sustainability

MDPI

Article

Techno-Economic Analysis of Integrated Solar Photovoltaic Winnower-Cum Dryer for Drying Date Palm Fruit

Surendra Poonia [1], Anil Kumar Singh [1], Dilip Jain [1], Nallapaneni Manoj Kumar [2,3,*] and Digvijay Singh [4]

[1] Division of Agricultural Engineering and Renewable Energy, ICAR—Central Arid Zone Research Institute, Jodhpur 342003, Rajasthan, India
[2] School of Energy and Environment, City University of Hong Kong, Kowloon, Hong Kong
[3] Center for Circular Supplies, HICCER–Hariterde International Council of Circular Economy Research, Palakkad 678631, Kerala, India
[4] Center of Excellence for Energy and Eco-Sustainability Research, Uttaranchal University, Dehradun 248007, Uttarakhand, India
* Correspondence: mnallapan2-c@my.cityu.edu.hk or nallapanenichow@gmail.com

Abstract: Date palm (*Phoenix dactylifera* L.) fruits are widely grown in rural areas of arid Rajasthan of India. The grown date palm fruits are generally dried in forced convection mode. However, given the socio-economic status of farmers, dryer facility affordability has become crucial. Additionally, there is a critical need for a simple winnower, especially with its operation. To address the highlighted issues with the dryer and winnower and given a location already receiving abundant solar radiation, a solar photovoltaic (PV) winnower cum-dryer was designed and developed. The developed winnower cum-dryer was tested in actual conditions to realize the performance. First, the drying experiment for dehydrating date palm fruits and, second, the winnower experiment for separating grains from straw were carried out. The date palm fruits used for experimentation have a moisture content of 65% on a wet basis. During the drying trial, the dryer reduced this moisture content by 39% in 6 days. In contrast, in the open sun drying, it took 8 days. The drying chamber's temperature gradient was reduced to 2–3 °C from 6–8 °C in the system provided with a preheater, resulting in uniform drying. The observed effective moisture diffusivity and the dryer's efficiency are 4.34×10^{-9} $m^2 \cdot s^{-1}$ and 16.1%, respectively. A high IRR of 57.4% and a shorter payback period of 2.10 years were found in the economic analysis, indicating that the dryer is cost-effective. The winnower operation results suggest that about 200–300 kg grains could be separated daily when used as a winnower without natural wind. Overall, the developed winnower cum-dryer produced better-quality dried date palms in a shorter time than open drying by efficiently using solar energy and separating the grains from straw to enhance the utility throughout the year.

Keywords: *Phoenix dactylifera* L.; date palm drying; solar dryer; PV winnower; economic evaluation; hybrid solar dryer

check for updates

Citation: Poonia, S.; Singh, A.K.; Jain, D.; Kumar, N.M.; Singh, D. Techno-Economic Analysis of Integrated Solar Photovoltaic Winnower-Cum Dryer for Drying Date Palm Fruit. *Sustainability* **2022**, *14*, 13686. https://doi.org/10.3390/su142013686

Academic Editor: Muhammad Ikram

Received: 30 September 2022
Accepted: 20 October 2022
Published: 21 October 2022

1. Introduction

Date palm (*Phoenix dactylifera* L.) is one of the first fruit trees in the world to be grown and the only crop capable of withstanding high temperatures and low humidity levels throughout the bearing stage. This fruit crop is significantly grown in most arid regions of the planet. Regarding nutritional value, due to its high sugar content, the date palm fruit is considered a high-energy food (300 calories/100 g), is low in fat, and is an excellent source of iodine, iron, calcium, and potassium [1–3]. In Indian conditions, among the date palm cultivars, Khadrawy is one of the critical cultivars grown commercially, mainly in the country's northwestern region. Once this fruit is transformed into chuhara (dry) form, it is excellent for ingestion. The primary issue with the dates grown in this area is that their maturation period falls in June, just before the monsoon season begins. Date fruits that have been exposed to rain develop fruit rot and deterioration, rendering them unfit for consumption as fresh dates. According to statistics, heavy rains cause up to 60% of the dates to rot. To avoid spoiling, dates are therefore picked early and sold before the rainy season. Given the aforementioned information, it is imperative to close the gap using some effective, realistic, and useful methods. Therefore, turning these immature dates into goods with the extra value could increase marketability [4,5]. Drying is the option mostly used by farmers to remove the moisture present in date palms, which is conventional. It is recommended to avoid traditional drying, as it has several detrimental consequences on plant materials, including shrinkage, discoloration, and vitamin oxidation. Given these conditions, it is imperative to come up with a drying technology that avoids all the issues. However, in general, when it comes to the agriculture in rural areas of developing nations, especially in India, drying and winnowing are the two essential tasks that farmers follow when aiming at a marketable product—drying reduces the moisture content, and winnowing removes the straw from grains. However, these two do not come in one system, and a farmer needs to have two separate systems—one for drying and the other for winnowing.

Drying enhances the storability of the date palm product by reducing the loss, and doing this at the farm level would be more productive [6,7]. However, most farmers rely on farming only and cannot afford costly devices; instead, they rely on open drying under the sun. This is commonly seen in India, and the central problems are product defiling and non-uniform drying. Mechanical or electric drying in the forced convection mode is suggested as an alternative to open sun drying to avoid defiling and non-uniform drying. However, the mechanical or electric drying was quite prominent only for industrial purposes, and it is a bit expensive. The small and marginal farmers cannot afford this hi-tech facility, especially people living in the Thar desert of India, where date palm farming is common. Regarding the solar energy potential, India is in a stronger position. The desert area is fortunate to have access to alternative energy sources including biogas, wind, and solar electricity. In India's dry region, solar energy ranges from 5.8 to 6.3 kWh m^{-2} day^{-1}, on average [8].

