COB-2023-0872 THIN LAYER DRYING KINETICS OF GRAPES DRIED IN A HYBRID SOLAR-ELECTRIC DRYER

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Abstract. *Solar energy is an abundant and free energy source that can be explored in sustainable technologies, which can increase energy security and make new production methods. This study aims at analyzing the drying process of grapes, which took 27 hours to remove all moisture, using a hybrid solar-electric dryer (HSED) built in Belo Horizonte, Brazil. The drying kinetics is evaluated, and five typical mathematical models are analyzed. The moisture content variation as the grapes dry in the HSED was measured to analyze the drying curve behavior and fitted to five thin layer drying models. For that, grapes were placed on a tray inside the HSED suspended by a load cell. The HSED used was equipped with sensors to analyze temperature and humidity variation throughout the drying process and with an electric heater that could be activated automatically to obtain a stable temperature. Firstly, it was concluded that the thermal pretreatment conducted for raisin production does not have a significant impact on the drying curve and on the initial moisture content, which was found to be 81.7%. Finally, it was concluded that the Midilli model yielded the best fit for BRS Vitória grape drying on the HSED when analyzing the chi-square, root mean square error, and mean bias error.*

Keywords: *hybrid solar-electric drying (HSED), grape drying, drying kinetics, statistical analysis.*

1. INTRODUCTION

According to the International Energy Agency (IEA), the world is facing a global energy crisis, in which energy supply and the accumulation of carbon dioxide in the atmosphere are serious world challenges. In a way, the energy market remains extremely vulnerable, and today's energy shock is a reminder of the fragility and unsustainability of the world's current energy system (IEA, 2022). Thus, a key question is whether the energy crisis will catalyze clean energy transitions or if it will be a setback. Therefore, using clean energy and investigating sustainable technologies is a way to increase energy diversification, by reducing the dependency on a single energy resource, and mitigating the risks posed by political unrest or natural disasters. In consequence, energy diversifications strengthen energy security and can yield positive economic development (Gozgor, Paramati, 2022). Considering that solar energy is an abundant and free energy source, hybrid solar dryers can provide means to minimize greenhouse-effect gas emissions on a commercial scale and mitigate global warming without losing economic feasibility in the agricultural sector. In addition, hybrid dryers can also ensure a stable and manageable drying process able to produce dried food with the quality required in terms of texture, moisture, appearance, taste, and nutritional value.

Studies on the application of solar technologies for raisin production are not new. Srivastava et al. (2021) conducted a comprehensive overview of solar dryers designed for grapes drying, in which energy, kinetics, environmental, and economic analyses were performed. Among their conclusions, mixed-mode type dryers and hybrid dryers require between 15 to 25% more initial investment, but it reduces drying time by 30 to 40%. When analyzing the drying kinetics, the Midilli and Two-term models could best depict the solar drying curve in multiple studies (Yaldiz et al., 2001; Essalhi et al., 2018; Hamdi et al., 2018; Srivastava et al., 2021). However, no studies on BRS Vitória grapes drying using solar technologies were found in the literature.

BRS Vitória is a variety of black seedless grape, exhibiting special flavor and tolerance to downy mildew, which is the most relevant grapevine disease in Brazil. This grape is usually cultivated in tropical and subtropical areas, with satisfactory horticultural performance. Its first harvest was in 2007 and its raspberry-like flavor, high sugar content, and absence of seeds caught market attention (Maia et al., 2014). This grape falls under the category of tabletop grapes, which are intended for consumption while fresh. Besides, BRS Vitória became relevant in the market, occupying around 15% of the grape production area in the Vale do São Francisco, Brazil (Zanella, 2019) Therefore, since drying is an effective alternative to extend shelf-life while adding value to the final product, Martineli et al. (2018) investigated the possibility of obtaining new raisins type while evaluating its acceptance, produced from BRS Vitória grapes. The authors concluded that BRS Vitória raisins presented satisfactory quality and were accepted by consumers for all the attributes under analysis.

Most of the raisins consumed in Brazil are imported due to their unfavorable production requirements in Brazil and to the international raisin market competitiveness (Souza et al., 2015). Electric cabinet drying is one common method for raisin production, which may be inaccessible in Brazil due to high electric energy consumption. Another common method is through sun drying. However, it requires high temperature and low relative air humidity. Therefore, the rain concentration between January and April in Brazil may compromise natural sun drying. Hence, the application of hybrid dryers can be an alternative to reduce electricity consumption while exploiting solar energy, a free and abundant resource.

