From Fresh to Dried: Evaluating Drying Kinetics of Sultana and Besni Grapes

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Abstract

This research investigates the thin-layer drying kinetics of Sultana and Besni grapes using the forced-air drying method. The study evaluates the applicability of three drying models (Lewis, Page, and Henderson & Pabis) to the experimental data and concurrently determines the effective moisture diffusivity and activation energy of dried grapes at varying temperatures. The grapes were dried at different temperatures (55, 65, and 75 °C) in an air-forced drying oven until a moisture ratio of 0.14 ± 0.01 kg water/kg dry matter was achieved. When evaluating the coefficient of determination (R2), chi-square (χ2), and root-mean-square error (RMSE) values for the dehydrated grapes, the results reveal that all three models provided a reasonable fit for the experimental data, with the Page model proving to be the best fit. Effective moisture diffusivity values increased significantly with rising temperatures, and higher temperatures accelerate the drying process. The conclusions drawn from the study underscore the importance of understanding grape-specific drying kinetics for improving energy efficiency and optimizing drying procedures. The Page model has been highlighted as particularly useful for future studies and industrial applications. This study provides valuable insights into both the academic community and the food industry, suggesting potential pathways for energy conservation and enhanced drying processes in dehydrated foods.

Keywords: Drying Kinetics, Sultana Grapes, Besni Grapes, Forced-air Drying.

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1. Introduction

The grape is a fruit widely consumed worldwide. Grapes can be enjoyed fresh or be transformed into various grape-based food products through numerous food processing methods. One such method is the drying process. This process extends the shelf life of grapes by reducing their water content. Simultaneously, it enhances their aroma and nutritional values, transforming them into a popular product - raisins.

Turkey occupies a significant place in agricultural production and boasts substantial potential in grape cultivation. Grapes constitute a commercially valuable agricultural product, cultivated extensively in different regions of Turkey. Raisins, derived from dried grapes, are among Turkey's most exported agricultural commodities. Besni and Sultana grapes are among the most widely grown and commercially valuable varieties used in raisin production in Turkey. Besni grapes, grown primarily in southeastern Turkey and particularly in Adıyaman, are comparatively larger and seeded, with a sweet-sour aroma profile. In contrast, Sultana grapes are seedless, sweet grapes grown in Turkey's Aegean Region, especially in the cities of Manisa, Aydın, and İzmir.

Sun drying and hot air drying methods are commonly utilized for drying grapes. While grapes were traditionally sun-dried, hot air drying methods have gained prevalence with the rise of industrial production. The rapid, standardized production capabilities offered by the hot air drying method make it industrially appealing. Forced air drying, a method that uses hot air to remove moisture from grapes, involves passing controlled airflow around the grapes (Karasu et al., 2016; Yalinkilic et al, 2023). This method results in high hot air circulation, potentially leading to the oxidation of vitamins and color compounds. However, unlike slower drying methods such as sun drying, it quickly inhibits yeast and mold formation and slows down the development of mycotoxins.

This study aimed to create thin-layer drying models for Sultana and Besni grape varieties, two popular white grapes in Turkey, using the forced-air drying method.

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Thus, grapes were dried at different temperatures, and their compatibility with three popular models was analyzed. This study also determined the effective moisture diffusivity and activation energy of dried grapes at varying temperatures.

2. Materials and Methods

2.1. Materials

Dehydration experiments were conducted utilizing, whole grape (Vitis vinifera L.): Sultana (syn. Thompson seedless) and Besni. The Sultana grapes were cultivated in Manisa, Turkey, while the Besni grapes were grown in Adıyaman, Turkey. Prior to the dehydration process, all samples underwent a traditional pretreatment, entailing a two-minute immersion in a Potas solution. This solution comprised a 5% potassium carbonate and 0.5% olive oil aqueous mixture, at temperature of 25°C.

