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Precision Measurement and Sustainable Preservation: Advancements in Solar Drying and Mathematical Modeling of Carrots

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ABSTRACT

This study investigates the solar drying of carrots by combining practical experimentation with mathematical modeling. The primary objective was to assess the physicochemical composition of carrots before and after undergoing solar drying, with an emphasis on maintaining the high quality of the dehydrated product. The accurate determination of the drying kinetics was accomplished, and the resulting curves were fitted using established mathematical models. Among these, the logarithmic model was identified as the most suitable for characterizing the drying process, given its effectiveness in capturing the complex dynamics involved. This research offers a comprehensive understanding of the solar drying of carrots, highlighting physicochemical attributes, kinetic aspects, and the application of mathematical modeling. Notably, the use of the logarithmic model is elucidated in relation to its pertinence to the drying process. The findings of this study are significant within the broader context of food preservation, providing valuable insights that could improve the efficiency of essential preservation techniques.

1. INTRODUCTION

Solar drying of carrots, an enduring method, has seen a resurgence due to its benefits for food preservation, sustainability, and safety. Utilizing solar energy for drying is particularly advantageous for environmentally conscious practices and serves as an effective solution in regions with scarce electricity.

Our study delves into the kinetics of carrot solar drying, drawing on prior research that has substantially informed our understanding of this practice. Key contributions from Ratti and Mujumdar [1] and Thirugnanasambandam et al. [2] are noteworthy. They have significantly propelled the field forward by melding two critical aspects of solar drying.

The first notable advancement is the development of a simulation code for predicting batch drying in solar dryers, tailored for packed particles such as carrot slices. Parameters derived from experimental data allowed the model to accurately reflect the published results for diced carrot drying, emphasizing essential process parameters.

Secondly, a study accentuating the economic and ecological benefits of solar energy underscores the efficacy of solar thermal technologies. It spans performance analyses, mathematical simulations, and the development of innovative designs, all contributing to the enhancement of the solar drying process of carrots for better food preservation and sustainable energy use.

Further contributions by Wagner et al. [3], Zhao et al. [4], and Yuan et al. [5] stress the nutritional advantages of solar drying, especially for developing areas. Wagner investigates high-temperature drying for lumber, aiming to reduce drying durations without quality loss. Zhao et al. optimize spray drying for Lycium barbarum L. polysaccharides, prioritizing product appearance and activity for industrial production. Yuan et al. demonstrate the applicability of solar drying to industrial-scale carpet drying, showcasing the versatility of solar energy. These findings collectively offer insights to improve drying efficiencies across various industries, with economic and environmental considerations in mind.

Natural outdoor sun drying [6] is prevalent for preserving agricultural products due to its effectiveness and low cost. However, this traditional method exposes products to contamination from pathogens like microorganisms and insects and is also subject to weather variability, which can affect quality [7]. Our study on the solar drying kinetics of carrots aims to develop more controlled methods to improve quality, safety, and optimal preservation.

In the realm of scientific literature, the superiority of forced convection solar dryers, or active solar dryers, over natural circulation models have been highlighted [8]. These dryers are gaining traction due to their minimal electrical energy requirements for fan operation.

Our analyses encompass energy consumption and a comprehensive quality assessment of the dried product, its scalability, and the methodologies applied. Shahriar et al. [9] commend the quality of maize grains dried using the HSTU multi-crop mobile dryer (HMMD), which uses LPG and electric heating, for its efficiency in reducing drying time and improving nutritional value, color, and microbial safety. Martens et al. [10] study the effects of drying time and intermittence on the quality of polished and brown rice, showing that accumulated drying time affects the temperature of the grain mass and thus the quality.

While exploring sorption isotherms, in-depth studies on specific technical aspects prove crucial for solar drying research [11, 12]. These detailed analyses, such as sorption isotherms, provide valuable insights into the relationships between moisture and agri-food products [13, 14], thus illuminating the path to enhance solar drying processes. Particularly, this knowledge contributes to refining drying kinetics and elucidating underlying mechanisms, thereby strengthening the scientific foundation of research in the field of solar drying.

At the heart of our study is a critical examination of the literature on carrot solar drying kinetics, with particular reference to the foundational works [1, 2]. Our research identifies gaps in the understanding of different drying methods, such as direct, indirect, and open-air drying, and seeks to determine optimal drying rates that maintain carrots' nutritional integrity and extend shelf life. This examination underscores the importance of our study in contributing substantively to the domain of carrot solar drying.

