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# Experimental Comparison of Open Sun and Indirect Convection Solar Drying Methods for Apricots in Uzbekistan †

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**Abstract:** Solar drying is an environmentally friendly and sustainable approach to preserve agricultural products, particularly in regions with abundant sunlight. In terms of apricot cultivation, the implementation of solar drying methods can significantly impact post-harvest handling and storage. In the conditions of Uzbekistan, the drying of apricot products in indirect solar dryers is the next stage of development. This research aims to investigate the effectiveness of solar drying techniques for apricots in Uzbekistan, focusing on optimizing drying parameters and assessing the quality of the dried products. This study involves the design and implementation of solar drying systems for apricots. It primarily focuses on comparing and evaluating the drying times of apricots, changes in product moisture, and alterations in apricot color during the drying process using an Open Sun Dryer (OSD) and an Indirect Natural Convection Solar Dryer (INCSD). Various drying parameters such as the temperature, humidity, and drying time are monitored and controlled during the experiment. Additionally, the quality of the dried apricots is evaluated through analyses of their color, texture, and nutrient retention. According to the results, when apricots were dried in a solar dryer at 55 °C and with 35% humidity outside, their moisture content decreased from 85–90% to 12–18% within 15 h. The solar radiation intensity and ambient temperature play a crucial role in the acceleration of the time in the drying process. In general, utilizing equipment-based solar drying methods for apricots in Uzbekistan has the potential to rival traditional drying systems in terms of both quality and drying duration.

**Keywords:** fruit drying; apricot; solar dryer; solar radiation

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## 1. Introduction

Apricots, recognized for their vibrant gold-orange hue, sweet taste, and velvety skins, are a highly nutritious fruit and cherished worldwide. Serving as a significant cash crop for numerous countries, apricots hold substantial agricultural and economic importance globally [1,2]. Uzbekistan is recognized as one of the world's leading producers of apricots. As of 2023, Uzbekistan produced 424.734 t of apricots [3]. This production level positions Uzbekistan as the second largest apricot producer globally, following Turkey. The country's apricots, renowned for their distinctive taste and high quality, are highly esteemed in the global market. The diverse climatic conditions and regional variations within Uzbekistan facilitate the cultivation of various apricot varieties, establishing the nation as a key contributor to the global apricot production and export [4].

Certainly, while the climate and growing conditions stand as primary determinants in identifying leading apricot producers, several additional factors significantly contribute to this distinction. For instance, the availability of water resources is essential, notwithstanding the preference of apricot trees for drier, sunnier climates. Adequate irrigation practices are crucial to ensure optimal growth and yield. Moreover, although apricot trees are generally self-pollinating, the presence of abundant pollinators, particularly bees, is instrumental in enhancing fruit quality and overall production volume. Additionally, a country's cultivar variety plays a pivotal role in its ability to offer diverse apricot options, thus potentially influencing its competitive edge in the global market [5,6].

To ensure the year-round availability of agricultural products such as vegetables, fruits, and grains, drying is increasingly gaining importance. By adjusting the water activity levels of these foods during the drying process, it becomes feasible to store them for extended periods without spoilage. In the food industry, drying serves primarily to preserve fruits and vegetables while retaining their nutritional integrity over time. The efficacy of the drying process is gauged based on the preserved color, aroma, flavor, nutritional content, and original shape of the dried product [7,8]. Additionally, the product's ability to rehydrate, restoring its moisture content when exposed to a humid environment, is another crucial aspect [9].

Drying serves as a method to decrease the moisture content of fresh fruits and vegetables, typically ranging from 80% to 95%. To ensure safe storage, it is essential to reduce the final moisture content of fruits to below 20% and vegetables to below 10% [10]. In the drying of agricultural products, the use of traditional energy sources such as coal, oil, and gas has been shown to have various negative environmental impacts [11]. These sources contribute to air and water pollution, pose risks to public health, threaten wildlife, and exacerbate global warming. Additionally, the high operational costs of dryers that rely on fossil fuels present ongoing economic challenges for farmers. In developing countries, the lack of resources for electrical grids further complicates energy supply issues for farmers in certain rural areas [12–14].