Open sun-drying can be replaced with solar dryers because of their low operating costs [6,7,9,10]. The solar dryer is very profitable, cheap, and eco-friendly, and it is cost-effective for rural people. It can be used in sun-drying to ensure the quality product [11]. Numerous studies demonstrate that the solar-based drying technology is preferable to open drying for the generated dried foods [12–15]. The thermal and PV equipment can support current energy sources. In comparison to solar thermal collectors and side-by-side PV modules, PV/T collectors produce more energy per unit of surface area [16]. The dryer is utilized in the forced convection mode, and the PV powers the fan. No traditional source is necessary. The integrated photovoltaic thermal hybrid system has a respectable return on investment [17]. According to Tonui and Tripanagnostopoulos, various inexpensive modifications could enhance the efficiency of air-cooled PV/T solar collectors [18]. Slices of tomato were dried, reducing their moisture content from 95% to 9% (wet basis) after 10 h of solar drying in an indirect-type hybrid solar dryer, and the overall drying efficiency of the system was estimated as 41% [19]. For drying grapes, Barnwal and Tiwari employed a photovoltaic/thermal greenhouse dryer [20]. In order to dry Indian jujube, a hybrid PV/T-forced solar convection dryer was constructed [6,7]. They reported that the forced convection mode's average thermal efficiency was higher (16.7%) than the mode's average thermal efficiency (15.6%). The greenhouse solar dryer is very effective in elevating the temperature by 10–14 °C over the surrounding temperature, and the dryer also has a quick payback period of 1.5–2.1 years [21]. Cerci and Hurdogan investigated a hybrid drying system for the low-temperature drying of peanuts [22]. Tuncer et al. revealed that the payback period of the PVT hybrid solar dryer varied between 2.98 and 3.51 years [23]. The optimal conditions for the drying of basil leaves in a hybrid solar dryer were a 63.8 °C air temperature and a bed thickness of 2 cm, and the exergy efficiency varied in the range of 31.78–86.55% [24].

CAZRI, Jodhpur, India, has developed a unique solar dryer that is used for both drying and winnowing simultaneously [25]. In this mixed mode dryer, the fan was used to circulate air inside the drying bin, and provisions were made to let the dehydration process continue at night through natural circulation. Although it was found to provide satisfactory results in drying different vegetables and fruits, retaining the color and aroma of the product, there had been a thermal gradient of 5–6 °C or more across the height inside the drying bin, leading to non-uniform drying, and, therefore, different trays needed to be reshuffled [25,26]. Moreover, the villagers find it difficult to clean the threshed material if there is a lull in natural winds. Sometimes, electrical or manual-driven fans are employed for winnowing. The intermittence of electricity makes the farmer handicapped in using the electrical device at the time of requirement. In contrast, the manual system is not only less efficient but adds to human drudgery. However, it was observed to have limited use only after the harvest, particularly in arid regions. Therefore, the utility of the PV dryer was extended by using it as a PV winnower [27]. As per the literature review, significantly less research exists on date palm solar drying; many studies reported on green transition and the use of renewables as a means for sustainable development, both at the centralized and decentralized levels [28–31].

Therefore, in this paper, a study was undertaken to develop a preheater to overcome the problem of the thermal gradient, assess the drying attributes of date palm and the thin-layer drying process for the solar drying of date palm fruit, and compare it with open sun-dried date palm fruits. There existed a temperature gradient of 5–6 °C inside the drying chamber, and drying trays had to be reshuffled. An economic analysis of a PV winnower cum hybrid solar dryer has been carried out.

2. Materials and Methods

2.1. Description of the Photovoltaic Winnower Cum Dryer

The components of the PV winnower cum dryer unit include a PV module-mirror booster assembly, a suitable winnower, a heating tunnel that is used to pre-heat air, and a solar drying cabinet that is specifically developed to utilize solar energy effectively. The interfacing arrangements made in the design will allow the product to be dried more quickly by using the winnower's fan. As shown in Figure 1, the winnower is simply a trapezoidal chamber with a PV-driven blower, a hopper, and a guide for feeding the material that is to be dried and for boosting the airspeed.

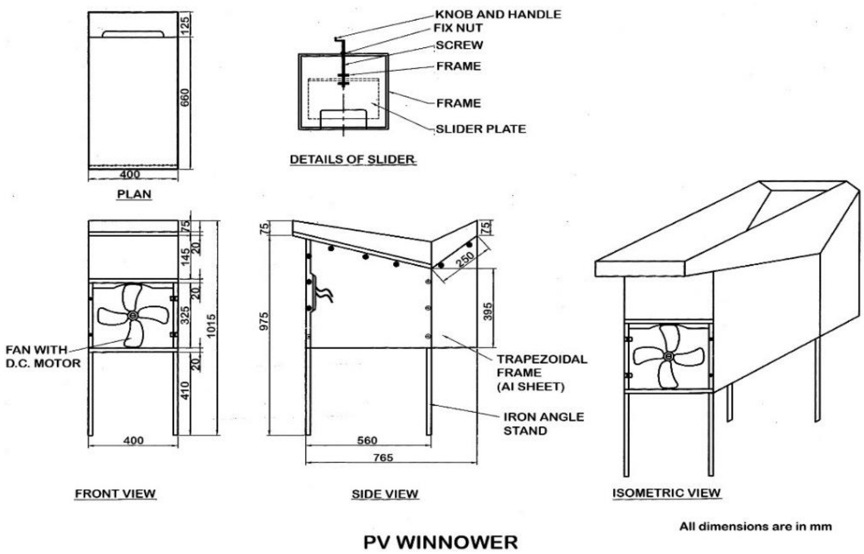

Figure 1. A design of the photovoltaic (PV) winnower.

The system comprises a three-sided aluminum sheet covering an iron-angle frame. A direct-current (DC) motor (35 W)-run fan is fixed at one of the vertical openings on the frame and is operated with an output of a PV module. A specifically made tray with a slope and a slit covers the top, having arrangements to reduce or increase the opening size. This tray serves as a hopper while also facilitating airflow toward the product that is descending from the slit. A dryer of the size 2006 mm × 1400 mm was made using 22 gauge galvanised sheet metal. It consists of twelve trays, each being 870 mm × 620 mm in size, made of angle frames and wire meshes made with stainless steel. The chamber is provided with a door facility. As shown in Figure 2, the dryer comprises two clear glass windows (980 mm × 680 mm) that are 4 mm thick—one was provided on the front side, and another glass window (450 mm × 700 mm) is fixed on the east side of the cabinet.

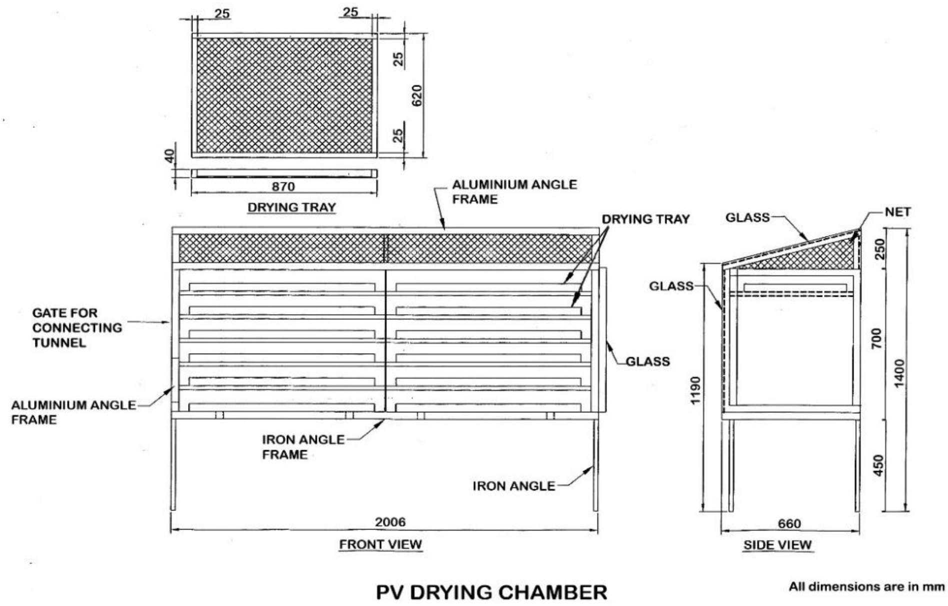

Figure 2. Schematic sketch with neat dimensions showing the design of the photovoltaic (PV) hybrid solar dryer.

