

## Article

# Bee Bread Granule Drying in a Solar Dryer with Mobile Shelves

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## Abstract

This paper presents the development and evaluation of an autonomous solar dryer designed to enhance the drying efficiency of bee bread granules. In contrast to natural open-air drying, the proposed system utilizes solar energy in an oscillating operational mode to achieve a controlled and accelerated drying process. The dryer comprises a solar collector integrated into the base of the drying chamber, which facilitates convective heating of the drying agent (air). The system is further equipped with a photovoltaic panel to generate electricity for powering and controlling the operation of air extraction fans. The methodology combines numerical modeling with experimental studies, structured by an experimental design framework. The modeling component simulates variations in temperature (288–315 K) and relative humidity within a layer of bee bread granules subjected to a convective air flow. The numerical simulation enabled the determination of the following: the time required to achieve a stationary operating mode in the dryer chamber (20 min); and the rate of change in moisture content within the granule layer during conventional drying (18 h) and solar drying treatment (6 h). The experimental investigations focused on determining the effects of granule mass, air flow rate, and drying time on the moisture content and temperature of the granular layer of Bee Bread. A statistically grounded analysis, based on the design of experiments (DoE), demonstrated a reduction in moisture content from an initial 16.2–18.26% to a final 11.1–12.1% under optimized conditions. Linear regression models were developed to describe the dependencies for both natural and forced convection drying. A comparative evaluation using enthalpy–humidity (I-d) diagrams revealed a notable improvement in the drying efficiency of the proposed method compared to natural drying. This enhanced performance is attributed to the system's intermittent operational mode and its ability to actively remove moist air. The results confirm the potential of the developed system for sustainable and energy-efficient drying of bee bread granules in remote areas with limited access to a conventional power grid.

**Keywords:** bee products; bee bread granule; solar dryer; shelving; solar energy; temperature; ANSYS Fluent; Python



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## 1. Introduction

Beekeeping products and their therapeutic properties have long been utilised in folk medicine due to their beneficial impact on human health [1,2]. There is growing demand for products such as honey, propolis, bee pollen, and bee bread (perga), driven by their rich content of bioactive compounds and potent healing properties [3,4]. These products are commonly marketed in the form of pills, capsules, granules, powders, and other food supplements, underscoring the necessity for high-quality processing that preserves their beneficial qualities. This processing must carefully consider external factors, including temperature and humidity, which significantly impact the physicochemical and biological properties of the products, as well as the preservation of active ingredients.

One of the most valuable beekeeping products is bee bread, also known as perga. It is derived from pollen collected by bees, mixed with nectar and salivary enzymes, and subsequently subjected to lactic acid fermentation within the honeycombs [5]. Bee bread is rich in carbohydrates, proteins, lipids, and various trace elements. Studies indicate that it possesses several therapeutic properties, including anti-inflammatory and antioxidant effects, as well as antimicrobial, anti-tumour, and antihypertensive activities [6,7]. Its nutritional value and chemical composition are highly dependent on botanical origin, geographical location, and climatic conditions [8–10]. Drying is a critical step in the processing of bee bread, essential for preserving its biologically active substances and preventing spoilage during long-term storage. Elevated moisture content can induce fermentation and rapid product degradation [11]. Consequently, many small-scale beekeepers resort to natural shade drying of bee bread granules. However, the duration of this process is heavily dependent on weather conditions, often resulting in inconsistent and suboptimal product quality [12].

Various drying methods are traditionally employed for bee bread, including repurposed fruit and vegetable dryers. Several drying techniques are currently available, each presenting distinct advantages and disadvantages [13].

Convective drying is based on heat transfer to the bee bread granules via a heated drying agent (air). Convective energy is transferred to the product surface and subsequently to its interior. The resulting heat flow increases the product temperature, facilitating moisture evaporation [14,15]. This method provides relatively gentle drying conditions and is suitable for processing large volumes simultaneously. Precise temperature control is crucial to avoid overheating and the degradation of thermolabile bioactive compounds.

Infrared drying accelerates moisture evaporation through the application of infrared radiation. The use of infrared rays helps preserve vitamins, bioactive substances, and the natural colour, taste, and aroma of the product by directly influencing its molecular structure. Despite its efficacy, a significant drawback for bee bread is the risk of sugar caramelization, which may reduce its nutritional value [16].

Vacuum drying is a thermal separation process where moisture is removed from the product under low-pressure conditions, allowing for evaporation at lower temperatures and shorter drying times. This method is particularly suitable for heat-sensitive products. Its main disadvantages are the complexity and high cost of the equipment, which can be economically prohibitive. Furthermore, a study [17] demonstrated that vacuum drying had a more destructive effect on the quality of bee bread compared to convective drying.

Freeze-drying (Lyophilisation) involves removing moisture from frozen bee bread via sublimation under a vacuum, bypassing the liquid phase. Although it yields a high-quality product, this method can lead to the degradation of certain beneficial substances in bee bread, including those highly susceptible to the Maillard reaction (MR), potentially compromising product quality and stability [13].

Selecting an appropriate drying method for bee bread requires a careful balance between the preservation of beneficial properties, process efficiency, and economic feasibility. Convective drying at moderate temperatures is currently regarded as one of the most prevalent and effective methods for producing high-quality bee bread. However, the performance of convective drying is highly influenced by the design specifics of the dryer unit. An analysis of numerous studies on dryer designs reveals common shortcomings. In shaft-type dryers, the trays are typically static and layered [13,18–21], leading to non-uniform moisture removal across the height of the unit. The drying agent, supplied from the bottom, becomes saturated with moisture in the lower layers, reducing its drying capacity for the upper layers. In tunnel dryers, an inverse moisture distribution pattern can occur: when air is supplied horizontally, the warm agent tends to rise, potentially resulting in higher residual moisture in the lower trays compared to the upper ones [22,23]. To mitigate these drawbacks, the technology developed by the authors, which incorporates a specific drying process, appears promising [24]. According to this technology, bee bread drying is conducted in two stages: first, drying within the honeycombs after honey extraction; second, drying in a granulated state after the wax mass has been separated. The proposed convective solar dryer for granulated bee bread is a portable drum-type device featuring suspended mobile shelves [13,25]. A distinctive design feature is the sequential loading of shelves, laden with bee bread granules, into the active flow area of the drying agent. The drying agent (air) is heated by solar radiation in a collector, and forced ventilation for humid air removal is provided by exhaust fans powered by a solar panel.

To evaluate the efficiency of this solar dryer, a comprehensive study of the drying process for bee bread granules was necessary to justify its optimal parameters and operational modes.

This study aims to enhance the efficiency of the solar drying process to produce high-quality granulated bee bread.

To achieve this objective, the following tasks were defined:

- Justify the drying chamber parameters and its operational modes through mathematical modeling.
- Experimental investigation of moisture variation within the layer of bee bread granules under different drying conditions (airflow rate, mass of granules, and residence time in the chamber).
- A comparative evaluation of drying efficiency using the traditional method (natural shade drying) and the proposed solar dryer.

**Hypothesis 1.** *The improved efficiency of solar dryers enhances the quality and yield of bee products, thereby increasing the profitability of beekeeping enterprises.*

## 2. Materials and Methods

### 2.1. Principle of Operation of the Developed Solar Dryer for Bee Bread Granules

The traditional method of drying bee bread granules, common in Kazakhstan and other post-Soviet countries, is limited by a slow drying process that restricts volume. To overcome this, a prototype solar dryer was developed as a key component of a new process line for producing dry bee bread granules and recyclable wax [24].

Drying was performed using two methods for comparison:

1. Traditional Method: Natural drying using a shaded wooden structure (Figure 1a).
2. Developed Solar Dryer: An active solar-driven drying system (Figure 1b).

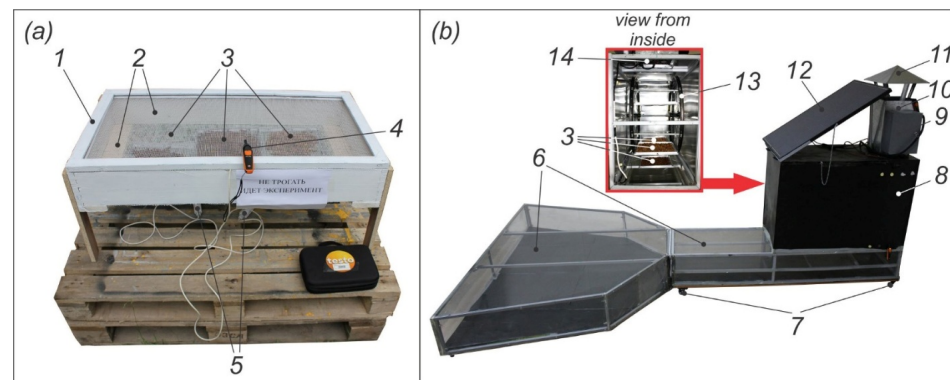


**Figure 1.** General view of the bee bread granule drying process: (a) traditional method; (b) developed solar dryer. Key: 1—support; 2—mosquito net (bottom and top); 3—shelves with bee bread granules; 4—Testo 605i thermo-anemometer; 5—HOBO U23-002 Pro v2 external temperature/RH sensor; 6—transparent film; 7—support rollers; 8—drying chamber; 9—controller panel; 10—exhaust pipe; 11—exhaust pipe umbrella; 12—solar panel; 13—shelving drum; 14—exhaust fans.