2. METHODOLOGY

This experimental study is centered around the carrot drying process (Figure 1), with the objective of determining kinetic curves, comparing the physicochemical composition of various carrot varieties, and developing a suitable mathematical model for carrot drying.

Figure 1. Carrots prepared for the study

2.1 Solar drying system

The trial of the solar dryer integrated with the PVT collector, conducted at the URER/MS in Adrar, Algeria, is elucidated by Figure 2, detailing the configuration of the system. The solar collector, inclined at 28º in alignment with the local latitude, consists of a glass cover and a black metallic absorbing plate, integrated on a wooden frame. This parallelepiped-shaped conduit with dimensions of 90 × 100 × 4 cm heats the incoming air through solar irradiation, featuring a perforated entrance for uniform air circulation. Divided into two parts, the collector incorporates a semi-transparent photovoltaic module of 125 watts-peak (Wp) above an insulated PVT air collector. The black metal cover is used to efficiently absorb solar radiation. As a component of the absorber plate, the black cover promotes maximum absorption of solar energy, contributing to heating the air circulating inside the conduit through solar radiation. This design aims to optimize the thermal efficiency of the solar dryer by harnessing the black material's ability to efficiently absorb and convert solar energy into heat.

The indirect drying chamber, connected to the collector, is equipped with trays for organizing carrot slices, with dimensions of (85 × 55 × 15) cm³. Manufactured with double-walled wood resins, it includes a 3 cm layer of polystyrene to minimize thermal losses. 6 W centrifugal fans expel humid air, maintaining an airflow of 120 m³/h and operating within a temperature range of -10 to 70°C. The intentional southward orientation of the system aims to maximize solar exposure.

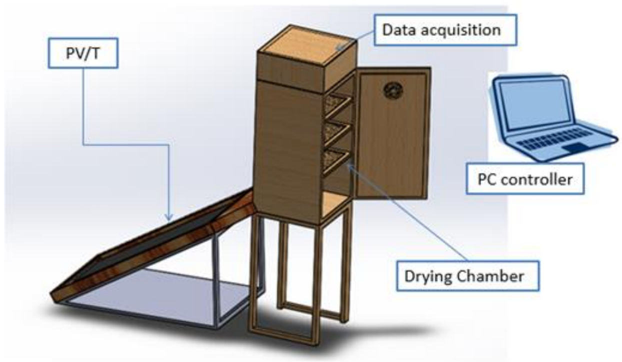

Figure 2. Determination of key components

2.2 Plant selection

We chose carrots based on several key criteria. Carrots are readily available and hold significant culinary importance both globally and particularly in Algeria. They are a year-round staple and play a vital role in the food industry. In the context of our study, the process of selecting the carrot variety has been meticulously carried out, considering several criteria such as water content, nutritional composition, and resistance to solar drying conditions. This rigorous selection aims to ensure that the chosen carrots constitute a meaningful sample to assess the effects of solar drying on nutritional quality. The chosen variety plays a crucial role in the relevance of the obtained nutritional information and its practical application.

The carrots used in this study were sourced from the Bouda market in Adrar in March 2022. Daucus Carotta, a biennial plant belonging to the Apiaceae family, is characterized by its fleshy, typically orange-colored taproot and high carotene content, providing approximately 31 kilocalories per 100g. Our study encompassed the determination of physicochemical composition, the establishment of drying kinetic curves, and the development of a pertinent mathematical model for the drying process.

2.3 Determination of key components

In this series of analyses conducted on a sample of crushed carrots, various aspects of their chemical composition were explored (Figure 3).

Figure 3. Determination of key components

a. Water Content Determination

Procedure: A 1g sample is meticulously crushed and heated at precisely 103 ± 2℃ until a constant weight is achieved.

Preparation of Capsules: Empty capsules are dried at 105°C for 15 minutes, cooled, and weighed after tearing.

Sample Measurement: The sample is accurately weighed (precision: 0.001g) in each capsule and placed in a 105℃ oven for 3 hours.

Optimization: Capsules are cooled, weighed at intervals until constant, minimizing drying time to 30 minutes.

b. Ash Content Determination

Procedure: Follows the standard method (NF V05-113, 1972). A 2-gram sample is dried at 105℃ for 24 hours to determine moisture content. Combustion at 550℃ is then conducted to ascertain the mass of organic matter present.

c. pH Determination

Procedure: A solution containing ground product pulp is prepared per NF V05-108, 1970. The pH is determined by measuring the potential difference between two glass electrodes immersed in the solution.