The dryer is about 45 cm above the floor. Four holes are provided for ventilation at the base with detachable caps. The dryer functions in both natural and forced circulation modes in east and north directions. The dryer is provided with GI wire mesh to ensure ventilation. Proper provisions have been made to use the fan as a dryer and winnower. Initially, the 35 Wp PV panel confirmed the dryer's operation for more than six hours daily. Later, a booster was provided to capture more solar radiation (22.6% and 35.4% from 9:00 to 11:00 h). The booster had 1.5 and 2 times more length than the length of the PV panel. An additional 2–3% cost of the booster can ensure 20% more power [25]. The device is installed as shown in Figure 3. The device worked on the principle of the greenhouse effect, where the solar radiation was converted into long-wave radiation and was trapped inside, giving rise to the inside temperature. The PV panel and fan were provided to use the system in the forced convection mode to ensure the faster drying of date palm fruits.

2.2. Experimental Procedure

The on-field trials were conducted from 13 to 18 June 2020 under clear skies at the CAZRI in Jodhpur, India (26°18′ N and 73°04′ E). In total, 20 kg of date palm fruit was purchased for the drying experiment from CAZRI's horticultural block in Jodhpur. Twenty kilograms of date palm were separated and evenly dispersed on the left- and right-side trays, and the experiments were conducted between the hours of 8:00 and 18:00. In these studies, a thermopile pyranometer was used to record the total solar radiation intensity (Gs) on a horizontal surface hourly. Using a DTM-100 thermometer with point-contact thermocouples with an accuracy of 0.1 °C, the temperatures inside the dryer chamber are measured. The temperature of the surrounding air was measured using a mercury thermometer with a 0.1 °C precision. Every 60 min, the moisture content of the drying product was determined using an electronic digital balance (Testing Instrument Pvt. Ltd

Faridabad, India) with a 0.001 g precision. The sample trays were used to collect 100 g of the sample.

Figure 3. Picture depicting the installation of the PV/T hybrid solar dryer with a winnower at the CAZRI solar yard in India.

2.3. Moisture Content and Moisture Ratio

The moisture, which is typically referred to as the initial moisture (M_i) content of the collected fruits, can be estimated using Equation (1).

$$Mi = \left(\frac{Wi - Wf}{Wi}\right) \times 100 \quad (1)$$

Equation (2) was used to estimate the drying rate [6,7]

$$DR = \frac{\Delta M}{\Delta t} \quad (2)$$

Equation (3) was used to estimate the moisture ratio.

$$MR = \frac{M - Me}{Mo - Me} \quad (3)$$

2.4. Effective Moisture Diffusivity

Using Equation (4), the effective moisture diffusivity (D_{eff}) is estimated, and it is defined by Fick's second law [6]:

$$MR = \frac{M - M_e}{M_o - M_e} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-\frac{n^2 \pi^2 D_{eff}{}^t}{4r^2}\right) \quad (4)$$

Equation (4) is further simplified and can be expressed in a logarithmic form (see Equation (5)), and its slope is given in Equation (6).

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}{}^t}{4r^2}\right) \quad (5)$$

$$Slope = \left(\frac{\pi^2 D_{eff}}{4r^2}\right) \tag{6}$$

2.5. Thermal Efficiency (η)

The thermal efficiency is the ratio of the moisture removal to the heat gained. Equation (7) is used to estimate the thermal efficiency [6,10,32]:

$$\eta = \frac{ML}{A\int_0^\theta H_T d\theta} \times 100 \tag{7}$$

2.6. Economic Analysis of the PV Hybrid Solar Dryer

The dryer's economic viability was examined using five economic factors: net present value (NPV), payback period (PBP), benefit–cost ratio (BCR), annuity (A), and internal rate of return (IRR).

2.6.1. Net Present Value (NPV)

Comparing the worth of future benefits to the cost of the initial investment while accounting for the appropriate interest rate is the goal of calculating the net present value. The capital cost of a company, or the net present value (NPV), was determined using a 12% interest rate to calculate the present value of anticipated future cash flow. The aforementioned rate was applied to all cash inflows and outflows. The NPV of solar devices was worked out using Equation (8) [33]. Here, the initial cost (IC) = INR 33,089/-, a = (0.12), and n = 10 years. The gross benefits from the sale of products (E) = INR 19,800/-, and the maintenance cost of the dryer (M) = INR 1166/-

$$NPV = \frac{(E-M)}{a}\left[1 - \left(\frac{1}{1+a}\right)^n\right] - IC \tag{8}$$

2.6.2. The Benefit–Cost Ratio (BCR)

The benefit–cost ratio was calculated as the original cost divided by the net present value, as shown in Equation (9).

$$BCR = \frac{IC + NPV}{IC} \text{ and } BCR = 1 + \frac{NPV}{IC} \tag{9}$$

2.6.3. Annuity (A)

The project's annuity (A) shows the average net annual returns, determined using Equation (10).

$$A = \frac{NPV}{\sum_{t=1ton}\left(\frac{1}{1+a}\right)^n} \tag{10}$$

2.6.4. Payback Period (PBP)

The amount of time needed to recover the initial investment made in a project or investment was calculated using the payback period formula; see Equation (11).

$$PBP = \frac{\log\frac{(E-M)}{a} - \left(\log\frac{(E-M)}{a} - IC\right)}{\log(1+a)} \tag{11}$$

2.6.5. Internal Rate of Return (IRR)

The IRR is determined using Equation (12). For this, the lower and upper discount rates are considered as 40% and 60%, respectively

$$IRR = lowerdiscountrate + \frac{Differenceofdiscountrate \times NPVatlowerdiscountrate}{(NPVatlowerdiscountrate - NPVathigherdiscountrate)} \quad (12)$$