Schematic diagrams of experimental setups for both drying methods are presented in Figure 2.

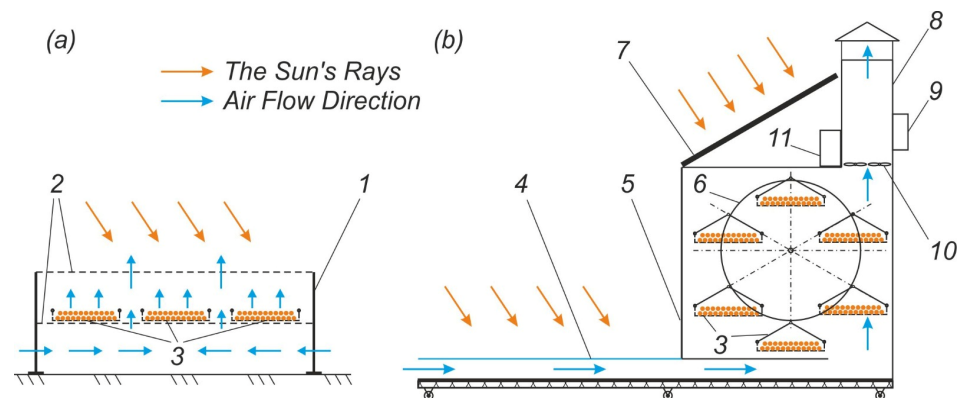


**Figure 2.** Schematic of experimental devices for bee bread granule drying: (a) traditional method; (b) developed solar dryer. Key: 1—support; 2—mosquito net; 3—shelves with granules; 4—transparent film; 5—solar dryer chamber; 6—drum; 7—solar panel; 8—exhaust pipe; 9—controller panel; 10—exhaust fans; 11—temperature sensor.

The traditional drying equipment consisted of a wooden box elevated on four legs. The lower and upper bases were covered with a mesh (mosquito net) material to facilitate air passage. Bee bread granules of varying masses were placed on shelves inside the box. The apparatus was consistently maintained in the shade to prevent direct sunlight exposure. Humidity and temperature were measured at three levels using Testo 605i and HOBO U23-002 Pro v2 sensors: below the box, inside the box, and above the box [26]. The moisture content of the granules was determined every 10 h by weighing samples before and after drying in a dry-air steriliser.

The developed system was a solar dryer operating exclusively on solar energy. Air heating was achieved via a solar collector integrated into the dryer's base. The surface of this collector was enclosed by a transparent polymer film, which performed two key functions: forming the air heating chamber and shielding the system from environmental contamination. The film sections were hermetically sealed at junctions of complex configuration using a heat welding process [27].

Electrical needs were met by an additional photovoltaic panel (7), which converted solar energy to electricity for powering a battery (11) and a fan unit (9) dedicated to exhaust

air extraction. Fan operation was governed by an electronic control unit, which dynamically adjusted the speed of four fans based on the air temperature at the chamber inlet (as measured by controller 5). A temperature threshold of 42 °C triggered the activation of additional fans to enhance airflow.

Conversely, as the temperature decreased, the number of active fans was reduced to maintain optimal drying conditions. A stationary airflow mode could also be configured via the control program for specific experimental or high humidity drying phases.

The dryer drum was equipped with six shelves (150 mm × 200 mm each), with bases constructed from a fine stainless-steel mesh (aperture size: 1.00 mm × 1.00 mm). The shelves were hinged to the drum, allowing them to remain parallel to the ground as the drum rotated. Drum rotation was induced gravitationally and by the upward flow of the drying agent (air), which occurred when the shelves were loaded with equal masses of material [27,28]. For uneven loading or specific testing scenarios, a manual mechanism was available to rotate and lock the drum at a specified angle for a required duration.

Heated air from the solar collector was channelled beneath the drum level, directed towards the shelving, and extracted vertically by the fan array, removing humidified air. The drying agent flowed upwards through the layer of bee bread granules, facilitating moisture exchange. The gradual reduction in granule mass due to moisture loss, combined with air pressure on the shelf bases, altered the drum's balance, generating a torque that prompted rotation. To optimise the parameters and operational modes of these heat exchange processes, numerical simulation was employed.

## 2.2. Numerical Simulation of Heat Exchange Processes During Bee Bread Granule Drying

Uniform distribution of hot air inside the drying chamber is crucial for process intensification. The parameters and operational modes of the chamber were evaluated using the Navier–Stokes equations for convective flow of the drying agent [29–31]. This approach allows for the determination of temperature and velocity fields within the chamber by varying dimensionless quantities.

Based on the structural diagram of the solar dryer (Figure 2b), the simulation scheme for numerical modelling is shown in Figure 3. The mathematical model for simulating the drying process was founded on the two-dimensional Navier–Stokes equations, encompassing continuity, motion, and energy equations. A concentration transfer equation was incorporated to model humidity dynamics, describing moisture distribution and evaporation within the bee bread granules (Table 1).

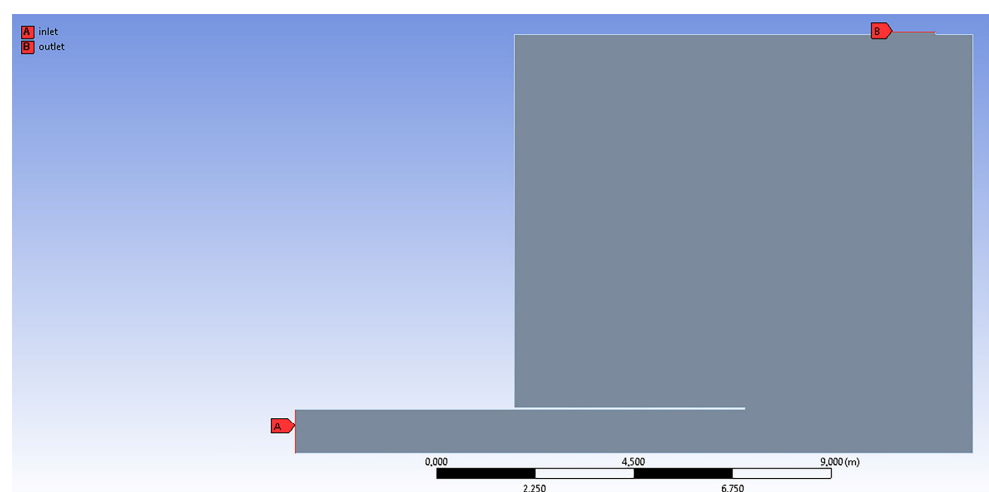


**Figure 3.** Simulation scheme for numerical modelling.

**Table 1.** Interpretation of the equations used in the drying process simulation.

| General Equation                                                                                  | Equation Name                     |
|---------------------------------------------------------------------------------------------------|-----------------------------------|
| $\nabla u = 0$                                                                                    | - continuity equation             |
| $\rho \left( \frac{\partial u}{\partial t} + u \nabla u \right) = -\nabla P + \mu \nabla^2 u + f$ | - motion equation                 |
| $\left( \frac{\partial T}{\partial t} + u \nabla T \right) = \alpha \nabla^2 T$                   | - energy equation                 |
| $\left( \frac{\partial C}{\partial t} + u \nabla C \right) = \gamma \nabla^2 C$                   | - concentration transfer equation |

The energy equation for temperature is given by:

$$\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \alpha \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right), \quad (1)$$

where

$a$ —coefficient of temperature conductivity, defined as  $a = \frac{k}{c_p \rho}$ ;

$k$ —thermal conductivity;

$\rho$ —density;

$c_p$ —the specific heat capacity at constant pressure.

