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Kinetics and Typical Drying Rate Curve of Cucumber (Cucumis sativus L.) Slices

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ABSTRACT

Using the experimental data obtained from the drying process of cucumber *(Cucumis sativus L.)* slices, the drying kinetics and the Typical Drying Rate Curve (TDRC) were developed, as presented in Table 1. This table includes: time and moisture increments; accumulated moisture and their respective units; the ratio between moisture variation and drying time; specific drying rate values; estimated and average moisture content; and the drying rate during the pre-critical period. Under stable drying operating conditions, the equipment was loaded with 1070 g of cucumber slice samples to obtain the experimental drying data, keeping constant the thickness, moisture, and hot-air temperature. The falling-rate period and drying rate depended on the internal moisture conditions and the water transport properties. From the drying kinetics, the following values were obtained: initial moisture content, critical moisture content, monomolecular layer moisture content, and equilibrium moisture content, corresponding to 3.40, 2.00, 1.95, and 0.38 grams of water per 100 grams of dry solid, respectively. The drying rate during the pre-critical period was 5.95 $kg.h^{-1}.m^{-2}$.

Keywords: Drying kinetics, Typical drying rate curve, Cucumber slices, Drying rate during the pre-critical period.

INTRODUCTION

Drying is an operation present in nearly all industrial sectors and constitutes a food preservation process that prevents microbial or enzymatic activity by removing a significant amount of water. It originated from the need to consume foods beyond their harvest or production season-foods that are prone to spoilage due to their chemical composition (Padilla et al., 2018).

Noroña (2018) states that during the drying process, heat and mass transfer occur simultaneously to remove moisture from a solid. When drying is conducted experimentally, data are obtained that relate the dry-basis moisture content as a function of time, or the drying rate as a function of time, in order to describe diffusion. The diffusion coefficient is calculated from the slope of the linear correlation obtained by plotting the natural logarithm of the moisture content against drying time. Calderón et al. (2019) indicate that drying is a necessary process for preservation; therefore, they evaluated drying by radiation to establish the correlation between drying rate and process temperature. Mejía et al. (2019) developed drying kinetics models for spaghetti, using mathematical models such as Fick's second law. In their study, the typical drying rate curve showed moisture values ranging from 0.40 to 4.00, and the results demonstrated that the Henderson-Pabis and logarithmic models provided the best fit to the experimentally obtained drying kinetics.

Díaz et al. (2018) evaluated the drying kinetics of *Moringa oleifera*, fitting mathematical models to the experimental data. The drying time was two hours, with the Page model providing the best description of the drying kinetics of moringa. The kinetic parameters of each model exhibited the expected dependence on temperature. Tafur (2018) conducted modeling of the drying kinetics of *Sachaculantro* (*Eryngium foetidum L.*) leaves, where the data were fitted to twelve empirical mathematical models using nonlinear regression. The Midilli model stood out for its coefficient of determination, which exceeded 0.99 in all experiments.

Cucumber (*Cucumis sativus* L.) is one of the most well-known cucurbit vegetables, characterized by its high-water content and low levels of carbohydrates, fats, and calories, as well as the presence of vitamin K, which is essential for public health. It also possesses diuretic properties (Flores et al., 2022). Cucumber is an important crop due to its high consumption rate, being used both fresh and processed for export (Espinoza, 2022). Hydroponics has become a viable method for greenhouse cultivation in all climates. Cucumbers have proven to be among the most successful hydroponic crops, as soil is unnecessary and water-use efficiency is considerably higher than in conventional cultivation (Beltrano & Giménez, 2015).

The objective of this study is to determine the typical drying rate curve and the kinetic parameters of the drying process of cucumber (*Cucumis sativus* L.) slices.

LITERATURE REVIEW

The high-water content of cucumbers makes them a natural diuretic that helps eliminate uric acid, providing benefits for individuals with arthritis. Additionally, their skin is rich in fiber, and their high levels of potassium and magnesium help regulate blood pressure and promote nutrient function. When performing drying kinetics, it is more efficient to correlate the drying rate with the drying time (Mendoza, 2021). When producing a cucumber-based snack, this raw material poses challenges due to its high-water activity, which affects its shelf life and flavor. Therefore, dehydration is applied during the preparation of this snack, along with additional processes and ingredients that help enhance its flavor (Flores et al., 2022). Drying is one of the oldest techniques used for food preservation. Sun drying of fruits, grains, vegetables, meats, and fish has been widely practiced since the dawn of humanity, providing people with a means of survival during periods of scarcity (Serna et al., 2017). It remains one of the most cost-effective processes for preserving food products, as it is based on water removal through heat application—an operation that significantly reduces the weight and volume of dehydrated foods, thereby decreasing transportation and storage costs (Jun et al., 2018).