3. Results and Discussion

3.1. Performance Evaluation of the PV Hybrid Solar Dryer

The performance of the system with the different number of fins inside the tunnel revealed that as the number of fins increased, the air temperature rise was greater, but the reduction in airspeed was substantial. The average airspeed at the tunnel's exit varied from 3.5 m/s to 5.5 m/s during different hours of the day without fins. In contrast, it ranged from 1.2 to 2.8 m/s with fins. Under loaded conditions of date palm fruits, the average temperature of the air at different points viz. the upper, middle, and lower trays of the drying chamber is given in Figure 4. The average drying chamber temperature on the left and right sides of the upper trays varied from 48 to 70 °C; in the middle trays, it varied from 45 to 67 °C; and in the lower trays, it varied from 42 to 64 °C. In June 2020, the average solar insolation ranged from 430 W.m^{-2} to 940 W.m^{-2}, and the average air temperature was 39.5 °C. A compromise was made to allow the temperature to rise to about 2.5–3 °C using a pre-heating tunnel, which matched the calculated values. The estimated values were for the mass flow rate of 0.02 kg s^{-1}, when the average ambient temperature was 30.5 °C and the solar insolation was 910 W.m^{-2}, respectively. When the dryer first started, the temperature was lower; but, as time went on, the temperature increased between 12:00 and 15:00. The dryer's inside was found to be cooler after 15:00 h. For the six days of drying time during the trial period, the temperature inside the dryer was essentially constant. The temperature has a great impact on the drying time of Indian Jujube (*Zizyphus mauritiana*) [6,7], date palm [5], and deglet-nour date fruits [34]. In general, the reduction in drying time was caused by stronger driving forces for mass transfer and heat transfer (owing to greater temperature differences due to more significant differences in the relative humidity).

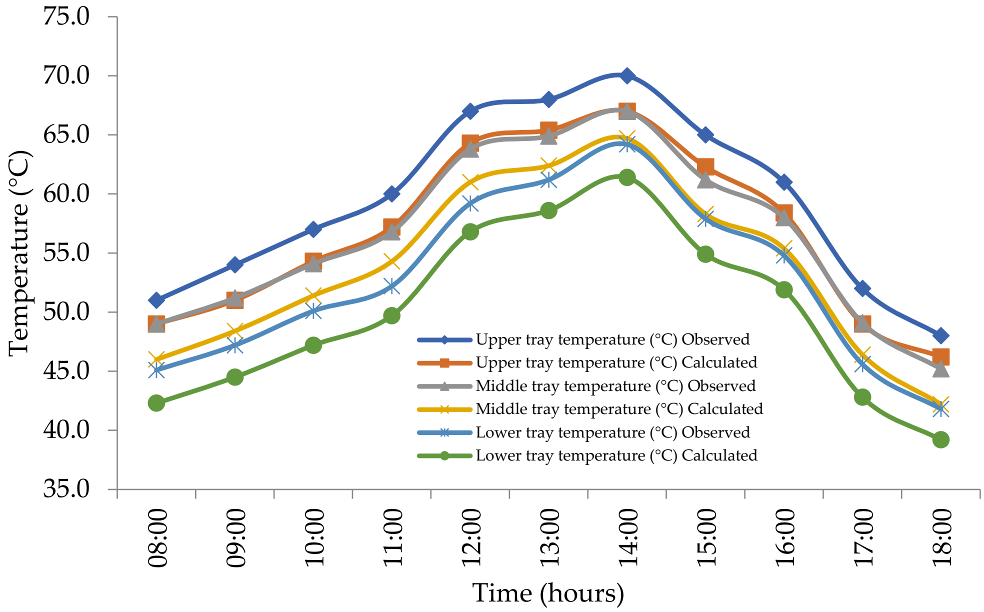

Figure 4. Observed and calculated average temperature in the drying chamber at different points of the PV dryer with the tunnel while dehydrating date palm fruits.

The variations in moisture content (w.b.) versus drying time in the PV dryer and the open sun drying of the fruit on each day of drying are compared in Figure 5. As can be observed, the solar dryer lowered the fruit's moisture content from 65% to 26% in just six days, and on the eighth day, it had fallen to 20%, but open-air sun drying required eight days to reach the same result. However, the moisture level dropped to 26% after 6 days of drying, allowing for secure storage for future use. Date palms that had been dried under various circumstances had a final moisture content that ranged from 20% to 26% on a wet basis. Figure 6 shows that the PV dryer's drying rate was significantly higher than that of the open-air solar drying [5] of Algerian deglet-nour dates [34–36]. When the moisture content went below 54%, the dryer's drying time rose significantly. As the drying time increased, the elimination of the moisture ratio decreased from its initial high level. As a result, as the drying time passed, the moisture ratio continued to decline. The internal mass transfer had been governed by diffusion, as evidenced by the moisture ratio's ongoing decline. This was consistent with research findings on Indian jujube and tomatoes [6,7]. This was also in agreement with the results of black grapes and pumpkin [37,38].

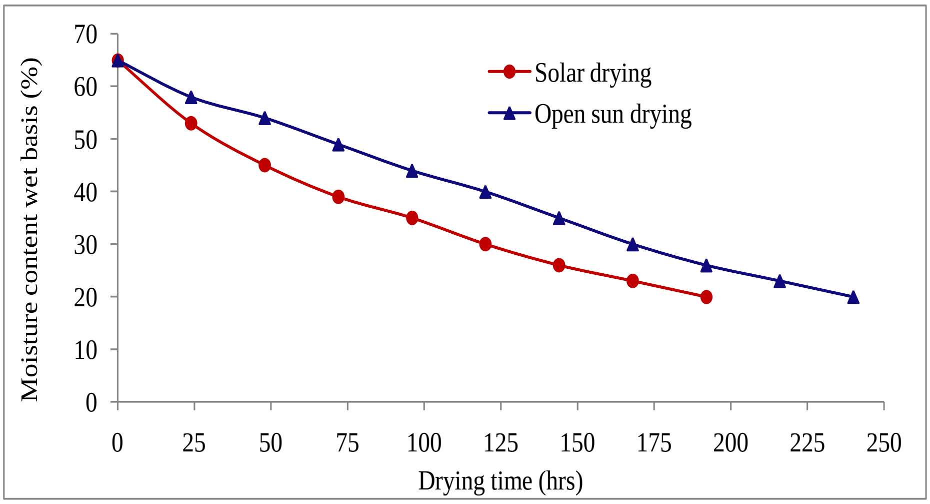

Figure 5. Changes in date palm moisture content as a function of drying time under the solar dryer and open sun drying.