The Boussinesq approximation was applied to account for buoyancy effects due to temperature changes. The motion equations for an incompressible fluid under this approximation are:

$$\rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = -\frac{\partial P}{\partial x} + \mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right), \quad (2a)$$

$$\rho \left( \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} \right) = -\frac{\partial P}{\partial y} + \mu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) + \rho_0 g (1 - \beta(T - T_0)), \quad (2b)$$

$$\rho \left( \frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} \right) = -\frac{\partial P}{\partial z} + \mu \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} \right). \quad (2c)$$

where the term  $\rho_0 g (1 - \beta(T - T_0))$  represents the buoyancy force driving natural convection.

The transport of water vapour concentration in air is governed by the diffusion equation:

$$\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} = \gamma \left( \frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} \right), \quad (3)$$

where  $\gamma$ —diffusion coefficient.

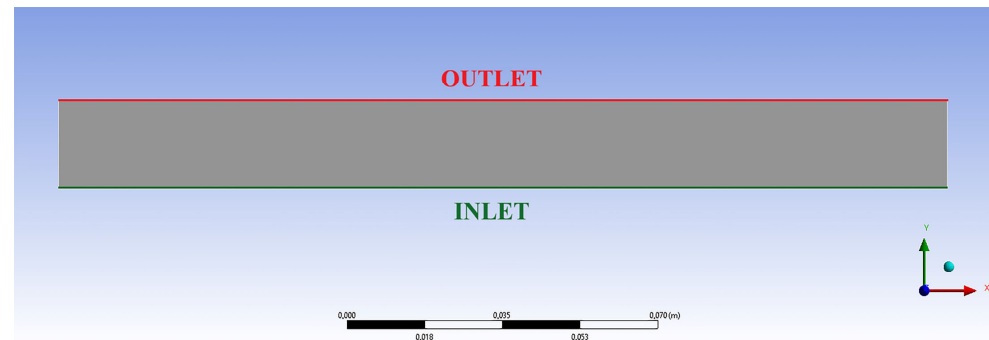
Boundary conditions for the numerical simulation of heat transfer are detailed in Table 2.

The initial temperature inside the dryer was set to  $T_0 = 20^\circ \text{C}$  (293.15 K). For the comparative natural drying simulation, the inlet velocity was set to  $u = 0.05 \text{ m/s}$ .

Subsequently, heat transfer and moisture evaporation within a layer of bee bread granules on a shelf were simulated. The computational geometry for this 2D simulation is shown in Figure 4 (length: 20 cm, height: 2 cm). The initial conditions for the two drying scenarios are provided in Table 3.

**Table 2.** Boundary conditions for numerical heat transfer modelling.

| Boundaries | Inside the Solar Dryer Chamber                                                                                                                                       | In Ambient Conditions (Natural Drying)                                                            |
|------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|
| Inlet      | Velocity : $u = 0.92 \text{ m/s}$ , $v = 0 \text{ m/s}$<br>Temperature : $T_1 = 318.15 \text{ K}$                                                                    | Velocity : $u = 0.05 \text{ m/s}$ , $v = 0 \text{ m/s}$<br>Temperature : $T_1 = 318.15 \text{ K}$ |
| Outlet     | Velocity : $\frac{\partial u}{\partial x} = \frac{\partial v}{\partial y} = 0$ (Same as solar dryer)<br>Temperature: $\frac{\partial T}{\partial n} = 0$ (Adiabatic) |                                                                                                   |
| Walls      | Velocity : $u = v = 0$ (Same as solar dryer)<br>Temperature: $\frac{\partial T}{\partial n} = 0$ (Adiabatic)                                                         |                                                                                                   |

**Figure 4.** Simulation scheme of the area for numerical modelling of heat-mass exchange of bee bread granules on a shelf.**Table 3.** Initial conditions for the granule layer simulation.

| Drying Methods | Air Temperature, °C | Air Velocity, m/s |
|----------------|---------------------|-------------------|
| Solar dryer    | 42                  | 0.45              |
| Natural drying | 30                  | 0.05              |

Simulations were performed using Ansys Fluent 2020, with validation against computations conducted in Python 3.11.9.

### 2.3. Experimental Research Methods

#### 2.3.1. Determination of Solar Radiation in the Study Area

Kazakhstan possesses significant solar energy potential, with annual solar radiation levels ranging from 1300 to 1800 kWh per square meter [32] (Figure 5). The study was conducted at the beekeeping farm “Ulan,” located on the border of the Almaty and Zhambyl regions. Solar potential and climatic conditions were assessed using the World Bank’s Global Solar Atlas, which confirmed the high suitability of this location for solar drying technology.

#### 2.3.2. Measurement of Solar Radiation Loss Through the Transparent Film

To quantify solar radiation loss through the transparent film covering the solar collector, two GSM/O-120 10337/12 pyranometers were installed: one above the film and one inside the collector chamber beneath the film (Figure 6). This setup allowed for the direct measurement of incident solar radiation and the transmitted radiation that effectively reached the absorber plate, enabling an evaluation of the film’s transmittance efficiency and its impact on thermal losses.

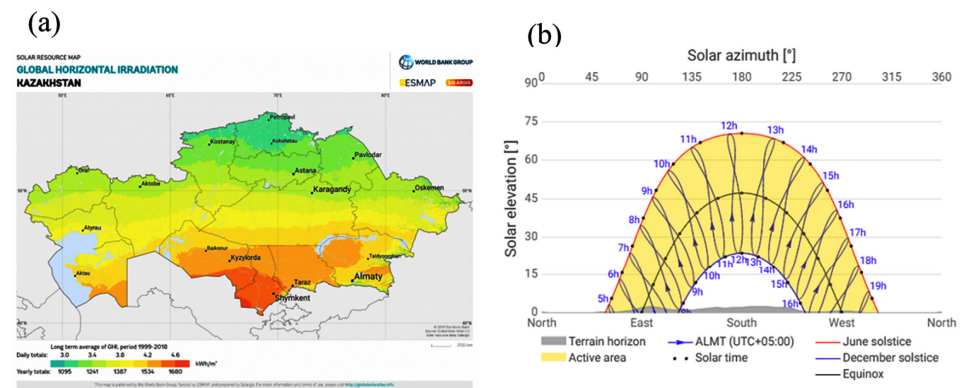


**Figure 5.** Solar radiation in the research area: (a) Global Horizontal Irradiation; (b) Solar azimuth.

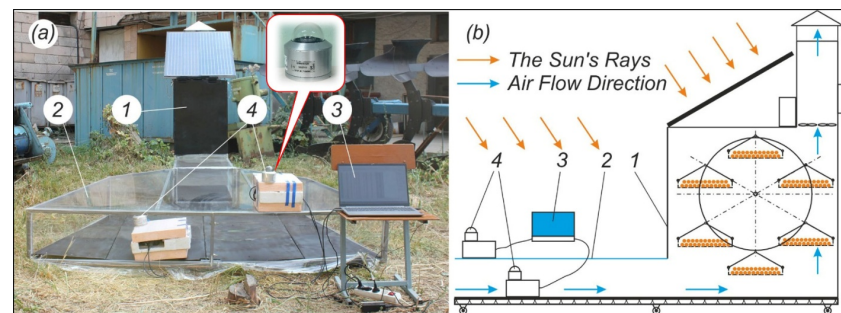


**Figure 6.** Measurement of solar radiation: (a) general view; (b) schematic diagram. Key: 1—solar dryer chamber; 2—transparent film; 3—recording device (tablet); 4—pyranometers.

### 2.3.3. Investigation of Temperature and Humidity Profiles During Traditional and Solar Drying

Multifactorial experimental investigations were conducted to determine the efficient operating modes and rational parameters for the drying process. The intervals and limits of the independent variables are presented in Table 4.

**Table 4.** Independent factor levels and intervals.

| Status of Factors | Coded Values  | Factors                |         |                  |         | Bee Bread Mass |
|-------------------|---------------|------------------------|---------|------------------|---------|----------------|
|                   |               | Air Flow Velocity, m/s |         | Exposure Time, h |         |                |
|                   |               | Solar Dryer            | Natural | Solar Dryer      | Natural |                |
| Basic level       | 0             | 0.44                   | 0.05    | 42               | 135     | 280            |
| Range             | $\varepsilon$ | 0.13                   | 0.05    | 18               | 62.5    | 70             |
| Upper level       | +1            | 0.57                   | 0.05    | 60               | 197.5   | 350            |
| Lower level       | −1            | 0.31                   | 0.05    | 24               | 72.5    | 210            |
| High point        | +1.68         | 0.66                   | 0.05    | 72               | 240     | 400            |
| Low point         | −1.68         | 0.22                   | 0.05    | 12               | 30      | 160            |
| Code mark         | $x_i$         | $x_1$                  |         | $x_2$            |         | $x_3$          |

Note: The values for natural drying velocity in this table appear fixed. The experimental matrix (Table 5) reflects this.

