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Thermophysical modeling of drying kinetics of Taliouine Saffron irrigated by the porous system

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Abstract— Our study focuses on the drying process of saffron from Taliouine (Southern Morocco), a spice derived from the flower of a crocus (Crocus sativus L.) of the Iridaceae family, after drying of its three red stigmas. This plant attracts the interest of researchers, farmers and exporters at the national and international scale. In this regard, optimizing the drying of saffron in the region seems imperative for quality improvement and the expansion of the marketing system.
The aim of this work is to experimentally determine the water content of the dry-base saffron, the kinetics of drying, the characteristic curve of drying and the proper mathematical model for the description of the drying of the saffron from Taliouine, irrigated by the microporous system in comparison with the drip irrigation system for four temperature values (35, 40, 45 and 50 °C).
The drying rate is determined empirically from the characteristic drying curve. Then, the influence of air heated velocity, temperature of drying air and air moisture content on the drying kinetics of product was studied. Six statistical models have been used for the description of drying curves. The Midilli-Kucuk's model seems to be the most appropriate to describe the drying curves of Saffron with a highest value of correlation coefficient and in various aero-thermal conditions.

Keywords: Saffron, Drying kinetics, Mathematical models, Characteristic drying curve, Porous system.

1. Introduction

Morocco is one of the Mediterranean countries that are most involved in the process of protection of natural resources and the enhancement of value of local products. In addition to the major products there is a whole variety of local products, the best of which are sent to the urban centers of the country and / or exported.

The local products in Southern Morocco include the cultivation of saffron (**Crocus sativus L**.) in the Taliouine circle in parallel with other crops. It is a production that is part of the identity of the local populations, closely linked to the traditions of the Berber people of this territory and part and parcel of their culture. Saffron was cultivated for centuries within an agro-pastoral livelihood system.

The Taliouine region is part of the Moroccan Atlas mountains at the juncture of the High Atlas and Anti-Atlas mountains, characterized by a continental climate trend, annual rainfall of about 200 mm/year, and an average temperature of 14.7 °C, that varies between -1 and + 40 °C in winter and summer respectively. It has an average annual rainfall of 119.5 mm in the plains, and 300 mm in mountain areas, and a very high degree of sunshine of 3 000 hours/year. The dominant soils are of the calcareous clay, sandy loam or silty clay types.

In fact, the production of saffron is one of the mainstays of the economy of the area, and the sale of stigma by the producers is the main, and sometimes the only, income of the families concerned. The improved performance of the cultivation of saffron and the development of fair marketing systems seems essential.

In this context, due to the fact that Morocco and Belgium wish to support applied research, a scientific partnership was established between the Agadir ENCG business school, the IFAS-Maghreb Institute in the city of Rabat, and the Belgian ILVO (Agricultural and Fisheries Research) Institute. This research partnership aims at the improvement of the efficiency of cultivation of saffron, the optimization of the consumption of water and energy resources, the development of the marketing system, and sustainable development through the introduction of modern operating and control technologies for the development of a local product with great potential for the region.

Several authors have worked on saffron such as **Mounira Lage** [1], who studied the quantification of saffron carotenoids (crocin, picrocrocin and safranal) after drying and in function of regional climatic conditions ; **Gresta et al** [2], who quantified the flowering and stigmas of saffron in relation to weather conditions ; Azizi Zohan et al., in Iran in 20084, who could review the coefficients of saffron evapotranspiration with respect to the autumnal and spring growth period of saffron ; and other researchers who have studied the drying of food and medicinal plants products, as is the case of **Hind Mouhanni et al**. [3], who conducted a study of the drying of Taliouine saffron process irrigated by drip system at four temperature levels (35, 40, 45 and 50 °C). The results of the drying kinetics processed by six mathematical models show that the Midilli-Kuckuk model is the most suitable drying saffron model, and the drying characteristic curve proves that it is a product with extended conservation. **Lahssassni et al**. [4], studied the drying of the prickly pear of the Cladode variety grown in Marrakech, Morocco. The product is dried in a solar dryer at three drying temperatures (50, 55 and 60 °C), and three air flowrates (100, 200 and 300 m^3/h). The drying curves treated with eight mathematical models have shown that the

Page model satisfactorily describes solar drying curves with r = 0.9995 and only the temperature of the drying air inflences the process.

