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# Modelling the dehydration kinetics of four onion varieties in an oven and a solar greenhouse

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A B S T R A C T

The Oven drying kinetics mathematical modelling of four Senegalese onion varieties is carried out in the temperature range from 50 °C to 70 °C.

The $R^2$ (dispersion test) and the $\chi^2$ (fit test) between the experimental data and the values predicted by the models show that whatever the temperature and the variety, the Verma et al. model is the one that best fits the oven drying kinetics. The $R^2$ average and $\chi^2$ average values for the Galmi Violet, Safari, Gandiol F1 and Orient F1 are respectively between 0.9848 to 0.9961 and 0.0010 to 0.006. This best model is validated on the solar greenhouse drying kinetics at variable temperatures during the drying process.

The Drying Characteristic Curves (DCCs) have identical patterns for the four onion varieties and are described with third order polynomials in the reduced moisture content range from 0.1 to 0.7. The Galmi Violet, with the slowest drying rate, is the limiting variety, followed by the Safari, Gandiol F1 and Orient F1. Furthermore, the critical and equilibrium reduced moisture content deduced from the DCCs are respectively between 0.55 to 0.70 and 0.05 to 0.15.

## 1. Introduction

The high moisture content of food has always been an obstacle to the availability of all-season products. The methods for reducing moisture content are the key solutions for improving storage life of products such as vegetables (Bonazzi et al., 2008; Jeantet et al., 2008).

Drying process is one of the oldest techniques used to master water in food products. This process involves heat and mass transfers both internally and externally, which can alter the nutritional and organoleptic quality of the dried products (Ali et al., 1999; Lombard et al., 2005). Several factors, such as the experimental conditions, the origin, the shape and the texture of the products, have an influence on these transfers and make complex the microscopic study of the kinetics of drying (Clemente et al., 2011; Doymaz, 2010). Thus, to ensure the control of the process, some researchers have resorted to the mathematical modelling of these transfers either separately (Ceaglske & Hougen, 1937; Sherwood, 1929), or coupled (Philip & De Vries, 1957; Whitaker, 1977). However, Empirical models based on simultaneous heat and mass transfers best describe the dehydration process. These models rely on fundamental physical phenomena such as diffusion, capillary theories and thermodynamics of irreversible phenomena. The solutions of these models refer to statistical methods of nonlinear regression (Erdoğdu, 2013; Manaa, 2017; Mujumdar, 2014; Soulier, 1994).

Previous research studies on different food products show that mathematical modelling allows to control these complex physical phenomena and to optimize the drying process. Nonetheless, these models do not provide enough information on the products shape changes during drying. Their validity depends on the experimental conditions, but also on the specificities of the products and implies a certain number of hypotheses.

Most of the studies related to the drying of food products in the literature refer to tomato (Prakash & Kumar, 2014), okra, ginger, cassava (Ahouannou et al., 2000), onion (Kiranoudis et al., 1992; Krokida et al., 2003; Sarsavadia et al., 1999) and carrot (Nguyen, 2015).

In Senegal, onions bulbs are one of the most commonly used staple foods, and this because of its flavours development in meals. The annual

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consumption ranges from 150,000 to 250,000 tons (DH, 2015).

However, onion perishability due to its high moisture content which ranges from 83% to 92% (Albitar et al., 2011; CIQUAL, 2017) and the non-mastery of drying process optimization lead to major post-harvest losses in Senegal.

The rationales of this research paper are the deficiencies noted above, as well as the influence of the origin of the products on drying kinetics and the lack of data in the literature on these four varieties.

The objective of this study is to optimize and master by mathematical modelling of both oven and solar greenhouse drying kinetics of four onion varieties grown in Senegal and to establish characteristic drying curves. Empirical mathematical models are tested in this paper to determine the best model for predicting drying kinetics for a better cost and quality control under different experimental conditions.

## 2. Materials and methods

### 2.1. Materials

#### 2.1.1. Plant materials

The main four local onion varieties grown in Senegal, namely Galmi Violet, Safari, Gandiol F1, and Orient F1, are used in this study. The maturity levels of the four onion varieties expressed in terms of percentage of leaf loss at the beginning of harvest are superior to 85% because it needs less activation energy for drying (Beye et al., 2018).

#### 2.1.2. Drying and analysis equipment

The equipments used for the drying process are an oven (Memmert brand with 0.1 °C accuracy), a solar greenhouse with a ventilation system to regulate the temperature and humidity of the ambient air, and pyrex cups and racks respectively for spreading the onion samples in thin monolayer in the oven and in the solar greenhouse (Fig. 1).

To ensure the homogeneity of the samples, a chopper was used for the cutting and a micrometer (RS PRO brand with a reading range of 0–25 mm and 0.001 mm accuracy) to measure the size of the samples.

The instruments used to monitor the critical parameters for the drying process are sensors set in the four corners of the solar greenhouse and on the racks for temperature and humidity reading, an anemometer (TFA Dotsmann brand with 0.05 m $s^{-1}$ accuracy), a thermohygrometer (Voltcraft brand with 1 °C accuracy), a precision scale (Denver instrument brand with 0.0001g accuracy) and laboratory glassware.

#### 2.1.3. Statistical analysis and modelling tools

Data exploitation and modelling are carried out with both the R version 3.4.0 (R Core Team, 2017) software for the comparison test between the two drying methods, the analysis of variance and measure concordances, and the scilab version 6.0.0 software as a scientific computing tool to calculate the parameters of different models, to identify the best drying kinetics mathematical model and to establish the characteristic drying curve for each variety.

### 2.2. Methods

#### 2.2.1. Drying kinetics protocol

The study and optimization of the drying kinetics of the local onion varieties were performed with the gravimetric method. The thicknesses of the onion slices are on average 1.7 mm (Brooks et al., 2008; Madamba et al., 1996; Mazza and Lemaguer, 1980).

For each of the four varieties, the drying was carried out three times in the same operating conditions and the samples are spread in thine monolayer on the pyrex cups for the oven and on the rack for the solar greenhouse.

The weight losses are monitored every hour until a constant weight reached, and the stability moisture target for dried products is ≤8% (ESA, 2004; Faiveley, 2012; Le Meste, Simatos and Lorient, 2002).

The initial moisture content ($X_0$) and the moisture at the end of each drying hour ($X_{exp,t}$) were determined via desiccation at 105 °C for 2 h:

➢ The initial moisture content

$$X_0 = \frac{m_0 - m_{s,0}}{m_{s,0}} \tag{1}$$

with $m_o$ the weight of the non-dried product and $m_{s,0}$ its weight after desiccation.

➢ The moisture content at the different drying hours

$$X_{exp,t} = \frac{m_t - m_{s,t}}{m_{s,t}} \tag{2}$$

with $m_t$ the weight of the product at the end of a given time and $m_{s,t}$ its weight after desiccation.

The drying experiences are set in an oven and a solar greenhouse in order to determine whether both processes provide identical drying kinetics or which one is more efficient.

##### 2.2.1.1. Oven drying protocol

First, the experiments were done at a temperature ranging from 50 °C to 70 °C with a step of 5 °C to determine the optimum temperature/time to obtain stable products. A drying air velocity of 2.4 m $s^{-1}$ and a relative humidity between 10 and 15% are the other important experimental conditions set up for the oven drying as suggested in the literature (Babalis and Belessiotis, 2004; Clemente et al., 2011; Doymaz, 2010; Kiranoudis et al., 1992; Krokida et al., 2003; Sarsavadia et al., 1999).

For each of the four varieties, ten grams of thinly chopped onions from three different bulbs are spread in the pyrex cups.

