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MATHEMATICAL MODELLING OF DRYING PROCESS

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Abstract. The aim of this study is to experimentally investigate the drying kinetics of common basil using a solar drying unit. The tests consist in studying the effect of constant and variable drying air temperature on the drying kinetics. In this empirical approach, we aim to determine and compare drying characteristic curves under conditions where the drying air temperature is constant or variable. Subsequently, correlations describing the drying rate will be developed, these will be used at a later stage to size and model the solar dryer. Few numerical models have been used in the literature to explain the drying kinetics of common basil, in fact, given the complexity of the transport mechanisms and the diversity of products, a single model cannot represent all situations. This justifies an experimental study in the laboratory to determine the drying kinetics of a particular product.

Keywords: *Basil, drying, temperature, humidity, heat, mass, heat transfer, drying kinetics.*

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1. Introduction

Last years the development of the mathematical models of the technological processes related to the agricultural and ecological issues becomes more attractive for the mathematicians and technologies (Guseynov *et al.*, 2024a; b; Shi *et al.*, 2013). Here we consider dehydration by drying common basil is a traditional and widespread method of its preservation in order to process it into new products that will be further used in perfumery, confectionery and pharmaceutical production (Mirzaev *et al*., 2021).

For modelling the drying process, we have defined the drying rate expressions, the characteristic curve of drying and the effective diffusion coefficient used in the calculations derived from experimental results of drying common basil leaves in an

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indirect convective dryer and partially solar heated. The solar convective drying of basil leaves laid in thin layers on drying trays was modelled for a drying time equal to the solar irradiation time. We studied the influence of different operating parameters of the modular dryer, in particular the temperature, the drying air flow rate and the mass of the product to be dried, on the thermal characteristics of the collector and the dryer (Samandarov *et al*., 2024).

An analysis of the state of grain drying equipment at food enterprises in Uzbekistan shows that in 48% of cases, domestically produced mine units are used, the energy consumption of which is 5.069 MJ/kg and higher. When modernizing enterprises, many farmers are going to pay attention to drying areas (up to 17%) as one of the most expensive parts of grain storage facilities. Disadvantages of mine convective grain dryers: low efficiency of using the volume of the drying apparatus; low specific moisture removal; uneven drying; high energy consumption. Much less frequently (5.20%) dryers using water vapor as a heat and moisture carrier are used for drying grain. Such dryers provide high heat transfer coefficients of 30-90 W/m^2 K. Disadvantages of the design: complex hardware and technical implementation, additional devices are required for supplying steam, removing condensate, the formation of water plugs in the tubes, low degree of mixing of the grain flow (Garibov, 2024; Bekpulatov *et al*., 2024).

In this regard, the issue of developing new types of grain drying equipment is relevant. The solution to the problem is the use of thermosyphons (TS), rotating thermosyphons (RTS), heat pipes in drying technologies, recovery of heat from exhaust gases of grain drying plants. The use of circuits based on RTS will allow saving up to 30% of energy (Barkaoui *et al*., 2022).

The drying was observed to be in the falling-rate drying period and thus liquid diffusion is the main mechanism of moisture movement from the internal regions to the product surface. The experimental drying data for the pumpkin fruits were used to fit Exponential, General exponential, Logarithmic, Page, Midilli-Kucuk and Parabolic model and the statistical validity of models tested were determined by non-linear regression analysis. The Parabolic model had the highest R_2 and lowest χ^2 and RMSE values. This indicates that the Parabolic model is appropriate to describe the dehydration behavior for the pumpkin (Ali & Imanova, 2022).

Thus, in the first drying period, the determining factors for mass transfer will be the conditions at the phase boundary - the mode of air movement outside the grain, the area of the grain, the surface temperature of the RTS condenser. In the second drying period, moisture transfer occurs in cramped conditions. The determining parameter is the coefficient of moisture diffusion inside the grain D. It is believed that the crystal structure is one of the most basic properties used to predict the photocatalytic activity; however, the main property that plays an important role is also well-known to be the surface area and the surface chemistry. It has been well accepted that surface area contact is an essential factor for the effectiveness of the catalyst. It is therefore, considered essential to have a nano-powder, in this case, which will have the smallest crystallite size in order to enhance the surface area of contact and therefore the photocatalytic activity. Generally, the latter approach deserve a more attention in the future because it might bring a new information about the details of grain boundary evolution during the sintering ceramic materials (Imanova, 2020).