2. Materials and Methods

2.1. Description of the experimental site

The Taliouine area is located in the region of Souss Massa Draa (Southwestern Morocco) and West of the Siroua Montain, representing the junction of the High Atlas and Anti-Atlas mountains as shown in Fig. 1. Its climate is semi-arid with low rainfall (200 mm/year). This area has the largest saffron production center: it has about 500 hectares of this crop spread over 1200 and 2400 meters above sea level.

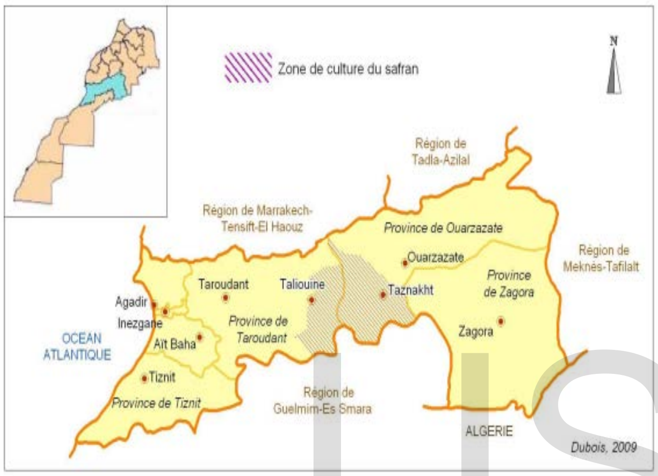
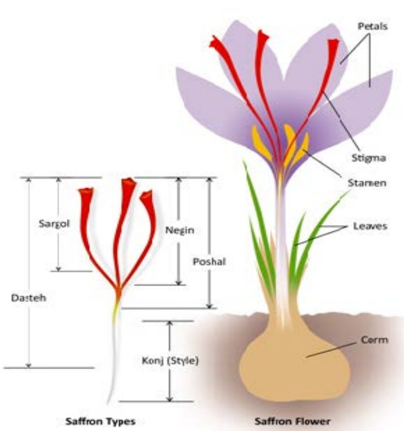


Fig. 1: Geographical location of the Taliouine Circle

2.2. Description of the saffron plant

Saffron, also known as (**Crocus sativus L**.), is herbaceous perennial species geophyte plant that belongs to the family Iridaceae and has a rather large corms or bulb of 10-30 cm. This is a monocotyledonous angiosperm whose seeds are not viable. **Crocus sativus L**. flowers are fragrant, appear in autumn (from September/October to November) and have three purple petals and three sepals to which three stamens are attached. The unique, yellow and skinny style ends with three fragrant and orange-red stigmas, constituting what we call "saffron" as a spice described in Fig. 2 [1, 5].

Fig. 2: Saffron plant



2.3. Planning of tests

Under the project, a 4 hectare area was arranged. The land selected that occupies 4 hectares (50 meters x 400m x2) is bare, with an East-West longitudinal orientation. The experimental site is initially arranged to apply two irrigation systems: Porous (3 ha) and drip (1 ha) for the cultivation of saffron and then for the exploitation of solar energy for the pumping of irrigation water as shown in Fig. 3.

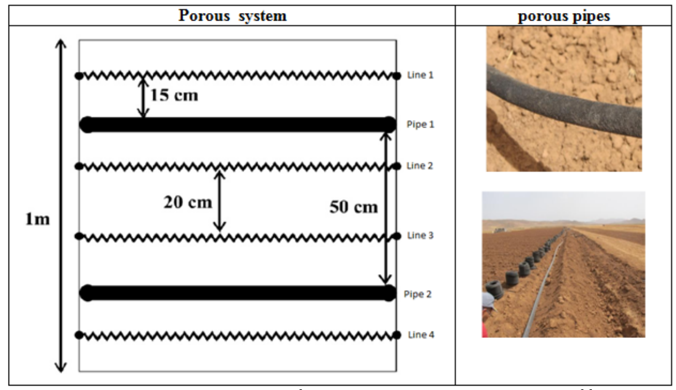


Fig. 3: Pumping water from irrigation porous saffron

On a plot of 1m, one places porous type of garden hoses (to 20 cm subsoil), spaced by 50 cm. Two lines of saffron 15 cm away from the pipe, on both sides, are seeded. Hence a total 4 lines of seeds and 2 lines of garden hoses of the porous type.
Saffron is harvested under experimental conditions of precise irrigation for two irrigation systems:

Flow rate of 4 Liters /hour with solar pumping	
Solar Pump	Water delivery head: 30 m
	Water production sought: 50 cubic meters /day
Irrigation timetable	

2.4. Experimental Protocol

During the harvesting of saffron, we conducted a field sampling for the study of the drying process of the saffron produced by the irrigation system: porous in comparison with the drip system. The samples were processed at the Ibn Zohr University in Agadir to determine the water content of saffron with a dry basis, the kinetics of drying, the characteristic drying curve (CDC) and the proper mathematical model for the description of this process.

2.5. Water content and characteristic drying curve

For all the experiments conducted in the laboratory, the drying of saffron is performed in an oven by setting the temperature and by monitoring the evolution of the wet mass Mh (t) over time by weighing the mass several times until such mass becomes stationary. This is followed by dehydrating the product in an oven at 105 °C for 24 hours in order to determine the dry mass (Ms) of saffron. The dry base moisture content (kg water/ kg dry matter) at a time t is defined by: $X(t)=(Mh-Ms)/Ms$.
The final water content is a characteristic of each product. This is the optimal value for which the product does not deteriorate and keeps its nutritional and organoleptic qualities (shape,

texture, color, smell and essential oils) [6].

The determination of the drying kinetics, by the base curve called characteristic drying curve (CDD) of reduced variables by means of the Van Meel processing [7], which proposes to convert the abscissa and the ordinate to gather all the experimental curves on a one single curve using appropriate software programs (**Curve Expert 3.1 and Origin 6.0**).

The principle of the method developed by Van Meel (1958) consists of a standardization representing the ratio of the drying rate at an instant t, $\left(-\frac{dX}{dt}\right)$ at the kinetics of the first phase $\left(-\frac{dX}{dt}\right)_I$ in the same temperature conditions as a function of the reduced water content $X^* = \frac{X(t)-X_{eq}}{X_{cri}-X_{eq}}$. Since the first phase is absent in the case of food products, so we take:

$$\left(-\frac{dX}{dt}\right)_I = \left(-\frac{dX}{dt}\right)_0 \text{ and } X_{cri} = X_0$$

Thus, the general form of the equation of the drying characteristic curve is given by $f = f(X^*)$.

$$\text{The x: } X^* = \frac{X(t)-X_{eq}}{X_{cri}-X_{eq}} = \frac{X(t)-X_{eq}}{X_0-X_{eq}}$$

$$\text{The y: } f = \frac{\left(-\frac{dX}{dt}\right)_t}{\left(-\frac{dX}{dt}\right)_I} = \frac{\left(-\frac{dX}{dt}\right)_t}{\left(-\frac{dX}{dt}\right)_0}$$

For a reasonable range of experimental conditions constant during drying (temperature, kinetics and dimensions of the product to dry), the drying characteristic curve (DCC) satisfies the following properties:

$$\begin{cases} f = 0 \text{ for } X^* = 0 \\ 0 \le f \le 1 \text{ for } 0 \le X^* \le 1 \\ f = 1 \text{ for } X^* \ge 1 \end{cases}$$

2.6. Modeling drying curve

Modeling of drying curves is to develop a function satisfying the equation: $X^* = f(t)$ tell drying characteristic equation (DCE).

Several empirical or semi-empirical models are used to describe the drying kinetics curves [8].

The equations of these models expressing the evolution during the drying of the reduced water content with time. These formulas contain constants that are adjusted to match the theoretical predictions with experimental curves of drying.

To describe the drying kinetics of Taliouine saffron and determine the most appropriate empirical equation, we used six drying models thin layer of medicinal plants summarized in Table 1 below.

