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Evaluation of Energy Performances of Solar Dryers

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A B S T R A C T

In solar drying, the moisture content of a product is reduced through the use of sunlight. Solar drying is practiced since civilization for the drying of crops. The dried crop has a longer shelf life and requires less storage space. For crop drying, hot air is required in the moderate temperature range of 40 to 75°C. Solar dryer makes it possible to obtain better product quality. Over the past 20 years, numerous experimental projects have been carried out in the field of solar dryers. Most conventional dryers are not able to operate continuously during the off sunshine time. However, attempts were made to develop uninterrupted solar drying systems by incorporating an energy storage facility and a hybrid mode of operation. Sensible and latent heat storage methods are widely used to store solar energy. Heat storage materials store energy in the form of heat during sunshine and release it whenever it is required. Biogas backup, Chemical heat pump, Photo Voltaic, and Fluidized bed methods were integrated with solar dryers for uninterrupted operation. In this article, the discussion is made about different dryers. Also, the challenges and scope in the area of the solar dryer are highlighted.

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INTRODUCTION

In 2018, according to the US Food and Agriculture Organization, 821 million people in the world were suffering from hunger [1]. The major causes of hunger are poverty, population, violence, gender discrimination and food waste [2]. In addition, the agricultural workforce is declining for socioeconomic reasons. It was found that the workforce reduced from 41 % in 1991 to 26 % in 2020, according to International Labour Organization Report. Therefore, the appropriate food supply chain management system must be developed to deal with hunger.

The 2011 report of the Food and Agriculture Organization showed that 1.3 billion tonnes of food are lost every year, as the Food and Agricultural Organisation reported. In developed countries, the loss of food occurs at the end stages, whereas in developing countries the loss occurs in much earlier stages [3] and the estimated loss of fruits and vegetables is 40 to 50 % of the total production [4]. With COVID–19 lockdowns in many countries, demand for fruits and vegetables has fallen and grown products have been wasted [5, 6]. The main problems associated with developing countries are non–mechanized farming techniques and inadequate systems to manage the food supply chain. According to the World Bank, agriculture is one of the main means of combating hunger. Unfortunately, the socio–economic situation of farmers in developing countries is not satisfactory and they do not have the means to buy costly equipment for their agricultural needs. Therefore, there is an urgent need to develop cost–effective techniques for the agricultural sector in developing countries. Solar drying is an economical method that can be used to dehydrate products at low cost.

The solar drying process, in its simplest form, is being carried out by spreading the products to be dried over a platform and the moisture evaporation takes place due to incident solar radiation and atmospheric airflow across the product layer. This method is known as the open sun drying process. The main problems associated with this process are the slowness of drying, the attack on animals and birds, contamination of products by dust, non–seasonal rains and uncontrolled drying [7]. Replacing open sun drying by solar dryers can reduce the above problems. Solar dryers are devices that use sunlight to

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deliver the controlled amount of heat needed for drying. Depending on the mode of heating, solar dryers are classified into three types, namely, direct mode solar dryers, indirect mode solar dryers, and mixed mode solar dryers. In the direct mode solar dryers, solar radiation is allowed to incident directly on the products to be dried whereas in indirect mode solar dryers, a separate solar collector is used to receive sunlight and provide heat for drying. In these dryers, the products are not exposed to direct sunlight. Mixed–mode solar dryers combine the features of the direct and indirect mode of dryers. Here, drying is carried out by direct incident solar light and heat supplied by the collector.

Research in the area of solar dryers has grown in importance and attention over the last 15 years, particularly in Asian and African countries. A wide range of solar drying systems has been developed by the researchers ranging from a dryer made of wood and glass to an advanced dryer with a temperature regulating system. Here an attempt is made to supply a complete review of recent developments on solar dryers.

