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Performance Analysis of a Solar Fruit Dryer under Controlled Conditions

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Abstract: *Solar energy is one of the most accessible and environmentally friendly sources of renewable energy, widely used in the drying of agricultural products. Compared to conventional methods, solar drying offers significant advantages such as improved energy efficiency, low operating costs, minimal environmental impact, and better preservation of the nutritional quality of food products.*
This paper analyzes the performance of a mixed-type solar dryer, consisting of an air collector and a drying chamber, used for the dehydration of fruits (apple, pear, and banana) under controlled theoretical conditions. A detailed calculation was carried out to determine the volumetric airflow required to dry 1 kg of fresh fruit, based on real moisture content data and standardized drying conditions. For instance, drying 1 kg of apple (initial moisture 85%, final moisture 15%) at 50°C required approximately 32.1 m³/h of dry air, under ideal operating conditions.
The results indicate that commonly cited values in the literature – estimating the need for 250 W and 62 m³/h of air to dry 1 kg of fruit – can be significantly optimized through proper system design and precise control of operational parameters. The study highlights the drying behavior differences between fruits and provides a basis for the efficient sizing of solar dryers, especially for small-scale producers and farmers seeking sustainable and low-cost food preservation solutions.

Keywords: *Solar drying, renewable energy, fruit dehydration, agricultural sustainability, controlled drying process*

1. Introduction

The continuous growth of the global population and accelerated urbanization have led to an increasing demand for fresh food, particularly fruits and vegetables. However, the lack of adequate storage and preservation facilities often results in significant post-harvest losses, reducing the availability of food products and contributing to price increases. Preserving these products is essential for extending shelf life, maintaining nutritional value, and reducing food waste. Among various preservation technologies, drying stands out for its simplicity and efficiency, being one of the oldest food processing methods used for millennia [1].
Agro-food products can be dried using several methods, but one of the most sustainable solutions is **solar drying**, which relies on a renewable, eco-friendly, and abundant energy source. The conversion of solar energy into heat is a direct and efficient application in this context, allowing for the reduction of moisture content in fruits and vegetables and consequently lowering their mass, which facilitates packaging, storage, and transport [2]. Removing water from the product inhibits microbiological and chemical processes that lead to food spoilage, thereby extending its shelf life [3].
Although traditional sun drying continues to be widely used, it presents significant limitations: high heat losses, exposure to contaminants, dependency on weather conditions, and lack of control over the drying process. These drawbacks have led to the development of **modern solar dryers**, in which drying takes place in a closed and controlled environment, with regulated temperature and moisture, using solar energy either directly or indirectly. These systems are commonly classified as direct, indirect, mixed, or hybrid dryers, and can operate in passive mode (natural convection) or active mode (forced convection).
It is also important to note that traditional sun drying suffers from substantial thermal energy losses, since only a fraction of the incident solar radiation is effectively used in the drying process. Direct exposure also increases the risk of product degradation due to extreme weather conditions

or contamination by foreign particles. Therefore, drying under controlled conditions is necessary for improved product quality. The evolution of sun drying has led to the development of **solar drying systems**, in which products are dried in enclosed environments, maintaining high internal temperatures [4]. In this context, solar dryers offer practical solutions to the challenges of open sun drying. They use solar energy as the primary heat source for drying, while also increasing thermal efficiency compared to traditional sun drying methods.

These solar-powered drying systems have been developed in various designs, and a significant portion of fossil fuel consumption can be reduced through their use [5]. All of these solar dryer configurations rely on the same fundamental mechanism—**evaporation of water molecules from within the product**. The method of heat transfer to the product depends on the system design and can occur through convection or radiation [6].

According to the literature, general estimates suggest that drying 1 kg of fruit with approximately 80% moisture content requires around **250 W of thermal energy** and an **airflow rate of about 62 m³/h**. However, the simulations conducted in this study, using a simplified solar dryer model composed of a solar collector and a drying chamber, indicate optimized values. For example, drying 1 kg of apples, with an initial moisture content of 85% and a final value of 15%, at a constant temperature of 50°C and air relative moisture of 30%, required only **32.1 m³/h of dry air** and resulted in **0.7 kg of water removed**. This approach demonstrates that, through careful design and rigorous control of operating parameters, the efficiency of the drying process can be significantly improved compared to general theoretical estimates.

Therefore, the present study aims to analyze the drying behavior of fruits such as apples, pears, and bananas, in the context of using a solar dryer under controlled parameters. It also seeks to highlight the differences in drying time and air requirements based on the internal structure and initial moisture content of each fruit. The results obtained may contribute to the optimization of solar dryer design, particularly for small-scale producers or farmers, offering a sustainable, cost-effective, and efficient alternative for agricultural product preservation.