A fundamental understanding of drying kinetics is crucial for designing an effective drying system. It describes the drying process, determining the endpoint to which the product must be dried to achieve a stable final product. Besides, the knowledge of the drying kinetics yields a figure for the theoretical minimum amount of energy required. Modeling the drying process is an important step for drying technology development, particularly for industrial applications. Drying models guide engineers to determine the most appropriate drying method for a given product and operation conditions. Nevertheless, conducting full-scale experiments for different system configurations with a variety of products can be expensive, time-consuming, and impractical. Thus, the prediction of drying kinetics for specific crops under different conditions is a valuable tool for designing and optimizing dryers (Khazaei, Daneshmandi, 2007). Generally, the water content of the product is measured during a drying process, in which the product is subjected to a constant relative humidity and temperature. Then, the data is correlated to the drying parameters and used to determine the thin layer drying mode (Midilli et al., 2002). As an example, Dhanushkodi et al. (2017) studied the drying behavior of cashew in a hybrid solar-biomass dryer (HSBD). They have used fifteen thin layer drying mathematical models to find the best one to describe the collected data of the moisture ratio change for cashew drying. For that, they analyzed the correlation coefficient (r), root mean square error ($RMSE$), and Reduced Chi-Square (χ^2). However, the correlation coefficient is an inadequate measure to assess the goodness of fit in non-linear models (Spiess, Neumeyer, 2010).

Thus, this study aims at modeling the drying kinetics of BRS Vitória grapes under a Hybrid Solar-Electric Dryer (HSED) built at Pontifical Catholic University of Minas Gerais (PUC Minas), Belo Horizonte. Five thin layer models selected from the literature were fitted to the drying data, and a statistical analysis was performed to select the best model expressing the drying curve. Besides, since there is a lack of studies analyzing the drying behavior of BRS Vitória grapes, an analysis of the pretreatment influence on the initial water content and on the drying curve was also performed.

2. MATERIALS AND METHODS

The Hybrid Solar-Electric Dryer, Figure 1, is located at the PUC Minas, Belo Horizonte, MG, Brazil (latitude 19.92 °S and longitude 43.99 °W). During the drying process, it is necessary to collect weight data to perform the drying kinetic analysis. Therefore, a load cell located on the top of the dryer measures the weight of one tray during the drying process. The model installed is the IMP-184WS, which can hold up to 5 kg in total, with a 0.002 kg accuracy at the end of the scale.

Figure 1. Hybrid Solar-Electric Dryer photograph.

Inside the dryer, there are two DHT22 temperature and humidity sensors, ranging from -40 to 80 °C and 0 to 100 % relative humidity (RH), with accuracy of ±0.5 °C and ±2.0 % RH recorded at the end of the measurement scale. One of them is located at the entrance of the dryer, and the other is at the exit of the solar collector. Besides, there are six DS18B20 temperature sensors inside the drying chamber, ranging from -55 to 125 °C, and with a ±0.5 °C accuracy at the end of the measurement scale.

Knowing the dimensions of the dryer, it is possible to determine the loading capacity of a solar food dryer (Leon, Kumar, Bhattacharya, 2002). On average, the total tray area can be calculated as 1.33 times the solar collector size. This means that the total tray area recommended for the studied HSED should be 3.0 m^2 total, or 8 trays in total. Besides, the dryer loading capacity can be defined as 4 kg per square meter of tray area. Therefore, the total loading capacity for the HSED is 12 kg, or 1.5 kg per tray. Moreover, the airflow rate is 0.75 cubic meters per minute per square meter of tray area. Thus, the airflow rate recommended for the HSED is 2.26 m^3/s.

2.1 Sample preparation and determination of moisture content

The purpose of pretreating fruits before drying is to reduce the skin's resistance to water transfer at the beginning of the process. In this study, a method of pretreatment presented by Mühlbauer and Müller (2020) was used. The grapes were dipped in boiling water for around 2 minutes to fissure the skin of the fruit. Then, the grapes were dipped in cold water with ice to reduce their temperature.

Generally, grapes have around 80% of initial moisture content (Mühlbauer and Müller, 2020). However, due to the lack of study of BRS Vitória grapes in the literature, the humidity meter ID200 was used to determine the initial water content and to verify if the pretreatment method changes its value significantly.