Scientists recognize the use of solar energy as a clean and renewable energy source and an important and effective solution for drying agricultural products [15]. There are various types of solar dryers, each distinguished by a sophisticated design that typically includes a solar collector for harnessing solar energy and a drying chamber where the heated air interacts with the products being dried. In some configurations, the solar collector and drying chamber are integrated into a single unit, while in other designs, these components are separately constructed. Regardless of the specific type of solar dryer employed, the products being dried are completely insulated from external environmental factors, ensuring that the drying process occurs in a controlled, enclosed environment [16,17].

This drying process helps preserve the dried product for extended periods without spoilage. The purpose of drying food is to remove the free water from the wet products and to stop the growth of biochemical reactions and micro-organisms in the products. Additionally, drying facilitates a reduction in both the volume and weight of the products, resulting in decreased transportation and storage expenses [18–24].

The proposed INCSD dryer demonstrated the ability to reduce energy consumption, as noted in the literature [14,25]. This dryer is utilized for drying fruits and various other agricultural products. This study aims to compare drying times and examine the effects of climatic conditions, such as temperature and humidity, on the quality of the dried product. The focus is specifically on regions situated at moderate elevations above sea level. Additionally, this study seeks to observe the drying times of apricots using both OSD and INCSD dryers, as well as changes in the product's moisture content and alterations in the apricots' color characteristics during the drying process.

## 2. Materials and Methods

In this study, an experimental method was employed to evaluate the effectiveness of different solar drying techniques for apricot preservation. Controlled experiments were conducted to measure key parameters such as the drying rate, moisture content, and inlet and outlet temperature of drying equipment under varying conditions. The results were analyzed to determine and compare the optimal drying method, including direct and indirect sun dryers, for achieving high-quality dried apricots in Uzbekistan.

The fresh Subhani apricots used in this study were procured from the Chorsu market in Tashkent during harvest season. The apricots, weighing between 45 and 55 g, were carefully sorted and washed with water. These selected apricots were then halved for the experiments. For each experiment type (OSD and INCSD), 500 ± 2 g of apricots was weighed and placed on trays for the INCSD device and on a flat surface plate for the OSD. The trays were placed in the drying chamber of the INCSD device, while the plate for the OSD experiment was positioned near the device and directly exposed to sunlight. The apricots were weighed using a digital scale (SF-400). The initial and final moisture contents of the drying product were measured using a moisture analyzer (DBS60-3). The drying process was performed utilizing the dryers illustrated in Figure 1. The experiments were conducted from 27 June to 28 June 2024 in the courtyard of the Tashkent Chemical Technology Institute.

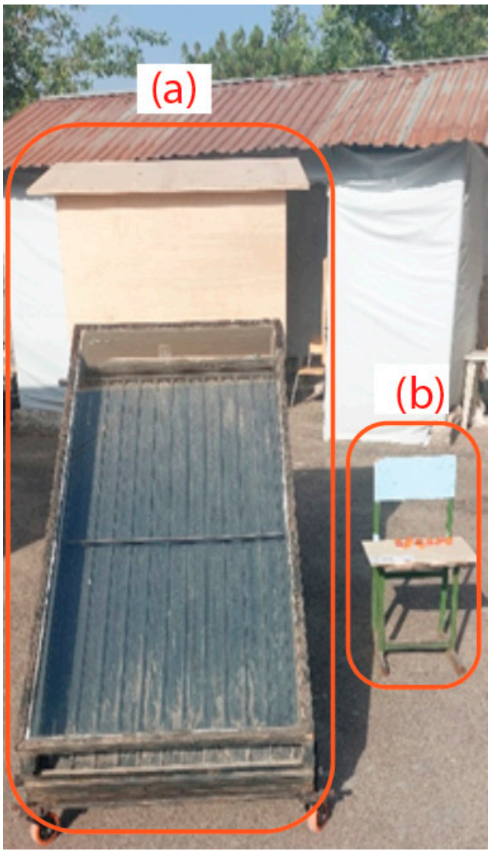


**Figure 1.** Appearance of the INCSD (**a**) and OSD (**b**) dryers.

### *2.1. Natural Convection Solar Dryer*

Due to Uzbekistan's relatively southern latitude, the solar radiation during summer is more direct and persists for extended periods. In Tashkent, the sun provides an average of 2.900 h of sunlight annually. In contrast, in the southern city of Karshi, this is 3.100 h. Throughout the year, particularly during the summer months, the weather in Uzbekistan is predominantly clear with minimal cloud cover. Consequently, during the growing season from May to October, which is crucial for agricultural crops, Tashkent receives 1.749 h of sunlight, while Karshi benefits from 2.012 h. Uzbekistan has over 320 days of sunshine each year, with an average annual solar irradiation ranging from 1400 to 1800 kWh/m$^2$. This abundant solar resource presents a significant opportunity for solar energy utilization in the country [26,27].