2. Classification and operating principles of solar dryers

Numerous researchers have developed and evaluated various types of solar dryers with the aim of improving operational efficiency and thermal performance. Solar dryers can be classified according to several criteria, such as the movement of heated air, structural configuration, airflow direction, exposure to solar radiation, or the inclusion of energy storage systems [7].

Based on their operating principles, the most common types of solar dryers include:

- direct solar dryers,
- indirect solar dryers,
- mixed-mode dryers (combining direct and indirect heat input),
- dryers with thermal energy storage,
- passive solar dryers (with natural convection) and active ones (with forced convection) [7].

In **direct-type solar dryers**, the product is exposed directly to solar radiation and is covered by a transparent cover that allows the passage of solar energy while protecting the product from weather conditions and contaminants [8]. These systems are structurally simple but limited in terms of temperature control and drying uniformity.

Indirect solar dryers use a solar air collector to heat the air, which is then directed into the drying chamber. In this setup, the product is not exposed to direct sunlight, and heat transfer occurs primarily through convection between the hot air and the product surface. This results in higher thermal efficiency and better product quality [9].

Mixed-mode systems combine the advantages of both direct and indirect types by using both direct solar radiation and heated air. This type of dryer offers superior thermal efficiency due to the combined heat transfer mechanisms—radiation and convection [6,7].

Air circulation within solar dryers can be achieved either:

- **naturally**, via thermal buoyancy (in **passive systems**, also known as greenhouse-type dryers) [10],
- or **mechanically**, using fans or blowers (in **active systems**) [11].

A major challenge associated with solar drying is the **variability of solar radiation**. Cloudy or rainy weather and night-time conditions significantly reduce system performance, increasing the risk of poor product quality or spoilage [12].
To mitigate this issue, **thermal energy storage solutions** are integrated into solar dryers to maintain adequate drying temperatures even in the absence of direct sunlight. Materials such as stone, sand, cast steel, iron, bricks, and salt have been explored for storing excess solar heat, which can then be released during periods of low radiation [13].
More recently, **phase change materials (PCMs)** have been used as latent heat storage units. These materials have been successfully integrated into both direct and indirect solar dryers, providing significant benefits such as reduced drying times, consistent temperature maintenance, and enhanced thermal efficiency, even during unfavorable weather or night-time operation [14-17].
Therefore, the incorporation of **thermal energy storage systems** in solar dryers significantly increases their thermal efficiency and shortens the drying time, improving overall system reliability.
In summary, solar dryers can be classified based on the following criteria:

- method of air movement (natural or forced),
- solar exposure (direct, indirect, or mixed),
- airflow direction,
- internal configuration of the drying system,
- type of solar energy contribution (with or without energy storage).

From a functional perspective, solar drying systems are divided into two major categories:

- **passive solar dryers** (operating without external energy input),
- **active solar dryers** (using external energy sources to assist airflow).

These categories can be combined with the three main heat transfer modes—**direct, indirect, and mixed—**resulting in a wide range of adaptable configurations, suitable for various user needs and local climate conditions.