##### 2.2.1.2. Solar greenhouse drying protocol

The four varieties are dried simultaneously. A total of 12 kg of thinly chopped onions of each variety were spread into three monolayers over the racks for one variety per rack.

(a) (b)

**Fig. 1.** (a) Photo of the pyrex cups for monitoring drying kinetics in the oven and (b) photo of a rack for monitoring drying kinetics in the solar greenhouse.

Inside the solar greenhouse, removable room sensors monitor the evolution of the temperature and the relative humidity, which are the two key parameters for drying. The relative humidity and the temperature in the solar greenhouse dryer vary respectively between 10 and 60% and 35 °C - 65 °C. The drying of the four onion varieties was done for two days in order to achieve moisture stability.

*2.2.1.3. Modelling of drying kinetics.* Nine empirical mathematical models are tested for modelling the four onion varieties thin layer drying kinetics. The models equations of Lewis, Henderson and Pabis, Page, Logarithmic, Two-term, Two-term exponential, Approximation of diffusion, Verma et al., Midilli et al. are used to calculate the predicted reduced moisture content (Xrpred) (Boughali, 2010; Hendreson & Pabis, 1961; Jannot, 2006; Lewis, 1921; Midilli et al., 2002; Nguyen, 2015; Page, 1949).

As for the experimental reduced moisture content (Xrexp), it is calculated with the following formula:

$$Xr_{exp,\,t} = \frac{X_{exp,\,t} - X_{eq}}{X_0 - X_{eq}} \tag{3}$$

Where

Xrexp,t is the experimental reduced moisture content at different drying times;
Xexp,t: the moisture content at the different drying times;
$X_0$: the initial moisture content;
Xeq: the moisture content at equilibrium, small in front of Xexp,t and $X_0$, is neglected.

The parameters of the model are estimated with nonlinear regression with Scilab software. The least squares method is used to determine the best model by calculating the determination coefficient $R^2$, which must be close to 1 to reflect a lower data dispersion. The fit between the experimental data to those predicted with the best model is evaluated with the chi-square test ($\chi^2$) whose value must be closest to 0. The formulas are as follows:

$$R^2 = \frac{\sum_{i=1}^{n}(Xr\,pred,i - \overline{Xr}\,pred)^2}{\sum_{i+1}^{n}(Xr\,exp,i - \overline{Xr}\,exp)^2} \tag{4}$$

$$\chi^2 = \frac{\sum_{i=1}^{n}(Xr\,exp,i - Xr\,pred,i)^2}{N-n} \tag{5}$$

With N the number of experimental data and n the number of parameters for the model.

The drying rates of the four onion varieties at different temperatures are plotted by deriving the equations of the best models.

$$\frac{dXrpred}{dt} = f(t) \tag{6}$$

*2.2.1.4. Drying characteristic curves.* The Drying Characteristic Curves (DCCs) allow to study the behaviour of the products without taking into account the complex phenomena of internal transfers. The drying rates depending on the predicted reduced moisture content are plotted on the same graph for all temperatures used in this experiment.

$$\frac{dXrpred}{dt} = f(Xrpred) \tag{7}$$

The DCC for each variety is obtained by regression on the drying rate curve depending on the reduced moisture content. It thus reflects the behaviour of the product regardless of the conditions of the experiments and represents the product identity card. The equations of the curves are set by regression using Scilab.

## 3. Results

The coefficient of LIN obtained with the numerical statistical test of LIN for all the different temperatures vary between 0.9994 and 0.9999 with a confidence interval of [0.9992; 0,9999]. And, this shows that there is a perfect match between the three measures done for each variety both for the oven and the solar greenhouse drying.

### *3.1. The evolution of the four onion varieties moisture content during drying by oven and solar greenhouse*

Figs. 2 and 3 respectively show, depending on the drying time, the evolution of the moisture content of Galmi violet, Safari, Gandiol F1 and Orient F1 varieties dried in an oven and in a solar greenhouse. The determination of the moisture contents is performed from Eqs. (1) and (2).

The moisture removal rate of the four onion varieties increases with the controlled drying temperature in the oven. For drying temperatures of 50 °C, 55 °C, 60 °C, 65 °C and 70 °C in the oven, the drying times, required to reach the stability moisture (≤8%), are respectively specified below:

- Galmi Violet after 8h, 7h, 6h, 5h et 4h;
- Safari after 10h, 9h, 7h, 6h et 5h;
- Gandiol F1 after 11h, 9h, 7h, 6h et 5h;
- Orient F1 after 9h, 8h, 7h, 5h et 5h.

It appears (Fig. 2) that the drying time decreases with the increase of temperature. Moreover, the best time-temperature drying couples in the oven are 55–65 °C/7h–8h with an optimum at 60 °C/6h (Galmi Violet) and 7h (Safari, Gandiol F1 and Orient F1).

The moisture stability of the four dried onion varieties in the solar greenhouse (Fig. 3) is reached after 8h for the Safari and Gandiol F1 varieties and 9h for the Galmi Violet and Orient F1 varieties. At the beginning of the first drying day, the temperature in the solar greenhouse increases and stabilizes at a maximum of about 65 °C after 2 h, then the temperature decreases to 35 °C at the end of the first drying day. The drying process was stopped for day 1 after 7 h because the water removal becomes weak and the low temperatures can affect the dried products quality. Depending on the variety, the onions moisture contents are between 8 and 10% after 7 h of drying in day 1. At the starting of drying on the second day, the drying process resumes with these same moisture contents (no variation in the dried onions moisture content is observed during the night due to storage in a desiccator). On the second drying day, the stability moisture content is reached after 1–2 h depending on the variety.

The statistical test results for the comparison of the oven drying kinetics data with that in the solar greenhouse, are between [-0.44906; 0.73362] for the Student parameter (t), [0.4697–0.9572] for the p-value and [24–26] for the degree of freedom (df).

Whatever the oven drying temperature, the p-values > 5% show that, there is no significant difference between oven drying and solar greenhouse drying kinetics (Beye et al., 2019).

### *3.2. Modelling oven drying kinetics*

#### *3.2.1. Determination of the best model for the reduced moisture content*

*3.2.1.1. Statistical parameters ranking of the different models.* The statistical criteria obtained by the least squares method are shown in Tables 1, 2, 3 and 4 respectively for Galmi Violet, Safari, Gandiol F1 and Orient F1 varieties.

The values of $R^2$ and $\chi^2$ (Table 1) show that the Verma et al. model fits better the Galmi Violet variety experimental reduced moisture in the temperature range of 50 °C to 60 °C, whereas for the 65 °C and 70 °C