**Table 5.** Planned matrix for the multi-factor experiment (traditional drying).

| Experiment No | Coded Value $x_2$ | Exposure Time (h) | Coded Value $x_3$ | Mass (g) |
|---------------|-------------------|-------------------|-------------------|----------|
| 1             | −1                | 72.5              | −1                | 210      |
| 2             | +1                | 197.5             | −1                | 210      |
| 3             | −1                | 72.5              | +1                | 350      |
| 4             | +1                | 197.5             | +1                | 350      |

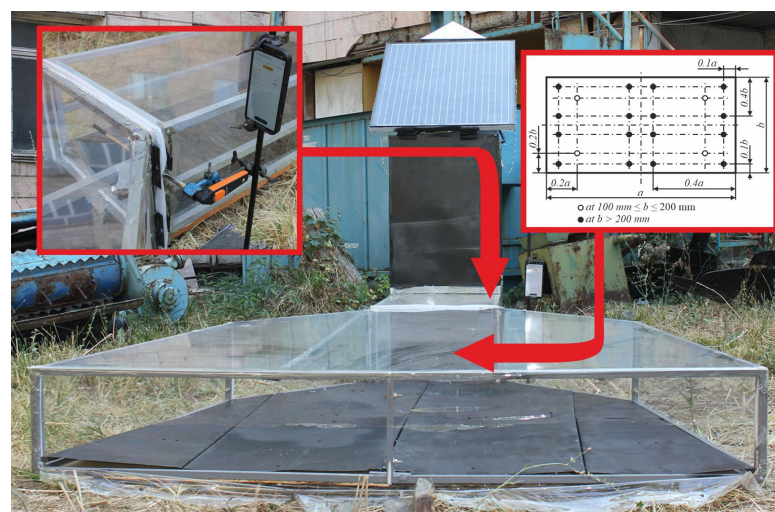
Table 5. Cont.

| Experiment No | Coded Value $x_2$ | Exposure Time (h) | Coded Value $x_3$ | Mass (g) |
|---------------|-------------------|-------------------|-------------------|----------|
| 5             | −1.68             | 30                | 0                 | 280      |
| 6             | +1.68             | 240               | 0                 | 280      |
| 7             | 0                 | 135               | −1.68             | 160      |
| 8             | 0                 | 135               | +1.68             | 400      |
| 9–12          | 0                 | 135               | 0                 | 280      |

The experimental designs for both traditional drying (a central composite design) and solar drying are shown in Tables 5 and 6, respectively. Each point included three repetitions. Airflow velocity at the dryer inlet was measured using a Testo 405i smart anemometer (Testo SE & Co. KGaA, Titisee-Neustadt, Germany) [26] according to standard methods (Figure 7).

Table 6. Planned matrix for the multi-factor experiment (solar dryer).

| Experiment No | Coded $x_1$ | Velocity (m/s) | Coded $x_2$ | Time (h) | Coded $x_3$ | Mass (g) |
|---------------|-------------|----------------|-------------|----------|-------------|----------|
| 1             | −1          | 0.31           | −1          | 24       | −1          | 210      |
| 2             | +1          | 0.57           | −1          | 24       | −1          | 350      |
| 3             | −1          | 0.31           | +1          | 60       | −1          | 210      |
| 4             | +1          | 0.57           | +1          | 10       | −1          | 210      |
| 5             | −1          | 0.31           | −1          | 24       | +1          | 350      |
| 6             | +1          | 0.57           | −1          | 24       | +1          | 350      |
| 7             | −1          | 0.31           | +1          | 60       | +1          | 350      |
| 8             | +1          | 0.57           | +1          | 60       | 0           | 280      |
| 9             | −1.68       | 0.22           | 0           | 42       | 0           | 280      |
| 10            | +1.68       | 0.66           | 0           | 42       | 0           | 280      |
| 11            | 0           | 0.44           | −1.68       | 12       | 0           | 280      |
| 12            | 0           | 0.44           | +1.68       | 72       | −1.68       | 160      |
| 13            | 0           | 0.44           | 0           | 42       | +1.68       | 400      |
| 14–20         | 0           | 0.44           | 0           | 42       | 0           | 280      |



### 3. Study Results

#### 3.1. Numerical Modelling Results

The simulation results are presented as velocity contours in Figure 8a,c,e,g,i, and temperature contours in Figure 8b,d,f,h,j for time intervals of  $t = 60, 300, 600, 900,$  and  $1200$  s, respectively.

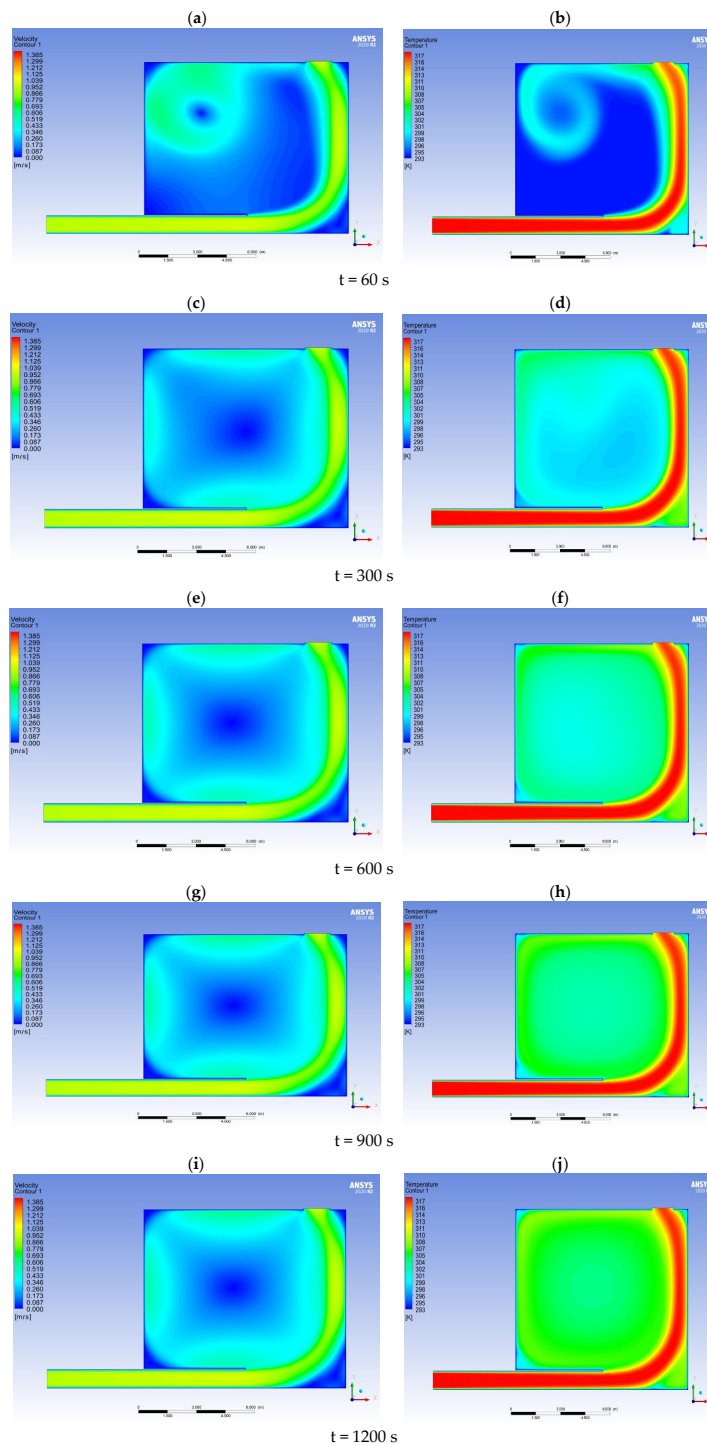


**Figure 8.** Profiles of the drying agent's velocity and temperature in the solar dryer chamber. (a) velocity contours ( $t = 60$  s); (b) temperature contours ( $t = 60$  s); (c) velocity contours ( $t = 300$  s); (d) temperature contours ( $t = 300$  s); (e) velocity contours ( $t = 600$  s); (f) temperature contours ( $t = 600$  s); (g) velocity contours ( $t = 900$  s); (h) temperature contours ( $t = 900$  s); (i) velocity contours ( $t = 1200$  s); (j) temperature contours ( $t = 1200$  s).

Figure 9 shows the results of heat transfer simulations within a bee bread granule, obtained using Python (left) and ANSYS Fluent (right) for the solar dryer chamber environment.