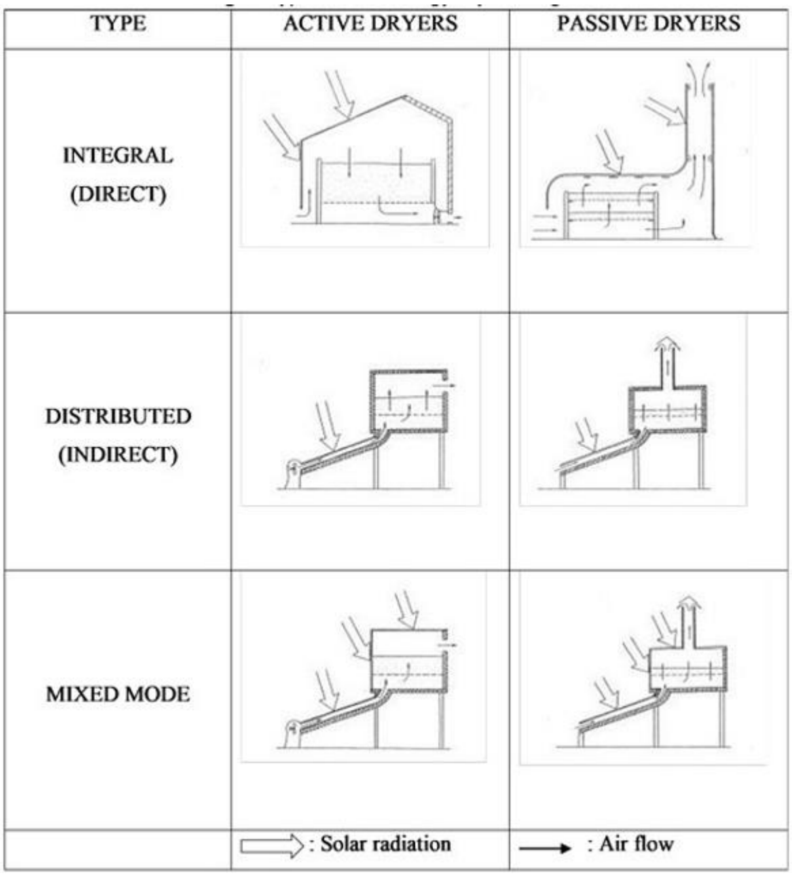


Fig. 1. Classification of solar-powered dryers

Active dryers use external means, such as fans or blowers, to move the heated air from the solar collector to the drying chamber. In contrast, passive dryers rely solely on the natural movement of heated air. Passive dryers are best suited for drying small batches of fruits and vegetables.

Applications of the solar dryer:
• Drying of agricultural crops.
• Food processing industries for dehydrating fruits and vegetables.
• Drying of fish and meat.
• Dairy industry for powdered milk production.
• Treatment of wood and lumber.
• Textile industries for drying fabrics, etc.

3. Methodology

3.1 Construction principles

The double-chamber solar dryer consists of a solar collector, which can also be referred to as an air heater, and a drying chamber that may, for example, contain three layers of trays on which the fruits are placed for drying. The trays in the drying chamber can be loaded with fruits estimated to weigh an average of 50 g per piece, with dimensions of 6 mm in length/width and 5 mm in thickness.
To measure the temperature inside the dryer, a digital thermometer can be used, and moisture loss is determined by weight loss, which is measured using an electronic scale.
For a double-chamber solar dryer, the basic principles are the greenhouse effect and natural convection (draft). The dryer should be placed outdoors with the collector oriented toward the sun. The collector is rigidly fixed to the dryer at an angle of 17.5° from the horizontal so that the beam of solar rays is approximately perpendicular to it.

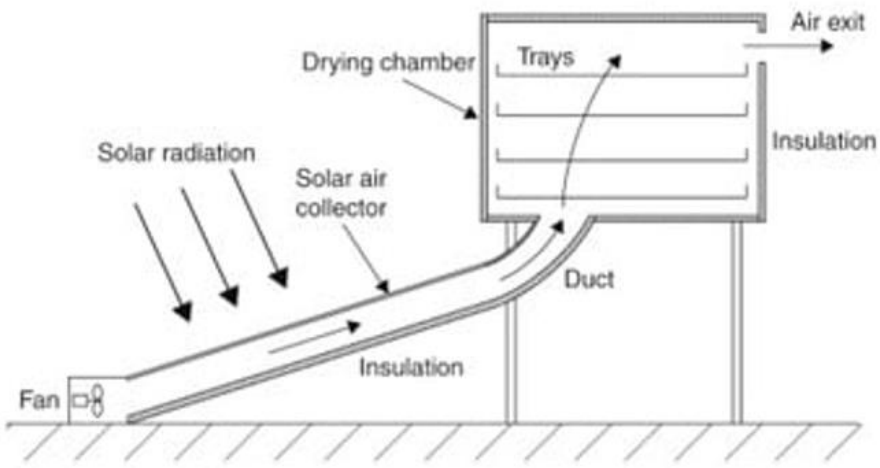


Fig. 2. Two-compartment dryer

3.2 Design principles

For the analysis of solar drying performance in the case of fruits, a simplified theoretical model was proposed, based on a solar dryer consisting of two compartments: a solar air collector and a drying chamber. The objective of the study was to estimate the volumetric airflow rate required to dry 1 kg of fresh product under ideal conditions, without significant thermal energy losses. The fruits analyzed in this study were: apple, pear, and banana.

3.2.1 Initial Data and Calculation Assumptions

A simplified example for calculating the volumetric airflow rate required to dry one kilogram of apples in a two-compartment solar dryer (solar collector + drying chamber) assumes the following data:

- Dried fruit: apple
- Quantity: 1 kg fresh apple
- Initial moisture content (w_1): ~85%
- Final moisture content (w_2): ~15%
- Relative moisture of inlet air: 30%
- Drying air temperature: 50°C
- Air density at 50°C: ~1.09 kg/m³

For each fruit, the following experimental data were used:

- Apple: initial moisture 85%, final moisture 15%
- Pear: initial moisture 86%, final moisture 15%
- Banana: initial moisture 75%, final moisture 15%

It is assumed that the dry air enters the drying chamber (at 50°C) with a moisture content of approximately 0.015 kg water/kg dry air, and at the outlet, the moisture content is ~0.035 kg water/kg dry air. The system efficiency is considered ideal (no heat loss), and the reference duration for complete drying is 1 hour.