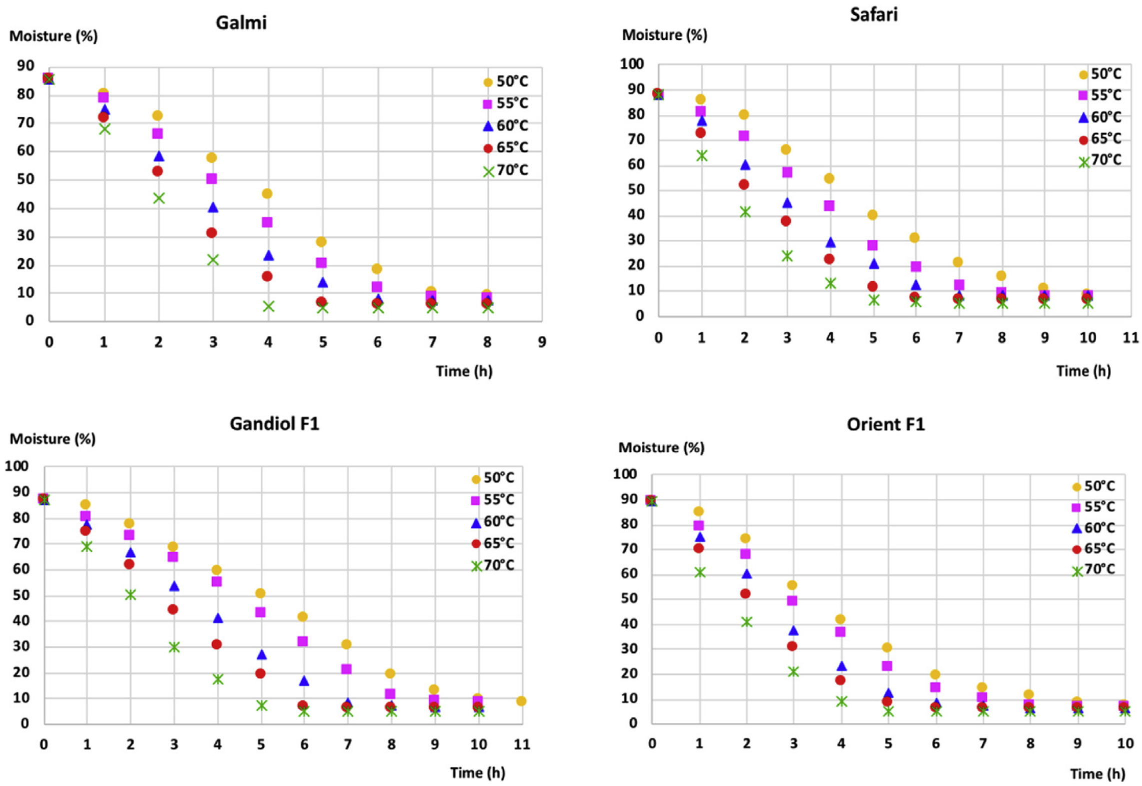


**Fig. 2.** Moisture content evolution of the four dried onion varieties in an oven.

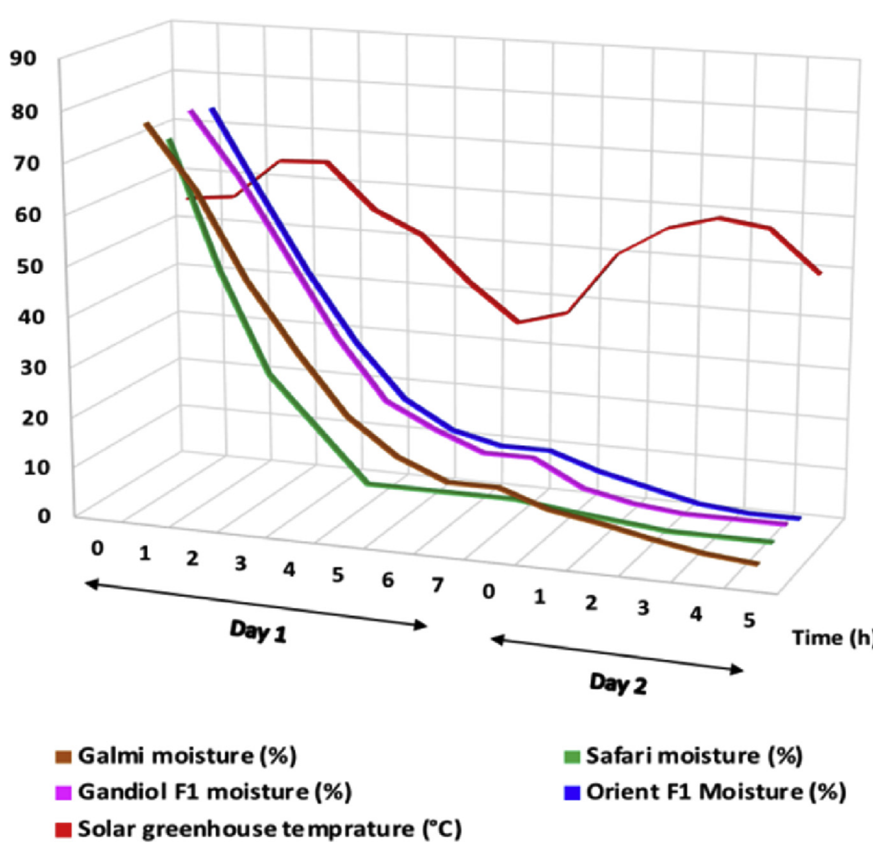


**Fig. 3.** Moisture content evolution of the four dried onion varieties in a solar greenhouse.

**Table 1**
Statistical criteria to choose the Galmi Violet best model.

| Galmi Violet Models | Temperature (° C) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 50 | | 55 | | 60 | | 65 | | 70 | |
| | $R^2$ | $\chi^2$ | $R^2$ | $\chi^2$ | $R^2$ | $\chi^2$ | $R^2$ | $\chi^2$ | $R^2$ | $\chi^2$ |
| Approximation of diffusion | 0.5805 | 0.0173 | 0.6254 | 0.0143 | 0.6774 | 0.0117 | 0.6840 | 0.0140 | 0.6955 | 0.0173 |
| Two-term exponential | 0.5805 | 0.0151 | 0.6254 | 0.0123 | 0.6774 | 0.0098 | 0.6840 | 0.0112 | 0.6955 | 0.0130 |
| Lewis | 0.5805 | 0.0135 | 0.6254 | 0.0108 | 0.6774 | 0.0084 | 0.6840 | 0.0093 | 0.6955 | 0.0104 |
| Two-term | 0.6354 | 0.0234 | 0.6740 | 0.0197 | 0.7178 | 0.0163 | 0.7193 | 0.0201 | 0.7263 | 0.0272 |
| Henderson &Pabis | 0.6354 | 0.0176 | 0.6740 | 0.0140 | 0.7178 | 0.0109 | 0.7193 | 0.0121 | 0.7263 | 0.0136 |
| Logarithmique | 0.8217 | 0.0089 | 0.8471 | 0.0072 | 0.8772 | 0.0056 | 0.8908 | 0.0060 | 0.9080 | 0.0066 |
| Midilli et al | 0.9493 | 0.0285 | 0.8908 | 0.0093 | 0.8825 | 0.0091 | 0.8135 | 0.0083 | 0.8382 | 0.0108 |
| Page | 0.9840 | 0.0009 | 0.9872 | 0.0006 | 0.9871 | 0.0004 | 0.9835 | 0.0004 | 0.9890 | 0.0006 |
| Verma et al. | 0.9848 | 0.0012 | 0.9925 | 0.0007 | 0.9965 | 0.0005 | 0.9829 | 0.0009 | 0.9672 | 0.0018 |