Developments in the direct–mode solar dryers

For domestic and small–scale applications, direct mode dryers are generally developed using low–cost materials such as plywood, glass, and iron mesh [8, 9]. To achieve the air circulation employing natural convection, two to four inlet vents are provided at the bottom and a vent with approximately four times the diameter of the inlet vents is provided at the top. Such solar dryers are fixed structures and have great weight and it is difficult to provide the solar tracking system for optimal performance. Typical direct mode sun–drying systems with wooden shelves covered with transparent polythene sheets is shown in Figures 1 [10-12].

To improve the performance of solar thermal systems, it is recommended to use the slope optimization technique [13]. There are solar dryers in direct mode with slot clamp layout to adjust the slope of the dryer glass [14].

The direct mode solar dryers discussed so far are simple in design and fabrication, but associated with major problems such as fluctuating temperatures, slow process and limited use in the areas where bright sunlight is available. The average thermal efficiency of the direct mode dryers is about 20% to 25% with operating temperature range 40–60 ^{0}C.

A box type direct mode dryer with reflective mirrors was developed [15] as shown in Figure 2. The system can be used for drying and cooking.

Developments in indirect–mode solar dryers

It is well–known fact that the wide diversity is present among the food crops. The crops such as lemon, cucumber and papaya [16] are sensitive to the sunlight and the direct exposure to the sunlight causes significant damage to the crop. Therefore, indirect mode solar dryers are suitable for such photo–sensitive crops. An indirect mode solar dryer is generally developed by many researchers by using the gravels for the energy collection and storage [17]. An air gap of 25 cm is provided between the collector materials and glass cover. Two trays are commonly used in the drying chamber. The average thermal efficiency of this system is about 22% and the fluctuations in the air temperature are prevented by the heat absorption and release by the gravels. The dryer shown in the figure is capable of drying 40 kg chilly per batch.

Researchers at Tanta University (Egypt) developed an indirect–mode solar dryer with two collectors. The first collector is an aluminium absorption plate. The second one is also an aluminium plate with sand at the bottom side of the absorber plate [18]. The experimental results showed that the heat stored during the day provides the heat needed for overnight drying. The use of sand as a heat storage material was also reported to have shown no significant increase in thermal efficiency. An attempt was also made to improve the effectiveness of an indirect–mode dryer with evacuated tubes for energy collection and sensitive storage [19]. Gravels are used as sensible heat storage materials and these gravels absorb the heat from a hot air stream which comes from the evacuated tubes and release the heat during the off–sunshine hours. Experimental results indicate that the use of heat storage

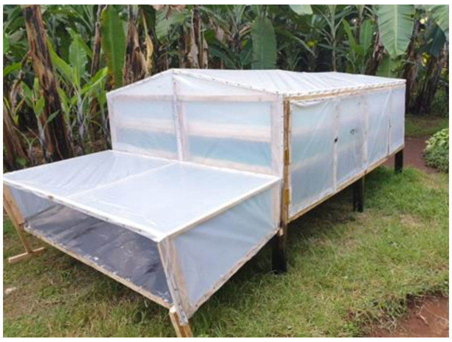

Figure 1. Direct mode dryer with wooden shelves and polythene cover

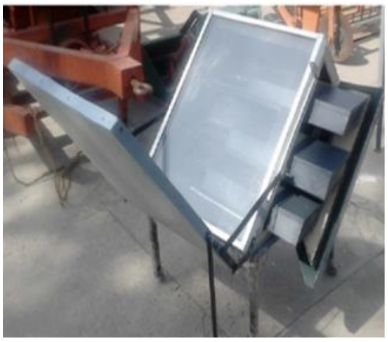

Figure 2. Solar dryer and cooker

materials results in high efficiency. To increase the amount of solar radiation incident on the collector, the reflecting mirrors could be used which further increases the overall efficiency and temperature gain. Use of fixed reflectors with a collector of the indirect mode solar dryer for the drying of the wafer, resulted in a significant increase in efficiency from 40% to 58.5% [20]. In addition, the heat increase can be achieved by providing extra U–shaped surfaces and V–shaped grooves in the absorbing plate [21-23].