A natural convection solar dryer is composed of a solar air heater and a drying chamber. The solar air heater features a flat glass plate with a surface area of 1.71 m$^2$ and dimensions of 1.9 × 0.9 × 0.2 m. The interior surface of the heater is coated with black paint to maximize the absorption of solar radiation. The drying chamber is constructed from 2 mm thick mild steel and measures 0.7 × 0.9 × 0.5 m in width, depth, and height. The interior of the drying chamber is fully insulated with 6 mm wood panels to maintain optimal drying conditions. The drying equipment is designed to handle a capacity of up to 5 kg of apricots per day.

Sunlight passes through the transparent glass cover, heating the air beneath it. This heated air then flows into the drying chamber. The solar air heater is positioned at a 30° angle to the horizon, which is the optimal angle for year-round operation in Uzbekistan. It is oriented to the south to maximize exposure to solar radiation.

A digital thermometer–hygrometer HTC-2 was employed to measure the air temperature and humidity within the system. This combined device includes a clock, alarm mode, and memory function to record the last maximum and minimum values of temperature and humidity. All readings are displayed in large characters on a prominent LCD screen. The HTC-2 is powered by a single 1.5 V AAA battery, which is included with the thermohydrometers. A natural convection solar dryer is shown in Figure 2b.

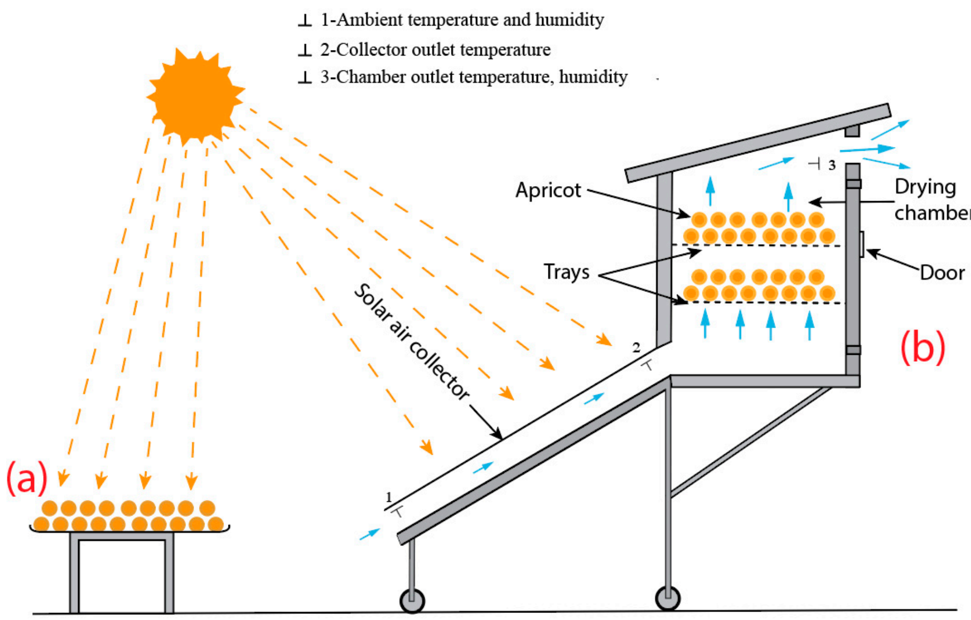


**Figure 2.** Schematic view of OSD (**a**) and INCSD (**b**) devices.

### *2.2. Drying in the Open Sun*

The OSD experiment was conducted at the end of June, similar to the INCSD experiment, on sunny days from 9:00 A.M. to 6:00 P.M. During these times, the ambient temperature ranged from 34 to 45.7 °C, the air humidity varied from 15 to 32%, and the average air speed was 8 km/h. For this experiment, 500 g of halved apricots was placed in a pan with internal dimensions of 500 × 25 mm. These apricots were dried under direct sunlight simultaneously with the sample in the INCSD device, allowing for a comparative analysis of the drying methods.