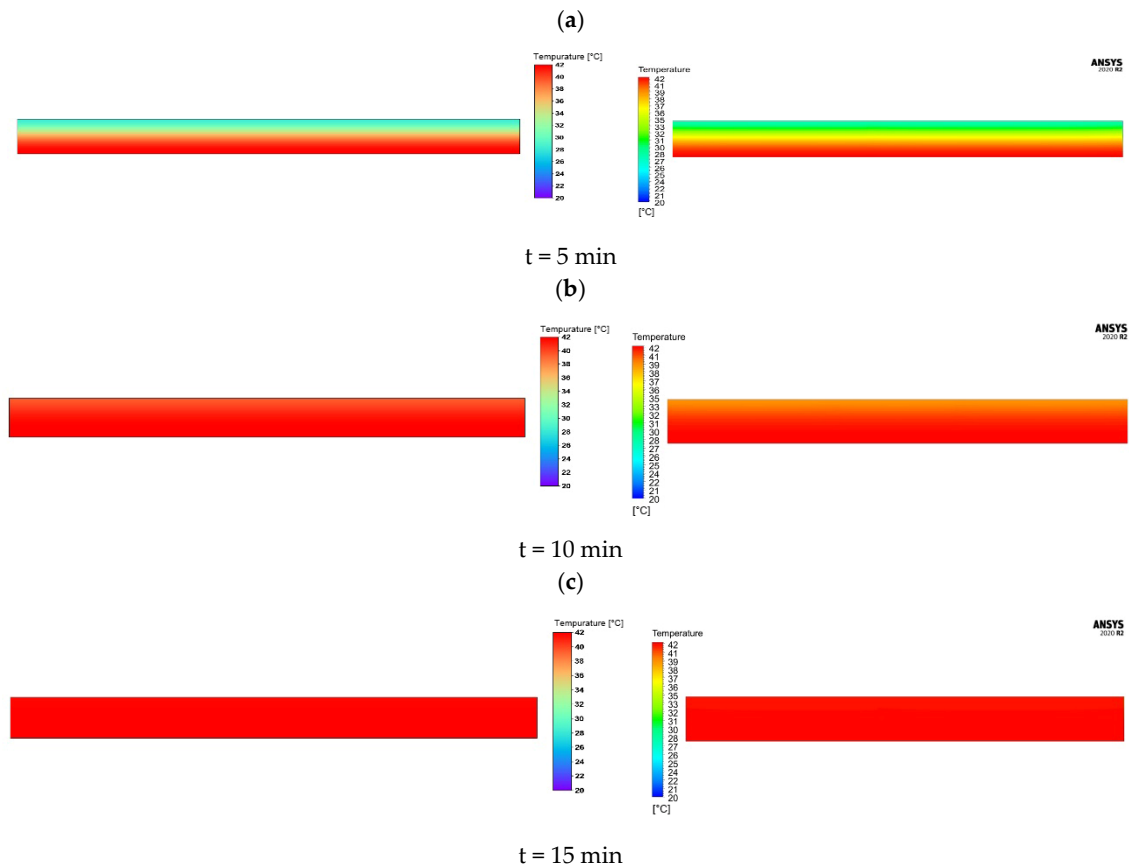


**Figure 9.** Contours of temperature changes simulated in Python (left) and ANSYS Fluent (right) at various time intervals. (a) at  $t = 5$  min; (b) at  $t = 10$  min; (c) at  $t = 15$  min.

Figure 10 presents the modelled temperature change in a layer of bee bread granules under natural drying conditions on shelves, comparing results from Python (left) and ANSYS Fluent (right).

The process of moisture evaporation from layers of bee bread granules of identical thickness was modelled in ANSYS Fluent for both natural open-air drying and drying in a solar dryer chamber. The results are shown in Figure 11 as a series of contours depicting moisture content over time for natural drying conditions (left) and solar drying (right).

### 3.2. Results of Experimental Research

#### 3.2.1. Solar Radiation in the Study Area

The graphs in Figure 12 show seasonal and diurnal variability in solar radiation intensity and its correlation with temperature. The peak values indicate heating efficiency across different months, with maximum activity observed in the summer months (July, August) and minimum activity in winter (December).

According to long-term observations, the annual average global horizontal radiation in the region is  $1478.3 \text{ kWh/m}^2$ , indicating high solar potential.

#### 3.2.2. Attenuation of Solar Radiation by the Transparent Film

Figure 13 shows the variation in solar radiation intensity during a sunny day, measured before and after transmission through the protective transparent film of the solar air heater collector.

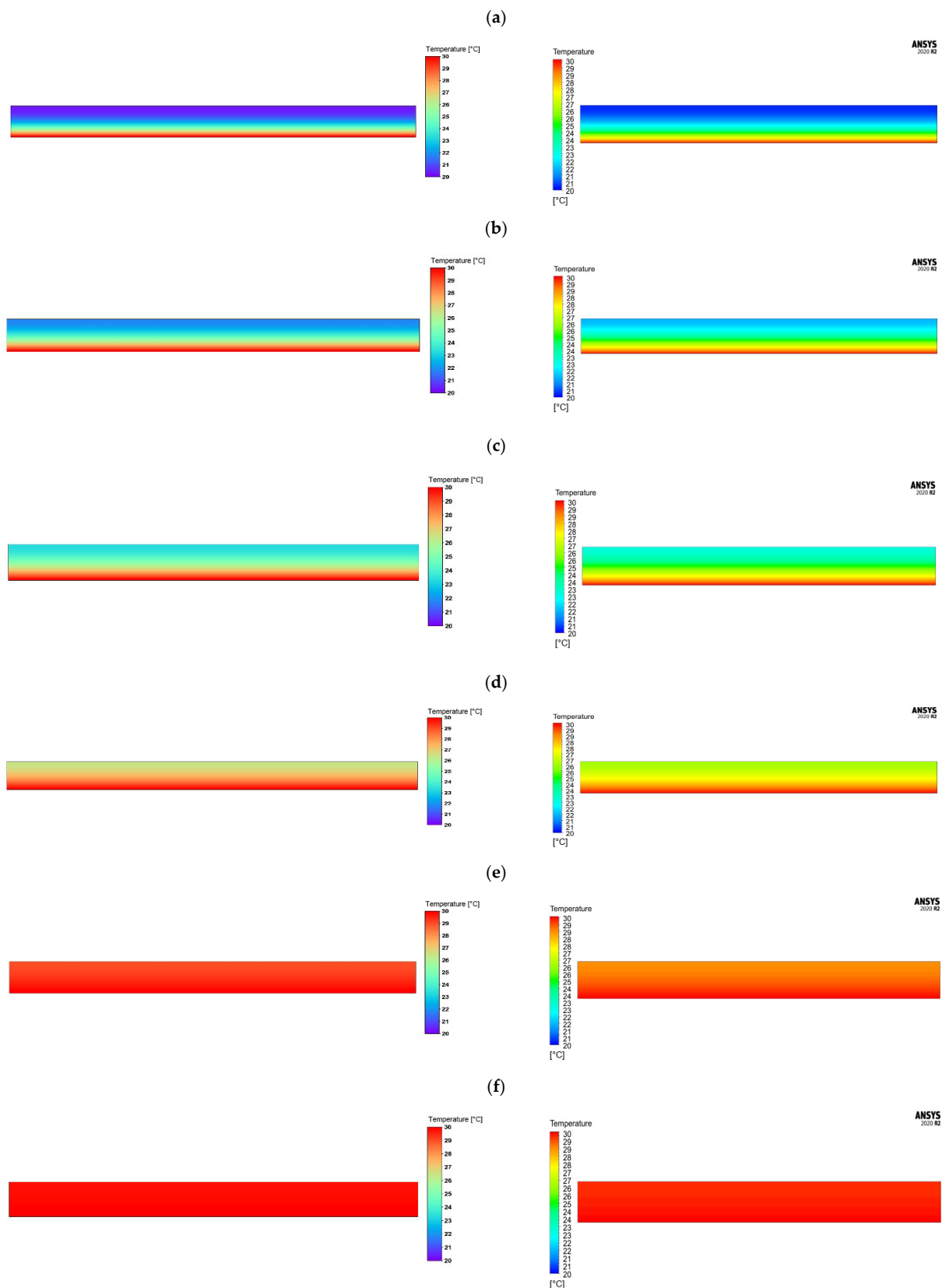


**Figure 10.** Contours of the temperature change in the bee bread granules during natural drying on shelves at various time intervals: (a)  $t = 5$  min; (b)  $t = 10$  min; (c)  $t = 15$  min; (d)  $t = 30$  min; (e)  $t = 60$  min; (f)  $t = 90$  min.

