Solar Drying in Controlled Environments: Sustainable Solution for Preserving Vegetable Products

Dipl. Eng. **Alina - Iolanda POPESCU[1,*]**, PhD. Eng. **Gheorghe ȘOVĂIALĂ[1]**,
PhD. Eng. **Gabriela MATACHE[1]**

[1] National Institute of Research & Development for Optoelectronics/INOE 2000, Subsidiary Hydraulics and Pneumatics Research Institute/IHP, Romania

* alina.ihp@fluidas.ro

Abstract: *The paper analyzes the drying process of vegetable products using solar systems, as an efficient and sustainable solution for reducing food losses. The fundamental differences between natural drying and dehydration are presented, as well as the technological classification of solar dryers (direct, indirect, mixed), depending on the operating mode (passive vs. active). The heat transfer principles involved (convection, radiation) are highlighted and the contribution of the constructive elements to optimizing energy efficiency is detailed. The application part includes a calculation breviary for sizing a convective dryer with a solar air collector, highlighting the correlation between the useful thermal power, the collector surface area, the operating mode and the water evaporation requirements. The results emphasize the potential of these systems in small and medium-scale agri-food and industrial applications.*

Keywords: *Solar dryers, calculation breviary, dryer types*

1. Introduction

Food waste is one of the most pressing challenges of our time. According to the Food and Agriculture Organization of the United Nations (FAO), approximately one third of global food production is lost along the chain from harvest to consumption, which is equivalent to approximately 930 million tons annually. Among the major causes are inadequate infrastructure for storing and preserving food, especially fruits and vegetables, which leads to product degradation, reduced supply and, implicitly, increased prices.

To counteract these effects, food preservation becomes essential, aiming to extend shelf life and maintain nutritional and organoleptic qualities. Among the traditional preservation methods, drying stands out as one of the oldest and most widely used techniques. It usually involves exposing food products to direct sunlight, thus reducing their humidity and, implicitly, their weight. By removing water – a key factor in the initiation of biological and chemical reactions that lead to food spoilage – drying allows for long-term storage and easy transport of products [1,3].

In recent decades, solar energy has become an increasingly viable option in the context of fossil fuel depletion and environmental pollution concerns. Being a renewable, free and abundant source, solar energy is frequently used in thermal processes, including food drying [2]. However, conventional solar drying has a number of disadvantages: significant heat loss, risk of contamination with impurities, exposure to weather and pest attacks.

To overcome these limitations, solar drying systems have been developed in controlled environments, which allow for the maintenance of optimal and constant temperatures. These modern solar dryers use dedicated equipment to capture and convert solar radiation into heat, thus improving the efficiency of the process compared to direct solar drying [4]. The essential difference between conventional solar drying and solar dryers lies in the control of the drying environment and the use of solar energy harvesting technology. The applicability of solar dryers has expanded beyond the agricultural field, finding applications in industries such as food (seafood), pharmaceuticals, paper, ceramics, and biomass processing [5].