**Table 2**
Statistical criteria to choose the Safari best model.

| Safari Models | Temperature (° C) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 50 | | 55 | | 60 | | 65 | | 70 | |
| | $R^2$ | $\chi^2$ | $R^2$ | $\chi^2$ | $R^2$ | $\chi^2$ | $R^2$ | $\chi^2$ | $R^2$ | $\chi^2$ |
| Approximation of diffusion | 0.5814 | 0.0142 | 0.6534 | 0.0107 | 0.7448 | 0.0059 | 0.8073 | 0.0042 | 0.9081 | 0.0017 |
| Two-term exponential | 0.5814 | 0.0126 | 0.6534 | 0.0094 | 0.7448 | 0.0050 | 0.8073 | 0.0036 | 0.9081 | 0.0015 |
| Lewis | 0.5814 | 0.0113 | 0.6534 | 0.0083 | 0.7448 | 0.0044 | 0.8073 | 0.0031 | 0.9081 | 0.0013 |
| Two-term | 0.6451 | 0.0196 | 0.6996 | 0.0145 | 0.7780 | 0.0080 | 0.8257 | 0.0055 | 0.9142 | 0.0022 |
| Henderson &Pabis | 0.6451 | 0.0153 | 0.6996 | 0.0108 | 0.7780 | 0.0057 | 0.8257 | 0.0039 | 0.9142 | 0.0015 |
| Logarithmique | 0.8448 | 0.0057 | 0.8730 | 0.0047 | 0.9010 | 0.0030 | 0.9112 | 0.0029 | 0.9389 | 0.0016 |
| Midilli et al. | 0.8450 | 0.0416 | 0.8749 | 0.0175 | 0.9843 | 0.0181 | 0.8672 | 0.0072 | 0.8761 | 0.0050 |
| Page | 0.9935 | 0.0003 | 0.9824 | 0.0004 | 0.9952 | 0.0003 | 0.9843 | 0.0006 | 0.9743 | 0.0005 |
| Verma et al. | 0.9884 | 0.0003 | 0.9928 | 0.0007 | 0.9949 | 0.0002 | 0.9887 | 0.0006 | 0.9780 | 0.0005 |

**Table 3**
Statistical criteria to choose the Gandiol F1 best model.

| Gandiol F1 Models | Temperature (° C) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 50 | | 55 | | 60 | | 65 | | 70 | |
| | $R^2$ | $\chi^2$ | $R^2$ | $\chi^2$ | $R^2$ | $\chi^2$ | $R^2$ | $\chi^2$ | $R^2$ | $\chi^2$ |
| Approximation of diffusion | 0.5977 | 0.0125 | 0.6280 | 0.0118 | 0.6785 | 0.0095 | 0.7098 | 0.0089 | 0.8070 | 0.0047 |
| Two-term exponential | 0.5977 | 0.0114 | 0.6280 | 0.0106 | 0.6785 | 0.0083 | 0.7098 | 0.0076 | 0.8070 | 0.0040 |
| Lewis | 0.5977 | 0.0105 | 0.6280 | 0.0097 | 0.6785 | 0.0074 | 0.7098 | 0.0067 | 0.8070 | 0.0035 |
| Two-term | 0.6468 | 0.0165 | 0.6741 | 0.0153 | 0.7167 | 0.0125 | 0.7400 | 0.0117 | 0.8207 | 0.0060 |
| Henderson &Pabis | 0.6468 | 0.0138 | 0.6741 | 0.0123 | 0.7167 | 0.0094 | 0.7400 | 0.0084 | 0.8207 | 0.0043 |
| Midilli et al. | 0.7428 | 0.0367 | 0.7772 | 0.0160 | 0.9764 | 0.0109 | 0.9640 | 0.0109 | 0.8874 | 0.0071 |
| Logarithmique | 0.8246 | 0.0066 | 0.8741 | 0.0048 | 0.8946 | 0.0037 | 0.9042 | 0.0037 | 0.9058 | 0.0034 |
| Page | 0.9832 | 0.0008 | 0.9665 | 0.0008 | 0.9796 | 0.0005 | 0.9835 | 0.0007 | 0.9731 | 0.0006 |
| Verma et al. | 0.9846 | 0.0012 | 0.9750 | 0.0018 | 0.9836 | 0.0010 | 0.9812 | 0.0012 | 0.9834 | 0.0006 |

**Table 4**
Statistical criteria to choose the Orient F1 best model.

| Orient F1 Models | Temperature (° C) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 50 | | 55 | | 60 | | 65 | | 70 | |
| | $R^2$ | $\chi^2$ | $R^2$ | $\chi^2$ | $R^2$ | $\chi^2$ | $R^2$ | $\chi^2$ | $R^2$ | $\chi^2$ |
| Approximation of diffusion | 0.6786 | 0.0086 | 0.7110 | 0.0076 | 0.7550 | 0.0068 | 0.8024 | 0.0050 | 0.9016 | 0.0022 |
| Two-term exponential | 0.6786 | 0.0077 | 0.7110 | 0.0066 | 0.7550 | 0.0059 | 0.8024 | 0.0042 | 0.9016 | 0.0019 |
| Lewis | 0.6786 | 0.0070 | 0.7110 | 0.0059 | 0.7550 | 0.0051 | 0.8024 | 0.0036 | 0.9016 | 0.0016 |
| Two-term | 0.7121 | 0.0114 | 0.7437 | 0.0101 | 0.7788 | 0.0090 | 0.8209 | 0.0067 | 0.9081 | 0.0029 |
| Henderson &Pabis | 0.7121 | 0.0091 | 0.7437 | 0.0075 | 0.7788 | 0.0064 | 0.8209 | 0.0044 | 0.9081 | 0.0019 |
| Midilli et al. | 0.7859 | 0.0114 | 0.9705 | 0.0176 | 0.8413 | 0.0097 | 0.8870 | 0.0063 | 0.9646 | 0.0021 |
| Logarithmique | 0.8207 | 0.0065 | 0.8803 | 0.0041 | 0.8857 | 0.0046 | 0.9255 | 0.0029 | 0.9530 | 0.0019 |
| Page | 0.9941 | 0.0010 | 0.9834 | 0.0005 | 0.9740 | 0.0008 | 0.9818 | 0.0005 | 0.9795 | 0.0007 |
| Verma et al. | 0.9844 | 0.0004 | 0.9939 | 0.0005 | 0.9833 | 0.0008 | 0.9937 | 0.0006 | 0.9815 | 0.0008 |

temperature, the Page model is the best. Depending on the drying temperature, the $R^2$ and $\chi^2$ values are respectively between 0.9835 and 0.9890 and 0.0004 and 0.0009 for the Page model; between 0.9672 and 0.9965 and 0.0005 and 0.0018 for the Verma et al. model. For all combined temperatures, the averages of $R^2$ and $\chi^2$ are respectively 0.9862 and 0.0006 with the Page model and 0.9848 and 0.0010 with the Verma et al. model. Thus, the Page model is the best model for the Galmi Violet variety with a $R^2$ slightly closer to 1 than that of Verma et al. model.

For the Safari variety (Table 2), it appears that, depending on the drying temperature, the best model is either Page ($R^2$ between 0.9743 and 0.9952, $\chi^2$ between 0.0003 and 0.0006) or Verma et al. ($R^2$ between 0.9780 and 0.9949, χ2 0.0002 and 0.0007). The evolution trend of the $R^2$ depending on the drying temperature is irregular with the Page model, whereas with the Verma et al. model, the trend is increasing for each 5 °C step temperature raise in the range of 50 °C to 60 °C and drops when temperature is higher than 65 °C. On the other hand, the averages of $R^2$ and $\chi^2$, for all combined temperatures, are respectively 0.9885 and 0.0004 with the Page model and 0.9961 and 0.0005 with the Verma et al. model. The empirical Verma et al. model, with the $R^2$ closest to 1, is the best model for the Safari variety at all temperatures.

Among the nine models implemented for Gandiol F1 variety drying kinetics, the best model is either the Page model or the Verma et al. model according to the drying temperature (Table 3). The evolution of the $R^2$ depending on the drying temperature is irregular for these two models. The $R^2$ values vary between 0.9665 to 0.9835 for Page model and 0.9750 to 0.9846 for Verma et al. model, whereas the $\chi^2$ values are relatively stable and range from 0.0005 to 0.0008 for the Page model and from 0.0006 to 0.0018 for the Verma et al. model.

