 0.0052; b = 1.0195

Continued

Verna <i>et al.</i>	45 °C	0.99296	9.2890E-04	0.0130	a = -54.94334; k = 0.00235; g = 0.00239
	60 °C	0.99590	7.6692E-04	0.00383	a = -40.58962; k = 0.00325; g = 0.00337
	70 °C	0.99291	1.3400E-03	0.00668	a = -49.61713; k = 0.00521; g = 0.00531

Table 5. Statistical parameter values for Tsiémé Market.

Model	T°	R ²	X ²	RMSE	Constant
Wang et singh	45 °C	0.99867	1.55E-04	0.00218	a = -0.00259; b = 6.40248E-7
	60 °C	0.99204	0.00135	0.00811	a = -0.0078; b = 1.35857E-5
	70 °C	0.99784	4.13E-04	0.00165	a = -0.0106; b = 2.54648E-5
Newton	45 °C	0.92376	0.00834	0.12507	0.00415
	60 °C	0.94182	0.00847	0.05927	0.01128
	70 °C	0.95808	0.0064	0.03198	0.01531
Page	45 °C	0.9841	0.00186	0.02608	k = 1.54176E-4; n = 1.59732
	60 °C	0.99586	7.04E-04	0.00422	k = 5.39518E-4; n = 1.65801
	70 °C	0.99483	9.87E-04	0.00395	k = 0.00153; n = 1.53304
Page modified	45 °C	0.98421	0.00185	0.02591	k = 0.0041; n = 1.62926
	60 °C	0.99588	7.00E-04	0.0042	k = 0.01068; n = 1.67446
	70 °C	0.99484	9.84E-04	0.00394	k = 0.01454; n = 1.54457
Approach of the diffusion	45 °C	0.99864	1.71E-04	0.00223	a = -2089.95187; k = 2.79626E-4; b = 1.00396
	60 °C	0.98953	0.00213	0.01066	a = -59.27138; k = 0.00275; b = 1.03169
	70 °C	0.99648	8.94E-04	0.00268	a = -43.78978; k = 0.00394; b = 1.03994
Verna <i>et al.</i>	45 °C	0.99864	1.71E-04	0.00223	a = -23.71983; k = 2.32173E-4; g = 3.27671E-4
	60 °C	0.98953	0.00213	0.01066	a = -56.42184; k = -56.42184; g = 0.00284
	70 °C	0.99648	8.94E-04	0.00268	a = -41.77113; k = 0.00394; g = 0.00411

For the 3 sites, of the six (06) models studied, the Wang and Singh model gave the highest R^2 value and the lowest X^2 and RMSE values for the different temperatures studied. The Wang and Singh model reported the best fit for hot-air oven drying of fermented chilli pepper.

It is followed by the Approach of diffusion model, which gives R^2 values lower than those of the Wang and Singh model and higher than those of the other models, while X^2 and RMSE values are higher than those of Wang and Singh and lower than those of the other models. Newton's model is the one that reports the poorest fit of thin-film drying of fermented chilli pepper for drying in a hot-air oven, with R^2 values lower than those of the other models and X^2 and RMSE values higher than those of the other models.

3.3. Discussion

Due to the particularity of fermentation in food safety and preservation, chilli pep-

per was fermented before being dried. During the fermentation of chilli pepper, the microorganisms responsible for fermentation acidify the environment by producing microbial peptides and organic acids such as lactic acid which makes the environment acidic [21].

In the case of microbial peptides, these substances have specific antimicrobial activity against many food pathogens, such as *Lactobacillus* and *Lactococcus* which produce bacteriocins that inhibit the growth of *Listeria*, *Monocytogenes* which are food pathogens.

For organic acids such as lactic acid, vegetables and cereals fermented by lactic acid bacteria mainly of the genus *Lactobacillus* transform the sugars present in food into lactic acid, the latter lowers the pH of the medium to values of 3.84 ± 0.13 and 4.2 ± 0.01 respectively for fermented corn porridge and *Capsicum frutescens* fruits preserved in jars [21] [29].

This acidification of the medium creates a hostile environment for many pathogenic microorganisms such as *Salmonella*, *E. coli*, and *Listeria* which are not acidophilic. This low pH, combined with the absence of oxygen in fermented products, also inhibits the growth of molds and other harmful bacteria. The product resulting from fermentation is, in view of these conditions, a product that can be preserved for a long time in an obvious food safety character.

Time differences in drying kinetics can be influenced by various factors such as temperature, air humidity and air velocity. Temperature is the factor that most influences the rate of water evaporation in products. A low temperature leads to slow drying. This explains the differences observed between drying times. By increasing the drying temperature, water evaporates quickly from the product to the outside, which reduces the drying time.

These results of drying times are close to 300 min, 240 min and 160 min respectively, at temperatures of 55°C, 60°C and 70°C, from those of [11], who reported on thin-layer drying of fresh peppers. The drying times found are lower than those of 16 hours to 33 hours found by [30] on the mathematical modeling of drying in a hot air oven of mango slices (*Mangifera indica* L.), those of 35 hours on the drying of cocoa beans in the sun [31] and those of 5.5 hours to 8.5 hours found by [32] on the modeling the drying kinetics of Pigeon Pea (*Cajanus cajan*). These results show that temperature has a significant influence on pepper drying time. An increase in temperature leads to a decrease in product drying time. This confirms that drying speed is a function of the time-temperature pair.

The analysis of the values of the coefficient of determination (R^2) revealed values greater than 0.92 [33]. This information thus reflects a good smoothing of the experimental and predicted data in this study.

Of the six (06) models used, the Wang and Singh model is the one that reports a better smoothing, it is followed by the Approach of diffusion model, the Verna model and the Newton model is the one that reports a poor smoothing. This result is close to that of [11] on the thin layer drying of red pepper whose best drying model is that of the diffusion approach and that of verna. The model chosen is

different from the logarithmic model chosen in the mathematical modeling of drying in a hot air oven of mango slices (*Mangifera indica* L.) [30]

These results differ from those of [11], who reported on thin-layer drying of fresh peppers at temperatures of 55°C, 60°C and 70°C that the best model is the approximate diffusion following by Verna model.

4. Conclusions

In this work, the drying kinetics of fermented chilli pepper in a hot-air oven were studied at three (03) temperatures, namely 45°C, 60°C and 70°C. The results show that the drying time decreases significantly from 480 min to 150 min with temperature from 45°C to 70°C. The speed of drying increases with the high temperature. Only the decreasing rate phase is present in chilli pepper drying. The moisture content and drying rate were influenced by the drying air temperature.

Among the six (06) semi-empirical and empirical mathematical models used, Wang and Singh's model, with R^2 , X^2 and RMSE values of 0.99861, 1.59×10^{-4} and 2.38×10^{-3} respectively, appears to be the most appropriate to describe the drying kinetics of fermented chilli pepper (*Capsicum chinense*) in hot-air oven under the experimental conditions studied.

Conflicts of Interest

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

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