2. Considerations regarding the drying process of vegetable products

Drying of vegetables and fruits is the technological process by which the natural water content is reduced to a level that prevents the activity of microorganisms, without destroying the tissues or depreciating the food value of the products.
The set of phenomena that occur during drying leads to the concentration of dry matter, the reduction of the volume of raw materials used, the increase in food value per unit weight and more or less profound physicochemical changes in the state of membranes and cellular components, which are externalized by the limits of the rehydration capacity.
Dehydration is the process by which fruits and vegetables lose a certain amount of water, as a result of which a conducive physicochemical state to maintaining their nutritional value and qualitative attributes is achieved: taste, smell, aroma.
Drying differs from dehydration by the lack of regulation of temperature, relative humidity and air movement, for which purpose the expression natural drying is also used, unlike dehydration, which is artificial drying.
In the first case, by simple exposure to air and ambient temperature, the moisture is removed from the products through the evaporation process. In the second case, to continue the dehydration process, an additional heat input is used, the water removal being done through the vaporization process.
Evaporation occurs by the passage of water in a vapor state in an environment in which, in addition to water vapor, there is also air and other gases, and vaporization by the passage of water in a vapor state, in an environment in which there is only water vapor.
The fruit and vegetable drying installation in which the air movement is done by itself, based on the thermal difference between the atmosphere in the drying chamber and the external atmosphere is known in the specialized literature as an *evaporator*.
The rate of dehydration depends on the relative humidity of the air in the installation; the lower it is, the shorter the drying time. If the temperature of the air in the drying installation increases, the relative humidity of the air decreases, so it will be able to take on new amounts of water vapor. On the contrary, if the air temperature decreases, it will become saturated with water vapor, and if it decreases even more, the water vapor in the air will condense. This is the *dew point* or dew temperature.
Therefore, during the drying process, the air in the installation must be in continuous circulation and be heated, in order to increase its capacity to take on new amounts of water vapor.
In drying installations, water evaporation occurs both based on the temperature difference between that of the product being dried and that of the heated air, and especially through the difference between the vapor pressure inside the tissues and that of the vapor contained in the air in the installation. Evaporation is also influenced by the surface tension (force) of the water vapor in the product. Evaporation occurs until an equilibrium is reached between the vapor pressures of the two media, in other words until the warm air in the installation has been saturated with water vapor.

3. Theoretical foundations of solar drying

Regardless of the constructive configuration, all types of solar dryers operate on the same fundamental principle: the removal of water from food by evaporation, a process determined by the transfer of heat to the product. This transfer can be achieved by convection, radiation or a combination of the two, depending on the technical solution adopted [6].
Over time, numerous researchers have developed and tested various configurations of solar dryers, evaluating them from the point of view of energy efficiency and the quality of the products obtained. Their classification can be done according to several factors: the direction and mechanism of hot air circulation, the type of heat transfer or the way in which solar radiation is captured and used [7].

3.1 Types of solar dryers

There are 3 types of solar dryers:

• **Direct-type dryers** (Fig. 1)
In this variant, the products are directly exposed to solar radiation inside a chamber covered with a transparent cover, which allows the radiation to pass through, but provides protection against external factors (precipitation, dust, pests) [8].

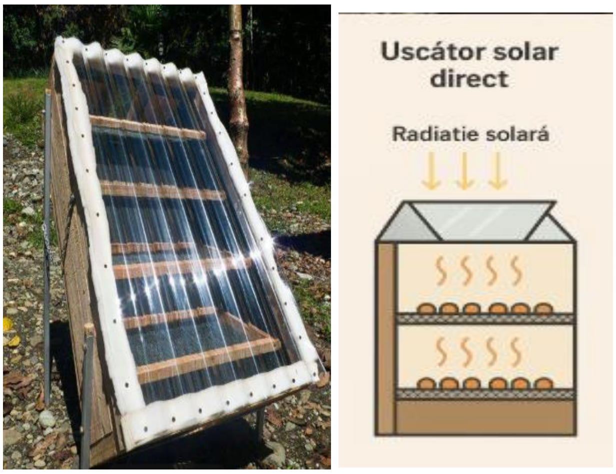

Fig. 1. Direct-type dryers

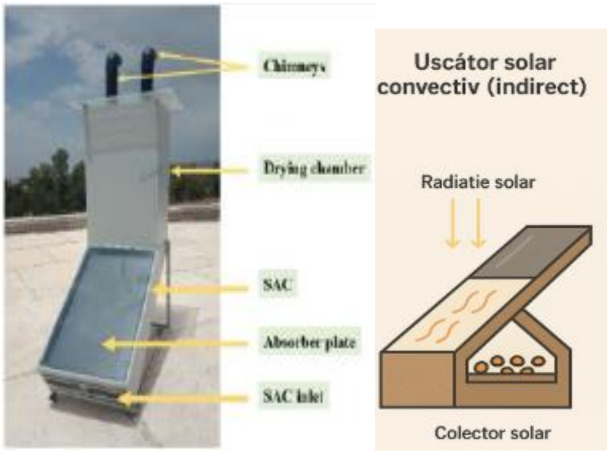

Fig. 2. Indirect-type dryers

• **Indirect-type dryers** (Fig. 2)
In this case, the air is heated in a solar collector and then directed to the drying chamber, where the heat is transferred to the product by convection. This method offers better control over the process and higher thermal efficiency [8].
• **Mixed dryers** (Fig. 3)
These systems combine the advantages of the direct and indirect types: the products are simultaneously exposed to direct solar radiation and preheated air. Heat transfer occurs both by convection and radiation, which accelerates the drying process and improves the uniformity of the results [9,10].