2. Materials and methods

For modelling the drying process we have determined the drying rate expressions, the characteristic curve of drying and the effective diffusion coefficient used in calculations based on experimental results of drying of basil leaves in an indirect convective dryer and partially with solar heating. The solar convective drying of basil leaves laid in thin layers on drying trays was modelled for a drying time equal to the solar irradiation time. We studied the influence of different operating parameters of the modular dryer, in particular the temperature, the drying air flow rate and the mass of the product to be dried, on the thermal behaviour of the collector and the dryer.

Statistical criteria. Let us define the following statistical parameters (Özdemir & Devres, 1999):

$$Y = \frac{\sum_{i=1}^{n}\left(W_{mod.} - W_{exp.}\right)}{\sum_{i=1}^{n}\left(W_{exp.} - \overline{W}^{*}_{,exp.}\right)} \tag{1}$$

Mean systematic error.

$$C = \frac{1}{N}\sum_{i=1}^{N}(W_{mod.} - W_{exp.}), \tag{2}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(W_{exp.} - W_{mod.})^2}{N-z}, \tag{3}$$

here Y is relative mean error; R^2 is correlation coefficient; C is mean systematic error; $W_{exp.}$ is experimental reduced moisture content; $W_{mod.}$ is modelling reduced moisture content; N is number of experimental points; z is number of variables in each model.

The use of experimental results leads to the search for a regression model that best describes the drying kinetics of the product, i.e. the change in reduced moisture content W (%) as a function of drying time (t). We present some regression models to describe the changes in moisture content.

For mathematical modelling, 13 expressions in Table 1 were tested to select a model suitable for the drying curve of common basil (Doymaz, 2004a; 2004b; Chottamom *et al*., 2012; Esmaeili *et al*., 2013; Shi *et al*., 2013; Li *et al*., 2013).

Table 1. Mathematical models of drying curves

№	Model name	Equations
1	Newton	$W=exp(-kt)$
2	Page	$W=exp(-kt^n)$
3	Modified Page (I)	$W=exp((-kt)^n)$
4	Modified Paige (II)	$W=exp(-(kt)^n)$
5	Henderson and Pabis	$W=aexp(-kt)$
6	Logarithmic	$W=aexp(-kt)+c$
7	Two terms	$W=aexp(-k_0t)+bexp(-k_1t)$
8	Two exponential terms	$W=aexp(-kt)+(1-a)exp(-kat)$
9	Wang and Singh	$W=1+at+bt^2$
10	Diffusion approximation	$W=aexp(-kt)+(1-a)exp(-kbt)$
11	Modified by Henderson and Pabis	$W=aexp(-kt)+bexp(-gt)+ cexp(-ht)$
12	Verma et al.	$W=aexp(-kt)+(1-a)exp(-gt)$
13	Midilli	$W=aexp(-kt^n)+bt$

Here W is the moisture content coefficient; k, k_0, k_1 is the drying constant; a, b, c, g are the coefficients; n is the drying constant; t is the time.

The correlation coefficient R^2 was the first selection criterion, where χ^2 represented the standard deviation between the experimental and calculated value.

After experimental obtaining of sorption-desorption isotherms of common basil, the process of reduced moisture content, drying rate, shape and size of common basil during drying and effective diffusion coefficient are determined. We will develop empirical relationships expressing shrinkage during drying of fresh basil leaves and the same basil leaves after drying depending on their moisture content, drying time, etc.

Fresh common basil (200 g), collected, was cleaned from stems and other from different things. The common basil were evenly distributed in thin layers on the drying tray. To investigate the shrinkage during drying, we selected a sample consisting of common basil weighing about 5 g. The thickness of the basil was measured using a mechanical micrometer (accuracy: 0.1 mm) (Figure 1) (Zulponov *et al*., 2023).