The water content of two groups of grapes was determined during a 5-hour drying experiment. Each experiment was conducted with the humidity meter set for 130 ºC drying. Time, temperature, and weight data were collected during the experiments directly from the equipment into a laptop. The temperature was set relatively high in relation to a grape drying process for raisin production because the objective of this analysis is only to access the impact of the pretreatment on the initial moisture content of the BRS Vitória grapes. The first group consists of pretreated grapes, Fig. 2a, while the second group consists of normal grapes with two shallow knife cuts in their skin, Fig. 2b. The purpose of the cuts is to facilitate the water transfer in a similar way to the pretreatment. However, with handmade cuts, there are no interactions between the grapes and an outside source of water, which may interfere with the moisture content.

Figure 2. a) Pretreatment grapes and b) untreated cut grapes.

As seen in Fig. 2, to estimate the characteristics of the whole population and decrease the variability of the measurement, each group consists of a sampling of 10 grapes, weighing around 26 g in total after being pretreated or cut.

2.2 Drying kinetics

The HSED was operated with the electric heater controlled automatically to sustain a temperature of 60 ºC, which is the optimum drying air temperature for raisin production (Mühlbauer, Müller, 2020). However, in order to obtain a complete drying curve, the grapes were dried extensively until all the moisture content is removed. However, the moisture content for dried fruits regulated in Brazil cannot exceed 25 % (Ministério da Saúde, 2005). Nevertheless, the most appropriate moisture content for raisins is between 14 to 16 % (Sharma, et al., 2013).

For the experiment, a tray inside the dryer will be filled with approximately 0.9 kg of grapes, spread in a single layer. Besides, to obtain weight measurement, the tray was suspended by the load cell. There should not be grapes stacked on top another, since the models that will be analyzed are for thin-layer drying.

Equation (1) reveals the moisture content, $MC(t)$, along the drying procedure described on a wet matter basis. Note that it is necessary to know the dry matter of the sample, m_{db}.

$$MC(t) = [m(t) - m_{db}]/m(t), \quad (1)$$

in which $m(t)$ is the mass of the sample measured during the drying process.

For mathematical modeling, it is common to use the moisture ratio, $MR(t)$, usually expressed as seen in Equation (2). However, if the relative humidity fluctuates continuously during the drying process, Equation (3) can be used instead.

$$MR(t) = \left[MC(t) - MC_{eq}\right]/\left[MC_0 - MC_{eq}\right], \quad (2)$$

$$MR(t) = MC(t)/MC_0, \quad (3)$$

in which $MR(t)$ is the relative moisture ratio, MR_0 is the initial moisture content ($t = 0$), and MC_{eq} is the equilibrium moisture content of the sample, according to the desorption isotherm.

Thin layer drying equations can be categorized as theoretical, semi-empirical, and empirical models. Theoretical models are based on Fick's second law of diffusion, in which the geometry is simplified as a sphere, cylinder, or cuboid, neglecting the volume shrinkage. Semi-empirical models are based on the diffusion theory by simplifying Fick's second law, and can be also derived from Newton's law of cooling. At last, empirical models are strongly dependent on experimental data and usually provide a better fit. However, empirical models lack an understanding of the transport processes involved (Mühlbauer, Müller, 2020). Table 1 shows five models that were used to fit the data from the experiment. Besides, a linear regression was also conducted to be used as a comparison.

Table 1. Mathematical drying models.

Model name	Model	Equation
Lewis/Newton	$MR = \exp(-k_0 \cdot t)$	(4)
Page	$MR = \exp(-k_0 \cdot t^n)$	(5)
Henderson/Pabis	$MR = \mathrm{a} \cdot \exp(-k_0 \cdot t)$	(6)
Midilli	$MR = \mathrm{a} \cdot \exp(-k_0 \cdot t) + b \cdot t$	(7)
Wang/Singh	$MR = a \cdot t^2 + b \cdot t + 1$	(8)

To fit the models and find the empirical constants and coefficients, non-linear regressions were performed in the integrated development environment RStudio version 2023.06.1-524. The proposed models in Tab. 1 are common drying kinetics models explored in studies found in the literature regarding grape drying (Adiletta et al., 2016; Yaldiz et al., 2001; Essalhi et al., 2018; Hamdi et al., 2018; Toğrul, Pehlivan, 2004).

2.3 Statistical analysis

To evaluate the consistency of all models, some statistical parameters were analyzed. The chi-square, χ^2, mean bias error, MBE, and root mean square error, $RMSE$, were used as criteria to select the best equation expressing the drying curves. These parameters can be calculated as demonstrated in Eqs. (9)-(11).