Table 1: Drying models applied to the description of the saffron drying curves

Model name	Model expression
Logarithmic [9]	$X^* = a\exp(-kt) + c$
Tow-term [10]	$X^* = a\exp(-k_0 t) + b\exp(-k_1 t)$
Wang et Singh [11]	$X^* = 1 + at + bt^2$
Diffusionapproach [12]	$X^* = a\exp(-kt) + (1-a)\exp(-kbt)$
Verma et al [13]	$X^* = a\exp(-kt) + (1-a)\exp(-k_0 t)$
Middili-Kucuk [14]	$X^* = a\exp(-kt^n) + bt$

To choose the appropriate model for describing the shape of the saffron drying kinetics are relying on the following criteria:

- (r) high correlation coefficient
- (ESM) minimum average Bias
- χ^2 minimum

These statistical parameters are defined by:

$$ESM = \frac{1}{N}\sum_{i=1}^{N}\left(X^*_{pre,i} - X^*_{\exp,i}\right)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(X^*_{pre,i} - X^*_{\exp,i})^2}{N-n}$$

$X^*_{pre,i}$: ith experimental reduced water content

$X^*_{\exp,i}$: ith reduced water content predicted by the model

N : Number of data points

n : Number of variables of each model.

The curves representing the water content reduced as a function of drying time are described by the abovementioned six patterns. The coefficients of each drying model were determined using the nonlinear optimization method based on the Marquard-Levenberg algorithm with the Curve-Expert 3.1 and Origin 6.1 software programs. The different models are compared based on their correlation coefficients (r) and statistical parameters chi-square (χ^2) and the average bias (ESM).

The method consists in determining, for each of the four temperatures, the settings for each model and then comparing their statistical parameters mentioned. The model that provides the highest value of r and the lowest values of χ^2 and ESM is considered as the best model to describe the drying kinetics of Taliouine saffron.

3. Discussion

The experimental curves describing the evolution of the drying rate as a function of time and the water content of saffron and shown respectively in Figures 4, 5 and 6 showed a decreasing drying kinetics. The curves of the water content of temperatures 40, 45 and 50°C have the same decreasing speed. Only the curve of the water content of the Taliouine saffron at the temperature of 35 °C shows a peak for the plant irrigated by the porous system which is explained by the phenomenon of swelling of the adsorption pores.

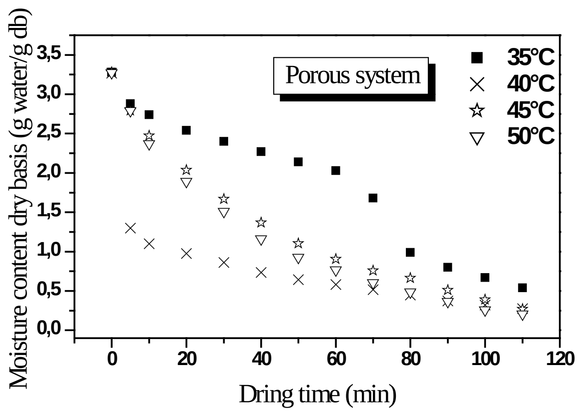


Fig. 4: Evolution of saffron water content in function of time for different temperatures

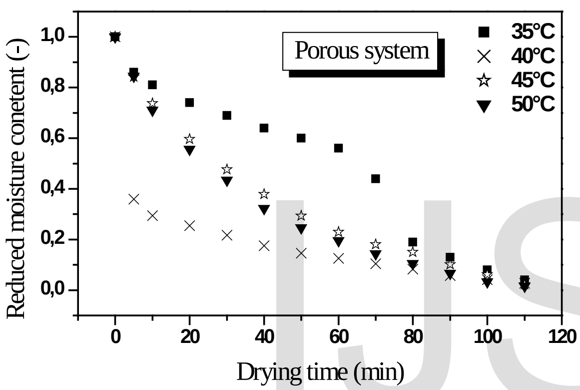


Fig. 5: Evolution of saffron water content reduced as a function of time for different temperatures

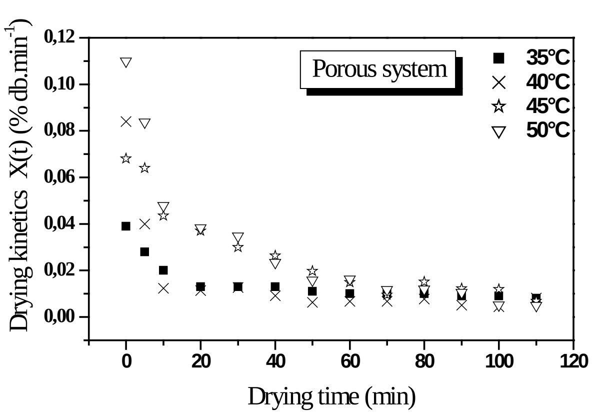


Fig. 6: Evolution of saffron drying rate as a function of time for different temperatures

However, one observes the absence of Phase 0 (increasing kinetics) and Phase I (constant kinetics), and the unique presence of Phase II (decreasing kinetics). The same results were obtained for different plant products [15]. The different drying curves obtained show the decreasing kinetics of the water content and of the drying rate as a function of time.