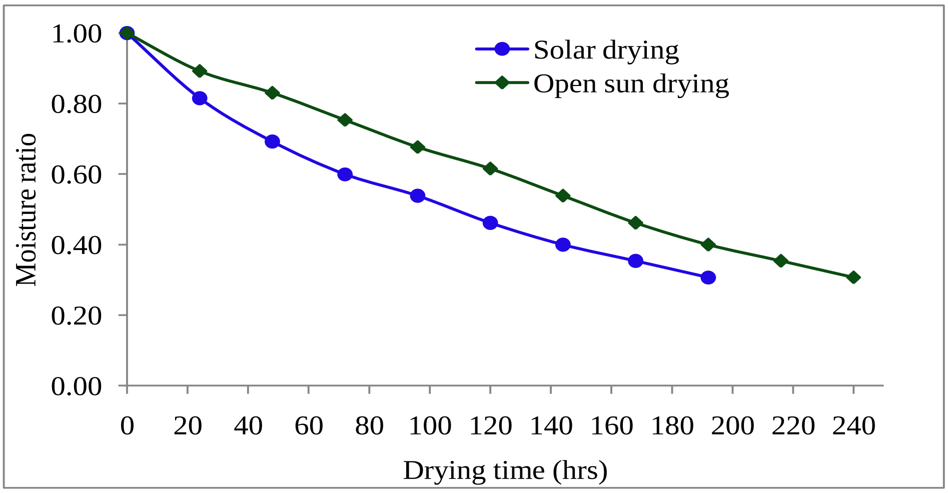

Figure 6. Moisture ratio of date palm during solar and open sun drying against drying time.

The thermal gradient varied from 2–3 °C inside the drying chamber initially, and then it increased to 4–6 °C as drying proceeded. The temperature rise is due to the energy gain primarily from the pre-air heater and the top plane due to the high altitude of the sun. The temperature difference at the top and middle trays of the bin was 6–8 °C without the pre-air heater. The pre-air heater was found to be 2–3 °C initially, which also varied in different seasons for dehydrating various drying materials. The data of this experiment were found by the mathematical model for air heating and for predicting the temperature in the bin to a reasonable extent. In this experiment, the color and aroma of the product were maintained. Figure 6 displays the variation in the moisture ratio for the drying time. Figure 6 clearly shows that both solar drying and open sun drying were found to have a decreasing moisture ratio. Additionally, when compared to open-air sun drying, the required moisture ratio of (0.3) was accomplished quickly with solar drying.

Figure 7 shows the date palm after solar and open sun drying, respectively. From Figure 7, it is clear that the quality of fruit in solar drying is much better than that in open sun drying.

Figure 7. Date palm photographs after drying.

3.2. Effective Moisture Diffusivity (D_{eff})

Equation (1) was used estimate the effective moisture diffusion coefficient (Deff) of date palm fruits against drying time. The Deff was then extrapolated. The straight lines were generated by linear regression, with good correlation coefficients r^2 ranging from 0.990 to 0.9957, and they sufficiently reflect the drying behavior over the moisture ratio range (0MR1.0), a range that comprises the majority of the drying process. Figure 8 ln (MR) graph against time was used to calculate the effective moisture diffusivity. The experiment measured the moisture diffusivity of date palm fruits at 30–65 °C for a loading rate of 20 kg in solar drying, which is 4.34×10^{-9} $m^2 \cdot s^{-1}$, and when the same fruits are dried under the open sun, the observed moisture diffusivity is 3.22109 $m^2 \cdot s^{-1}$. Because of this, the majority of food ingredients have Deff values that fall within the broad range of 10–12 to 10–8 $m^2 \cdot s^{-1}$ [6,7,39,40]. This is comparable to the outcomes for the thin-layer drying of date palm at 50–80 °C (from 7.53×10^{-9} to 1.11×10^{-8} $m^2 \cdot s^{-1}$) [40], for the convective drying of pumpkin at 30–70 °C (4.08×10^{-8} to 2.35×10^{-7} $m^2 \cdot s^{-1}$) [41], and for the thin-layer solar drying of Indian jujube (*Zizyphus mauritiana*) fruits at 50–70 °C (3.34×10^{-7}) [6,7]. The use of varied drying temperatures, the physical or chemical pretreatment, the moisture content and sample variety, the composition, and the geometrical properties of drying materials could all contribute to the difference in D_{eff} for different biological materials.

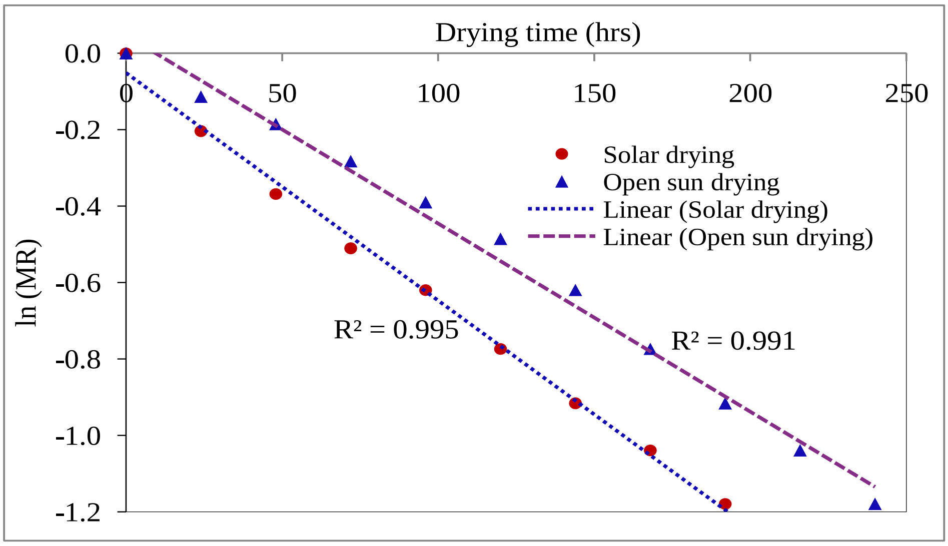

Figure 8. Date palm drying under sunlight and open sun: ln (MR) vs. drying time.

3.3. Dryer Overall Efficiency

According to Equation (4), which yielded a result of 16.1%, the dryer's effectiveness is dependent on the amount of drying time, the temperature, and the sun radiation. Due to the fact that unbound moisture is initially removed and is influenced by surface area, it was originally high and decreased in response to a decrease in moisture content. The outcome was consistent with earlier studies that found that a forced convective, flat-plate solar heat collector dryer for drying cauliflower had an average thermal efficiency of 16.5% [42]. Similarly, the average thermal efficiency is around 12.1% for drying ber (Zizyphusmauritiana) fruit using a low-cost solar dryer [10], and it is 16.7% for drying Indian jujube using a PV/T hybrid solar dryer [6,7].