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2\right]^{1/2}, \quad (9)$$

$$\chi^2 = \left[\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2\right]/[N - n], \quad (10)$$

$$MBE = \frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right), \quad (11)$$

in which $MR_{exp,i}$ is the i-th experimental moisture ratio and $MR_{exp,i}$ is the predicted moisture ratio at the same instant, N is the number of observations, and n is the number of constants respectively to each model.

2.4 Uncertainty analysis

In general, the final uncertainty is a given function in terms of independent variables. Therefore, the uncertainty in the result can be given by Eq. (12).

$$u_R = \left[\left(\frac{\partial R}{\partial x_1} u_1\right)^2 + \left(\frac{\partial R}{\partial x_2} u_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} u_n\right)^2\right]^{1/2}, \tag{12}$$

in which R is the result, u_R is the uncertainty in the result, u_1, u_2, …, u_n are the uncertainties in the independent variables, x_1, x_2, …, x_n are the independent variables.

The temperature measurement total extended uncertainty, $u_{Temperature}$, can be estimated with Eq. (13) with the accuracy values of the thermometers previously presented. Note that the coverage factor considered is k=2, meaning that there is a confidence that 95% of data points lie within two standard deviations. These temperatures are used to control the automated electric heater.

$$\begin{aligned} u_{Temperature} &= 2 \cdot [6 \cdot (u_{\mathrm{DS18B20}})^2 + 2 \cdot (u_{\mathrm{DHT22}})^2]^{1/2}, \\ &= 2 \cdot [6 \cdot 0.5^2 + 2 \cdot 0.5^2]^{1/2} = 2.8\ °C, \end{aligned} \tag{13}$$

in which the subscripts $DS18B20$ and $DHT22$ are the sensors models.

The humidity measurement total extended uncertainty, $u_{Humidity}$, can be estimated with Eq. (14), similar to Eq. (14).

$$\begin{aligned} u_{Humidity} &= 2 \cdot [(u_{\mathrm{DHT22}})^2]^{1/2}, \\ &= 2 \cdot [2.0^2]^{1/2} = 4.0\ \%. \end{aligned} \tag{14}$$

The mass loss measurement total uncertainty, $u_{Mass\ loss}$, can be estimated with Eq. (15), which is also the same as the drying kinetics modeling uncertainty. Notice that the air friction uncertainty is a general estimation proposed by Akpinar (2010), expressing the friction between the cable sustaining the tray with the top cover.

$$\begin{aligned} u_{Mass\ loss} = u_{drying\ kinetics} &= \left[(u_{load\ cell})^2 + \left(u_{friction}\right)^2\right]^{1/2}, \\ &= [0{,}002^2 + 0{,}5^2]^{1/2} = 0{,}5\ kg. \end{aligned} \tag{15}$$

3. RESULTS AND DISCUSSION

3.1 Pretreatment analysis

Before analyzing BRS Vitória grapes drying in the HSED, the interference of the pretreatment on the drying curve and the initial moisture content were evaluated. Two experiments were conducted on the ID200 humidity meter, automatically measuring temperature and percentage mass loss every 10 s. The experiments were conducted at 130 °C for 5 hours: one with pretreated grapes, and the second with untreated grapes, but with two knife cuts on their skin, to facilitate the water transfer in a similar way to the pretreatment. These cuts were made to analyze if the interaction with water during the pretreatment has any interference on the initial moisture content. The results can be found in Figure 3.

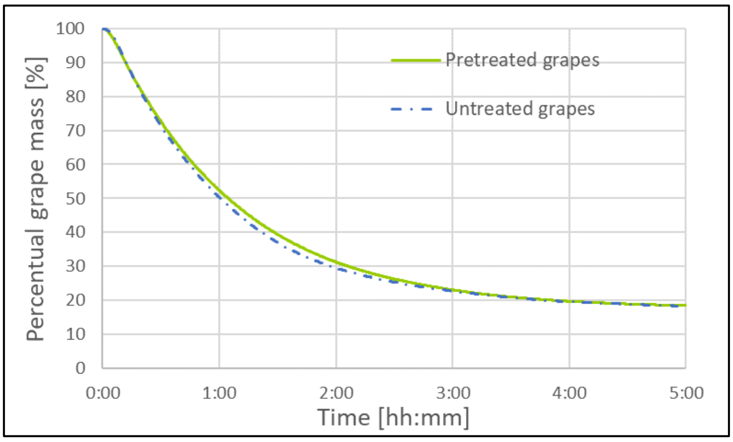

Figure 3. Drying curve of grapes under the ID200.