The decrease in the drying rate as a function of time is explained by the fact that at the beginning of drying, evaporation of the water present in the product surface does not require much energy. Nevertheless, the dissemination of water from the internal part of the product towards the surface is time-consuming. This is complex mechanism involving water in two liquid and vapor states, which is often characterized by effective dissemination. This property depends on the temperature, pressure and water content of the product.

From the four drying tests (35, 40, 45 and 50°C), we established the correlation expressing the normalized drying speed of the Taliouine saffron under a polynomial form of order 4 in X^*.

Drip system:

$$f = 1.0977X^* - 2.0896X^{*2} + 6.8241X^{*3} - 4.7502X^{*4} ;$$

$$r = 0.9586 \quad ESM = 0.0731$$

Porous system:

$$f = 0.9078X^* + 1.8723X^{*2} - 3.2028X^{*3} + 1.4197X^{*4} ;$$

$$r = 0.9370 \quad ESM = 0.0776$$

This curve makes it possible to reduce all the experimental data and to make them usable for all similar cases. These aerothermal conditions of the drying operation were studied without the organoleptic and nutritional quality of saffron being impaired.

The drying characteristic curve of saffron (**Crocus sativus L.**) irrigated by the drip system, as shown in Fig. 7, has a bulky appearance for the lower moisture content reduced and lower than 60%. This is explained by the fact that the stigmas have a significant production of plant material compared to the fluid retention that is lower than normal (80%).

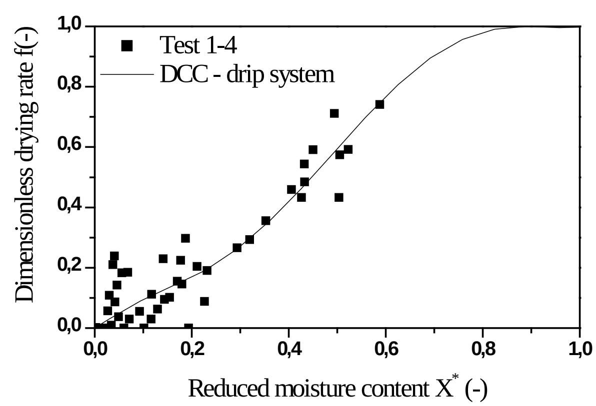


Fig. 7: Characteristic drying curve of the drip irrigation system

Figure 8 shows the drying characteristic curve of saffron irrigated by a porous system. By difference with Fig. 7, the reduced moisture content is spread throughout the interval [0, 1].

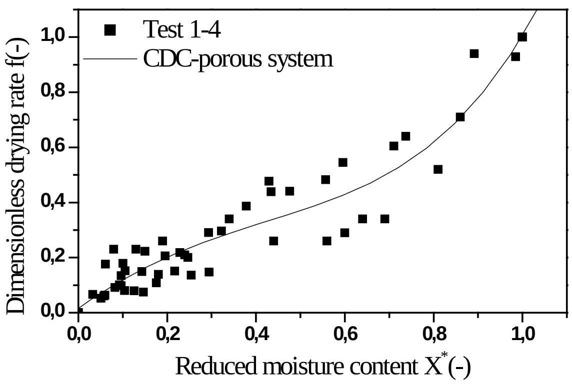


Fig. 8: Characteristic drying curve of the porous irrigation system

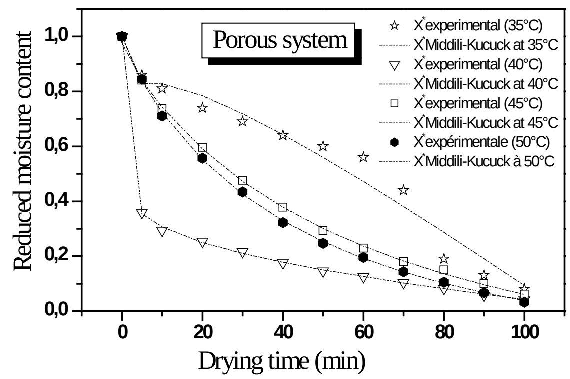


Fig. 9: Experimental reduced moisture content and predicted by the Middili-Kucuk model for each temperature

Nonetheless, the drying characteristic curve of saffron (Crocus sativus L.) irrigated by the porous system, shows a spreading over all the reduced moisture contents ($0 < X^* < 100\%$). This is related to fluid retention of the stigmas that are higher than the plant requirements.