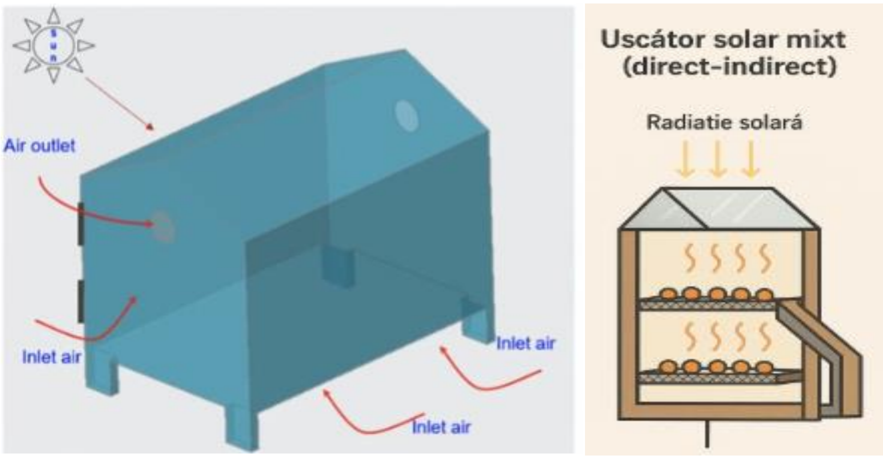

Fig. 3. Mixed dryers

3.2 Operating mode: passive vs. active

• **Passive systems**
These are direct-type dryers. In these dryers, air circulates naturally through the thermal effect of buoyancy or pressure differences. They usually consist of a drying chamber with transparent covers and openings for ventilation. Solar radiation penetrates the chamber, heating the opaque walls and generating a greenhouse effect that facilitates product drying. Passive dryers are simple,

economical and suitable for small volumes of fruit, vegetables or cereals. However, their efficiency varies between 20–40%, depending on climatic conditions and system geometry [11].
The limitations related to the low air circulation speed can lead to product overheating and quality loss. For this reason, passive dryers are rarely used for intensive loads or sensitive products [12].

• **Active systems**

These can be indirect or mixed-type dryers. In these installations, air circulation is achieved by force, using fans or blowers, allowing for more precise control over the process. They are recommended for products with high humidity (e.g. tomatoes, kiwi, papaya), offering reduced drying times and minimal quality losses. The integration of external heat sources or preheating systems contributes to uniform and efficient drying, even in adverse weather conditions [12].
Studies show that the use of active systems, in combination with thermal energy storage components, can increase the efficiency of the process by up to 28%. For example, in arid conditions, drying meat with direct and indirect active systems has demonstrated efficiencies of 7–10% and 15–18%, respectively.

3.3 Hybrid solar drying systems

Hybrid systems integrate solar drying with *other energy sources or auxiliary technologies* to increase efficiency and process continuity. They may include *thermal energy storage systems* (TES), *solar electrical components* (SES), or *phase change materials* (PCM), which allow drying to be extended outside of direct sunlight hours [13].