3.4. Performance Evaluation of the Winnower

As a winnower, the airspeed at the exit of the winnower was found to vary from 1.6 m/s to 3.5 m/s with a single PV panel, while it was 2.3 to 3.7 m/s with PV panel-reflector assembly. In contrast, with two panels, it works quite satisfactorily for extended hours. The system works better with PV panel reflector assemblies compared to the PV panel. Still, with two PV panels, it works better for extended hours and provides a scope to store the surplus energy in the battery for use at night. The device was tested for the winnowing of different threshed materials such as pearl millet, mung bean, moth bean, cluster bean, and mustard. The system could be operated even with a single panel for a winnowing of pearl millet. An additional mirror reflector of an extended length could be used more comfortably to clean mustard and cluster beans. However, if the system needs to be used for cleaning and illumination in the night, two PV modules with a storage battery are preferable. On average, 900 kg of cluster bean, threshed manually, could be winnowed by operating it for 5.5 h each for four days; 350 kg of pearl millet could be winnowed by operating it for 3.5 h a day for two days; and 450 kg of mustard could be winnowed by operating it for 8.5 h in two days, indicating that, on average, 34–52 kg of cleaned grains/seeds could be separated in an hour from threshed material weighing three to four times more. The device helps to save manpower in completing an important post-harvest agricultural task, especially during those days when natural winds are not available.

3.5. Analysis of Economic Viability

The calculations, as per the parameters shown in Section 2.5, were carried out to assess the dryer's viability from an economic standpoint. The dryer unit had a 33,089 INR initial investment (Pi). The annual maintenance cost (M), which is INR 1166, was calculated as

5% of the initial cost (INR 23,300), and it includes minor replacements, if required. A 10% deduction from the initial investment was made for the salvage value.

The yearly benefit is mainly accrued from drying date palm, sangri (Pods of Prosopis cineraria), and Lasora (Cordiamyxa), the labor-saving in winnowing operations, and the benefits gained through lightning. The benefit accrued from drying date palm and sangri was INR 3500/each, and the labor-saving in winnowing amounted to INR 9000/-, and that from lighting amounted to INR 300/-. Thus, the benefits amounted to INR 19,800/year, whereas the present value of the life cycle cost was INR 33,089, including the initial cost and the battery replacement charge, the fan replacement, and the drying chamber replacement cost. By discounting the values to the present, the entire cash inflow and outflow for the production of the solar dryer's net present value was determined. The dryer has a ten-year lifespan and an initial cost of INR 33,089, or 12% of the total cost. Sales of the goods will generate a profit of INR 19,800. The dryer's net present value (NPV) was calculated using Equation (15), which indicates that the investment in the solar dryer had an NPV of INR 113,023. Based on the NPV, it is determined that the fabrication of the dryer is more affordable than that of the hybrid solar/biomass dryer [43], the hybrid PV/T greenhouse dryer [20], and the PVT hybrid solar dryer [6,7].

Equation (9) has been used to determine the benefit–cost ratio by dividing the present value of the benefit stream by the current price of the cost stream. It comes out, for the dryer, as 4.41. Swain et al. examined the effectiveness of copra drying equipment powered by biomass [44]. The findings showed that it required 22 h for biomass-fired equipment to reduce the initial moisture content from 57.4% (Wb) to 6.8%. (Wb) [44]. For two dryers tested for producing high-quality copra, the cost–benefit ratio was determined to be 1.4 and 1.19, respectively. The cost–benefit ratio is estimated to be 1.86 for the PVT hybrid solar dryer [6]. The dryer's annuity was calculated using Equation (7), which shows that its average net yearly return is INR 14,415. The payback period, which is 2.10 years, is shorter than the dryer's anticipated lifespan of around 10 years. A solar tunnel dryer's payback period is four years for basic mode dryers and three to four years for optimum mode dryers [14]. An analysis of the cost of a hybrid photovoltaic greenhouse dryer was conducted in [37]. Grapes have been dried using a hybrid PV/T integrated greenhouse dryer in the forced mode of operation [20]. With an initial expenditure of INR 27,400, the system's payback period is approximately 1.25 years. The payback period of the PVT hybrid solar dryer is 2.26 years, with an initial investment of INR 14,000 [6]. The internal rate of return can be determined using Equation (9). Table 1 provides the values of the NPV at various discount rates.

Table 1. Net present values for different rates of discount/interest (i).

	Interest Rate *i* (%)		
	12	40	60
Net present value (INR)	113,023	13,485	−2032

From Table 1, it may be deduced that the NPV is INR 113,023 at a 12% interest rate. The net present value is INR 13,485 at a 40% interest rate. However, with a 60% interest rate, the NPV is negative (i.e., NPV = INR −2032/-). The internal rate of return (IRR) is as high as 57.4%. Compared to the cost of capital, the IRR is higher. The option with the highest IRR may be viewed as the superior choice when all other factors are held constant and may be used as the decision-making criterion. This conclusion is based, in part, on the fact that a greater IRR denotes a lower risk [33]. The important economic parameters are given in Table 2.

Table 2. Economic parameters of the solar PV dryer system.

Parameters	Values
Benefit–cost ratio	4.41
Net present value	113,023
Annuity	14,415
Internal rate of return (percent)	57.38
Payback perid (years)	2.10

4. Conclusions

This paper presented a novel design of a solar photovoltaic powered dryer cum winnower used for drying date palm and separating grains from straw. The date palm grown in rural arid regions of Rajasthan was used for studying the drying experiment. The characteristics of the date palm fruit dried in a photovoltaic hybrid solar dryer were analyzed using a mathematical model for the pre-air heating tunnel to reduce the thermal gradient in the drying chamber. The proposed system provided better a moisture diffusivity and efficiency. Additionally, the economic evaluation of the hybrid solar dryer unit also indicated a favorable IRR and a shorter PBP, suggesting it to be cost-effective. The winnower also showed a good potential for the grain separation from straw. Using such a novel system considerably reduced the drying time, and, at the same time, it was fully operational using renewable energy consumption. Using such PV hybrid forced solar convection dryers at remote locations/rural areas can ensure value addition in dried produce and reduce pollution.

This dryer could be used for dehydrating various fruits and vegetables in arid regions and for determining their cost-economics and CO_2 mitigation potential. The heat generated by the PV panel can be diverted to the drying chamber using a fan. This can be carried out by covering the back position of the PV panel, where the temperature rises to 70 °C. Thus, PV panels could be used in the hybrid mode.