After five hours of drying the pretreated grapes and the untreated cut grapes at 130 °C, the results were considerably similar. Both the pretreated and the untreated grapes stabilized at 18.3%, concluding that the initial moisture content of BRS Vitória grapes is around 81.7%. Besides, the difference between each data recorded at the same time diverges only 0,9% on average from one another. This means that the pretreatment does not significantly affects the initial moisture content nor the drying curve for the proposes of this study.

3.2 Grapes drying analyses

Initially, Fig. 4, shows the drying conditions during the experiment measured in the HSED, executed between the 29th and 30th of June, 2023.

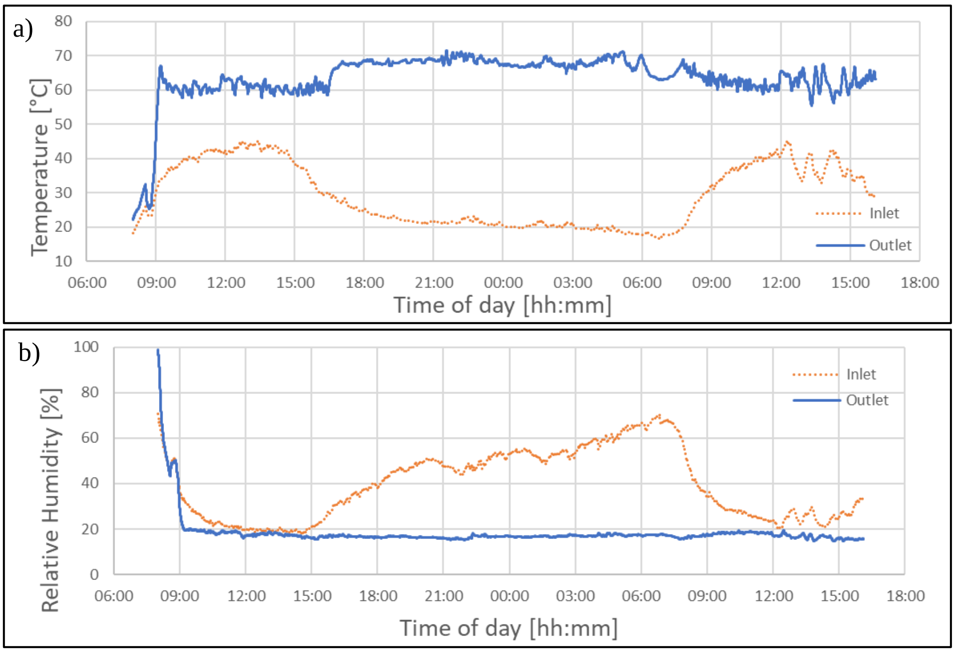

Figure 4. a) Temperature and b) relative humidity during the drying process.

Note in Fig. 4a that the outlet temperature remained stable between 60 and 70 ºC during the drying process, concluding that the automated system could sustain the desired temperature during day and night. Besides, as seen in Fig. 4b, the relative humidity of the air at the outlet remained below 20% and stable, which is desired for the drying process (Mühlbauer, Müller, 2020).

Figure 5 demonstrates the total grape mass loss during the experiment and the moisture ratio, which was used for mathematical modeling.