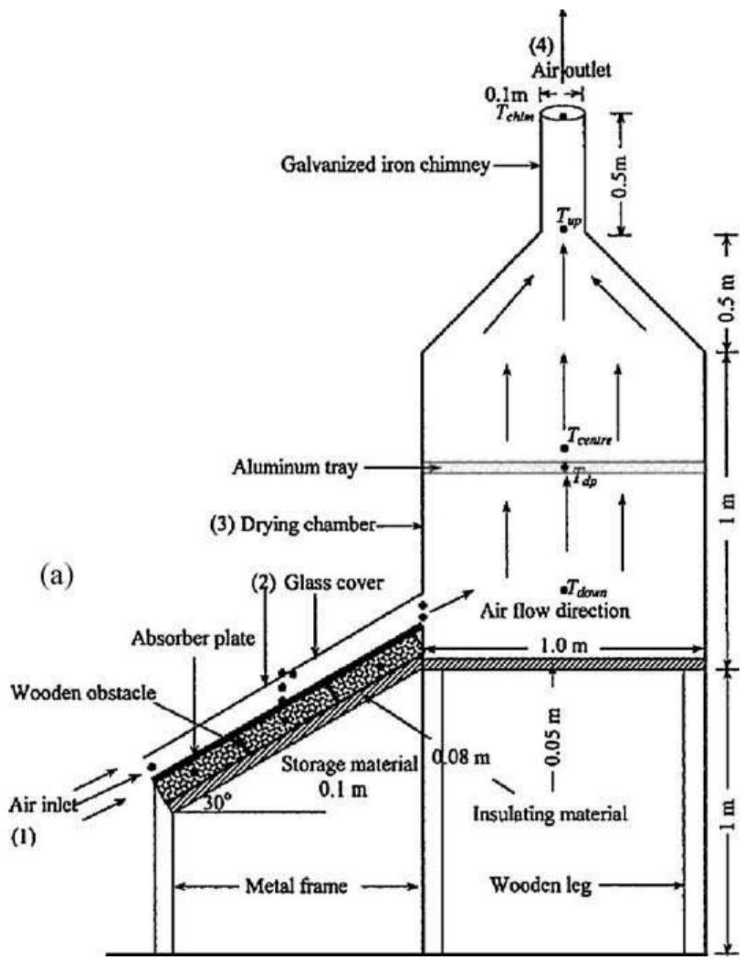

Fig. 4. The operating principle of a dryer using solar energy [14]

A relevant example is the hybrid solar-LPG dryer, built in Mexico, which achieved a 75% moisture reduction of nopal and achieved a solar fraction of 80%. The system combines direct and indirect heating sources, along with a backup system, and has demonstrated an economic payback period between 28 and 68 months [14] - fig.4.

3.4 Optimizing dryer performance

To improve the efficiency of the drying process, *numerous technical innovations can* be applied:
• the use of collectors with an extended surface and high roughness for increased turbulence and more efficient heat transfer;
• fans driven by photovoltaic panels, to reduce operating costs;
• air collectors with multiple passes (double/triple), to intensify the air flow;
• thermal energy storage systems, for continuous drying outside the sun's intervals.
All these improvements contribute to increasing yield, reducing process time and maintaining the quality of food products, especially in rural or medium- and large-scale agricultural applications.

4. Calculation breviary (sizing) for a solar-heated convective dryer with air collector

4.1. Theoretical framework and basic equation

For a solar-heated convective dryer with air collector, *the instantaneous useful thermal power* is classically expressed by the relationship:

$$P_u = G[W/m^2] x A[m^2] x\ \eta_c,$$

where the parameters of instantaneous useful thermal power (Table 1) are:

Table1: The parameters of instantaneous useful thermal power

Symbol	Significance	Typical values from literature
G	solar irradiation on the collector surface	600 – 800 W m⁻² as a daily average; can reach ≈ 1000 W m⁻² at noon on clear days [15,16]
A	useful collector area	established at design
η_c	instantaneous collector efficiency	0.30 – 0.75 (30 – 75 %) as a function of geometry and air flow [15,17]

4.2. Available thermal power range

Combining the limits in the tables, the instantaneous useful thermal power can be evaluated:

- **Minimally realistic**: $G=600\ W\ m^{-2}$; $\eta_c=0,30 \Rightarrow Pu \approx 180\ W\ m^{-2}$
- **Reported maximum**: $G=1000\ W\ m^{-2}$; $\eta_c=0,75 \Rightarrow Pu \approx 750\ W\ m^{-2}$

This results in a practical range of 0.18 – 0.75 kW for each m² of collector.