The initial moisture content of the grapes was determined by employing the oven drying method as described by the Association of Official Analytical Collaboration (AOAC, 2000). In this process, grape samples were subjected to drying at a temperature of 105 °C until a stable weight was reached, indicating the evaporation of all free water content.

2.3. Drying experiments

The samples (approximately 60g) were dehydrated with air-forced drying oven (Memmert UF 110, Germany) set at 55, 65 and 75 °C. Dehydration continued until the moisture ratio (MR) hit an approximate target of 0.14 ± 0.01 kg water/kg dry matter (d.b.), correlating to about 12% of moisture content. The sample weights were periodically measured throughout the dehydration process for obtaining drying curves. The weighing procedures were performed within a 15-30 second post sample removal from the drying system. In addition, the energy consumption during the dehydration was tracked using an energy meter (PeakTech 9035, Germany). For validation, all experiments were replicated.

2.3. Mathematical Modelling

The experimental grape drying data were modeled using three prevalent thin-layer drying models: Lewis (Bruce, 1985), Page (Madamba et al., 1996), and Henderson & Pabis (1961). These models represent the moisture ratio (MR) at any given drying time (t) (Başlar et al., 2014). Moisture transfer throughout thin-layer drying of food materials is generally characterized by diffusion. The effective moisture diffusivity is determined by plotting ln (MR) versus time (min) using the experimental drying data. The activation energy can be calculated using a modified form of the Arrhenius equation. The moisture ratio (MR), the effective moisture diffusivity (Deff), and activation energy (Ea) were calculated using equations provided in the study by Başlar et al. (2014).

2.4. Statistical Analysis

Drying kinetics data from the samples were analyzed using a non-linear regression procedure in SPSS 15.0 software program (SPSS Inc., Chicago, IL, USA). The fitness of the experimental data to the models was evaluated by the coefficient of determination (R2) provided by the program, in addition to the chi-square (χ2) and root-mean-square error (RMSE) values, calculated using the equations in the study by Togrul and Arslan (2004).

3. Results and Discussion

3.1. Drying kinetics of grapes

The initial moisture content (d.b.) was established at 3.979 kg water/kg dry matter for Sultana grapes and 3.258 kg water/kg dry matter for Besni grapes. Dehydration was executed until the moisture content reached 0.14 ± 0.01 kg water/kg dry matter (d.b.),

approximating about 12% moisture content. While the drying times of the Sultana grapes at 55, 65, and 75 °C were 2100, 1080, and 660 minutes respectively, the drying times of Besni grapes at the same temperatures were 1875, 960, and 645 minutes respectively. For both grape types, an increased temperature significantly truncated the drying time. As an example, drying at 55°C extended the drying time approximately three times compared to drying at 75°C (Table 1). It was seen that the drying time of the grapes was close to that of the study by Doymaz and Altıner (2012).

According to Table 1, when an evaluation is made in terms of the energy consumption of the drying system at different temperatures, the temperature increase provided energy savings, but it was twice as much as in the drying time.

Table 1. Drying time, energy consumption, and effective moisture diffusivity of grapes

Grape	T (°C)	t (min)	E (kW.h)
Sultana	55	2100	5.689
	65	1080	3.756
	75	660	2.925
Besni	55	1875	5.080
	65	960	3.339
	75	645	2.859

T: Drying Temperature(°C), *t*: Drying time (min). *E*: Energy consumption measured in the oven during drying (kW.h)

The plots of moisture ratio versus time at 55, 65, and 75°C for Sultana and Besni grapes are shown in Figure 1. The drying curves are typical of those for similar fruits and vegetables. The moisture content of grapes decreased exponentially depending on the elapsed drying time.

3.2. Fitting of thin-layer drying models

Mathematical modeling serves as a beneficial and practical approach for creating new designs and optimizing the drying process. In this study, the drying kinetics of Sultana and Besni grapes at various temperatures were examined, fitting the experimental data to three commonly used drying models: Lewis (Bruce, 1985), Page (Madamba et al., 1996), and Henderson & Pabis (1961). The parameters estimated from fitting these models to the grape drying data are presented in Table 2.