## **3. Result and Discussion**

Figure 3 illustrates the changes in ambient temperature and the temperature at the collector outlet, corresponding with the variations in solar radiation intensity. The experiment on Day 1 began at 11:00 A.M. and concluded at 6:00 P.M. During this period, the maximum ambient temperature reached 45.7 °C at 1:00 P.M., while the collector outlet temperature peaked at 67.7 °C. These data indicate that on the first day of the experiment, the apricot product lost approximately 50% of its moisture. On Day 2, which was slightly cooler, the ambient temperature at midday was 42.1 °C, and the collector outlet temperature was

55.3 °C. Observations from the experiment showed that the drying of apricots was slower on the second day when they were dried in the open air.

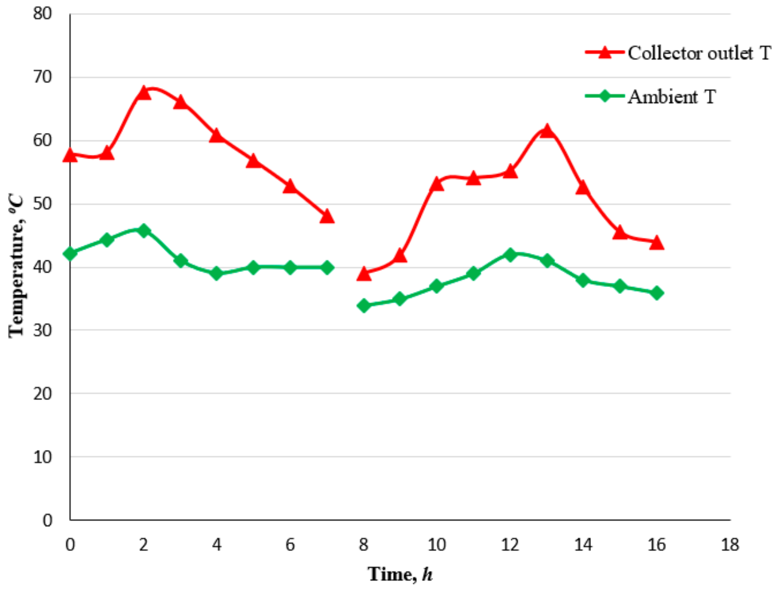


**Figure 3.** Variation in ambient temperature and air temperature in the solar air heater in relation to drying time.

The experiment lasted for 7 h on the first day and 8 h on the second day. Figure 4 shows the changes in the moisture content of the apricot products. On the first day, the moisture content of the apricots dried in the INCSD dryer decreased from 84% to 48%, while the moisture content of those dried using the OSD method decreased to 62%. On the second day, the drying process was slower due to slightly higher humidity levels. Specifically, the OSD method had a significant impact on the apricots, reducing their moisture content from 55% to 35%. In contrast, the moisture content of the apricots dried in the INCSD dryer decreased from 45% to 18%. Overall, the experiment was conducted for a total of 15 h during sunny periods.

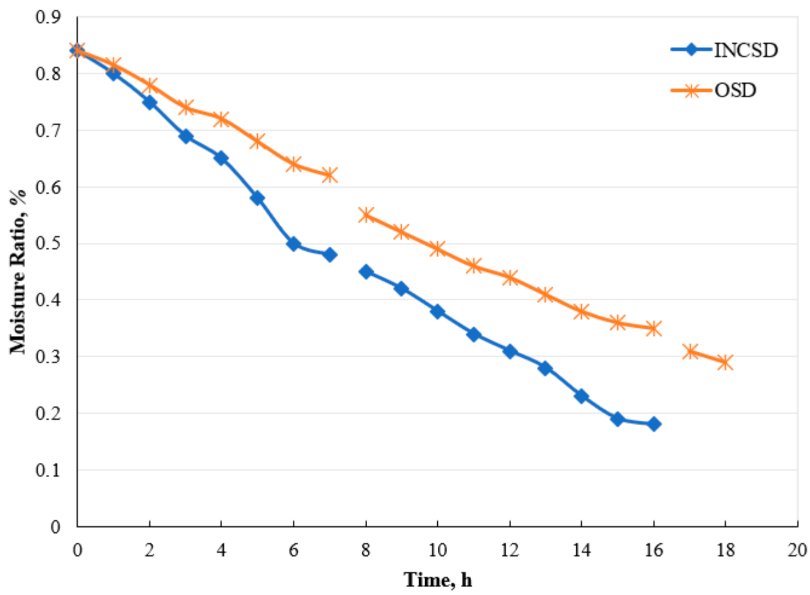


**Figure 4.** Graph depicting the change in product moisture over time.

Table 1 displays the drying data for apricots using two different methods: INCSD and OSD. Essential parameters such as apricot mass, collector outlet temperature, chamber outlet temperature, ambient humidity, and ambient temperature were recorded every hour.