4.3 Numerical example (instantly)

Common assumptions in fruit/vegetable dryer design work:

- sunny day, $G=800\ W\ m^{-2}$
- glazed flat collector, $\eta_c=0.60$ (typical forced yield)
- collector surface $A=2.0\,m^2$

$Pu=G \cdot A \cdot \eta_c = 800 \cdot 2.0 \cdot 0.60 \approx 960\,W$ (0.96 kW), so, almost 1 kW of useful heat is instantly available for heating the drying air.

4.4. Daily useful energy and water evaporation capacity

$E_{useful} = Pu[kW] \cdot t[\text{operating hours/day}] = 0.96 \cdot 8 = 7.68$ kWh (≈ 27.648 MJ)

1 kWh= 3.6 MJ; 1 MJ = 0.277778 kWh

In relation to the drying requirements of vegetable products, the specialized literature mentions the *thermal energy required to evaporate one kg of water in solar/hybrid convective dryers*, depending on the product and configuration [18] *at 12.6 – 38 MJ*.

Therefore, with 27.648 MJ available, the following amounts of water can be removed from the product daily:

- to superior efficiency (12.6 MJ kg^{-1}) → ≈ 2.194 kg
- to medium efficiency (25 MJ kg^{-1}) → ≈ 1.105 kg.

This calculation confirms that **the sizing of the collector surface** (Table 2) must be correlated with:

1. the amount of water to be removed per batch,
2. the desired drying time,
3. the overall efficiency (collector + chamber + air flow).

Table 2: The sizing of the collector surface

Steps	Algorithm	Observations
1.	The following are determined: product mass and humidity that must be eliminated	Determine the amount of water to be removed [kg]
2.	The $E_{specific}$ value (MJ kg^{-1}) is chosen from the bibliography for a similar product/construction.	Lower values for forced mix-mode dryers, higher for passive ones
3.	Calculate the total energy required $E_{tot.}$	$E_{tot}=m_{water}\times E_{specific}$
4	The daily operating duration (h) is chosen and the average power required Pmed is determined.	$P_{med}=E_{tot}/t$
5.	The equation $Pu=GA\eta_c$ is used, with the average value of G from the respective location.	The area A is dimensioned.

The process parameters and equations used to estimate the performance of the solar dryer are given below.
m_i = mass of the sample before drying;
m_f = mass of the sample after drying.
Humidity content of the sample:

$$m_w = m_i - m_f \text{ (kg)} \quad (1)$$

Amount of heat required to evaporate the humidity:

$$Q = m_w \times h_{fg} \text{ (kJ)} \quad (2)$$

where h_{fg} = is the latent heat of water vaporization (kJ/kg).

$$\text{Average drying rate} = \frac{m_w}{m_i \times t_{total\ of\ drying}} \text{ (kg / kgh)} \quad (3)$$

The energy efficiency of the greenhouse solar dryer is estimated by:

$$\eta_{energ} = \frac{Q_d}{Q_c} \quad (4)$$

where the heat used for drying (dissipated heat), Q_d is:

$$Q_d = \frac{Q}{t_{\text{total of drying}}} = \frac{Q}{8x3600} \quad (5)$$

and the heat received by the collector, Q_c is:

$$Q_c = (\alpha \times I \times A_c) - h \times A_c \times (T_1 - T_5) \tag{6}$$

To determine the convection heat transfer coefficient, h (W/m²K),

$$T_e = T_1 - 0.25\,(T_1 - T_5) \tag{7}$$

For the air drying agent, the *parameters leading to the calculation of the convection heat transfer coefficient h* are the thermal conductivity of the acrylic collector k (W/mK), the Nusselt number N_u and the vertically length L.

$$h = \frac{N_u \,.k}{L} \tag{8}$$

$$Nu = 0.56\,(Gr \times Pr \times \cos\theta)^{0.25} \tag{9}$$

where G_r is Grashof number, Pr is Prandl number, θ = 23°.

$$Gr = \frac{g\,\beta L^3}{\gamma 2}\Delta T \text{ , where } \beta \frac{1}{T5+273} \tag{10}$$

γ (m² / s) is the kinematic viscosity and g (m/s²) is the gravitational acceleration.