For all combined temperatures, the averages of $R^2$ and $\chi^2$ for the Gandiol F1 variety are respectively 0.9772 and 0.0007 for the Page model and 0.9882 and 0.0012 for Verma et al. model. With a $R^2$ higher than that of the Page model, the empirical Verma et al. model is the best model to fit the experimental drying kinetics data for the Gandiol F1variety.

As for the three other varieties, the evolution trend of the $R^2$ is irregular with both the Page and Verma et al. models (Table 4). The averages of $R^2$ and $\chi^2$ for the Orient F1 variety are respectively 0.9826 and 0.0007 with the Page model and 0.9873 and 0.0006 with the Verma et al. model for all combined temperatures. Therefore, the empirical Verma et al. model is the best all-temperature model for the Orient F1 variety. Nonetheless, for the four varieties, the Student statistical test indicates a non-significant difference (p-value > 5%) between the $R^2$ and $\chi^2$ values obtained with the Page and Verma et al. models.

*3.2.1.2. Evolution of the experimental reduced moisture content and that predicted by Verma et al. Model for drying in an oven.* Fig. 4 (a) and (b) show, depending on the drying time, the evolution of both the

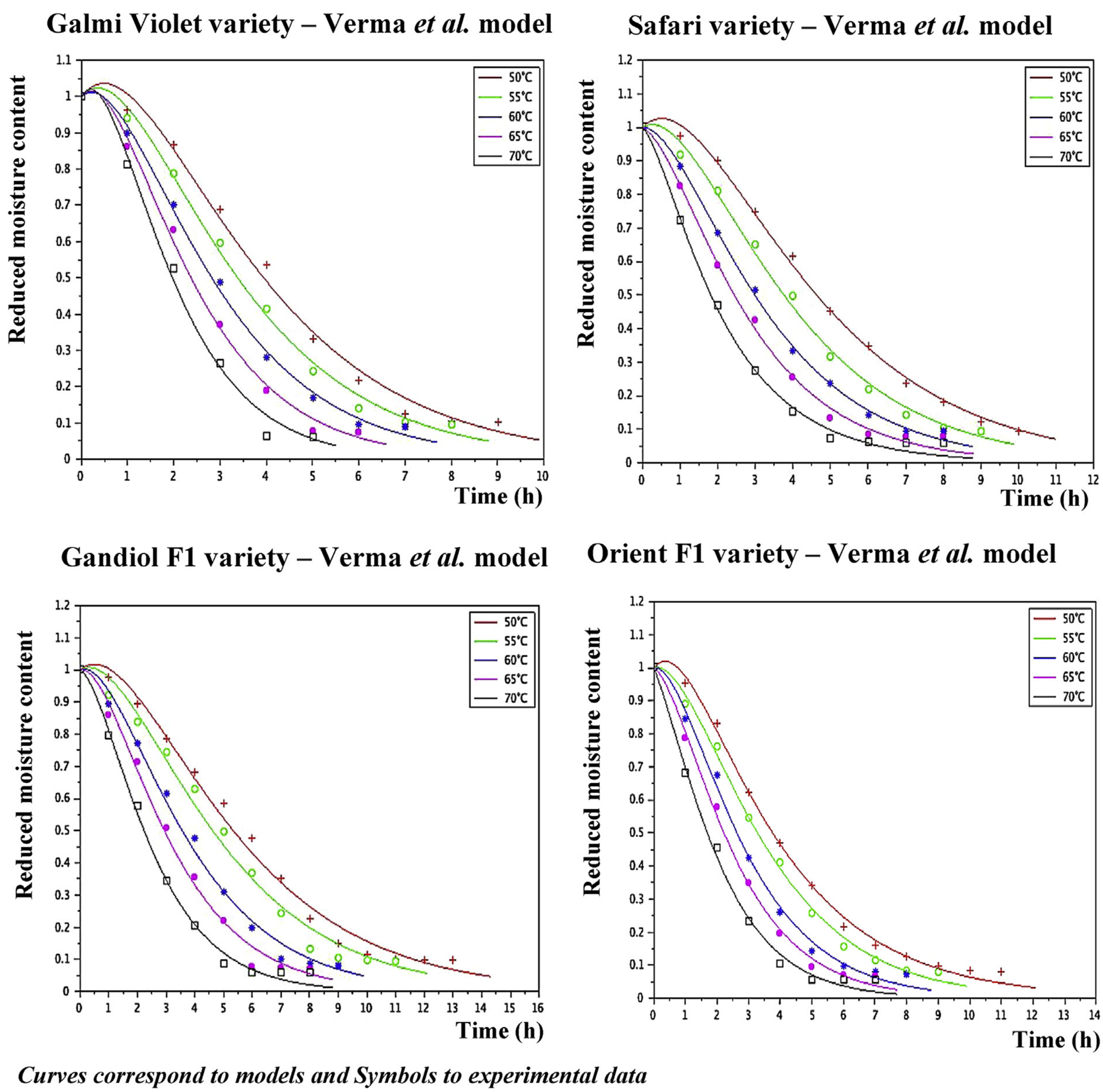


**Fig. 4.** Evolution of the reduced moisture content depending on drying time (marks correspond to experimental values and lines to mathematical model predicted values).

experimental reduced moisture content values and the predicted values with the best empirical mathematical Verma et al. model.

The equation for the best model is:

$$X_{rpred,t} = ae^{-kt} + (1-a)e^{-gt} \quad (8)$$

With "a", "k" and "g" being the parameters of the model determined by multiple regression at each temperature.

Whatever the drying temperature of Galmi Violet, Safari, Gandiol F1 and Orient F1 varieties in the oven, these curves indicate an almost perfect fit between the experimental reduced moisture contents and those predicted by the Verma et al. model. In fact, for this model, to each 5 °C step temperature raise, the temperatures that allow to observe a better dispersion ($R^2$ closest to 1) and a better fit ($\chi^2$ closest to 0) are:

- For the Galmi Violet variety, the temperature range from 50 °C to 60 °C with $R^2$ values varying between 0.9848 to 0.9965 and $\chi^2$ values between 0.0005 to 0.0012. From 65 °C the dispersion ($R^2$ 0.9672 and 0.9829) and the fit ($\chi^2$ 0.0009 and 0.0018) are less perfect;
- For the Safari variety, the temperature range from 50 °C to 65 °C with $R^2$ values varying between 0.9884 to 0.9949 and $\chi^2$ values between 0.0002 to 0.0007. At 70 °C, the dispersion begins to delete ($R^2$ 0.9780);
- For the Gandiol F1 variety, the temperature range from 50 °C to 70 °C with $R^2$ values varying between 0.9812 to 0.9846 and $\chi^2$ between 0.0006 to 0. 0012 except at 55 °C ($R^2 = 0.9750$ and $\chi^2 = 0.0018$);
- For the Orient F1 variety, the temperature range from 50 °C to 70 °C, with $R^2$ values varying between 0.9815 to 0.9939 and $\chi^2$ between 0.0004 and 0.0008.