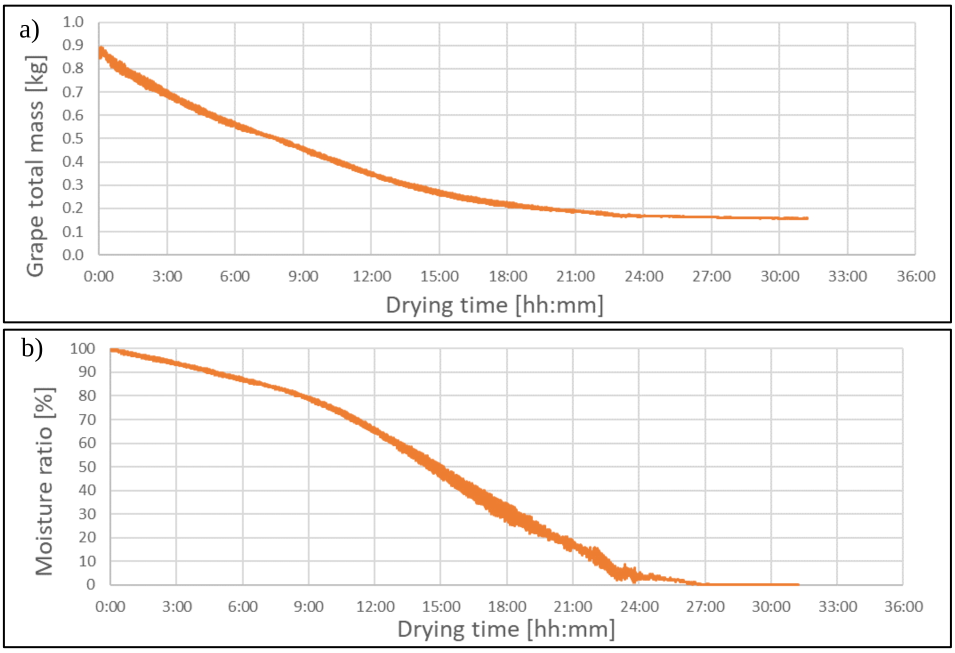

Figure 5. a) Mass loss and b) moisture ratio during the drying process.

Note that after 27 hours of drying, the grape's total mass stabilized, reaching 0% of moisture content and indicating that the drying process is finished.

3.3 Drying kinetics analyses

All the regression was executed in RStudio. Besides all drying models presented in Table 1, a linear regression was also conducted. As presented in Fig. 6, the dashed colored lines are the fitted model results, while the black line is the actual moisture ratio measured during the drying process, presented in Fig. 5b. Note that the drying duration time presented in the x-axis was standardized from 0 to 1.

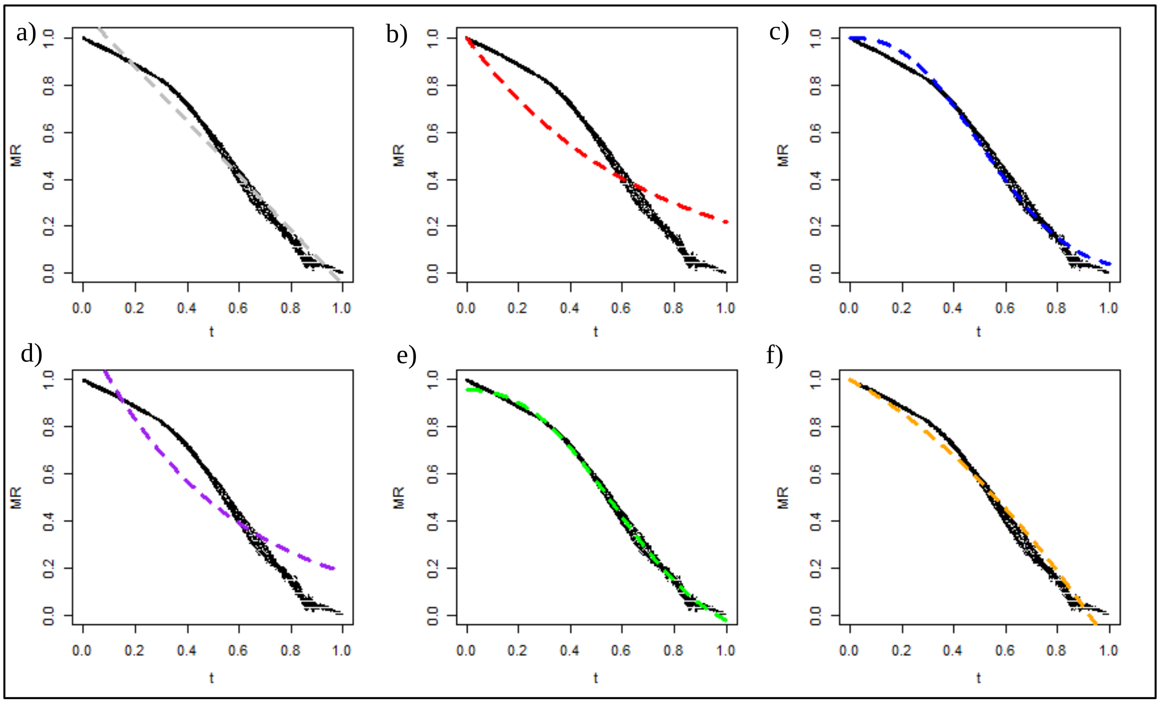

Figure 6. Regression results: a) linear, b) Lewis/Newton, c) Page, d) Henderson/Pabis, e) Midilli, f) Wang/Singh.

All the model's initial constants and coefficient values were estimated automatically by RStudio. Besides, all the regressions converged within 1 to 8 iterations.