Average drying rate, $V_{m\,us}$:

$$V_{m\,us} = \frac{m_w}{m_i \cdot t_{t\,us}} \tag{11}$$

where $t_{t\,us}$ is total drying time.

The nomenclature of quantities in the equations above:
T_1 =Temperature of the glass exterior (°C)
T_2 =Temperature of the glass interior (°C)
T_3 =Temperature of the drying enclosure (°C)
T_4 = Temperature of the output air (°C)
T_5 = Ambient (atmospheric) temperature (°C)
T_e = Exterior (outlet from the drying chamber) temperature (°C)
H_1 = Relative humidity of the exterior surface (%)
H_2 = Relative humidity of the interior surface (%)
H_3 = Relative humidity of air in the drying enclosure (%)
H_4 = Relative humidity of air at the output (%)
α = Acrylic collector absorption = 0.26
I= Average intensity of solar radiation per day (W/m²)
A_c = Surface of the collecting plate = 0,1375 m²
g = Gravitational acceleration (m/s²)
h = Thermic transfer coefficient by convection (W/m²K)
Nu = Nusselt number
Gr = Grashof number
Pr = Prandtl number
k = Thermal conductivity of acrylic collector (W/mK)
γ = Cinematic viscosity (m² /s)
L = Vertically length on which the heat transfer occurs by free convection (m)

5. Useful conclusions from the specialized literature

Based on what is presented in the article, it can be observed that food waste is a major problem globally, and one of its main causes is the lack of effective preservation solutions, especially for perishable products such as fruits and vegetables.
Food drying is a traditional, efficient and accessible method of preservation, which contributes to extending the shelf life of products, reducing their volume and facilitating transport.
The use of **solar energy** in the drying process offers a sustainable alternative, with reduced impact on the environment, in the context of the depletion of conventional resources and increasing energy costs.

Solar dryers in controlled environments – whether direct, indirect, mixed, passive or active – allow the optimization of the dehydration process by maintaining stable thermal conditions and reducing the risks of contamination.
Also, from the specialized literature it is observed that:
- Glazed flat-plate collectors with fins can exceed $\eta_c \approx 0.70$, especially at high forced air flows [15].
- In tropical/semi-arid climates, a design heat flux of 400–500 W m^{-2} is usually used, offering a reasonable compromise between surface area and cost.
- Reduction of specific energy (MJ kg^{-1}) is achieved by partial air recirculation and latent heat storage (PCM). Recent examples have dropped to ≈ 12 MJ kg^{-1} [18].

The literature places the instantaneous solar thermal power between 0.18 and 0.75 kW per m^2 of collector; choosing average values (≈ 0.4–0.5 kW m^{-2}) realistic estimates can be made for most small convective dryers. The final sizing must always be linked to the specific drying energy of the product and the overall efficiency of the system.
Active and **hybrid** systems, which use auxiliary components such as fans, multiple air collectors or thermal energy storage, significantly improve the drying efficiency and allow the technology to be used even in adverse weather conditions.
Modeling the drying process and **correctly sizing the installations** based on physical and energy parameters ensures operating efficiency and constant results, being essential in the design of high-performance solar dryers.
Expanding the use of these technologies in rural areas or in industries with limited access to conventional energy can significantly contribute to reducing post-harvest losses and increasing food security.

Acknowledgments

This work was supported by a grant of the Ministry of Research, Innovation and Digitization, CCCDI - UEFISCDI, project number PN-IV-P7-7.1-PTE-2024-0039, within PNCDI IV.