The most effective model for thin-layer drying kinetics was assessed based on the coefficient of determination (R2), chi-square (χ2), and root-mean-square error (RMSE) values for the dehydrated grapes. Upon evaluating the models using these parameters, all of them were generally found to fit well. However, the Page model provided a better fit for both grape varieties. This finding is consistent with the studies conducted by Doymaz and Pala (2002), where the Page model was identified as the most suitable model for drying seedless grapes, and by Doymaz (2006), where the Page model was found to be the best fit for drying black grapes. Furthermore, a study by Doymaz and Altıner (2012) on the drying kinetics of seedless grapes also found a good fit with the Page model, though they ultimately concluded that the Parabolic model was the optimal fit for their seedless grapes.

The primary aim of developing drying models is to facilitate mathematical analysis of the drying process over time and temperature, particularly in industrial applications. Consequently, it is crucial that these models strike a balance between accuracy and simplicity of use. This study concludes that the Page model meets this criterion, displaying a commendable level of both accuracy and ease of application.

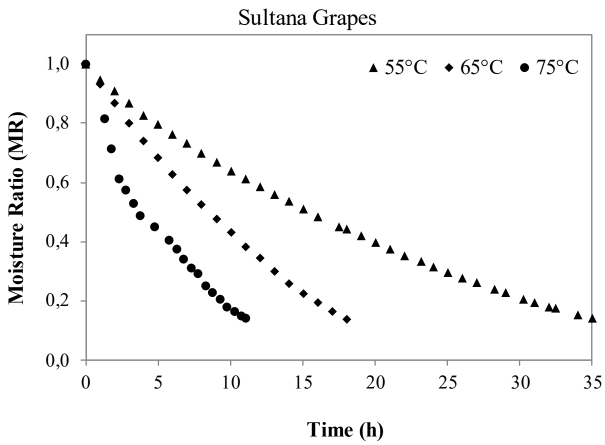
3.3. Effective moisture diffusivity

The effective moisture diffusivity (Deff) values for Sultana and Besni grapes, provided in Table 3, range from 1.265×10-9 to 4.915×10-9 m2/s. The Deff value substantially increases with rising temperature. This pattern could indicate that an increase in vapor pressure, which is induced by the temperature rise, accelerates the drying process. Drying at 75°C yields the highest value of effective moisture diffusivity, whereas the lowest value is obtained at 55°C for both grape varieties. Notably, the Deff values increase by almost a factor of 3.6 for Sultana grapes and Besni grapes when the temperature is increased from 55°C to 75°C, highlighting the significant impact of temperature on the drying efficiency.

Table 2. Estimated model parameters and statistical parameters obtained from fitting of the drying models for grapes

Model	Parameters	Sultana Grape			Besni Grape		
		55 °C	65 °C	75 °C	55 °C	65 °C	75 °C
Lewis	k (×10^{-4})	8.079	14.942	28.895	8.337	16.278	30.745
	R^2	0.994	0.984	0.985	0.972	0.978	0.986
	RMSE	0.01970	0.03291	0.02827	0.04444	0.03991	0.02798
	χ^2	0.00040	0.00114	0.00084	0.00204	0.00169	0.00083
Page	k (×10^{-4})	4.377	3.839	5.014	0.892	2.667	49.057
	N	1.087	1.212	0.906	1.320	1.287	0.920
	R^2	0.996	0.997	0.990	0.997	0.999	0.989
	RMSE	0.01490	0.01472	0.02365	0.01364	0.00999	0.02462
	χ^2	0.00024	0.00024	0.00062	0.00020	0.00011	0.00068
Henderson & Pabis	k (×10^{-4})	8.202	15.714	27.753	9.041	14.469	29.900
	a	1.012	1.041	0.966	1.066	1.058	0.976
	R^2	0.994	0.988	0.987	0.981	0.985	0.987
	RMSE	0.01912	0.02871	0.02586	0.03670	0.03267	0.02692
	χ^2	0.00039	0.00092	0.00074	0.00144	0.00121	0.00081

k: constant of drying velocity (min^{-1}). a and n: dimensionless drying constant. RMSE: Root-mean-square error. χ^2: chi-square, R^2: Coefficient of determination