The drying operation involves a series of physical, chemical, and sensory changes in the food product, which depend on its composition and on the severity of the drying method. These changes include shrinkage, crystallization, depolymerization, variations in color, flavor, texture, viscosity, rehydration rate, nutritional value, and storage stability (Parada et al., 2017).

In the drying process, the wide variety of dehydrated foods currently available on the market has generated interest in quality specifications and energy conservation, emphasizing the need to understand drying processes. When a moist solid food is subjected to a drying process, two subprocesses occur: (1) the transfer of internal moisture from the solid to its surface and its subsequent evaporation—the movement of moisture within the solid being a function of the solid's physical nature, temperature, and moisture content—and (2) the transfer of energy in the form of heat from the surrounding environment to the solid, which depends on external conditions such as temperature, humidity, and airflow, as well as on pressure, exposure area, and the type of dryer used (Barboza & Torres, 2017). The factors involved in the drying process are as follows: (1) Air temperature, which plays a key role in drying; in general, as its value increases, moisture removal accelerates within feasible limits, and the temperature is selected considering the specific material to be processed; (2) Relative humidity of the air, defined as the ratio between the actual water vapor pressure and the saturation vapor pressure at the same temperature, usually expressed as a percentage; as air temperature increases, its moisture absorption capacity also increases, and vice versa; and (3) Air velocity, which in the dryer serves two main functions: first, to transmit the energy required to heat the water contained in the material to facilitate its evaporation; and second, to help remove the moisture released from the material. During the initial stages of drying, air velocity plays a critical role—particularly when the material has a high moisture content—since higher air velocity results in a greater evaporation rate and shorter drying time, ensuring fast and uniform drying (Cervantes, 2020).

The type of dryer used was a simple, easy-to-operate convection dryer, one of the most commonly used in agricultural industries. Known as an oven or cabinet dryer, it is the simplest design and consists of a small parallelepiped-shaped chamber with two levels and a capacity of no more than 20 kilograms (Cervantes, 2020).

Other types of dryers include: Tunnel dryers (similar to tray dryers but operating in a semi-continuous manner); Radiation dryers (which operate through electromagnetic radiation within the solar and microwave spectrum range); and Dielectric dryers (characterized by generating heat inside the solid itself by means of a high-frequency electric field that induces intense agitation of polar molecules, whose friction produces the heat required for evaporation); among others (Peralta, 2017).

CONCEPTUAL FRAMEWORK

Figure 1 shows the moisture content over time during the drying process, where the change in moisture within the material is illustrated by curve **A–B**. At the end of this first stage, the drying process becomes linear, corresponding to a period of constant drying. During stage **B–C**, the drying rate remains stable for a certain period until it reaches a critical point (**point C**), where the straight line begins to curve and forms an asymptote with the equilibrium moisture content, Xeq, which represents the minimum moisture value in the drying process. This indicates that point **E** is never actually reached (Ramos, 2019).

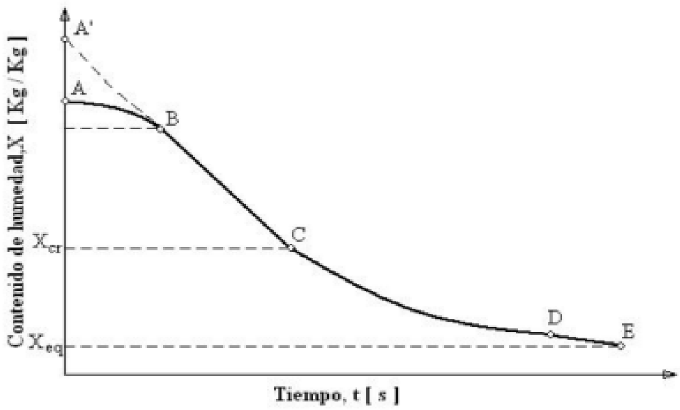

Figure 1. Drying curve.