In contrast, the plant irrigated by the drip system and having a characteristic drying curve is differentiated by extended storage in comparison with the plants irrigated through the porous system. Nonetheless, the quality of the dried saffron is determined by the conditions of storage according to [9], who showed that darkness is required to increase the maturity of crocin, the carotenoid known for its solubility in water and its saffron tinting strength [16]. The appropriate model for describing the kinetics of the drying of saffron irrigated by the porous system is the Midilli-Kucuck model (large r, Average bias (ESM) and χ^2 low). By taking into account the effects of the drying temperature on the Midilli-Kucuk coefficients, the values of a, k, n and b are expressed as a function of the drying temperature as follows:

$$a = 99.1638 - 7.0568\ T + 0.1664\ T^2 - 0.00129\ T^3$$
$$K = -86.3691 + 6.04806\ T - 0.1397\ T^2 - 0.001\ T^3$$
$$n = 103.42 - 7.4611\ T + 0.1777\ T^2 - 0.0013\ T^3$$
$$b = -1.5947 + 0.1068\ T - 0.0023\ T^2 + 1.76.10^{-5} T^3$$

The relationship between the coefficients of the Midilli-Kucuk model and the drying temperature is highly significant, with r = 1 and an average bias (ESM) = 0.

One notes that the predicted reduced moisture content decreases when the temperature increases, and therefore the time required for drying decreases (Fig. 9). We can therefore conclude that the Midilli-Kucuk model describe adequately the drying kinetics of saffron irrigated by the porous system in an automatic oven for a temperature of 50 °C with a correlation coefficient (r) of 0.9998 and an average bias (ESM) of 0.0071 (Fig. 10).

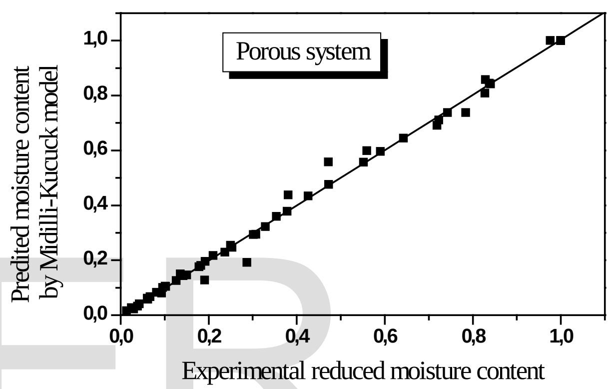


Fig. 10: Reduced moisture content predicted by Middili-Kucuk model depending on the experimental reduced moisture content

4. Conclusion

The experiments of drying Saffron stigmas (Crocus sativus L.) irrigated by the porous system conducted for four temperatures (35, 40, 45, and 50°C), showed us a different behavior compared to the kinetics of drying saffron irrigated by drip system. In addition, the experimental curves have a decreasing pace and there is a lack of the constant phase and of the growth phase that describe the water content and the drying rate in function of time, for most food products.

The size of the reduced moisture content (X^*<60 %) in the drying characteristic curve of saffron irrigated by drip system reveals prolonged storage in comparison with the plants irrigated through the porous system that presents a spreading of the reduced water content between $0 < X^* < 100\%$, and this is due to the position of the porous system in the subsoil hat promotes water retention that is higher than the needs of the plant.

The statistical analysis of experimental results in reduced coordinates X (t), smoothed by the most famous food process engineering models, has allowed us to conclude that the Midilli-Kucuk model is the most appropriate for describing the kinetics drying of the saffron plant at a temperature of 50°C with a correlation coefficient r of 0.9998, an average bias (ESM) of 0.0071 and a chi-square of $\chi^2 = 5.13\ 10^{-3}$. The effect of drying temperature on the coefficients of this model has been studied and is expressed by polynomial equations of the 3rd degree.

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