Sample Preparation: The sample is cut into small pieces, mixed with distilled water, heated in a water bath while stirring for 30 minutes, and ground in a mortar.

d. Titratable Acidity Determination

Procedure: Follows NF V05-101, 1974 standard. Titrated using a solution of sodium hydroxide (NaOH) and phenolphthalein as an indicator.

Sample Preparation: At least 25g of the sample is mixed with distilled water, heated, filtered, and titrated until the solution turns pink.

e. Protein Content Determination (Kjeldahl Method)

Procedure: The sample is mineralized with copper sulfate and potassium, and sulfuric acid is added. The mixture is heated for 4-5 hours, and after cooling, the excess ammonia is titrated.

f. Fat Content Determination

Procedure: Lipids are extracted from a 10g sample using a Soxhlet apparatus with hexane. The resulting solution undergoes distillation in a Rota steamer to remove solvent, leaving purified lipids.

g. Sugar Content Determination (Dubois Method)

Procedure: Involves the formation of orange-yellow chromophores using phenol and sulfuric acid. The increase in optical density at 490 nm is measured to determine sugar content.

Sample Preparation: 1g of sample is heated with 300 ml of distilled water containing 3g of $CaCO_3$. The mixture is filtered twice, and the optical density is measured. Results are expressed in µg/ml of α-D(+) glucose and converted into grams/liter using a calibration curve.

2.4 Exploration and modeling

The experimental data of the water content of the cores obtained at different temperatures were simulated using 4 empirical equations presented in Table 1.

Table 1. Mathematical models provided by various authors for the drying kinetics

Model	Equation
Wang and Singh [15]	$Y = 1 + at + bt^2$
Two-Term Exponential [16]	$Y = a\exp(-kt) + (1 - a)\exp(-kt)$
Newton [17]	$Y = \exp(-kt)$
Logarithmic [18]	Y=aexp(-kt)+c

The Wang and Singh model postulates a polynomial relationship with linear and quadratic terms, suggesting intrinsic complexity in drying kinetics. The underlying assumptions of this model require precise experimental data for adequate interpretation. In contrast, the two-term exponential model assumes that drying kinetics can be described by a combination of two exponential terms. Although this approach provides some flexibility, its specificity may be limiting in capturing real variations in the drying process. The Newton model further simplifies kinetics by linking it to a simple exponential decay. However, this simplicity may lead to limitations when the drying process exhibits distinct phases not captured by a single exponential term. Finally, the logarithmic model, with the addition of a constant term, offers a more flexible representation. However, introducing this complexity requires a strong theoretical justification and careful selection of experimental data.

In the evaluation of models through statistical methods, parameters such as the coefficient of determination (R^2), the reduced ki-square (x^2), and root mean square error (RMSE) are judiciously employed. These metrics provide valuable insights into the quality of the models' fit to experimental data.

The criteria for evaluating the quality of smoothing of the experimental results are the coefficient of determination (R^2), the reduced ki-square (x^2) and the square root of the root mean square error (RMSE). These parameters are calculated according to Eq. (1).

$$x^2 = \frac{\sum_{i=1}^{n}(X_{ei} - X_{Pi})}{N - n}$$

and (1)

$$\text{RMSE} = \sqrt{x^2}$$

where, X_{ei} is the 1st experimental value; X_{Pi}, the 1st value predicted by the model; N, the number of observations and n, the number of model constants.

The coefficient of determination R^2 is one of the first criteria for evaluating the quality of smoothing of experimental results. The model which best describes the drying kinetics is the one for which the value of R^2 is the greatest and the values of x^2 and RMSE the lowest.

The different mathematical models examined are adjusted to the experimental data by applying the nonlinear regression method. The software used is "Curve-Expert".

3. RESULTS AND DISCUSSION

3.1 The physicochemical components of the products

Upon conducting product analyses, the following results of Table 2 were obtained. The symbols in the dataset correspond to different parameters that characterize the properties of carrots at various stages, including before and after different drying methods and exposure to outdoor conditions.