Typical Drying Rate Curve (TDRC)

This type of curve indicates the rate at which the material dries, making it incredibly useful for various purposes, such as determining the amount of moisture removed from the dried material per unit of time and per unit of drying surface. It is a graphical representation of the drying rate as a function of the product's moisture content, known as the Typical Drying Rate Curve **(TDRC)**. This curve reveals both the constant-rate and falling-rate periods of drying. Moreover, the shape of the drying curve is related to the processes of mass and heat transfer. Additionally, it facilitates the interpretation and determination of key parameters such as initial moisture content, critical moisture content, monomolecular layer moisture, equilibrium moisture content, and the drying rate during the pre-critical period (Ramos, 2019).

Drying Kinetics

The drying kinetics of a material establishes the correlation between the variation in the water content of the material and the rate of evaporation over time, and the factors that influence the kinetics include the humidity of the drying air, the water content of the product to be dried, as well as the dimensions and design of the drying equipment; based on the drying kinetics curves, which can be obtained at the laboratory level, it is possible to estimate the drying time, the energy consumption, the mechanism of moisture migration, the predominant conditions in heat and mass transfer, and the influence that process variables have on the drying rate, such as temperature, inlet humidity, and air velocity; when modeling a drying process, the following conditions are assumed: 1) the shape and size of the active exchange surface are considered constant, 2) at the beginning of the process, the solid has the same initial water content at every point, showing a homogeneous distribution of water in the solid matrix, 3) the heat and mass transfer coefficients remain constant throughout the drying process, and 4) at the interface, the solid and the air are in equilibrium (Calderón et al., 2019).

Mathematical Models for Food Drying

Fick's Model. This model is used by considering the sample as an infinite flat plate, assuming constant effective diffusivity, neglecting sample shrinkage, and the absence of any resistance to mass transfer (Mejía et al., 2019):

$$X = \frac{X_{(t)} - X_e}{X_c - X_e} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n+1)^2} \times e^{\left[-(2n+1)^2 \times \frac{\pi^2}{4 \times L^2} \times D_e \times t\right]}$$

Where:

$X_{(t)}$: Average moisture content on a dry basis at time t
X_c: Critical moisture content
X_e: Equilibrium or surface moisture content
L: Thickness of the layer or cataphyll of the onion (m)
n: Number of repetitions of the series
D_e: Effective diffusion coefficient (m^2 /s)
t: time (s)

METHOD AND MATERIALS

An average of 1070 grams of cucumber slices, 5 millimeters thick with an average circumference of 45 millimeters and a moisture content of 88%, were used.

Experimental Equipment. To obtain the typical drying rate curve (TDRC) of the cucumber slices, a laboratory tray dryer was employed.

Drying Curves. Once stable drying operating conditions were achieved (approximately 10 minutes), in terms of airflow velocity and drying air inlet temperature, the equipment was loaded with 1070 g of cucumber slice samples, evenly distributed to obtain the drying time history, the mass of the cucumber slices, and the corresponding drying curve. The variety, thickness (5 millimeters), moisture content (88%), and hot air temperature (68 °C) were kept constant. The drying process of the cucumber slices was carried out in triplicate.

During the falling-rate drying period, the drying rate depends on the internal moisture conditions and the water transport properties within the material or through the peripheral layer. This complicates the development of mathematical models that account for such parameters; therefore, it is assumed that, during this period, there exists a correlation between the drying rate and the average moisture content of the product, expressed as follows: $W = \frac{S}{A}\left(-\frac{dx}{dt}\right)$.

Interpretation of the Correlation (r) and Determination (r^2) Coefficients of the Mathematical Models

Statistical Treatment. The Pearson correlation coefficient $\boldsymbol{r}$ and the standard error of $\boldsymbol{r}$ re used to determine the correlation between accumulated moisture loss ($\boldsymbol{\psi_{ac}}$) and the estimated moisture loss obtained from models 3 and 6 ($\widehat{\psi_3}$) and ($\widehat{\psi_6}$). e parameters allow for the interpretation of the correlation (r) and determination (r^2) coefficients of the two mathematical models used to estimate moisture content. According to Hernández, *et al.*, (2014), the statistical treatment of correlated bivariate data involves determining the validity of mathematical models through the correlation and determination coefficients, validated by the significance test of the Pearson correlation coefficient $\boldsymbol{r}$**.** This test assesses whether the $\boldsymbol{r}$ value represents a **real correlation** between the two variables. The standard error of $\boldsymbol{r}$ is evaluated using the following expression:

$$t_{cal} = \frac{|\boldsymbol{r}|}{\sqrt{1 - \boldsymbol{r}^2}} \times \sqrt{N - 2}$$