**Table 5**
Equations of drying characteristic curves of the Galmi Violet, Safari, Gandiol F1 and Orient F1 varieties.

| Variety | Equation |
|---|---|
| Galmi Violet | $dXr/dt = 7,75\,Xr^3 - 7,98\,Xr^2 + 0,52\,Xr - 0,220$ |
| Safari | $dXr/dt = 4,90\,Xr^3 - 4,15\,Xr^2 - 0,85\,Xr - 0,096$ |
| Gandiol F1 | $dXr/dt = 6,50\,Xr^3 - 6,44Xr^2 + 0,024\,Xr - 0,16$ |
| Orient F1 | $dXr/dt = 4,54\,Xr^3 - 3,77\,Xr^2 - 0,96\,Xr - 0,082$ |

When comparing the average $R^2$ and the average $\chi^2$ between the four varieties for all combined temperatures, it appears that the ranking according to the least dispersion criterion is Safari, Gandiol F1, Orient F1 and Galmi Violet, while the ranking according to the best fit criterion is Safari, Orient F1, Galmi Violet and Gandiol F1.

### 3.2.2. *Determination of drying characteristic curves*

Fig. 5 (a) and (b) represent the Drying Characteristic Curves (DCCs) of Galmi Violet, Safari, Gandiol F1 and Orient F1 varieties. These curves describe the behaviour of the four onion varieties at the macroscopic level.

The drying characteristic curves of the four varieties (Fig. 5) indicate that the drying rate increases at the beginning of drying process and shows a pseudo-plateau corresponding to a constant drying rate for values of reduced moisture content between 0.55 and 0.7. From 0.55, the more the reduced moisture contents decrease, the more the drying rates decrease for the four varieties. For the four varieties drying characteristic curves, the models (Table 5) set by multiple regression are third order polynomials.

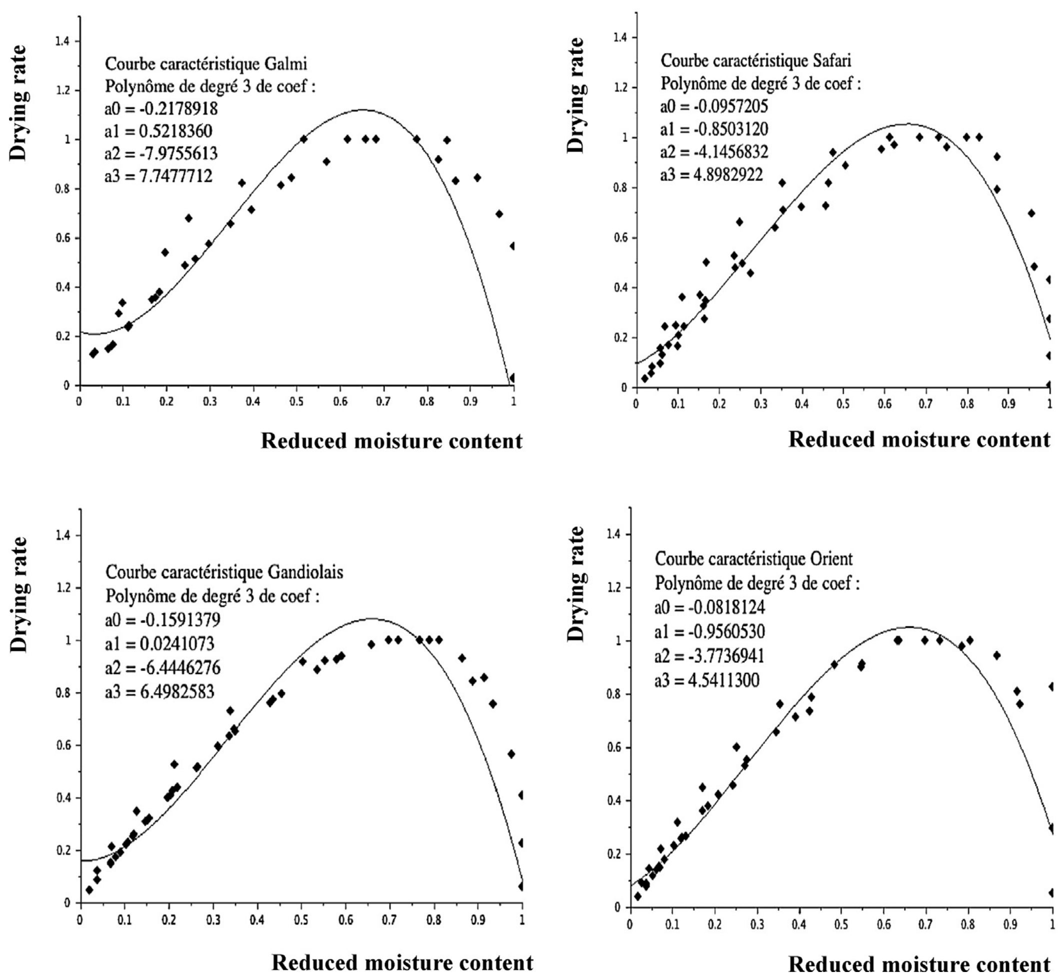


**Fig. 5.** Drying characteristic curves of Galmi Violet, Safari, Gandiol F1 and Orient F1 varieties.

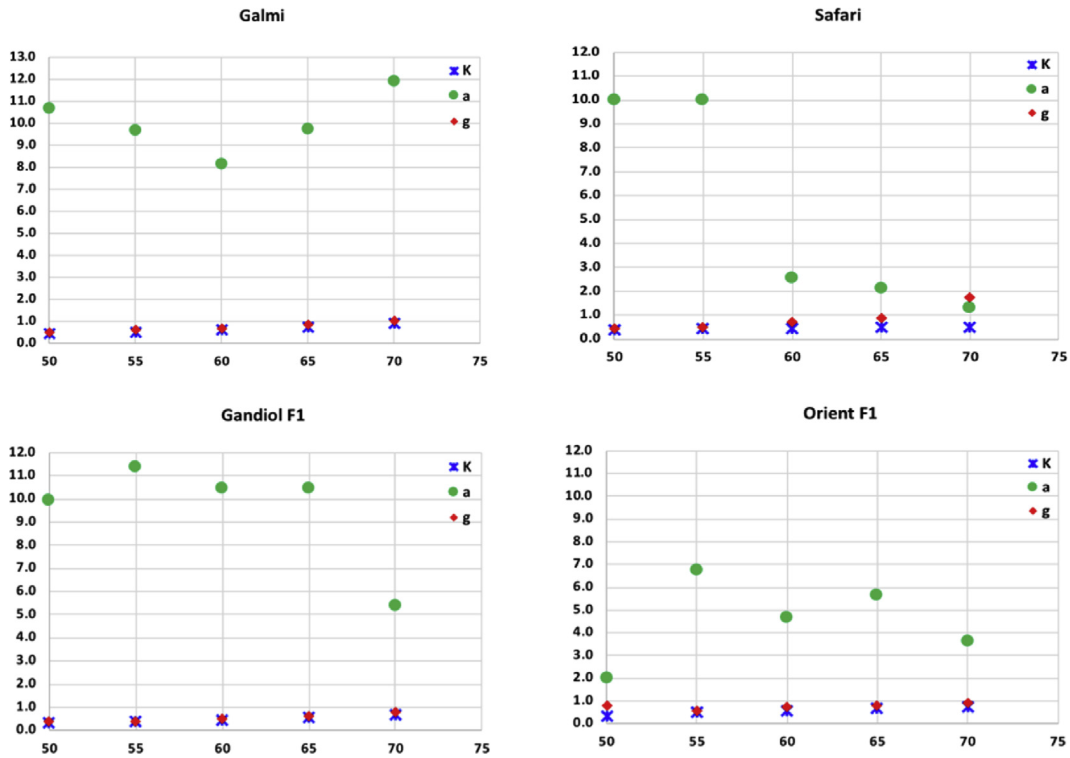


**Fig. 6.** Temperature-dependent evolution of the parameters of the Verma et al. best model for Galmi Violet Safari, Gandiol F1 and Orient F1 varieties.