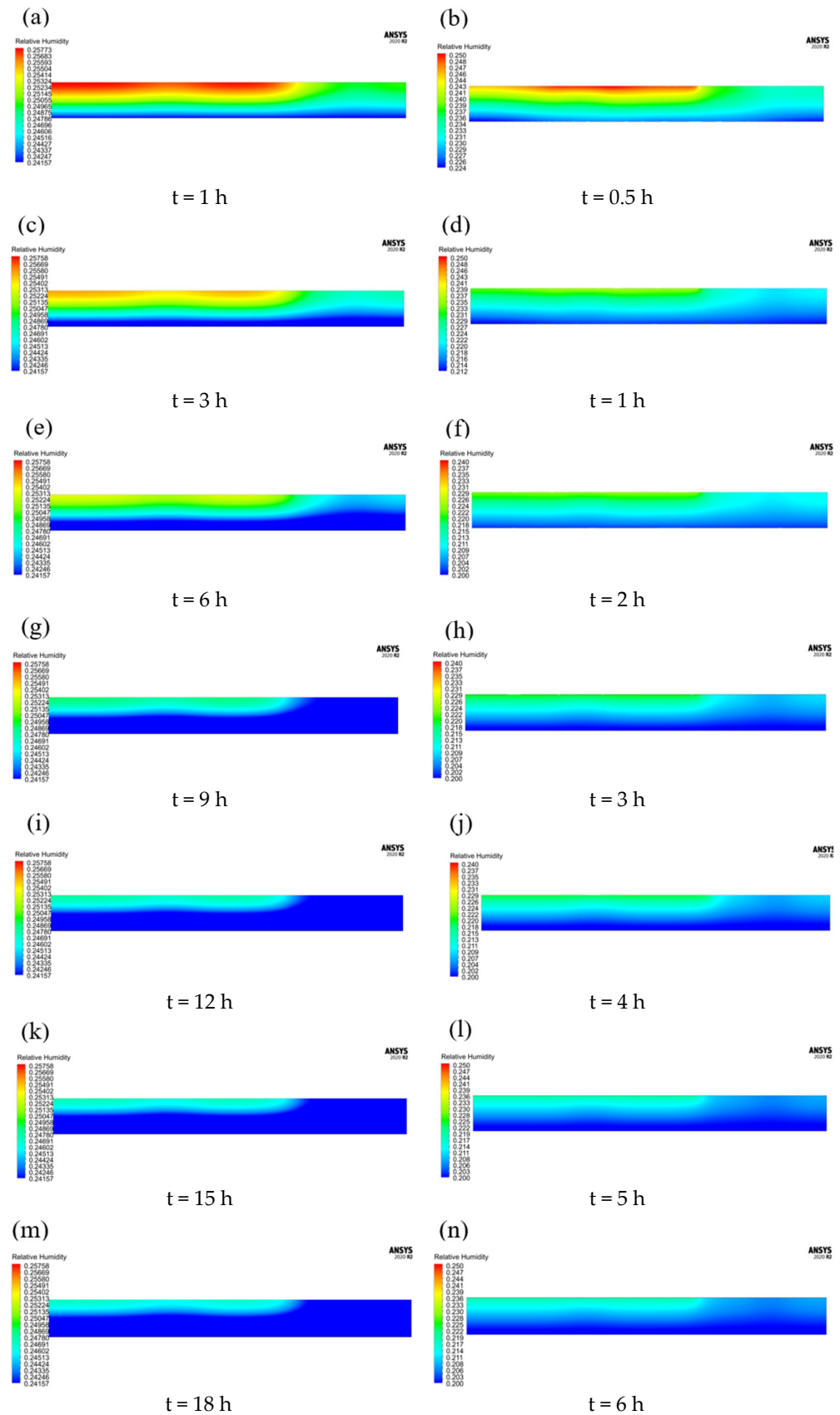


**Figure 11.** Contours of moisture content change over time in the layer of bee bread granules during drying under natural conditions (left) and in the solar dryer chamber (right). (a) at  $t = 1 \text{ h}$ ; (b) at  $t = 0.5 \text{ h}$ ; (c) at  $t = 3 \text{ h}$ ; (d) at  $t = 1 \text{ h}$ ; (e) at  $t = 6 \text{ h}$ ; (f) at  $t = 2 \text{ h}$ ; (g) at  $t = 9 \text{ h}$ ; (h) at  $t = 3 \text{ h}$ ; (i) at  $t = 12 \text{ h}$ ; (j) at  $t = 4 \text{ h}$ ; (k) at  $t = 15 \text{ h}$ ; (l) at  $t = 5 \text{ h}$ ; (m) at  $t = 18 \text{ h}$ ; (n)  $t = 6 \text{ h}$ .

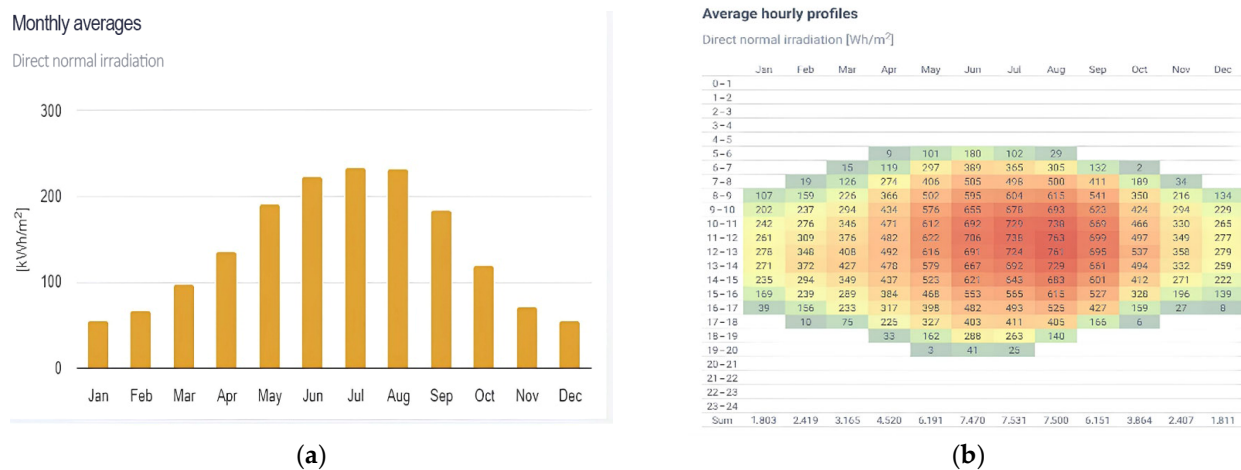


**Figure 12.** Solar radiation in the research area: (a) monthly averages; (b) average hourly profiles.

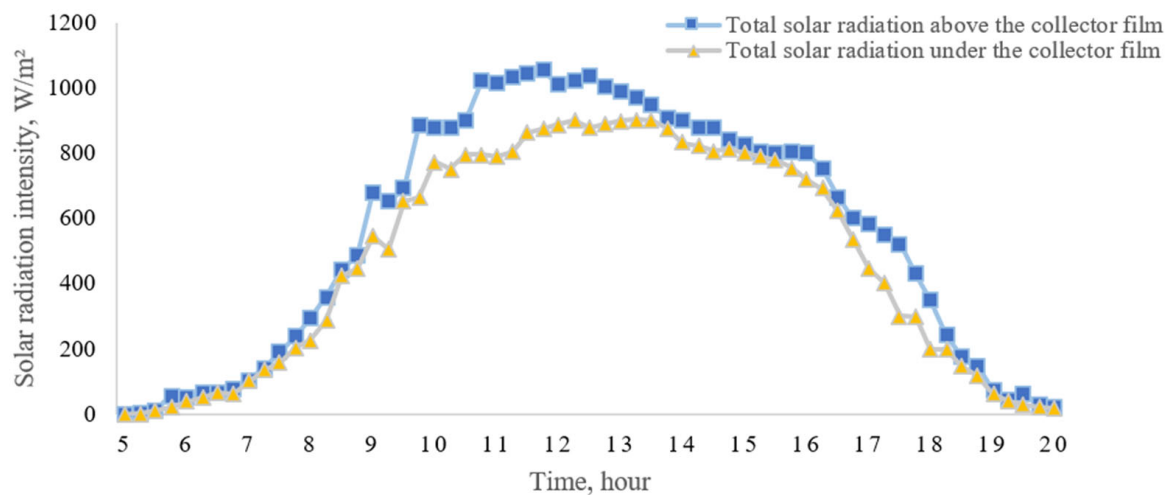


**Figure 13.** Comparative measurement of solar radiation intensity before and after transmission through the protective film of the solar collector.