**Table 1.** Overview of the experimental data collected over two days.

| **Day** | **27 July 2024** | | | | | | | | **28 July 2024** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Time** | **11:00** | **12:00** | **13:00** | **14:00** | **15:00** | **16:00** | **17:00** | **18:00** | **9:00** | **10:00** | **11:00** | **12:00** | **13:00** | **14:00** | **15:00** | **16:00** | **17:00** |
| INCSD (g) | 500 | 400 | 320 | 258 | 228 | 190 | 160 | 153 | 145 | 137 | 129 | 121 | 115 | 111 | 103 | 98 | 97 |
| OSD (g) | 500 | 432 | 364 | 308 | 286 | 250 | 222 | 210 | 178 | 167 | 157 | 148 | 143 | 135 | 129 | 125 | 123 |
| Collector outlet temperature (°C) | 57.8 | 58.2 | 67.7 | 66.1 | 60.9 | 56.9 | 52.8 | 48.1 | 39.1 | 42 | 53.2 | 54.1 | 55.3 | 61.6 | 52.6 | 45.6 | 44 |
| Chamber outlet temperature (°C) | 45 | 48.1 | 50.4 | 52.3 | 47.6 | 52.1 | 50.2 | 46.3 | 35.4 | 38.7 | 40 | 44 | 46.3 | 51.8 | 48.3 | 44 | 41.8 |
| Ambient humidity (%) | 20 | 18 | 17 | 17 | 17 | 17 | 16 | 15 | 28 | 27 | 32 | 19 | 21 | 24 | 17 | 17 | 16 |
| Ambient temperature (°C) | 42.2 | 44.3 | 45.7 | 41.1 | 39.1 | 40.3 | 40.2 | 40 | 34.4 | 35.6 | 37.3 | 39.5 | 42.1 | 41.0 | 37.8 | 37.6 | 36 |

*Day 1:*

- INCSD: The initial mass of the apricots was 500 g, which decreased to 153 g by the end of the day, indicating significant moisture loss.
- OSD: Starting at 500 g, the mass dropped to 210 g by 6:00 P.M., showing a slower drying rate compared to INCSD.

The collector outlet temperature ranged from 57.8 °C to a peak of 67.7 °C at 1:00 P.M., before gradually decreasing to 48.1 °C by 6:00 P.M. This high temperature facilitated efficient drying in the INCSD method. The temperature inside the drying chamber started at 45 °C, peaking at 52.3 °C at 2:00 P.M., and then decreased to 46.3 °C by the end of the drying period. This consistent temperature range supported effective moisture removal. The ambient humidity was relatively stable, starting at 20% and slightly decreasing to 15% by 6:00 P.M. Lower humidity levels contributed to the drying process by enhancing moisture evaporation. The ambient temperature began at 42.2 °C, reached its highest at 45.7 °C at 1:00 P.M., and then gradually declined to 40 °C by the end of the day. High ambient temperatures complemented the solar drying process.

*Day 2:*

- INCSD: The mass started at 145 g and decreased to 97 g by 5:00 PM, indicating continued drying efficiency.
- OSD: The mass reduced from 178 g to 123 g, showing a slower drying rate compared to INCSD.

The collector outlet temperature ranged from 39.1 °C in the morning to peaking at 61.6 °C at 2:00 P.M., and then dropping to 44 °C by 5:00 P.M., showing significant variance due to fluctuating solar radiation. The chamber outlet temperature started at 35.4 °C, peaked at 51.8 °C at 2:00 PM, and then decreased to 41.8 °C by 5:00 P.M., maintaining a conducive environment for drying. Humidity levels started at 28% and decreased to 16% by the end of the day, positively influencing the drying rate. The ambient temperature began at 34.4 °C, reached a maximum of 42.1 °C at 1:00 P.M., and then decreased to 36 °C by 5:00 P.M. Lower temperatures compared to Day 1 led to a slightly reduced drying efficiency.