The constants of the Galmi Violet variety polynomial equation are higher, followed by those of Gandiol F1, Safari and Orient F1. The $R^2$ values of the polynomial models set for the Drying Characteristic Curves (DCCs) of the four varieties are better in the reduced moisture content range between 0.1 and 0.7 than between 0 and 1. These values are respectively in the range of 0.932–0.987 and 0.719 to 0.819 depending on the varieties. Thus, for all the varieties, the polynomial trend curves better describe the DCCs for reduced moisture contents from 0.1 to 0.7. More general trend curves are to be developed for reduced moisture contents from 0 to 1. The best fit between the trend curve and the experimental data of the DCC is observed with first Gandiol F1, then Orient F1, Safari and Galmi Violet. The ranking of the varieties by order of slowest drying rate is Galmi Violet, Safari, Gandiol F1 and Orient F1.

### 3.3. *Kinetic modelling in the solar greenhouse dryer*

The Student statistical test between the moisture content results of oven-dried products (all temperatures combined) and those dried in a solar greenhouse reveals a non-significant difference because all the p-values are greater than 5% (Beye et al., 2019). This lack of significant difference makes it possible to set the following hypothesis that the kinetics of drying in the solar greenhouse follow the same mathematical model as the one in the oven. Therefore, the Verma et al. model, which best describes oven drying kinetics, can be implemented with solar greenhouse drying data. Prior to this implementation, as the temperature in the solar greenhouse is not stable during drying, determining the temperature dependence of the parameters of the drying kinetics best model on the different temperatures in the oven allows to develop a model integrating the variables time and temperature for the solar greenhouse drying.

The equation of the best drying kinetics model is:

$$X_{rpred,T,t} = ae^{-kt} + (1-a)e^{-gt} \tag{9}$$

With “a”, “k” and “g” being the parameters of the model whose evolution depending on the temperatures is presented in Fig. 6.

The kinetics drying constants “k” and “g”, ($s^{-1}$), increase overall with the four varieties drying temperature, except for the “k” values of the Safari variety in the temperature range from 55 °C to 60 °C. (multiplicative factor 0.98) and the Orient variety “g” value from the temperature 50 °C to that of 55 °C (multiplication factor 0.70).

The temperature sensitivity of the parameters “k” and “g” is reflected by multiplicative factors depending on the variety respectively between:

- ➢ 1.13 and 1.24/1.13 and 1.21 for Galmi Violet;
- ➢ 1.05 and 1.17/1.15 and 1.95 for Safari;
- ➢ 1.13 and 1.25/1.10 and 1.29 for Gandiol F1;
- ➢ 1.10 and 1.41/1.06 and 1.28 for Orient F1.

As for the “a” parameter, a dimensionless constant of the drying mathematical model, its evolution trend depending on the temperatures is irregular. The multiplicative factors for Galmi Violet, Safari, Gandiol F1 and Orient F1 are respectively between 0.84 to 1.22, 0.26 to 1; 0.52 to 1.14 and 0.70 to 3.41.

The trend curves of the parameters of the best Verma et al. model determined, by nonlinear regression, are second order polynomials. The equation of the parameters “a”, “k” and “g” are presented in Table 6.

The trend curves equations of the parameters of the Verma et al. model depending on the temperatures indicate that a good correlation is observed with $R^2$ values close to 1 ($R^2$ between 0.915 and 0.999) except for the parameter “a” of the Orient F1 and the Safari varieties and the parameter “g” of the Orient F1 variety.

Fig. 7 shows the evolution of the experimental moisture content and the one predicted by the Verma et al. temperature-dependent model in the solar greenhouse.

All in all, it appears that the Verma et al. temperature-dependent model set for the solar greenhouse drying did not fit very well the experimental reduced moisture data. In fact, except for the Galmi Violet whose experimental curve seems identical to the one predicted, the dissimilarity is very pronounced for the three other varieties between 3 and 8 h of drying.

**Table 6**
Equation of the parameters of the Verma et al. best model depending on the temperature.

| Variety | Equation of parameter | Determination coefficient ($R^2$) |
|---|---|---|
| | $a =$ | |
| Galmi Violet | $2.70010^{-2}T^2 - 3.190\,T + 102.883$ | 0,915 |
| Safari | $1.53310^{-2}T^2 - 2.344\,T + 89.873$ | 0,847 |
| Gandiol F1 | $-3.43210^{-2}T^2 + 3.919\,T - 100.312$ | 0,912 |
| Orient F1 | $-3.01210^{-2}T^2 + 3.659\,T - 105.020$ | 0,625 |
| | $k =$ | |
| Galmi Violet | $8.335\ 10^{-4}T^2 - 0.078\,T + 2.294$ | 0,999 |
| Safari | $-6.760\ 10^{-5}T^2 + 0.014\,T - 0.143$ | 0,912 |
| Gandiol F1 | $3.23510^{-4}T^2 - 0.022\,T + 0.627$ | 0,997 |
| Orient F1 | $-4.76310^{-4}T^2 + 0.075\,T - 2.237$ | 0,998 |
| | $g =$ | |
| Galmi Violet | $7.201\ 10^{-4}T^2 - 0.062\,T + 1.857$ | 0,999 |
| Safari | $4.31110^{-3}T^2 - 0.457\,T + 12.605$ | 0,962 |
| Gandiol F1 | $7.65910^{-4}T^2 - 0.071\,T + 2.023$ | 0,996 |
| Orient F1 | $1.71510^{-3}T^2 - 0.198\,T + 6.416$ | 0,680 |

## 4. Discussion

The two best models, which describe the drying kinetics of the Galmi Violet, Safari, Gandiol F1 and Orient F1 varieties, are the Page and Verma et al. models whatever the experimental temperatures.

Over the temperature range from 50 °C to 70 °C, the average $R^2$ and $\chi^2$ (Tables 1, 2, 3 and 4) determined with the least-squares method make it possible to rank the Verma et al. as the best model ($R^2$ 0.9873 to 0.9961 and $\chi^2$ 0.0005 to 0.0012) followed by the Page model ($R^2$ 0.9772 to 0.9885 and $\chi^2$ 0.0004 to 0.0007) for the Safari, Gandiol F1 and Orient F1 varieties, whereas the inverse ranking is observed for the Galmi Violet variety ($R^2$ and $\chi^2$ averages respectively of 0.9862 and 0.0006 with the Page model and 0.9848 and 0.0010 with the Verma et al. model).

When we consider only the range from 55 °C to 65 °C, best drying conditions for the four onion varieties (Beye et al., 2019), the comparison of the $R^2$ average and $\chi^2$ average values obtained with these two best models rank the Verma et al. model before the Page model.

Moreover, the Student's statistical test indicates the absence of significant difference (p-value> 5%) between the $R^2$ and $\chi^2$ values obtained with the Page and Verma et al. models for all the varieties.

Thus, whatever the oven drying temperature, the Verma et al. model is the best model selected for all the varieties with $R^2$ average and $\chi^2$ average respectively ranging from 0.9848 to 0.9961 and 0.0005 to 0.0012.

The ranking of the varieties in the order of least dispersion is Safari, Gandiol F1, Orient F1 and Galmi Violet; while in the order of best fit, the ranking is Safari, Orient F1, Galmi Violet and Gandiol F1.

Under the experimental conditions of this study, the Verma et al. model set for the four onion varieties drying kinetics is a two-term exponential model. The latter differs from that one term exponential model implemented by Sarsavadia in 2003 for onion drying kinetic.