### 3.2.3. Change in Moisture Content of Bee Bread Granules as a Function of Drying Parameters

For natural drying, where the air velocity is stationary, the regression equation for moisture content ( $W$ ) as a function of drying time ( $\tau$ ) and the total mass ( $m$ ) of the bee bread granule layer is:

$$W = 18.741 - 0.015 \tau + 0.007 m. \quad (4)$$

For the solar dryer, the regression equation incorporates three factors, including the air flow velocity ( $v$ ):

$$W = 17.583 - 4.22 v - 0.077 \tau + 0.005 m. \quad (5)$$

A graphical interpretation of these functions is presented in Figure 14. The 3D models show the change in moisture content of the bee bread granule layer: the left column represents the humidity dependence for natural drying on a fixed rack, and the right column represents the change in humidity during processing in a solar dryer with mobile shelves.

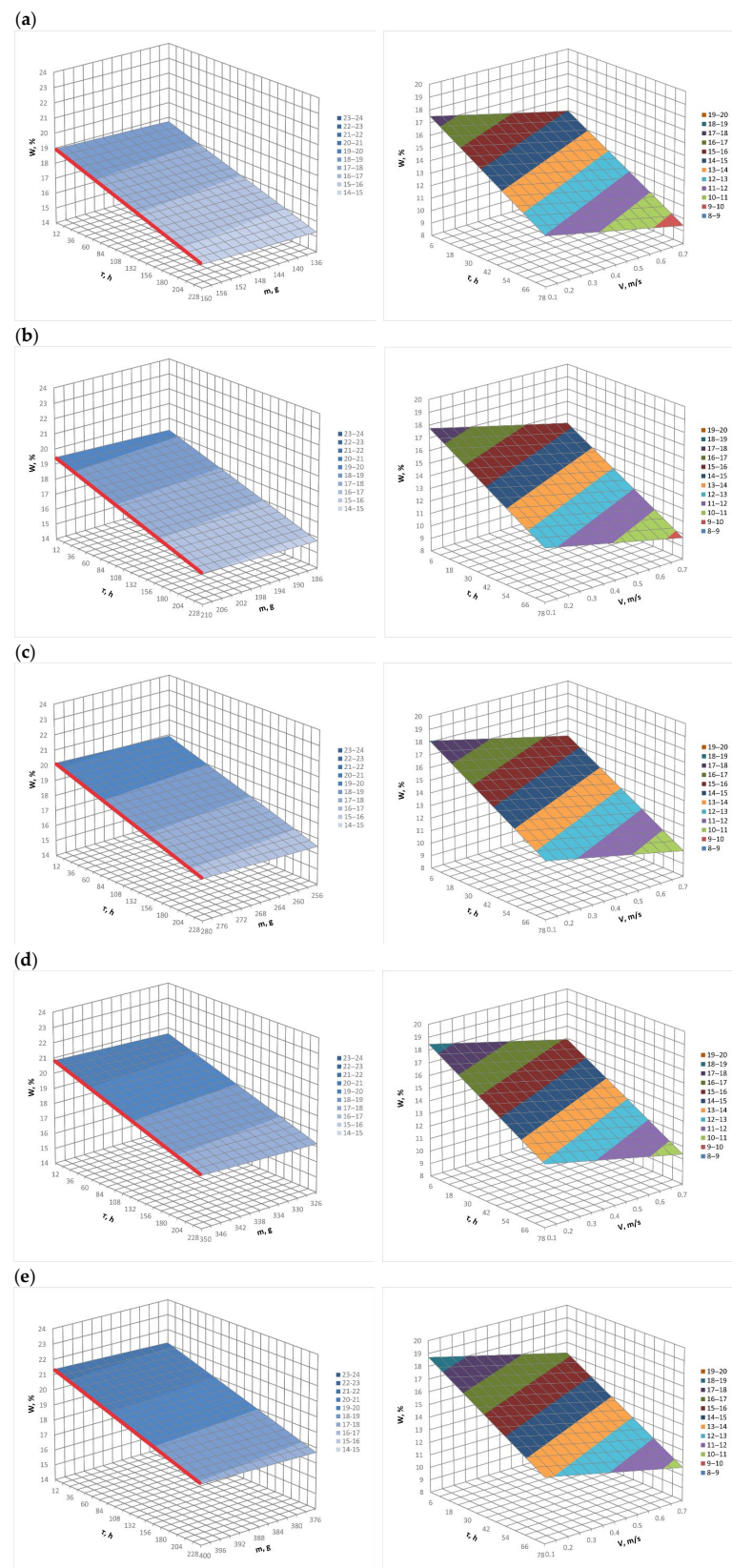


**Figure 14.** Modelled moisture content ( $W$ ) of bee bread granules after drying with variation in controlled factors: flow velocity ( $v$ ) of the drying agent (solar dryer only); drying time ( $\tau$ ); and mass ( $m$ ) of bee bread on the shelf. Results are shown for masses of (a) 160 g, (b) 210 g, (c) 280 g, (d) 350 g, and (e) 400 g.

### 3.3. Change in Moisture Content of the Drying Agent

Based on the measured temperature and humidity of the drying agent before and after the drying process, the change in the moisture content of the air was determined. Figure 15 presents a graphical interpretation of this parameter for both natural drying and solar drying processes.

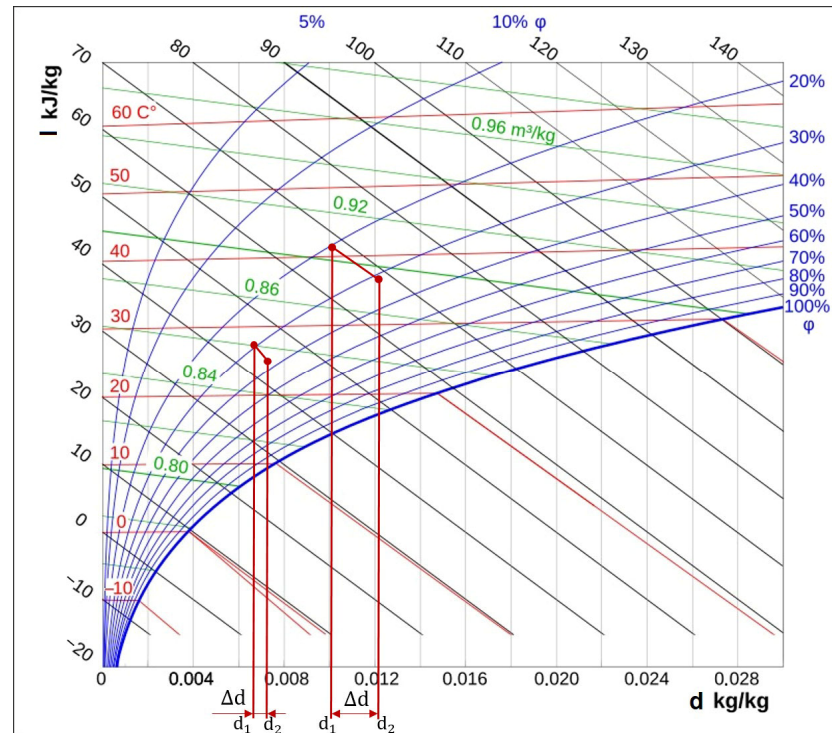


**Figure 15.** Relative moisture content of the drying agent (air) for: natural drying (left); solar drying (right).

## 4. Discussion of Research Results

The intensification of granulated bee bread drying necessitates research into the drying chamber's temperature regime and air velocity, underscoring the need for optimized solar dryer designs and operating modes in hot climates.

Figure 8b,d,f,h,j illustrate the temperature field inside the solar dryer, showing a distribution between 293 K and 318 K. Hot air enters the chamber through a horizontal channel on the left (X-axis), as indicated by the red area corresponding to the maximum temperature of approximately 318 K. The flow subsequently ascends along the right chamber wall, forming a distinct recirculation zone characterized by high temperatures (310 K to 318 K). In contrast, the central part of the chamber and the area near the left wall exhibit significantly lower temperatures (295 K to 305 K), indicating insufficient mixing and the potential formation of “cold spots”. This temperature gradient facilitates moisture evaporation, leading to a reduction in the mass of the drying shelf. The combined effect of the upward warm air flow, driven by exhaust fans at the top, and the changing mass distribution generates a torque that rotates the drum by a certain angle (counterclockwise). This rotation ensures sequential exposure of all shelves to the high-temperature zone (one by one), thereby enhancing moisture evaporation without overlapping from upper shelves. The simulation does not account for the resistance of the shelves to active airflow. This limitation pertains to the objective of determining the onset time of a stable temperature regime under specified airflow velocities. Future research should involve a more comprehensive investigation, incorporating the presence of racks through numerical modeling).