The Student's $\boldsymbol{t}$ value (t_{cal}) will be compared with the tabulated $\boldsymbol{t}$ value (t_{tab}) to determine the correlation between drying time, $\boldsymbol{t}$ (minutes) and moisture loss ψ (grams), e degree of difference, and the accuracy of the model estimation, as well as to interpret the correlation (r) and determination (r^2) coefficients of the predictive models.

RESULTS

The experimental data used to obtain the typical drying rate curve (TDRC) of cucumber slices (*Cucumis sativus* L.) are shown in columns I and II of Table 1. The time increments (Δt) are presented in column III, the moisture increments ($\Delta\psi$) in column IV; the accumulated moisture data (ψ_{ac}) in column V; and the moisture data in their respective units (ψ_{ur}) in column VI. Subsequently, the ratio ($\boldsymbol{\Delta\psi/\Delta t}$) is calculated, as shown in column VII. Finally, columns I and VII are plotted on specialized graph paper.

The midpoint values (with a "distinct" signal) are considered, leveling to the next value (regardless of whether it is slightly higher or lower), and plotting continues until completion. The points with a "distinct" signal are then connected using proper technical drawing criteria, and even the final point is projected according to how the process concludes. On the same graph paper used for graphical differentiation, all values of the dependent variable corresponding to the independent variable are read and recorded in column VIII, which represents the values of $\boldsymbol{d\psi/dt}$.

Column IX corresponds to the estimated moisture ($\hat{\psi}$) . Column X represents the simple mean of two consecutive values from column VI, and column XI corresponds to the drying rate ($\boldsymbol{W}$).

Table 1. Time (minutes) and mass loss (grams) data of cucumber slices (*Cucumis sativus L.*).

Time, t (min.)	**Mass loss, ψ (grams)**	Δt	$\Delta\psi$	ψ_{ac}	ψ_{ur}*	$\Delta\psi/\Delta t$	$d\psi/d$	$\hat{\psi}$*	$\bar{\psi}$*	W
0	1070	-	-	-	3.28	-	-	-	-	-
5	1030	5	40	40	3.12	8.00	7.75	40	3.20	6.0000
13	970	8	60	100	2.88	7.50	7.70	113.47	3.00	5.6250
18	930	5	40	140	2.72	8.00	8.00	156.01	2.80	6.0000
25	870	7	60	200	2.48	8.57	8.20	215.54	2.60	6.4286
30	830	5	40	240	2.32	8.00	6.20	248.52	2.40	6.0000
38	770	8	60	300	2.08	7.50	7.75	303.35	2.20	5.6250
43	730	5	40	340	1.92	8.00	8.30	335.11	2.00	5.9500
50	670	7	60	400	1.68	8.57	7.70	376.55	1.80	5.3000
56	630	6	40	440	1.52	6.67	6.40	409.48	1.60	5.0000
66	570	10	60	500	1.28	6.00	5.10	459.47	1.40	4.5000
75	530	9	40	540	2.12	4.44	4.15	499.72	1.20	3.3333
91	470	16	60	600	0.88	3.75	3.00	561.60	1.00	2.8125
113	430	22	40	640	0.72	1.82	1.60	629.82	0.80	1.3636
169	370	56	60	700	0.48	1.07	0.75	741.52	0.60	0.8036
248	330	79	40	740	0.32	0.51	0.40	814.32	0.40	0.3797
810	270	562	60	800	0.08	0.11	0.06	862.14	0.20	0.0801

- Grams of water per 100 grams of dry solid

By plotting the values from columns X and XI, the graph of the typical drying rate curve (TDRC) is obtained, as shown in Figure 2.