Author Contributions: Conceptualization, S.P. and N.M.K.; Data curation, S.P., A.K.S., D.J., N.M.K. and D.S.; Formal analysis, S.P., A.K.S., D.J. and N.M.K.; Funding acquisition, S.P. and N.M.K.; Investigation, S.P. and A.K.S.; Methodology, S.P., A.K.S., D.J. and N.M.K.; Project administration, S.P. and N.M.K.; Resources, D.J., N.M.K., and D.S.; Software, S.P. and D.J.; Supervision, N.M.K.; Validation, S.P. and N.M.K.; Visualization, S.P., A.K.S. and D.J.; Writing—original draft, S.P., A.K.S. and D.J.; Writing—review & editing, N.M.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

M_i	Initial moisture content of the sample (w.b.) %
W_i	Initial weight of the sample (g)
W_f	Final weight of the sample (g)
ΔM	Loss of mass of fruit (kg water·kg^{-1} dry matter)
Δt	Interval of time (min)
DR	Drying rate
M	Moisture content of the sample at a given time
M_0	Initial moisture content of the sample
Me	Equilibrium moisture content of the sample (kg water. kg^{-1} solids)
D_{eff}	Effective diffusivity coefficient (m^2·s^{-1})
r	Half thickness of the sample (m)
n	Positive integer
t	Drying time (s)
η	Efficiency of the solar dryer (%)
A	Absorber area (m^2)
HT	Solar radiation on the horizontal plane (J.m^{-2}·h^{-1})
L	Latent heat of vaporization (J·kg^{-1})
M	Mass of moisture evaporated from the product (kg)
θ	Period of test (h)
a	Compound interest rate per annum
IC	Initial cost of the dryer (INR)
E	Gross benefits from the sale of products (INR)
M	Maintenance cost of the dryer (INR)
n	Number of years
NPV	Net present value (INR)
BCR	Benefit–cost ratio
A	Annuity (INR)
PBP	Payback period (years)
IRR	Internal rate of return (%)

References

1. Ahmed, I.A.; Ahmed, A.W.K.; Robinson, R.K. Chemical composition of date varieties as influenced by the stage of ripening. *Food Chem.* **1995**, *54*, 305–309. [CrossRef]
2. Al-Turki, S.; Shahba, M.A.; Stushnoff, C. Diversity of antioxidant properties and phenolic content of date palm (*Phoenix dactylifera* L.) fruits as affected by cultivar and location. *J. Food Agric. Environ.* **2010**, *8*, 253–260.
3. Uchoi, J.; Nikhumbhe, P.H.; Kumar, A.; Patidar, A.; Harish, G.D. Impact of inclined solar drier for dehydration quality in khadrawy dates during doka maturity stage at north western arid India. *Int. J. Curr. Microbiol. Appl. Sci.* **2020**, *9*, 119–125. [CrossRef]
4. Kulkarni, S.G.; Vijayanand, P.; Aksha, M.; Reena, P.; Ramana, K.V.R. Effect of dehydration on the quality and storage stability of immature dates (*Pheonixdactylifera*). *LWT-Food Sci. Technol.* **2008**, *41*, 278–283. [CrossRef]
5. Sagarika, N.; Kapdi, S.S.; Sutar, R.F.; Patil, G.B.; Akbari, S.H. Study on drying kinetics of date palm fruits in greenhouse dryer. *J. Pharmacogn. Phytochem.* **2019**, *8*, 2074–2079.
6. Poonia, S.; Singh, A.K.; Jain, D. Mathematical modelling and economic evaluation of hybrid photovoltaic-thermal forced convection solar drying of Indian jujube (*Zizyphusmauritiana*). *J. Agric. Eng.* **2018**, *55*, 74–88.
7. Poonia, S.; Singh, A.K.; Jain, D. Design development and performance evaluation of photovoltaic/thermal (PV/T) hybrid solar dryer for drying of ber (*Zizyphusmauritiana*) fruit. *Cogent Eng.* **2018**, *5*, 1–18. [CrossRef]
8. Poonia, S.; Singh, A.K.; Jain, D. Design development and performance evaluation of concentrating solar thermal desalination device for hot arid region of India. *Desalination Water Treat.* **2020**, *205*, 1–11. [CrossRef]
9. Purohit, P.; Kumar, A.; Kandpal, T.C. Solar drying vs. Open Sun drying: A framework for financial evaluation. *Sol. Energy* **2006**, *80*, 1568–1579. [CrossRef]
10. Poonia, S.; Singh, A.K.; Santra, P.; Jain, D. Performance evaluation and cost economics of a low-cost solar dryer for ber (*Zizyphusmauritiana*) fruit. *Agric. Eng. Today* **2017**, *41*, 25–30.
11. Sharma, A.; Chen, C.R.; Vu Lan, N. Solar-energy drying systems: A review. *Renew. Sustain. Energy Rev.* **2009**, *13*, 1185–1210. [CrossRef]
12. Mahapatra, A.K.; Imre, L. Role of solar agricultural drying in developing countries. *Int. J. Ambient. Energy* **1990**, *2*, 205–210. [CrossRef]