References

[1] Ahmad, M., J.C. Hauser, C. Heijnen, and M.A. Chaudry. “Solar drying of fruits and vegetables.” *Pakistan Journal of Agricultural Research* 17, no. 3 (2002): 237–244.
[2] Scheer, Hermann. *The Solar Economy: Renewable Energy for a Sustainable Global Future*, vol. 3. Earthscan Publications Ltd., 2002.
[3] Fortunatus, R., R. Marealle, N. Nenguwo, and T. Stoilova. *Solar Dryers. Principles and basics*. World Vegetable Center, 2017.
[4] Rajkumar, P., S. Kulanthaisami, G.S.V. Raghavan, Y. Gariépy, and V. Orsat. “Drying Kinetics of Tomato Slices in Vacuum Assisted Solar and Open Sun Drying Methods.” *Drying Technology* 25, no. 7-8 (2007): 1349-1357.
[5] Wafa, B.C., M. Ahmed, M.E.A. Slimani, L. Akil, A. Hamid, and A. Khellaf. “Experimental investigation of an active direct and indirect solar dryer with sensible heat storage for camel meat drying in Saharan environment.” *Solar Energy* 174 (April 2018): 328-341.
[6] Chavan, A., V. Vitankar, A. Mujumdar, and B. Thorat. “Natural convection and direct type (NCDT) solar dryers: a review.” *Drying Technology* 39, no. 13 (2021): 1969-1990.
[7] Mohana, Y., R. Mohanapriya, T. Anukiruthika, K.S. Yoha, J.A. Moses, and C. Anandharamakrishnan. “Solar dryers for food applications: Concepts, designs, and recent advances.” *Solar Energy* 208 (September 2020): 321-344.
[8] Ameri, B., S. Hanini, A. Benhamou, and D. Chibane. “Comparative approach to the performance of direct and indirect solar drying of sludge from sewage plants, experimental and theoretical evaluation.” *Solar Energy* 159 (January 2018): 722-732.
[9] Shalaby, S.M., M.A. Bek, and A.A. El-Sebaii. “Solar dryers with PCM as energy storage medium: a review.” *Renewable and Sustainable Energy Reviews* 33 (May 2014): 110-116.
[10] Dhalsamant, K., P.P. Tripathy, and S.L. Shrivastava. “Heat transfer analysis during mixed-mode solar drying of potato cylinders incorporating shrinkage: Numerical simulation and experimental validation.” *Food and Bioproducts Processing* 109 (May 2018): 107-121.
[11] Udomkun, P., S. Romuli, S. Schock, B. Mahayothee, M. Sartas, T. Wossen, E. Njukwe, B. Vanlauwe, and J. Müller. “Review of solar dryers for agricultural products in Asia and Africa: An innovation landscape approach.” *Journal of Environmental Management* 268 (August 2020): 110730.

[12] Chauhan, P.S., A. Kumar, C. Nuntadusit, and J. Banout. “Thermal modeling and drying kinetics of bitter gourd flakes drying in modified greenhouse dryer.” *Renewable Energy* 118 (April 2018): 799-813.
[13] Mishra, L., A. Sinha, and R. Gupta. “Recent Developments in Latent Heat Energy Storage Systems Using Phase Change Materials (PCMs)—A Review.” Paper presented at The 1st International Conference on Green Buildings and Sustainable Engineering GBSE 2018, Kochi, India, January 24-25, 2018.
[14] Fudholi, A., K. Sopian, M.H. Ruslan, M.A. Alghoul, and M.Y. Sulaiman. “Review of solar dryers for agricultural and marine products.” *Renewable & Sustainable Energy Reviews* 14, no. 1 (January 2010): 1-30.
[15] Gulcimen, F., H. Karakaya, and A. Durmus. “Drying of sweet basil with solar air collectors.” *Renewable Energy* 93 (August 2016): 77-86.
[16] Lingayat, A.B., V.P. Chandramohan, V.R.K. Raju, and V. Meda. “A review on indirect type solar dryers for agricultural crops – Dryer setup, its performance, energy storage and important highlights.” *Applied Energy* 258 (January 2020): 114005.
[17] Prakash, O., V. Laguri, A. Pandey, A. Kumar, and A. Kumar. “Review on various modelling techniques for the solar dryers.” *Renewable and Sustainable Energy Reviews* 62 (September 2016): 396-417.
[18] Alinia, A.M., and M. Sheikholeslami. “Development of a new solar system integrating photovoltaic and thermoelectric modules with paraffin-based nanomaterials.” *Scientific Reports* 15 (2025): 1336.