3.2.2 Calculation of the amount of water to be removed

The amount of water that needs to be removed is determined by the difference between the initial and final moisture contents, relative to the total mass of the fruit. The formula used is:

$$m_{apa} = m_{fruct} \cdot \frac{w_1 - w_2}{100}$$

Where:
m_{fruct}= 1 kg
w_1 = initial moisture content (%)
w_2 = final moisture content (%)
Example for apple:

$$m_{apa} = 1 \cdot \frac{85 - 15}{100} = 0.7\ kg\ apa$$

3.2.3. Determination of the required dry air mass

Each kg of dry air can take in a quantity of water determined by the difference between the moisture content at the outlet and at the inlet:

$$\Delta x = x_{iesire} - x_{intrare} = 0.035 - 0.015 = 0.02 \frac{kg\ apa}{kg\ aer\ uscat}$$

Therefore, the air mass required for complete drying is:

$$m_{aer} = \frac{0.7}{0.02} = 35\ kg\ aer\ uscat$$

3.2.4. Volumetric airflow calculation

With the air density at the drying temperature (~1.09 kg/m³), the required volumetric airflow is determined by relating the air mass to the density:

$$V = \frac{m_{aer}}{\rho_{aer}} \frac{35}{1.09} \cong 32.1\ \frac{m^3}{h}$$

If this volume is needed for one hour of drying (the duration differs, but we use as an example):
Volumetric air flow = 32.1 m³/h for drying 1 kg of apple in one hour. Observations:

- If you have several layers in the drying room, the air must have sufficient speed and flow rate to penetrate the lower layers as well.
- Depending on the actual drying time, the flow rate adjusts. For example, if drying takes 4 hours, you need a flow rate of:

$$\frac{32.1}{4} = 8.025 \frac{m^3}{h}$$

- These steps can be integrated into a solar dryer sizing, including solar collector sizing (depending on the energy required to heat the air).

3.2.5. Observations on the comparative behaviour of fruits

The differences in internal composition and cell structure between the 3 types of fruits significantly influence the drying time and the efficiency of moisture transfer. We chose for example: apple, pear and banana and we represented a graphic model (fig. 3) that shows how the moisture decreases over time for apples, pears and bananas during drying in a solar dryer.

- The apple starts with a higher moisture (~85%) and reaches 15% in about 10 hours.
- The pear has a slightly slower pace, and
- The banana starts from lower moisture and dries faster.