In order to quantify the consistency of the models, a statistical analysis was performed, in which three parameters were calculated: root mean square error, chi-square, and mean bias error. The results of the statistical computations and the values of the constants are presented in Tab. 2. Note that small values of the parameters indicate a better model fit and how well the model can predict the moisture ratio. $RMSE$ measures the average difference between the predicted values and experimental data. χ^2, on the other hand, determine if a difference between the predicted and experimental data is due to chance, or if it is due to a relationship defined by the mathematical model. At last, MBE indicates the average deviation between the two datasets. Besides, the sign of the mean bias error also indicates if the prediction was underestimated, for negative values, or overestimated, for positive values. Therefore, it is expected that MBE value of a linear regression would be approximately zero, due to its definition.

Table 2. Constant values and statistical parameters results.

Models	k_0	n	a	b	$RMSE$	χ^2	MBE
Linear	-	-	-1.15579	1.108069	0.049049	0.002407	0.000000
Lewis/Newton	1.517900	-	-	-	0.144048	0.020754	0.015441
Page	3.280439	2.466935	-	-	0.033311	0.001110	-0.013769
Henderson/Pabis	1.89418	-	1.21406	-	0.1205541	0.0145393	-0.014421
Midilli	2.647263	2.564278	0.960756	-0.09014	**0.016941**	**0.000287**	**0.000120**
Wang/Singh	-	-	-0.52949	-0.59659	0.042477	0.001805	0.004876

When analyzing the statistical parameters in Tab.2, the Midilli model presented the best fit. Lewis/Newton and Henderson/Pabis models obtained the worst fit based on the statistical parameters, with values below the linear model.

Figure 7 illustrates the consistency of the models. Typically, the moisture ratio predictions are compared to be banded around a straight line, which would happen if all the predicted values match the experimental results.

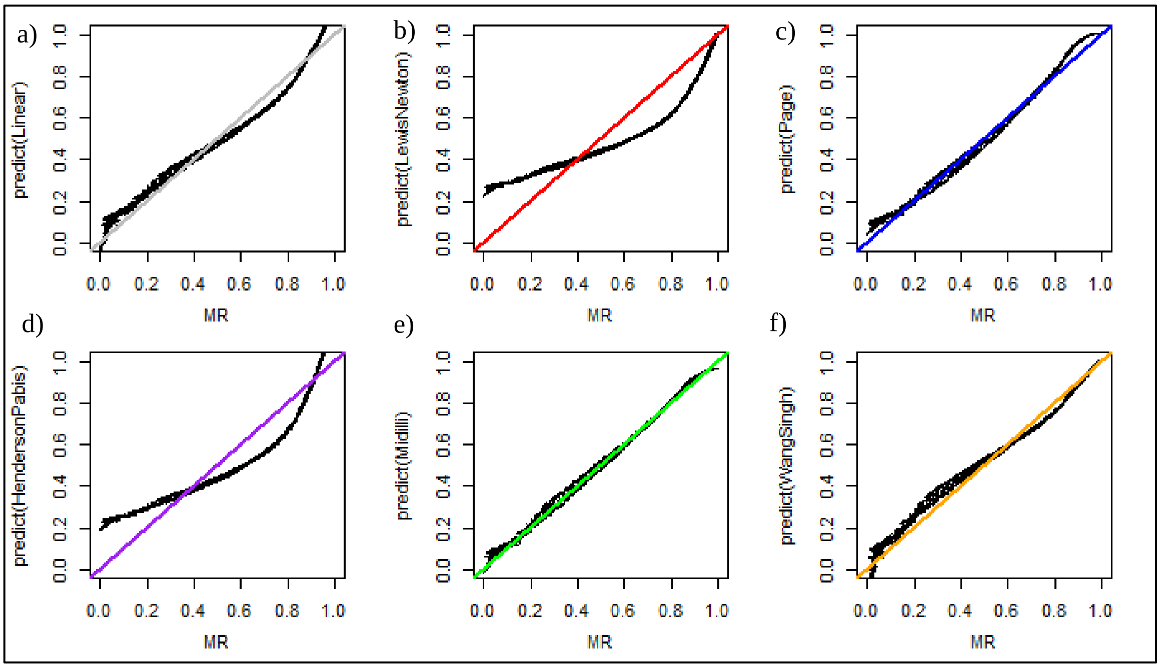

Figure 7. MR comparison: a) linear, b) Lewis/Newton, c) Page, d) Henderson/Pabis, e) Midilli, f) Wang/Singh.