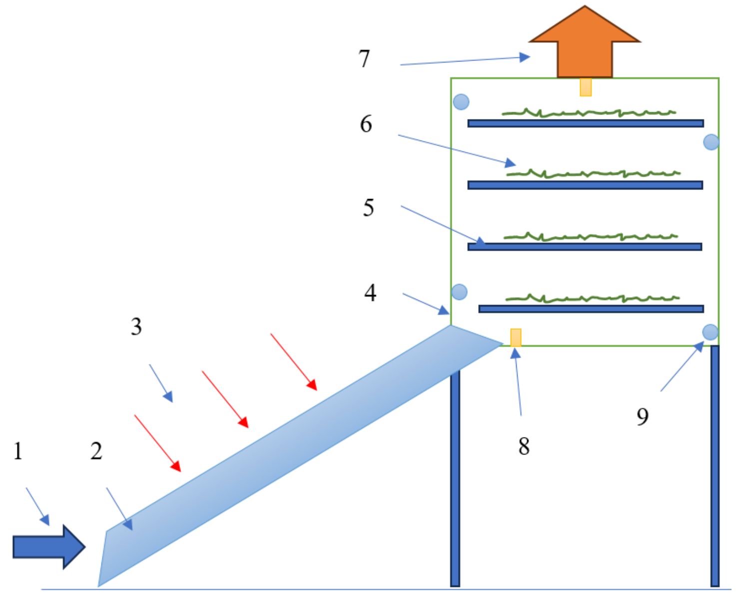

Figure 1. Schematic diagram of laboratory solar drying equipment:
1-inlet air; 2-helio-collector; 3-solar radiation; 4-drying chamber; 5-pan; 6-suds;
7-outlet air; 8-air velocity measurements; 9-temperature measurements

There are different drying methods, ideally to obtain the best results it is necessary to use a dryer with controlled conditions (temperature and rate of air heat flux, relative humidity of the ambient air), but given the unavailability of this type we chose a solar dryer with forced convection production drying by thermal air. Drying of a thin layer of common basil in this modular solar dryer was also used to measure the effect of drying on surface shrinkage and to determine the relationship between surface shrinkage and moisture content of common basil. An image acquisition system was developed for image capture and processing. All shape related parameters (area, perimeter, larger and smaller diameter of common basil) were determined from photographs captured by a digital camera. In each experiment, common basil was placed on a perforated white coloured cloth attached to a tray in a drying chamber to record shrinkage on drying by recording photographs. During drying, the sample was continuously monitored and images of basil common were recorded by a digital camera. After completion of drying, the value of the mould related surfaces was determined using image processing software (Bajomo *et al*., 2022).

Common basil (200 g) were placed on a pallet suspended on a wire on precision scales. To monitor the weight loss of the product during drying, we measured the weight every 10 minutes, then 20 minutes and 30 minutes using 0.01 g scales. For each time, we measured the relative humidity outside the dryer using a hygrometer with a sensitivity of ±2%. We carried out the drying operation at 4 temperatures 45°C, 55°C, 65°C and 75°C.

Moisture content in the product at time t is calculated by the relationship (Gurkan & Hayaloglu, 2023):

$$W(t) = \frac{m_h(t)-m_s}{m_s}. \tag{4}$$

It should be known that the drying experiment ends when the final moisture content Wf of the product, determined by the sorption isotherm (here $W_f \approx 12\%$), is reached. This is the value at which the product retains its essential oils and the color and aroma degradation reactions are slowed down. Thus, drying time is the time required to dry the product until the desired final moisture content is reached (Mbegbu *et al*., 2021).

Using a chromel-alumel thermocouple (type K) with a diameter of d=1 mm and an accuracy of 0.1°C, the temperature at the inlet of the drying chamber is measured throughout the drying experiment. The tests are carried out at four thermal air temperatures: 45°C, 55°C, 65°C and 75°C. It takes more than twelve hours for the product to dry completely. Since we are interested in utilizing solar energy, drying in this temperature range is excluded because the duration of sunlight is shorter than the required drying time. Above 75°C, the dried product turns brown, which characterizes the decomposition of the main components of the dried product (dyes, flavorings, sugars, etc.) (Oladele & Jimoh, 2017).