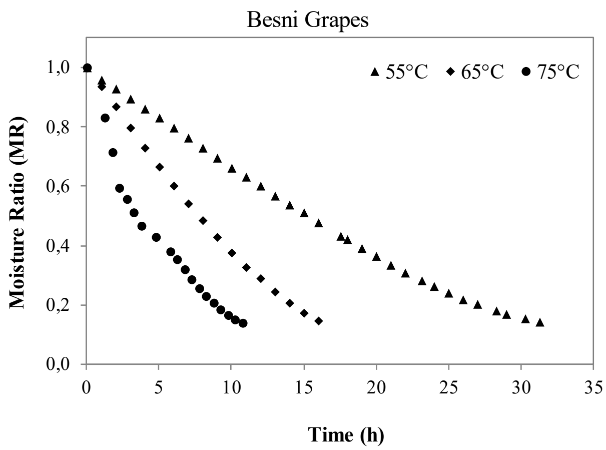


Figure 1. Drying curves of dried Sultana and Besni grapes

The Deff values procured in this study fall within the generally desirable range for drying food materials (Zogzas et al., 1996). This further validates the experiment and provides strong grounds for its application in practical settings.

The activation energy of Sultana and Besni grapes, as determined by the Arrhenius equation, was found to be 60,804 J/mol (R2=0.999) and 57,797 J/mol (R2=0.998) respectively. These results suggest that Besni grapes are relatively less sensitive to changes in drying temperature. Therefore, increasing the temperature for Besni grapes has a less significant impact on the drying rate compared to Sultana grapes. A comparison of the activation energy found in this study with the literature reveals that the obtained results are slightly higher than those reported in other studies. This could be attributed to the specific properties of the studied grape varieties, the drying method used, or both.

Table 3. Effective moisture diffusivity of the grapes

Grape	T (°C)	D_{eff} (m²/s)	R^2
Sultana	55	1.265×10^{-9}	0.724
	65	2.420×10^{-9}	0.687
	75	4.612×10^{-9}	0.825
Besni	55	1.351×10^{-9}	0.674
	65	2.632×10^{-9}	0.667
	75	4.915×10^{-9}	0.835

T: Drying Temperature (°C). D_{eff} : Effective moisture diffusivity (m²/s). R^2: Coefficient of determination.

4. Conclusions

This study sought to explore the drying kinetics of Sultana and Besni grapes, providing crucial insights into the impact of drying temperature on these processes. Our observations revealed a significant decrease in drying time with the increase in temperature for both grape varieties. Upon fitting the experimental data to three established drying models (Lewis, Page, and Henderson & Pabis), it was found that all models generally provided a good fit for our data. But the best compatible model was the Page model. This compatibility highlights the Page model's practicality for future studies and industrial applications. Our investigation into the effective moisture diffusivity (Deff) of Sultana and Besni grapes also yielded noteworthy results. There was a substantial increase in Deff values with rising temperatures, suggesting an acceleration in the drying process due to heightened vapor pressure. In conclusion, this study underscores the importance of understanding grape-specific drying kinetics for improving energy efficiency and optimizing drying procedures. Researcher thinks that these findings will prove valuable to both the academic community and the food industry, stimulating further exploration and innovation in this field.

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Declaration of Competing Interest

The authors declare that they have no financial or non-financial competing interests.

Author's Contributions

M. Başlar (0000-0002-8369-0769): *Definition, Data Collection,* Investigation, Conceptualization, Methodology, Writing, Editing.

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