When analyzing Fig. 7, it is possible to assess the moisture ratio predicted by each model as a function of the experimental moisture ratio. The prediction values when applying the Midilli model (Fig. 7e) best surround the straight line, demonstrating the pertinence of the model to describe the drying characteristics of the BRS Vitória grapes. Besides, the curves presented in Fig. 7 demonstrate if the model underestimates or overestimates the moisture ratio, e.g., the Wang and Singh model underestimates the MR at the first half of the process, and overestimates the MR at the end of the drying. Besides, based on the high χ^2, MBE, and $RMSE$ results, and on the curves presented in Fig. 6b,d and 7b,d, it can be assumed that the Lewis/Newton and Henderson/Pabis drying models are the only two among the five models in Tab. 1 that does not satisfy the drying data adequately, performing worse than a simple linear regression.

Figure 8 presents a comparison between the MR predicted results obtained in this study and the results obtained by Essalhi et al. (2018) using the Midilli model. To purpose of this comparison is to assess the impact of different experimental conditions on the drying kinetic curves. The Midilli model was selected for demonstration purpose due to its superior fit in both studies.

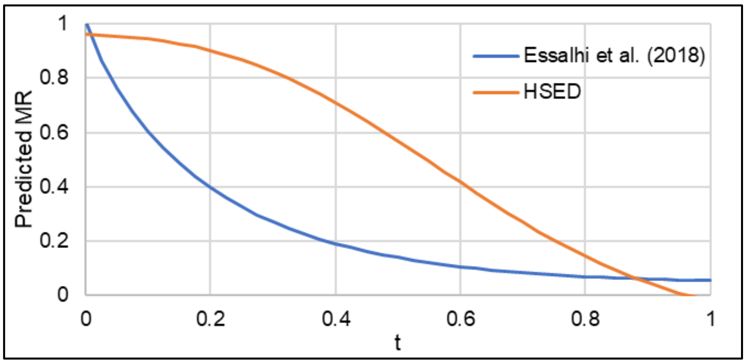

Figure 8. Midilli drying curve model comparison from different studies.

In this study, BRS Vitória grapes were dried in an HSED at a 60-70 ºC range for 27 hours. On the other hand, Essalhi et. al (2018) study analyzes the drying behavior of an unspecified type of grapes in a solar dryer for 120 hours at lower temperatures, below 47 ºC. Besides, the solar dryer used by Essalhi et al. (2018) did not provide a continuous drying process, as did the HSED, because their dryer has no backup heating sources for periods with low or no insolation. Therefore, as expected, the drying curve in Fig. 8 would differ from one another, despite being the same model used for grape drying.

4. CONCLUSIONS

This study aimed at evaluating the drying process of BRS Vitória grapes, due to the lack of study of this grape species, and to its commercial success and relevance in Brazil's grape production. Since the production of raisins in Brazil is not commercially competitive, an evaluation of the grape drying behavior is the first step for future economic analysis and large-scale production. Since Brazil lacks cheap electric energy and the natural low humidity necessary for grapes production, the study of the drying kinetics in an innovative hybrid solar-electric dryer, built at PUC Minas, Belo Horizonte, is relevant to explore new feasible and sustainable alternatives.

Initially, the pretreatment influence on the drying curve and on the initial moisture content was evaluated using a humidity meter. For this study, a thermal pre-treatment was executed, in which the grapes were submerged in boiling water for 2 minutes. Among all the pretreatment methods for grape drying, this treatment was chosen due to its execution ease and low price. It was concluded that the chosen method does not have a significant influence on the drying curve nor on the final grape moisture content, which was found to be 81.7 %. The result was in agreement with the literature, which expected a value of around 80 %.

During the experiment, around 0.9 kg of grapes were dried in the HSED using the electric heater automatically activated, to sustain a temperature between 60 to 70 ºC. The process was finished after 27 hours of drying time. When analyzing the temperature and humidity within the dryer, it was concluded that the HSED was capable to manage the drying process, sustaining the desired temperature and humidity necessary for raising production.

Five drying models were analyzed for the moisture ratio data of the drying process, and compared with a linear model. The non-linear regressions were conducted in RStudio, and three statistical parameters were calculated to quantify the consistency of the models: chi-square, χ^2, mean bias error, MBE, and root mean square error, $RMSE$. It was concluded that the Midilli model yielded the best fit for the drying kinetics of BRS Vitória grapes on the HSED. However, the Lewis/Newton model was considered improper, due to an incompatible drying curve prediction, and unsatisfying statistical parameters results.

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