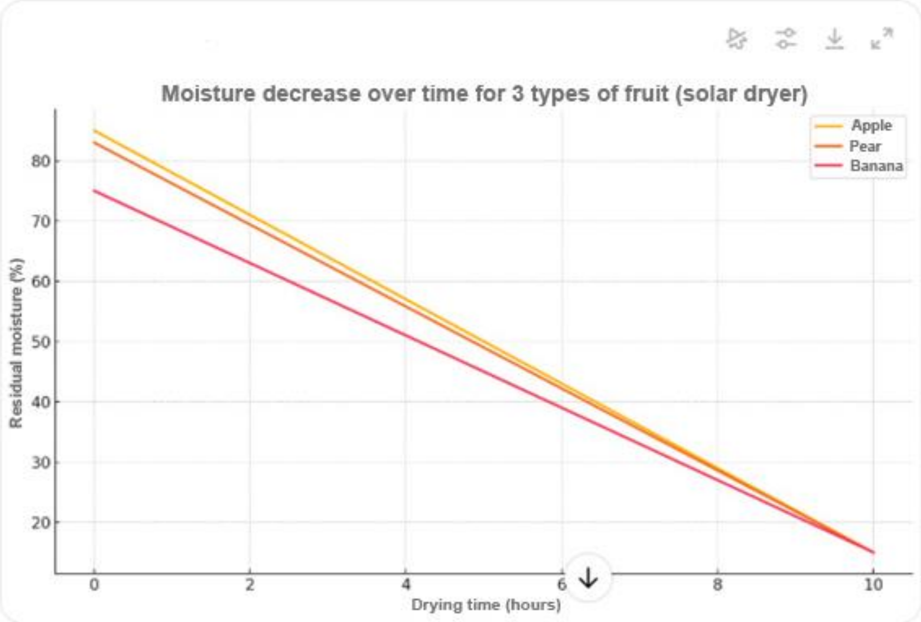
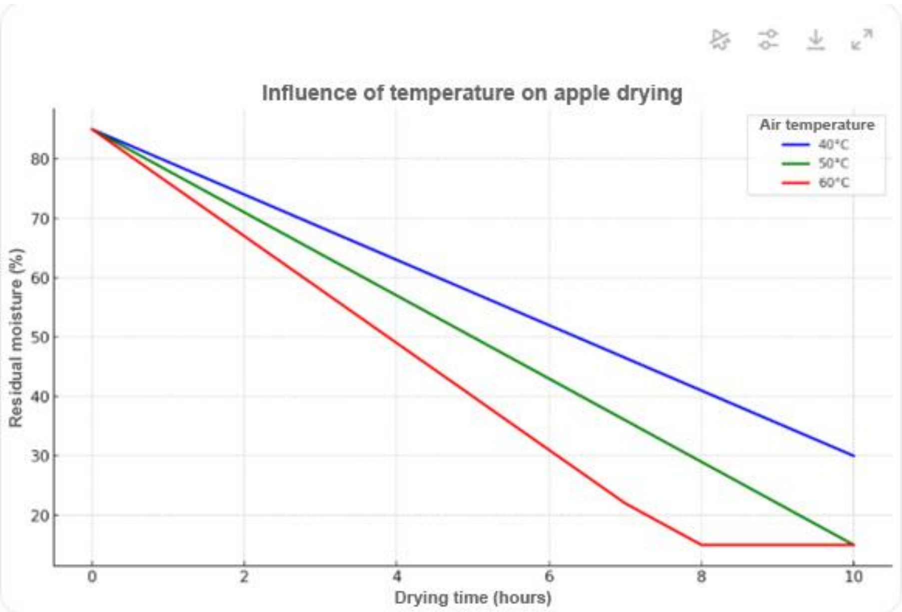
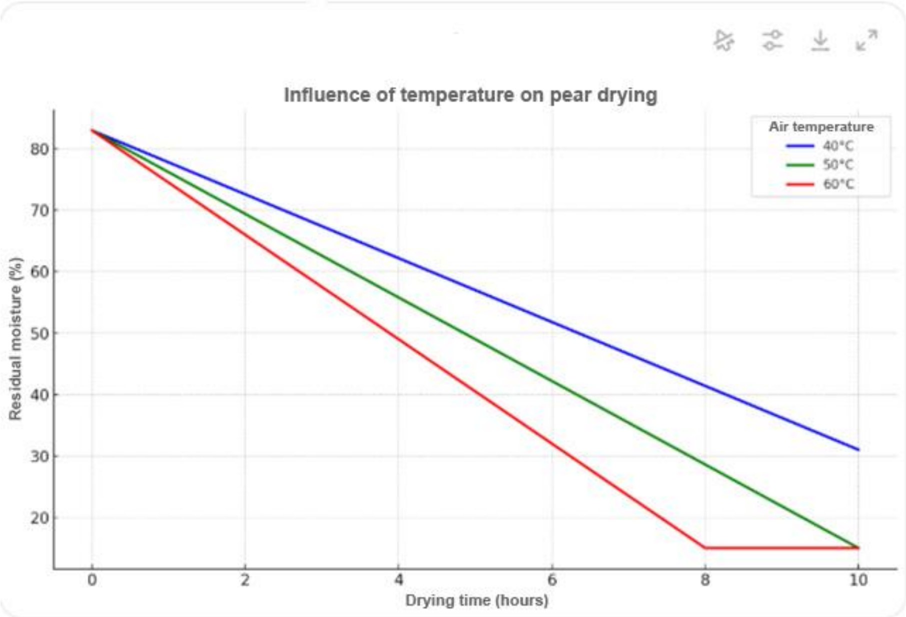


Fig. 3. Moisture decrease

We can extend the model and see how the drying air temperature influences the rate of moisture decrease for the 3 fruits, figure 4. Drying at three different temperatures is simulated: 400 C (slower); 500 C (medium, optimal for many fruits); 600 C (faster, but with a risk of caramelization of sugars).