The relative humidity of the air at the inlet of the drying chamber is measured using a Humicolor brand digital display sensor with sensitive buttons with an accuracy of ±2%, calibrated for a decreasing humidity environment, allowing direct measurement of the average air humidity.

Air velocity is measured using a velocimeter connected to a 2 mm diameter Pitot tube located at the outlet of the air intake duct just below the first drying tray.

Modeling of drying shrinkage. Shrinkage is defined as a decrease in volume, surface area or thickness of a product (basil). The shrinkage volume (reduced volume) of a dried product is formulated as follows (Oladosu-Ajayi *et al*., 2017).

$$S = \frac{V}{V_0}, \tag{5}$$

here, S is area, m^2; V is velocity, m/s.

In this study, product shrinkage is assumed to be uniform (isotropic) so that the decrease in thickness is proportional to the decrease in surface area. The relationships between surface area, thickness and reduced volume are as follows (Gumus & Banigo, 2015):

$$\frac{L}{L_0} = \left(\frac{S}{S_0}\right)^{1/2}, \tag{6}$$

$$\frac{V}{V_0} = \left(\frac{V}{V_0}\right)^{3/2}, \tag{7}$$

here, L is length.

Shrinkage is considered to be perfect (complete), meaning that the volume reduction to which the product undergoes is proportional to or equal to the volume of evaporated moisture, which explains that the reduced volume is a linear function of the moisture content (Ergasheva *et al*., 2023; Juraeva *et al*., 2023).

$$\frac{\Delta S}{S_0} = (A + B_1 W + B_2 W^2)\ . \quad (8)$$

Combining equations (6), (7) and (8), we obtain equation (9). This equation is useful for calculating the shrinkage length of common basil (Juraeva *et al*., 2023).

$$L(m) = L_0(A + B_1 W + B_2 W^2). \quad (9)$$

3. Results and analyses

The average thickness and surface area are 0.25 mm and 7.037 cm^2, respectively (Table 2). Digital camera image processing software was used to characterize the surfaces of common basil. The thickness of these basil leaves is more or less constant, but the specific surface area varies from 4.885 cm^2 to 9.506 cm^2 due to the width and oval shape of these basil leaves. The average length of common basil was used to determine the diffusion coefficient and activation energy of common basil during convective drying (Saparov *et al*., 2023).

Table 2. Dimensions of common basil

Sample	Thickness (mm)	Area (cm^2)
1	0,28	5,994
2	0,24	9,506
3	0,26	7,442
4	0,28	8,218
5	0,26	6,847
6	0,27	7,03
7	0,25	7,678
8	0,24	4,885
9	0,23	5,098
10	0,26	6,992
11	0,26	7,055
12	0,25	7,708
Average	0,25	7,037

Table 3. Values of characteristic thermal air flux for each experimental test

Experiment	Heat flux velocity, m/s	Temperature, °C	Time, min
1	0,5	45	365
2	0,5	55	330
3	0,5	65	280
4	0,5	75	240
5	0,75	45	325
6	0,75	55	270
7	0,75	65	210
8	0,75	75	180

Drying kinetics. The drying experiments of common basil were carried out in July 2023. The curves were obtained with good experimental reproducibility. We first start by describing the experimental conditions under which we operated. These conditions are summarized in Table 3 (Usenov *et al.*, 2020).

4. Conclusion

The drying results describe the process of change in time of moisture content in the dried product by a characteristic drying curve, we analyze, on the one hand, the process of change of moisture content in the product as a function of time and on the other hand, the influence of some parameters of thermal air (speed and temperature) on the drying curve. The kinetics of helioconvective drying of common basil at constant and variable temperature rise and fall has been studied experimentally. The experimental drying curves showed the presence of a period of drying rate drop (phase 2) and a significant effect of temperature on this phase. Drying at variable temperature rise was the most efficient in terms of drying time and cost of this operation. Thirteen mathematical models were compared to explain the drying behavior of common basil. Among these models, Midilli gave the highest R^2 and the lowest χ^2. The coefficients of this model as a function of temperature were considered and determined.

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