- H% (Moisture Content): This symbol indicates the percentage of water content in the carrots.
- MS% (Soluble Solids Content): It represents the percentage of soluble solids in the carrots.
- MO% (Ash Content): This symbol reflects the percentage of ash content in the carrots.
- MM% (Methanol Content): Denotes the percentage of methanol content.
- MG% (Glycerol Content): Represents the percentage of glycerol content.
- pH: Indicates the pH level of the carrots.
- Acidity: This symbol represents the acidity level of the carrots.
- Reducing Sugar: Indicates the concentration of reducing sugars in the carrots.
- Water Activity: Represents the level of water activity.
- Protein: Denotes the protein content in the carrots.

Table 2. Physicochemical components of the products

	Before Drying	After Direct Drying	After Indirect Drying	Outdoors
H%	90.26	6.07	6.38	6.93
MS%	9.74	93.92	93.61	93.06
MO%	6.83	80.47	89.88	78.08
MM%	2.9	13.44	3.72	14.97
MG%	0.65	1.69	1.32	0.76
pH	6.43	6.14	6.16	6.22
Acidity	0.07	1.96	2.17	1.05
Reducing sugar	8.3	15.73	14.6	7.4
Water activity	0.90	0.061	0.06	0.07
Protein	0.5	0	0.284	1.26

The analysis of the data extracted from the table reveals substantial variations in the chemical composition of carrots before and after the drying process, conducted using three different methods: direct, indirect, and open-air drying.

Prior to drying, the carrot core exhibited a high water content (H%) of approximately 90.26%, which decreased significantly after drying, with the indirect method displaying the lowest water content. Simultaneously, the dry matter (DM%) increased significantly after drying, almost reaching 94% with the direct method.

Organic matter (OM%) also underwent notable variations, increasing substantially under all drying conditions, with the indirect method showing the most significant increase.

Mineral content (MM%) fluctuated depending on the method used, with the indirect method displaying the lowest mineral content after drying.

The fat content (MG%) remained consistently low, with a slight increase observed after drying.

pH decreased slightly after drying, with values close to 6, while acidity increased in all methods after drying, with the indirect method registering the most significant increase.

The reducing sugar content increased after drying, indicating a higher concentration of sugars in the dried carrots.

Water activity decreased significantly after drying, which is favorable for food preservation.

Lastly, the protein content varied after drying, reaching 1.26% in the case of the indirect method.

These data underscore the significant impact of the drying process on the chemical composition of carrots, particularly concerning water content, dry matter, and essential nutrients. It's worth noting that these variations can be influenced by the specific drying method employed, making this information crucial for understanding the evolution of the properties of dried carrots.

Our study revealed significant changes in the physicochemical properties of carrots after different drying methods. These variations can be attributed to several factors. Firstly, the drying process itself can induce structural alterations, affecting the chemical composition and physical characteristics. For instance, direct and indirect drying may lead to differences in temperature and humidity, thus influencing water content, acidity, and other components.

Moreover, complex chemical reactions during drying, such as enzymatic degradation or the Maillard reaction, can impact the color, flavor, and nutritional composition of carrots. The influence of environmental conditions during outdoor drying, such as exposure to sunlight and air, could also contribute to these variations.

It is crucial to emphasize that the proper selection of drying parameters and experimental conditions can play a major role in preserving the initial properties of carrots.

3.2 Drying kinetics

Temperature and Humidity Fluctuations:

Gilago et al. [19] investigated the thermal characteristics of natural convection indirect solar dryers (setup A) and forced convection dryers (setup B) during the drying of carrot slices. Setup B, enhanced with features such as a trapezoidal tunnel and fans powered by photovoltaic panels, exhibited superior drying efficiency (9.55%) compared to setup A (7.5%). Mass and heat transfer coefficients, as well as activation energy, were also enhanced in setup B, demonstrating improved moisture extraction and more efficient energy consumption.

In our study, once the samples are placed inside the dryer, we record humidity levels and temperature using the "Opus" device.

The variation in temperature and humidity at the entrance and center of the indirect chamber during the solar drying test on March 15-16, 2022, is illustrated in Figures 4 and 5.