Nevertheless, the expression of these two models shows that diffusion is one of the physical phenomena for water migration during onion drying process (Kiranoudis et al., 1992; Nguyen, 2015).

This difference is due to the drying complex phenomena which depend on the onion varieties, the climatic and experimental conditions, but also on the size of the samples.

The characteristic curves of the four onion varieties describe their

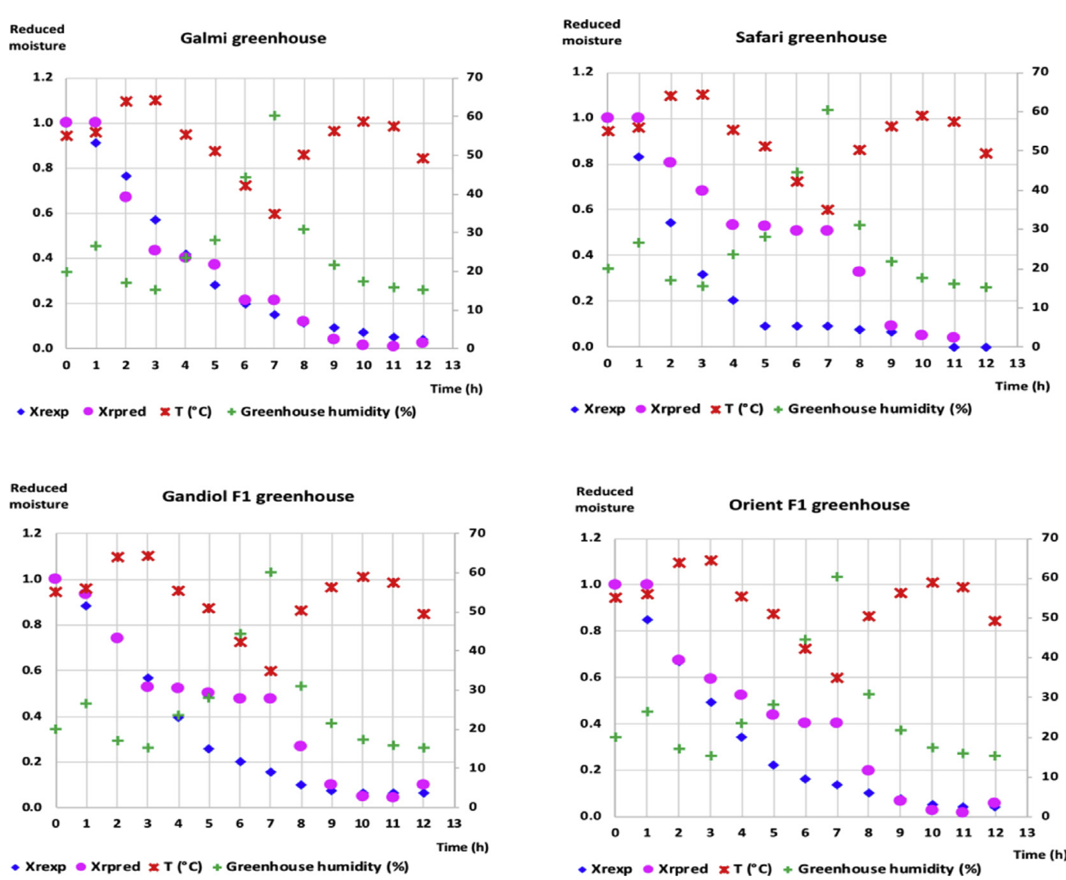


**Fig. 7.** Evolution of the experimental reduced moisture contents and those predicted by the Verma et al. temperature-dependent model during the solar greenhouse drying.

behaviour on a macroscopic level, ignoring complex phenomena at the microscopic level and especially experimental conditions (Van Meel, 1958). The appearance of the four onion varieties characteristic curves (Fig. 5) is identical to the one found in the literature for other plant products such as onion (Kiranoudis et al., 1992; Sarsavadia et al., 1999), mint leaves (Touati, 2008), tomato (Boughali, 2010), and carrot (Nguyen, 2015).

The capillary forces involved mainly in the water migration cause a rapid decrease of the four onion varieties drying rates in the initial stage (polymolecular water layer), then stabilization in the final stage to a value close to the equilibrium reduced moisture (Xreq 0.05 to 0.15 depending on the variety). In the final drying step hygroscopic water trapped inside the product diffuses slowly (water monolayer). Therefore, the drying characteristic curves equations are third degree polynomials (Ahouannou et al., 2000; Boughali, 2010; Jannot, 2006; Nguyen, 2015; Touati, 2008).

As for the modelling of the Galmi Violet, Safari, Gandiol F1 and Orient F1varieties drying kinetics in the solar greenhouse, the Verma et al. model integrating the evolution of the parameters of the model depending on the solar greenhouse temperature does not indicate a perfect fit between the experimental values (Fig. 7) and the predicted values calculated from Eq. (9) and the equation of the parameters (Table 6). Two major reasons seem to explain this shift in the solar greenhouse model:

- ➢ On the one hand, the temperature sensitivity of the parameters “a”, “k” and “g” determined with nonlinear regression shows a regular trend for the drying kinetic constants “k” and “g”, whereas the trend for the constant of the model “a” is irregular. For each 5 °C step temperature raise in the range of 50 °C to 70 °C, the multiplicative factors of “a”, “k” and “g” vary respectively between 0.26 to 3.41/1.05 to 1.41/1.06 to 1.95 for the four onion varieties;
- ➢ On the other hand, the parameters of the model also depend on other experimental conditions particularly the solar greenhouse humidity (Akpinar et al., 2003; Ndapeu et al., 2013; Nguyen, 2015; Prakash & Kumar, 2014; Simal et al., 2005).

## 5. Conclusion

The empirical mathematical Verma et al. model, a two-parameter exponential model, is the model that best fits the oven drying kinetics of the Galmi Violet, Safari, Gandiol F1 and Orient F1 varieties with $R^2$ average and $\chi^2$ average values of respectively 0.9848/0.0010; 0.9961/0.005; 0.9882/0.0012 and 0.9873/0.006. This model, validated on the drying kinetics performed at variable temperatures during the drying process in solar greenhouse, is not perfect between 3 and 8 h of drying because certain parameters of the model seem not to depend only on the temperature ($R^2$ in the range of 0.625–0.847). This Verma et al. model, depending on the solar greenhouse temperature, is to be refined taking into account the influence of the relative humidity on the parameters of the model.

The Drying Characteristic Curves (DCCs) of the four varieties are described with third degree polynomials with $R^2$ values (0.932–0.987) in the reduced moisture content range from 0.1 to 0.7, higher than the $R^2$ values (0.719–0.819) in the reduced moisture content range from 0 to 1.

The critical reduced moisture content and the equilibrium reduced moisture content both deduced from the DCCs are respectively between 0.55 to 0.70 and 0.05 to 0.15. The Galmi Violet, with the slowest drying rate at all combined temperatures, is the limiting variety in case of simultaneous drying of the four varieties.

## Declarations

### *Author contribution statement*

Ngoné Fall Beye: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Cheikhou Kane: Conceived and designed the experiments; Analyzed and interpreted the data. Nicolas Cyrille Ayessou: Conceived and designed the experiments. Cheikh Mouhamed Fadel Kebe, Cheikh Talla: Contributed reagents, materials, analysis tools or data. Codou Mar Diop: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data. Abdou Sène: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

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### *Competing interest statement*

The authors declare no conflict of interest.

### *Additional information*

No additional information is available for this paper.

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