The Subhani apricot variety is the most commonly prepared apricot in Uzbekistan. In Figure 5a, a fresh apricot of the Subhani variety was taken, and the split apricots were labeled as shown in Figure 5b. These apricots were then dried using the INCSD and OSD methods. At the end of the experiment, the apricots dried using the INCSD method are shown in Figure 5c, while the apricots dried using the OSD method are shown in Figure 5d.

From these results, it can be concluded that the apricots that were dried using the OSD method retained more moisture and exhibited a more significant color change due to direct sunlight. In contrast, the apricots dried using the INCSD method were better preserved.

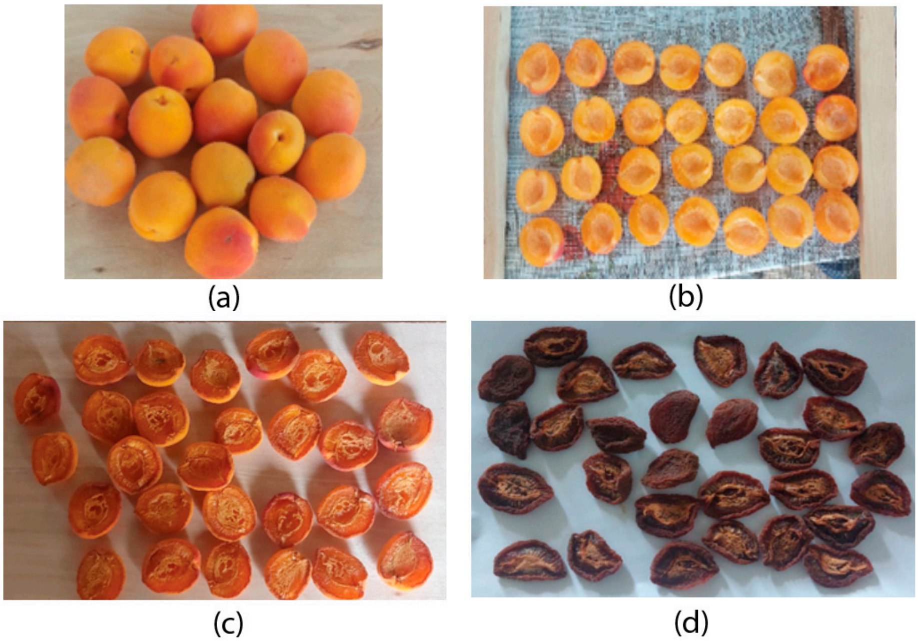


**Figure 5.** Preparation of samples and color comparison of dried products from INCSD and OSD dryers: fresh (**a**), sliced (**b**), and dried apricots in INCSD (**c**) and in OSD (**d**).

## 4. Conclusions

This study evaluates the drying efficiency and product quality of the OSD and INCSD methods. The INCSD method proved significantly more effective in reducing apricots' moisture content and preserving color compared to the OSD method. Over two days, the apricots dried using INCSD showed greater reductions in mass and moisture content.

The INCSD dryer maintained higher and consistent temperatures, facilitating efficient moisture removal and faster drying times. Its controlled environment minimized direct sunlight exposure, preserving the apricots' color and quality. Climatic conditions, such as ambient temperature and humidity, influenced the drying process. The INCSD method excelled in managing these conditions for optimal performance.

Overall, this study highlights the advantages of using INCSD for drying apricots, especially in regions with similar climates to Uzbekistan. The findings suggest that INCSD is a viable solution for reducing energy consumption and improving the quality of dried agricultural products, contributing to sustainable agricultural practices.

Moreover, there is substantial potential for the integration of solar dryers with photovoltaic modules to further enhance the drying efficiency. Future research should focus on the development and application of simulation models to optimize the design and structure of these integrated systems in the case of Uzbekistan. Optimizing the operation of solar dryers is crucial to maximizing their efficiency. Existing research has demonstrated a high degree of accuracy in predicting the performance of solar dryers across various conditions. Additionally, it is imperative to assess the potential for solar dryer deployment across different regions of Uzbekistan and to develop advanced control algorithms that can enhance their operational performance. Such advancements would ensure the widespread and effective adoption of solar drying technologies, supporting sustainable development goals in agriculture.

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**Conflicts of Interest:** The authors declare no conflicts of interest.

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