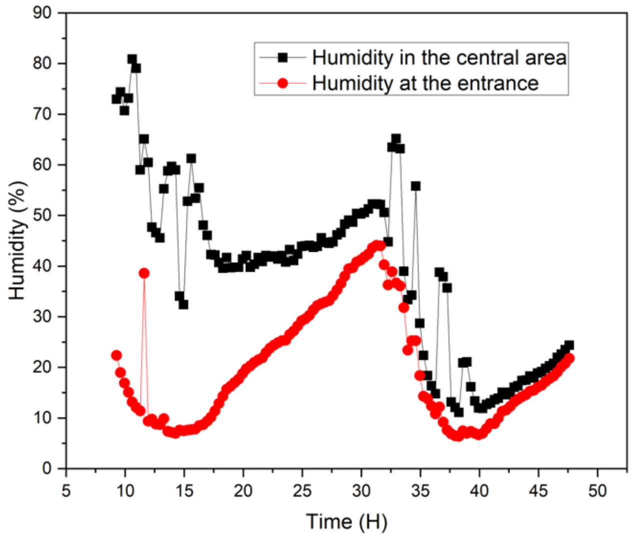

Figure 4. Changes in humidity at the inlet and in the center of the indirect chamber

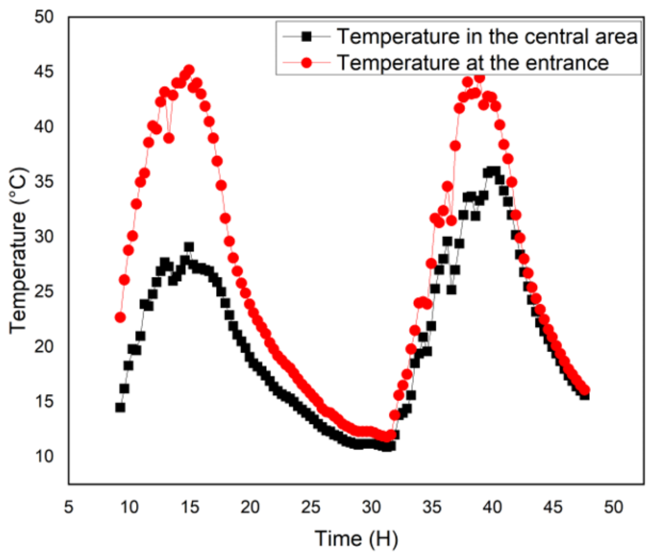

Figure 5. Changes in temperature at the inlet and in the center of the indirect chamber

During the day, we observe a substantial fluctuation in air humidity between the inlet and outlet of the dryer. This contrast is especially noticeable during periods of high solar irradiation when temperatures reach their zenith. It's crucial to note that air humidity and temperature share an inverse relationship, meaning that as temperature rises, humidity levels decrease. This connection plays a pivotal role in the drying process.

As the temperature escalates, the drying solar rate proportionally increases. Consequently, we experience a substantial evaporation of the water content within the product being dried. This implies that the moisture content decreases more rapidly when temperatures are elevated, which is a desirable aspect of the drying process.

These observations underscore the critical importance of vigilant monitoring of air temperature and humidity within the dryer, as these factors have a direct impact on the efficiency of the drying process. To ensure an effective drying rate and sufficient reduction in product moisture content, it is imperative to maintain optimal temperature and humidity conditions. Prudent management of these parameters contributes to a higher quality of the dried product.

3.3 Solar drying kinetics study

To examine the drying kinetics, 800g carrot slices were evenly distributed across four shelves. Two of them were placed inside the solar dryer chamber for indirect drying, one was exposed to the open air for natural drying, and the last one was positioned at the top of the dryer for direct drying. Mass measurements were taken after each hour of drying until a constant value was achieved. This drying process spanned 48 hours to reach consistent values.

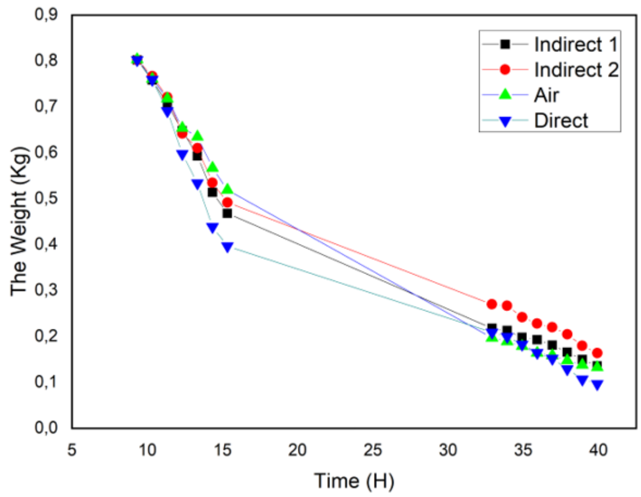

Figure 6. The kinetics of product drying in the solar dryer

Figure 6 provides an overview of the drying kinetics over a 48-hour period. The changes in product mass are clearly discernible, with stabilization occurring after 48 hours of drying.