13. Sodha, M.S.; Chandra, R. Solar drying systems and their testing procedures: A Review. *Energy Convers. Manag.* **1994**, *35*, 219–267. [CrossRef]
14. Ekechukwu, O.V.; Norton, B. Review of solar energy drying systems II: An overview of solar drying technology. *Energy Convers. Manag.* **1999**, *40*, 615–655. [CrossRef]
15. Hossain, M.A.; Woods, J.L.; Bala, B.K. Optimisation of solar tunnel drier for drying of chilli without color loss. *Renew. Energy* **2005**, *30*, 729–742. [CrossRef]
16. Zondag, H.A. Flat-plate PV-Thermal collectors and systems: A review. *Renew. Sustain. Energy Rev.* **2008**, *12*, 891–959. [CrossRef]
17. Huang, B.J.; Lin, T.H.; Hung, W.C.; Sun, F.S. Performance evaluation of solar photovoltaic/thermal systems. *Sol. Energy* **2001**, *70*, 443–448. [CrossRef]
18. Tonui, J.K.; Tripanagnostopoulos, Y. Air-cooled PV/T solar collectors with low-cost performance improvements. *Sol. Energy* **2007**, *81*, 498–511. [CrossRef]
19. Sharma, M.; Atheaya, D.; Kumar, A. Exergy, drying kinetics, and performance assessment of Solanumly copersicum (tomatoes) drying in an indirect type domestic hybrid solar dryer (ITDHSD) system. *J. Food Process. Preserv.* **2022**, e16988. [CrossRef]
20. Barnwal, P.; Tiwari, G.N. Grape drying by using hybrid photovoltaic–thermal (PV/T) greenhouse dryer: An experimental study. *Sol. Energy* **2008**, *82*, 1131–1144. [CrossRef]
21. Philip, N.; Duraipandi, S.; Sreekumar, A. Techno-economic analysis of greenhouse solar dryer for drying agricultural produce. *Renew. Energy* **2022**, *199*, 613–627. [CrossRef]
22. Çerçi, K.N.; Hürdoğan, E. Performance assessment of a heat pump assisted rotary desiccant dryer for low temperature peanut drying. *Biosyst. Eng.* **2022**, *223*, 1–17. [CrossRef]
23. Tuncer, A.D.; Khanlari, A.; Afshari, F.; Sözen, A.; Çiftçi, E.; Kusun, B.; Şahinkesen, I. Experimental and numerical analysis of a grooved hybrid photovoltaic-thermal solar drying system. *Appl. Therm. Eng.* **2023**, *218*, 119288. [CrossRef]
24. Parhizi, Z.; Karami, H.; Golpour, I.; Kaveh, M.; Szymanek, M.; Blanco-Marigorta, A.M.; Marcos, J.D.; Khalife, E.; Skowron, S.; Adnan Othman, N.; et al. Modeling and optimization of energy and exergy parameters of a hybrid-solar dryer for basil leaf drying using RSM. *Sustainability* **2022**, *14*, 8839. [CrossRef]
25. Pande, P.C. Design and development of PV winnower-cum-dryer. In Proceedings of the International Congress on Renewable Energy (ICORE 2006), Hyderabad, India, 8–11 February 2006; Sastry, E.V.R., Reddy, D.N., Eds.; Allied Publishers Pvt. Ltd.: Mumbai, India, 2006; pp. 265–269.
26. Pande, P.C.; Singh, A.K.; Dave, B.K.; Purohit, M.M. A preheated Solar PV dryer for economic growth of farmers and entrepreneurs. In Proceedings of the International Congress on Renewable Energy (ICORE 2010), Chandigarh, India, 3 December 2010; Solar Energy Society of India: New Delhi, India, 2010; pp. 68–73.
27. Pande, P.C. A Solar PV winnower. In Proceedings of the 2003, 26th National Renewable Energy Convention and International Conference in New Millennium, Coimbatore, India, 17–19 January 2003; pp. 22–26.
28. Ikram, M.; Zhang, Q.; Sroufe, R.; Shah SZ, A. Towards a sustainable environment: The nexus between ISO 14001, renewable energy consumption, access to electricity, agriculture and CO_2 emissions in SAARC countries. *Sustain. Prod. Consum.* **2020**, *22*, 218–230. [CrossRef]
29. Chand, A.A.; Prasad, K.A.; Mar, E.; Dakai, S.; Mamun, K.A.; Islam, F.R.; Kumar, N.M. Design and Analysis of Photovoltaic Powered Battery-Operated Computer Vision-Based Multi-Purpose Smart Farming Robot. *Agronomy* **2021**, *11*, 530. [CrossRef]
30. Solangi, Y.A.; Tan, Q.; Mirjat, N.H.; Valasai, G.D.; Khan MW, A.; Ikram, M. An integrated Delphi-AHP and fuzzy TOPSIS approach toward ranking and selection of renewable energy resources in Pakistan. *Processes* **2019**, *7*, 118. [CrossRef]
31. D'Adamo, I.; Gastaldi, M.; Morone, P.; Rosa, P.; Sassanelli, C.; Settembre-Blundo, D.; Shen, Y. Bioeconomy of sustainability: Drivers, opportunities and policy implications. *Sustainability* **2021**, *14*, 200. [CrossRef]
32. Leon, A.M.; Kumar, S.; Bhattacharya, S.C. A comprehensive procedure for performance evaluation of solar food dryers. *Renew. Sustain. Energy Rev.* **2002**, *6*, 367–393. [CrossRef]
33. Singh, A.K.; Poonia, S.; Jain, D.; Mishra, D.; Singh, R.K. Economic evaluation of a business model of selected solar thermal devices in Thar Desert of Rajasthan, India. *Agric. Eng. Int. CIGR J.* **2020**, *22*, 129–137.
34. Mennouche, D.; Boubekri, A.; Chouicha, S.; Bouchekima, B.; Bouguettaia, H. Solar drying process to obtain high standard "deglet-nour" date fruit. *J. Food Process Eng.* **2017**, *40*, e12546. [CrossRef]
35. Boubekri, A.; Benmoussa, H.; Mennouche, D. Solar drying kinetics of date palm fruits assuming a step-wise air temperature change. *J. Eng. Sci. Technol.* **2009**, *4*, 292–304.
36. Boubekri, A.; Benmoussa, H.; Courtois, F.; Bonazzi, C. Softening of over dried 'DegletNour' dates to obtain high-standard fruits: Impact of rehydration and drying processes on quality criteria. *Dry. Technol.* **2010**, *28*, 222–231. [CrossRef]
37. Domyaz, I. Drying kinetics of black grapes treated with different solutions. *J. Food Eng.* **2006**, *76*, 212–217. [CrossRef]
38. Doymaz, İ. The kinetics of forced convective air drying of pumpkin slices. *J. Food Eng.* **2007**, *79*, 243–248. [CrossRef]
39. Babalis, S.J.; Belessiotis, V.G. Influence of drying conditions on the drying constants and moisture diffusivity during the thin-layer drying of figs. *J. Food Eng.* **2004**, *65*, 449–458. [CrossRef]
40. Falade, K.O.; Abbo, E.S. Air-drying and rehydration characteristics of date palm (*Phoenix dactylifera* L.) fruits. *J. Food Eng.* **2007**, *79*, 724–730. [CrossRef]
41. Hashim, N.; Daniel, O.; Rahamann, E. A preliminary study: Kinetic model of drying process of pumpkins (*Cucurbita Moschata*) in a convective hot air dryer. *Agric. Agric. Sci. Procedia* **2014**, *2*, 345–352. [CrossRef]

42. Kadam, D.M.; Samuel DV, K. Convective flat-plate solar heat collector for cauliflower drying. *Biosyst. Eng.* **2006**, *93*, 189–198. [CrossRef]
43. Dhanushkodi, S.; Vincent, H.W.; Kumarasamy, S. Life cycle cost of solar biomass hybrid dryer systems for cashew drying of nuts in India. *Environ. Clim. Technol.* **2015**, *15*, 22–33. [CrossRef]
44. Swain, S.; Din, M.; Chandrika, R.; Sahoo, G.P.; Roy, S.D. Performance evaluation of biomass fired dryer for copra drying: A comparison with traditional drying in subtropical climate. *J. Food Process. Technol.* **2014**, *5*, 294. [CrossRef]