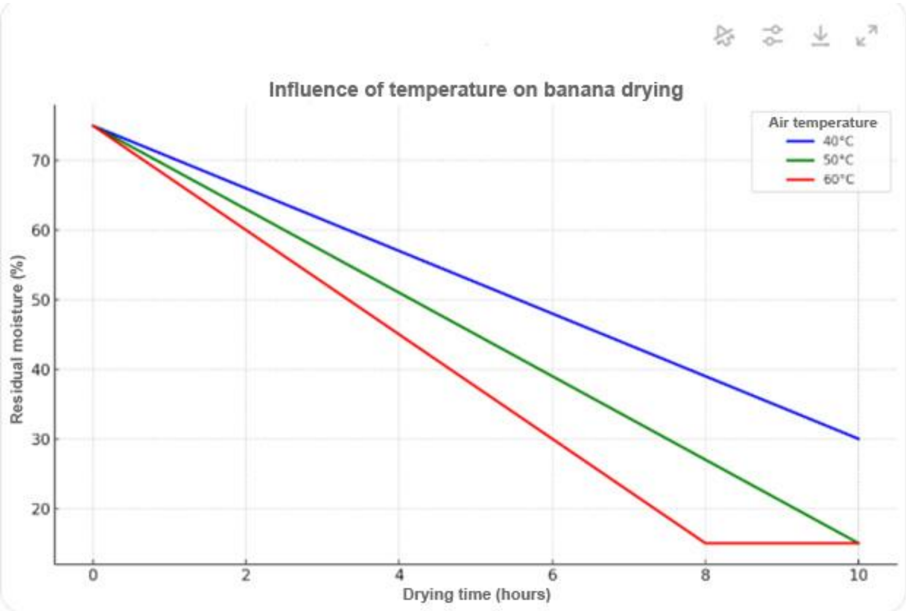


Fig. 4. Influence of temperature on fruit drying

As can be seen, the air temperature influences the drying process of the fruits, so that at 400 C - drying is slower after 10 hours, the moisture has not yet reached 15%; at 500 C – drying is efficient, the target moisture of ~ 15% is reached in about 10 hours; at 600 C – drying is faster, reaching the desired moisture even after 7-8 h, but with the risk of affecting the quality (oxidation, caramelization).

What we can say is that higher temperatures accelerate drying, but a balance must be found between drying speed and preserving fruit quality. Observing this, we must also analyze the influence of air velocity on the drying process.

We will consider a constant temperature—specifically 50°C—since it is regarded as optimal for fruit drying. We will focus only on apples and vary the drying air velocity, starting with 0.5 m/s, 1 m/s, and 1.5 m/s.

From the following graph, Figure 5, we can observe how increasing air velocity influences moisture transfer, accelerating the drying process. However, it should be noted that excessively high air velocities can lead to changes in flavor or texture (especially in soft fruits).

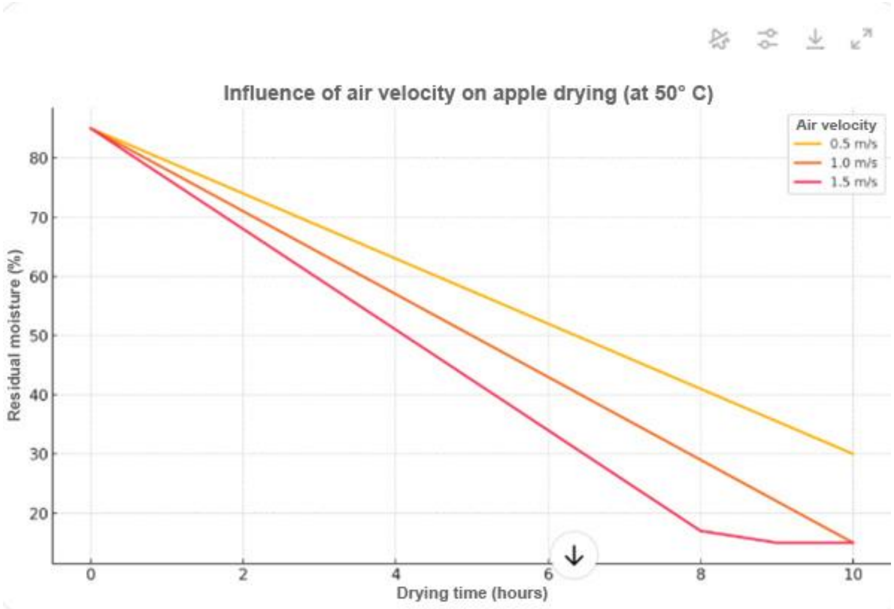


Fig. 5. The influence of air velocity on drying

3.2.6 Calculation of the thermal energy and the average power required for drying a kilogram of fruit (apple, pear, banana)

Let us make some common assumptions:

a. Drying time:

For apple: 10 hours
For pear: 10 hours
For banana: 8 hours

b. Moisture to be removed [18,19]**:**

For apple: 0.7 kg of water (from 85% to 15%)
For pear: 0.68 kg of water (from 83% to 15%)
For banana: 0.6 kg of water (from 75% to 15%)

c. Latent heat of vaporization: LV = 2300 kJ/kg

d. Efficiency of the solar dryer: η = 50% [20]

Based on these common assumptions, we calculate the required energy ($Q = \frac{m_{apa} \cdot L_v}{\eta}$) [21]

For apple $Q = \frac{0.7 \cdot 2300}{0.5} = 3220kJ \approx 0.894kWh$

For pear $Q = \frac{0.68 \cdot 2300}{0.5} = 3128kJ \approx 0.869kWh$

For banana $Q = \frac{0.6 \cdot 2300}{0.5} = 2760kJ \approx 0.767kWh$

After this calculation of the energy we can estimate the average power that is given by the energy divided by the duration of drying, thus we obtain:

For apple (10h): $P = \frac{0.894}{10} = 0.0894kW = 89.4W$

For pear (10h): $P = \frac{0.869}{10} = 0.0869kW = 86.9W$

For banana (8 h): $P = \frac{0.767}{8} = 0.0959kW = 95.9\,W$

As a summary of the estimate we have:

Fruits	Water removed (kg)	Energy (kWh)	Time (h)	Medium power (W)
Apple	0.7	0.894	10	89.4
Pear	0.68	0.869	10	86.9
Banana	0.6	0.767	8	95.9

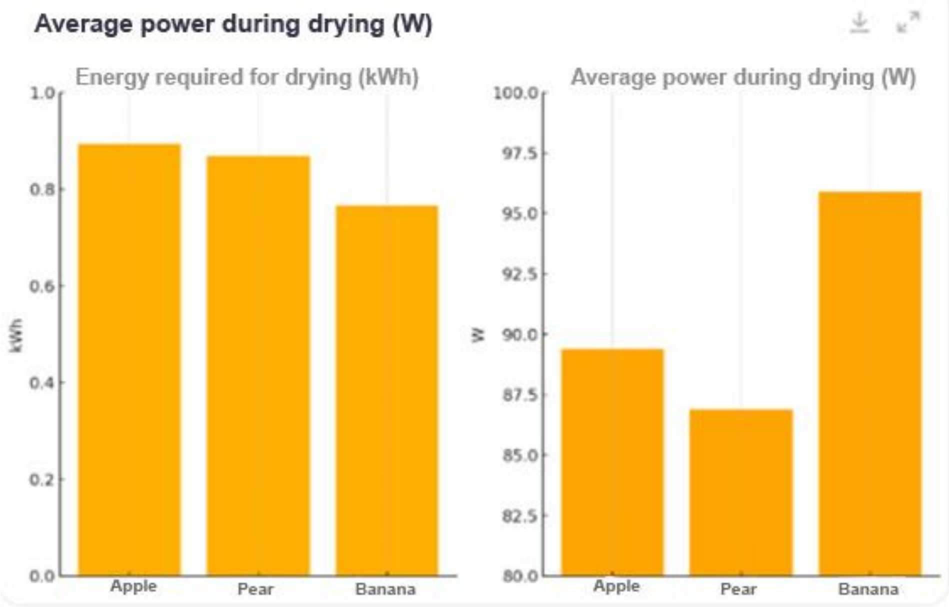


Fig. 6. Average power during drying

An interesting conclusion that results from these calculations and graphs is that bananas, although they require less total energy, having a shorter drying time, need a higher average power during drying

4. Conclusions

The use of solar drying for fruits, vegetables, and other crops holds considerable potential, not only from the perspective of energy savings but also in terms of maintaining product quality. Two main categories of solar dryers can be distinguished: passive dryers (with natural circulation) and those with forced convection. These are further divided into four functional subtypes – direct, indirect, mixed, and hybrid dryers – differentiated by the method of solar energy capture and use, as well as by the architecture of the drying system.

A general estimate from the literature suggests that drying one kilogram of fruit with a moisture content of approximately 80% would require around 250 W of thermal energy and an airflow rate of about 62 m^3/h. However, experimental data obtained using a simplified model of a two-compartment solar dryer (collector + drying chamber) shows that these values can be significantly optimized. In an idealized yet realistic scenario, drying 1 kg of apples with an initial moisture content of 85% and a final moisture content of 15%, at a constant temperature of 50°C and an inlet air relative moisture of 30%, required an airflow rate of only ~32.1 m^3/h and the removal of 0.7 kg of water. The calculation assumed a hygrometric content of air ranging from 0.015 at the inlet to 0.035 kg water/kg dry air at the outlet. The air density used in the simulation was 1.09 kg/m^3, specific to the drying temperature.

These results demonstrate that, in an efficiently designed and well-insulated system, both the energy and airflow requirements can be significantly reduced, contributing to the sustainability of the process. Moreover, the drying behavior of fruits varies depending on their internal structure and water content. In the experiments conducted, it was observed that apples (with a high water content) required approximately 10 hours to reach the desired final moisture level, while bananas, with a lower initial moisture content (~75%), dried more quickly. Pears showed a slower drying rate, indicating higher diffusional resistance in the final stages of the process.

The performance of solar dryers can be significantly improved by reducing heat losses, optimizing air circulation, and precisely controlling operating parameters (temperature, moisture, and airflow). Integrating thermal storage systems and using real-time meteorological data would allow the dryer to dynamically adapt to local climatic conditions. Thus, farmers or small-scale producers can achieve a more efficient, predictable, and regionally adapted drying process, while also reducing conventional energy consumption.