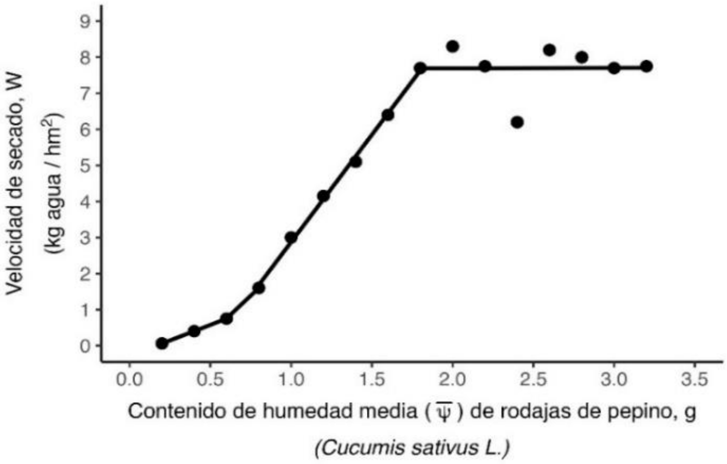

Figure 2. Typical Drying Rate Curve (TDRC) of Cucumber Slices (*Cucumis sativus L.*).

From Figure 2, the following parameters are evaluated, respectively: the initial moisture (φ_i) of 3.40 grams of water per 100 grams of dry solid; the critical moisture (φ_c) of 2.00 grams of water per 100 grams of dry solid; the moisture in the monomolecular layer (φ_m) of 1.95 grams of water per 100 grams of dry solid; the equilibrium moisture (φ_e) de 0.38 gram grams of water per 100 grams of dry solid; and the drying rate in the precritical period (W) of 5.95 kilograms.h^{-1}.m^{-2}.

Kinetic Calculations:

1. Correlation between Drying Rate ($d\psi/dt$) vs Drying Time (t)

$\boldsymbol{d\psi/dt} = A \times e^{k\times t}\ldots$ (1)

Applying this to columns I and VIII yields the following correlation:

$\boldsymbol{d\psi/dt} = 6.7739 \times e^{-0.0062\times t}\ldots$ (2)

Solving equation (2) under the initial conditions: $t = 5\ minutes;\ \psi = 40\ g$

$\widehat{\psi_1} = 1083.9980 - 1087.1837 \times e^{-0.0062\times t}\ldots$ (3)

2. Correlation between Drying Rate ($d\psi/dt$) vs Accumulated Moisture ($\boldsymbol{\psi_{ac}}$)

$\boldsymbol{d\psi/dt} = A + B \times \psi\ldots$ (4)

Applying this to columns V and VIII yields the following correlation:

$\boldsymbol{d\psi/dt} = 10.1218 - 0.0117 \times\ \psi\ \ldots$ (5)

Solving equation (5) under the initial conditions: $t = 5\ minutes;\ \psi = 40\ g$

$\widehat{\psi_2} = 862.2047 - 871.7384 \times e^{-0.0117\times t}\ldots$ (6)

Table 2. Data of time (minutes), accumulated moisture loss ($\boldsymbol{\psi_{ac}}$**),** estimated accumulated moisture loss ($\widehat{\psi_1}$) and estimated accumulated moisture loss ($\widehat{\psi_2}$) of cucumber slices (*Cucumis sativus L.*)

Time, t (min.)	$\boldsymbol{\psi_{ac}}$	$\widehat{\boldsymbol{\psi_3}}$	$\widehat{\boldsymbol{\psi_6}}$
0	-	-	-
5	40	40.00	40.00
13	100	91.00	113.47
18	140	111.01	156.01
25	200	162.62	211.54
30	240	191.34	248.52
38	300	235.02	303.35
43	340	261.24	335.11
50	400	296.61	376.55
56	440	325.72	409.48
66	500	371.91	459.47
75	540	411.10	499.72
91	600	475.59	561.60
113	640	554.44	629.82
169	700	712.71	741.52
248	740	860.37	814.32
810	800	1086.83	862.14

Significance Test of $\boldsymbol{r}$. The Pearson correlation coefficients for accumulated moisture loss ($\boldsymbol{\psi_{ac}}$) versus the estimated moisture loss obtained from models ($\widehat{\psi_3}$) y ($\widehat{\psi_6}$), were $\boldsymbol{r = -0.9374}$ and $\boldsymbol{r = -0.9908}$; respectively. In both cases, the correlation is acceptable and reliable, showing no significant difference at a $p = 0.05$. According to Hernández et al., (2014) this indicates a "**very strong correlation"** between the accumulated moisture and the moisture values estimated by the models. Furthermore, the determination coefficients show that 87.87% and 98.17% of the variance in the moisture estimated by models ($\widehat{\psi_3}$) y ($\widehat{\psi_6}$); respectively, are explained by the accumulated moisture ($\boldsymbol{\psi_{ac}}$**)** during the drying of cucumber (*Cucumis sativus L.*) slices.