It's worth noting that the direct drying curve, depicted in green, exhibits the lowest values. This underscores the effectiveness of direct drying in rapidly reducing water content to minimal levels within a short period. This observation implies that direct drying is particularly adept at swiftly eliminating moisture from the product. These findings are essential to consider when planning and optimizing drying processes to ensure the highest product quality.

3.4 Exploration and modeling of the carrot profile

Solar drying models, such as the Newton model, logarithmic model, Wang and Singh model, and Two-Term model, aim to describe the complex processes of drying based on variables like temperature, humidity, and time. The Newton model simplifies the process by proposing a simple exponential decrease in moisture over time. Adding a constant term, the logarithmic model provides increased flexibility. The Wang and Singh model uses a polynomial relationship for a more complex representation. The Two-Term model assumes that drying kinetics can be described by two exponential terms, offering flexibility to represent different drying phases. The evaluation of these models relies on parameters such as the coefficient of determination, and root mean square error (RMSE) to measure their fit to experimental data.

Table 3 illustrates the performances of several models under different drying conditions: Direct, Indirect, and in the Open Air. The examined models include the Newton model, the Logarithmic model, the Wang and Singh model, and the Two-Term model. Each of these models is assessed using various parameters such as coefficients (A, B, K), X^2, RMSE (Root Mean Square Error), and R^2 (Coefficient of Determination).

The Newton model stands out for its consistency, showcasing robust performance across all conditions. High R^2 values signify precise fitting to the data, with low RMSE values suggesting accurate predictions. Similarly, the Log model demonstrates strong performance, particularly notable in the Open-Air condition, with coefficients A and B, as well as X^2, contributing to its effectiveness.

Table 3. Model equations and parameters for characterization

Models	**Constant**	**Solar Drying**		
		Direct	**Indirect**	**In the Open Air**
Newton model	K	0.11	0.09	0.09
	X^2	0.98	0.99	0.99
	RMSE	0.05	0.02	0.03
	R^2	0.97	0.99	0.99
Log model	A	0.97	1,00	1,10
	B	0.07	0.02	-0.09
	K	0.01	0.11	0.07
	X^2	0.99	0.99	0.99
	RMSE	0.04	0.02	0.01
	R^2	0.98	0.99	0.99
Wang and Singh model	A	-0.08	-0.08	-0.07
	B	0.00	0.00	0.00
	X^2	0.97	0.99	0.99
	RMSE	0.08	0.05	0.02
	R^2	0.94	0.98	0.99
Two-Term model	A	0.33	0.65	1,71
	K	0.23	0.11	0.13
	X^2	0.99	0.99	0.99
	RMSE	0.04	0.02	0.01
	R^2	0.98	0.99	0.99

The Wang and Singh model exhibits reasonable performance, although variations are observed across different conditions. It appears to be less accurate in Indirect solar drying compared to other models. Lastly, the Two-Term model distinguishes itself with overall satisfactory performance. Coefficients A, K, and X^2 contribute to its efficiency, and high R^2 values and low RMSE values indicate precise predictions.

All models demonstrate positive performances, but the consistency of the Newton model and the outstanding performance of the Log model make them two options worth considering based on the specific needs of the study on drying processes.

4. CONCLUSION

Our research has significantly deepened our understanding of the carrot drying process by highlighting the physicochemical transformations occurring before and after this operation. The results reveal substantial variations, with a significant decrease in water content and a notable increase in dry matter, particularly pronounced during indirect drying. These changes have marked impacts on essential parameters such as acidity, reducing sugar concentration, and protein content, underscoring the crucial importance of a meticulous selection of drying methods.

Simultaneously, our study reaffirms the decisive role of temperature and humidity in the solar drying process. The observed fluctuations in these parameters emphasize the need for vigilant monitoring to optimize the efficiency of the drying process. Our analyses validate the consistency of the Newton model and the resilience of the logarithmic model. This precise mathematical modeling, favoring the logarithmic model, enables reliable predictions of the moisture content of dried products over time and process parameters.

These findings offer substantial prospects for the agro-food industry, facilitating the optimization of the carrot drying process while preserving their nutritional and sensory attributes. Moreover, they highlight the efficiency of solar drying as a sustainable and non-polluting energy alternative. Thus, our study makes a significant contribution to improving carrot drying practices, paving the way for optimal utilization in various food and industrial applications.

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