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Reference

[1] Ahmad, Maqbool, J.C. Hauser, C. Heijnen, and M.A. Chaudry. "Solar drying of fruits and vegetables." *Pakistan Journal of Agriculture Research* 17, no. 3 (2002): 237-244.
[2] Silveira, Semida. "The Solar Economy: Renewable Energy for a Sustainable Global Future: Hermann Scheer, Earthscan Publications Ltd., UK, 2002, 367 pp., £17.99, ISBN I-85383-8357." Book review. *Climate Policy* 3, no. 4 (December 2003): 467-469.
[3] Fortunatus, R., R. Marealle, N. Nenguwo, and T. Stoilova. *Solar Dryers*. *Principles and Basics.* World Vegetable Center. Shanhua, Taiwan. Publication 17-827, 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. 10.1080/07373930701438931.
[5] El Hage, H., A. Herez, M. Ramadan, H. Bazzi, and M. Khaled. "An investigation on solar drying: A review with economic and environmental assessment." *Energy* 157 (August 2018): 815-829. 10.1016/j.energy.2018.05.197.
[6] Chavan, U., V. Vitankar, A. Mujumdar, and N. Thorat. "Natural convection and direct type (NCDT) solar dryers: a review." *Drying Technology* 39, no. 13 (2021): 1969-1990. 10.1080/07373937.2020.1753065.
[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. 10.1016/j.solener.2020.07.098.
[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. 10.1016/j.solener.2017.11.032.
[9] Moses, J.A., D.S. Jayas, and K. Alagusundaram. "Resistance to Airflow through Bulk Grains, Oilseeds and Other Agricultural Products – A Review." *Journal of Agricultural Engineering (India)* 50, no. 4 (2013): 1-13. 10.52151/jae2013504.1526.
[10] El Khadraoui, A., I. Hamdi, S. Kooli, and A. Guizani. "Drying of red pepper slices in a greenhouse solar dryer and under open sun: Experimental and mathematical investigations." *Innovative Food Science & Emerging Technologies* 52 (March 2019): 262-270. 10.1016/j.ifset.2019.01.001.
[11] Chaouch, W.B., A. Khellaf, A. Mediani, M.E.A. Slimani, A. Loumani, and A. Hamid. Experimental investigation of an active direct and indirect solar dryer with sensible heat storage for camel meat drying in Saharan environment." *Solar Energy* 174 (November 2018): 328-341. 10.1016/j.solener.2018.09.037.
[12] Sarsavadia, P.N. "Development of a solar-assisted dryer and evaluation of energy requirement for the drying of onion." *Renewable Energy* 32, no. 15 (2007): 2529-2547. 10.1016/j.renene.2006.12.019.
[13] Koçak, B., A.I. Fernandez, and H. Paksoy. "Review on sensible thermal energy storage for industrial solar applications and sustainability aspects." *Solar Energy* 209 (October 2020): 135-169. 10.1016/j.solener.2020.08.081.
[14] Jain, D., and P. Tewari. "Performance of indirect through pass natural convective solar crop dryer with phase change thermal energy storage." *Renewable Energy* 80 (August 2015): 244-250. 10.1016/j.renene.2015.02.012.
[15] Pankaew, P., O. Aumporn, S. Janjai, S. Pattarapanitchai, M. Sangsan, and B.K. Bala. "Performance of a large-scale greenhouse solar dryer integrated with phase change material thermal storage system for drying of chili." *International Journal of Green Energy* 17, no. 11 (2020): 632-643. 10.1080/15435075.2020.1779074.
[16] Singh, D., and P. Mall. "Experimental investigation of thermal performance of indirect mode solar dryer with phase change material for banana slices." *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 46, no. 1 (2020): 15268-15285. 10.1080/15567036.2020.1810825.
[17] Swami, V.M., A.T. Autee, A. T R. "Experimental analysis of solar fish dryer using phase change material." *Journal of Energy Storage* 20 (December 2018): 310-315. 10.1016/j.est.2018.09.016.
[18] Ratti, C. "Hot air and freeze-drying of high-value foods: a review." *Journal of Food Engineering* 49, no. 4 (2001): 311-319. 10.1016/S0260-8774(00)00228-4.
[19] Esper, A., and W. Mühlbauer. "Solar drying – an effective means of food preservation." *Renewable Energy* 15, no. 1–4 (1998): 95–100.
[20] Ekechukwu, O. V., and B. Norton. "Review of solar-energy drying systems II: an overview of solar drying technology." *Energy Conversion and Management* 40, no. 6 (April 1999): 615-655.
[21] Heldman, D.R., and D.B. Lund (eds.). *Handbook of Food Engineering*. 2nd edition. Boca Raton, CRC Press, 2006.