Temperature profiles within the layer of bee bread granules (Figure 9) demonstrate that the material heats to 42 °C within 15 min. The close agreement between the results obtained from the Python model and the ANSYS Fluent simulation validates the implemented numerical scheme and boundary conditions. The heating process is relatively gradual, which can be attributed to the air spaces between the granules. In comparison, Figure 10 illustrates a scenario with a reduced air velocity of 0.92 m/s, resulting in a significant decrease in circulation intensity and a lower temperature range of 20 °C to 30 °C. Under these conditions, indicative of natural drying, heat transfer occurs much more slowly, requiring 1.5 h to fully heat the granules.

Simulation of the moisture evaporation process from granule layers under natural drying and using of solar dryer (Figure 10) indicates that evaporation initially occurs from the lower layers due to a vertical temperature gradient starting from the bottom.

A sharp initial drop in relative humidity is observed (Figure 10a,b), followed by a period of stabilization and gradual evaporation. The evaporation process in the solar dryer proceeds 2.5–3.0 times faster. Analysis of the relative humidity range from ~0.24 to ~0.25 shows the time required to reduce humidity by 1. After 18 h, the lower section of the chamber reached a relative humidity of 0.24, while the upper section remained at approximately 0.245. It is estimated that a full 1% reduction would require over 24 h.

An investigation of the solar radiation patterns in the region (Figure 12) reveals significant seasonal and diurnal variability in temperature correlated with solar intensity. Peak heating efficiency occurs during the summer months (July, August), with minimum activity in winter (December). The maximum radiation flux density was recorded between 12:00 and 13:00, reaching approximately 1000 W/m<sup>2</sup> on the outer surface and 870 W/m<sup>2</sup> inside the collector, indicating high insolation at midday. Radiation gradually decreases to minimal values (0–200 W/m<sup>2</sup>) during the morning (05:00–08:00) and evening (17:00–20:00) hours, consistently with natural diurnal cycles. The annual direct normal irradiance is 1495.2 kWh/m<sup>2</sup>, and the diffuse irradiance is 600.9 kWh/m<sup>2</sup>, which are key parameters for designing systems utilizing both direct and scattered solar radiation. The potential annual photovoltaic energy output under standard conditions is estimated at 1418.2 kWh, supporting the feasibility of solar-based technologies, including drying systems [31,32]. The optimal tilt angle for solar panels to maximize energy generation was determined to be 35° with a south-facing orientation (azimuth 180°).

Comparative analysis of external and internal irradiance on the solar collector (Figure 13) showed an average solar radiation loss of 13%, corresponding to a film transmittance factor of 0.87. This value complies with regulatory requirements for solar power installations and confirms the efficacy of the coating used in the drying chamber design. The experimental data align closely with the values provided by the Global Solar Atlas for the region, validating the measurement reliability and supporting the use of these results for designing and operating solar dryers in similar climatic conditions.

Analysis of the bee bread granule drying process yielded the following insights. The regression equations for natural drying and solar drying differ primarily in the influence of air flow velocity, which is absent in the natural drying model due to the stationary, non-forced air flow. Furthermore, the air temperature in natural drying is considerably lower (up to 30 °C) because the shelves are placed in the shade to prevent direct sunlight from compromising product quality. Conversely, the solar dryer chamber maintains a constant temperature of 42 °C, the maximum allowable for this product [33]—via solar collectors, without exposing the product to direct sunlight.

The change in moisture content of the bee bread granules is presented graphically (Figure 14), depicting five surfaces derived from regression equations. Each surface corresponds to a fixed mass of granules (i.e., a fixed layer thickness for constant shelf dimensions).

The left-facing edge of the surface in Figure 14a (left) represents a fixed mass of 160 g. The illustrated moisture change for a mass reduction to 135 g shows only minor variations in humidity, a pattern consistent across all fixed mass values in the left columns.

The right columns in the figure present graphs of humidity change as a function of air flow velocity and drying time, for similar fixed granule masses. All graphs consistently demonstrate that natural drying requires approximately 2–3 times longer than using solar dryer to achieve the same moisture reduction. These results corroborate the relative drying rates obtained in the theoretical simulations conducted with ANSYS (Figure 11).

A reality assessment of the process control based on the I-D diagram (Inter-state standard [34]) for moisture removal by the drying agent (air) visually confirms the solar dryer's efficiency, showing a more than threefold increase in effectiveness compared to natural drying on a shelf.

## 5. Conclusions

The utilization of solar dryers with mobile shelves for the cyclic drying of bee bread granules can be considered a promising energy-efficient technology, particularly under off-grid conditions where access to conventional electricity is limited. The adoption of such systems contributes to the development of sustainable drying techniques that reduce dependency on fossil-based energy sources.

To ensure the feasibility of this approach, regional solar radiation parameters were analyzed using GIS-based data from the Global Solar Atlas, developed by the World Bank and ESMAP. The reliability of these data was confirmed by experimental measurements, thereby validating their applicability to the studied region.

Experimental investigations were carried out to determine the energy losses occurring during the transmission of solar radiation through protective polymer films, as well as to assess the performance of solar air collectors used for heating the drying agent. These findings provided a quantitative basis for the optimization of the system's thermal efficiency.

Numerical simulations were performed using Python and Ansys Fluent software packages. The models allowed for a detailed analysis of the isotherm distribution of the drying agent within the solar dryer chamber, the spatial temperature fields, and the dynamic changes in humidity across the bee bread granule layers. Comparisons were made between natural drying and solar dryer, thereby highlighting the thermophysical advantages of the developed design by shorting of drying time to 3 time.

The kinetics of the drying process were further described through the derivation of a regression equation, obtained via a designed experiment. The methodology incorporated controlled factors, including the mass of granules per shelf, airflow velocity, and drying duration, which enabled the systematic evaluation of their influence on moisture removal efficiency.

The reliability and consistency of the drying process were assessed using I–D diagrams describing air–moisture interactions. A comparative analysis of the moisture content index ( $\Delta d$ ) demonstrated the superior performance of the solar dryer (0.0022 kg/kg) relative to natural drying (0.00073 kg/kg), thus confirming the practical significance of the developed system.

Overall, the efficiency of bee bread granule drying in the proposed solar dryer was ensured through the implementation of cyclic drying with forced removal of moisture-laden air and the design improvement eliminating shelf overlap. These measures enhanced airflow distribution and contributed to a higher rate of moisture reduction. The obtained results underscore the potential of the developed solar drying technology for application in decentralized agricultural processing, offering both ecological and economic benefits.

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## Nomenclature

### Latin Symbols

|           |                                                |
|-----------|------------------------------------------------|
| $m$       | Meter                                          |
| $s$       | Second                                         |
| $t$       | Time                                           |
| $P$       | Pressure (Pa)                                  |
| $T$       | Temperature (°C)                               |
| $T_0$     | Reference temperature (°C)                     |
| $x, y, z$ | Spatial coordinates                            |
| $u, v, w$ | Velocity's components                          |
| $C$       | Concentration                                  |
| $g$       | Gravitational acceleration (m/s <sup>2</sup> ) |
| $c_p$     | Heat capacity (J/K)                            |

### Greek Symbols

|                               |                                                            |
|-------------------------------|------------------------------------------------------------|
| $\varepsilon$                 | Range                                                      |
| $\rho$                        | Density (kg/m <sup>3</sup> )                               |
| $\rho_0$                      | Reference density                                          |
| $\mu$                         | Dynamic viscosity                                          |
| $\beta$                       | Thermal expansion coefficient                              |
| $\alpha = \frac{k}{c_p \rho}$ | Coefficient of temperature conductivity                    |
| $k$                           | Thermal conductivity (W·m <sup>-1</sup> ·K <sup>-1</sup> ) |
| $\gamma$                      | Diffusion coefficient of concentration                     |

### Subscripts

|     |                   |
|-----|-------------------|
| kg  | Kilogram          |
| g   | Gram              |
| K   | Kelvin            |
| kW  | Kilowatt          |
| V   | Volts             |
| RH  | Relative humidity |
| $h$ | Hour              |
| $s$ | Seconds           |

### Acronyms

|        |                                    |
|--------|------------------------------------|
| Testo  | Measuring instruments              |
| HOBO   | Data logger                        |
| GOST   | State Standard of the Soviet Union |
| ANSYS  | Engineering simulation software    |
| Python | Programming language               |

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