Student's $\boldsymbol{t}$-test:

- Para $\boldsymbol{\psi_{ac}}$ **y** $\widehat{\psi}_3$: $t_{cal} = \frac{|\mathbf{0{,}9374}|}{\sqrt{1-(\mathbf{0{,}9374})^2}} \times \sqrt{16-2} = 9{,}00$ and $t_{tab(16;0{,}95)} = 1{,}75$
- Para $\boldsymbol{\psi_{ac}}$ **y** $\widehat{\psi}_6$: $t_{cal} = \frac{|\mathbf{0{,}9908}|}{\sqrt{1-(\mathbf{0{,}908})^2}} \times \sqrt{16-2} = 202{,}40$ and $t_{tab(16;0{,}95)} = 1{,}75$

Interpretation:

- Since $t_{cal} = 9{,}00$ is greater than $t_{tab} = 1{,}75$; is concluded that the correlation between the accumulated moisture loss ($\boldsymbol{\psi_{ac}}$) and the estimated moisture loss obtained from model ($\widehat{\psi_3}$) is real. Therefore, there is no significant difference, and the model obtained (Equation 3) provides a high estimation accuracy for the correlated data, showing a **"very strong correlation**".
- Similarly, since $t_{cal} = 202.40$ is greater than $t_{tab} = 1.75$; it is concluded that the **correlation** between the accumulated moisture loss ($\boldsymbol{\psi_{ac}}$) and the estimated moisture loss obtained from model ($\widehat{\psi_6}$) **is real**; Hence, there is no significant difference, and the model obtained (Equation 6) exhibits a high estimation accuracy for the correlated data, also showing a ***"very strong correlation"***.

DISCUSSION

The mathematical kinetic drying models are used to obtain the typical drying rate curve (TDRC), in which moisture values range from 0.40 to 4.00 grams of water per 100 grams of dry solid in cucumber (Cucumis sativus L.) slices, showing a better fit to the experimental drying kinetics. These results are highly consistent with those reported by Mejía et al. (2019). The high-water content in cucumbers makes them beneficial and promotes nutrient functions during the drying kinetics process; therefore, the correlation between drying rate and drying time becomes more efficient, in close agreement with the findings reported by Mendoza (2021). To achieve and ensure a fast, efficient, optimal, and uniform drying process, strong and regular air circulation is essential while maintaining constant drying conditions. Statistical and mathematical models facilitate the estimation of moisture content and its comparison with the experimental values, closely matching both the conducted experiment and the findings reported by Cervantes (2020). Regardless of the product being dehydrated, the shape of the typical drying rate curve (TDRC) is complex; once established, it facilitates the reading and determination of the initial moisture, critical moisture, monomolecular layer moisture, equilibrium moisture, and drying rate in the pre-critical period, fully consistent with the concepts reported by Ramos (2019).

CONCLUSIONS

It is concluded that the initial moisture, critical moisture, monomolecular layer moisture, and equilibrium moisture were 3.40, 2.00, 1.95, and 0.38 grams of water per 100 grams of dry solid, respectively, and that the drying rate in the pre-critical period was 5.95 kilograms.h^{-1}.m^{-2}. The significance tests of the Pearson correlation coefficients between accumulated moisture loss and estimated moisture loss yielded $r = -0.9374$ and $r = -0.9908$; respectively, both indicating an acceptable and reliable correlation, with no significant difference at $p = 0.05$. A "very strong correlation" was observed, and the coefficients of determination indicated that 87.87% and 98.17% of the variance in the estimated moisture are explained by the accumulated moisture in the drying of cucumber *(Cucumis sativus L.)* slices.

It is recommended that, for future drying kinetics and typical drying rate curves, the warm air temperature should be controlled within 0.5 °C, and the experimental samples should be weighed with a precision of up to 0.5 grams using a calibrated analytical balance.

Ethical Considerations: The authors state that all national and international ethical standards were fully observed.

Conflicts of Interest: The authors declare that they have no conflicts of interest or financial relationships related to this research that could have influenced the results, analysis, or interpretation of the findings presented in this manuscript.

Authors' Contributions: The entire research team participated in the design, structure, and compilation of the article.

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