Hot air entering the drying chamber of an indirect–mode dryer manifold should be evenly distributed for good quality dried products. A swirl element could be used to achieve this at the entrance of the dryer [24].

The efficiency of a solar collector can be improved due to increased turbulence. Nabi et al. [25] used turbulence induced elements and nano-fluids to enhance the heat transfer rate. Element shown in the case 3 given the higher turbulence. SWCNT–CuO/H_2O hybrid nano fluid exhibit the better heat transfer rate.

Ubale et al. [26] used evacuated tubes in the collector for grape drying. Easily available materials; aluminium alloy sheet, stainless steel and polyethylene foams were used. Experimental and drying kinetics analysis was performed. To reduce the moisture content from 76 % to 15 %, the drying time taken was 37 hours.

Phase change materials (PCMs) can also be incorporated with solar dryers in indirect mode, which increases the drying time after sunset from 5 to 8 hours. The important PCMs that can be used include paraffin wax and lauric acid [27-37]. Although the PCMs have higher energy storage density and are capable of providing air at a constant temperature [38], they are very expensive, in addition to the high cost associated with installing the heat storage systems. The choice of a specific type of storage method depends mainly on the temperature range, thermochemical properties and cost. Most of the researchers purposed rock bed heat storage techniques because of the lower cost and easy availability of rocks [39-43].

Developments in the mixed–mode solar dryers

The combined solar dryer combines the characteristics of the direct and indirect dryer. These dryers are more efficient than the two others due to the combined heating method. A mixed–mode dryer is essentially a drying cabin and a collector (air heater).

A mixed–mode drying system with galvanized sheet metal air collector has been developed for drying beans [44]. The air collector was covered in black to improve the absorption of incident radiation and rock wool insulation was provided to avoid heat loss to the environment. The maximum registered temperature was 61°C. The maximum and minimum manifold efficiencies were 61.82% and 45.4%, respectively. A similar type of mixed–mode dryers with copper and aluminium absorbing plates also has been reported in the literature [19, 45, 46]. Low–cost heat aborting materials such as pebbles were used in a mixed–mode dryer for drying chilly [47]. It is reported that the use of pebbles helped to avoid fluctuating hot air temperature with an intensity of solar radiation.

A mixed–mode dryer has a chimney–type drying booth [48]. The chimney arrangement reduces the moisture content of the cabin. In addition, the layout of the footboards was used to minimize the shading effects of the upper trays on the lower trays.

In most underdeveloped countries, proper recycling of automotive engine oil is not yet present and drained engine oil is barely burned or wasted. Using SAE 20/40 drained oil, a mixed–mode solar drying system has been developed. The system consists of a dryer cabin and a solar collector. The collector was filled with 20/40 drained SAE oil and the spiral–shaped aluminium tube was submerged.

A direct mode solar dryer with inverted absorber and reflector has been developed with a full bed. The packed bed stores the heat during the day and provides the heat for duration of the night [49].

To address the issue of intermittent solar energy and the continuous drying process, systems with biogas combustion and heat storage are developed. An indirect mode solar dryer with free convention was developed by using solar collector, thermal mass, and biogas burning unit and a chimney [50]. The experimental results have shown that the use of thermal mass helps to store the energy of solar radiation as well as the heat of the biogas burner.

A biogas heat storage and heating system has been developed to provide the warm air required for cold drying at a temperature between 55 and 60°C [51]. The system consists of a gasifier stove, heat exchanger, pebble bed, solar collector, and mixing chamber. Solar collectors supply the hot air during the daytime and heat is extracted from the pebble bed when the solar collector is unable to supply the required temperature. The heat supply for the pebble bed was provided by the gasifier as needed. A similar system was developed by incorporating direct combustion of biomass into the bottom of the drying chamber in a mixed–mode dryer [52]. The combustion chamber was built of bricks and direct combustion of biomass was performed whenever necessary.

For uninterrupted operation with constant air temperature hybrid dryers have been developed and few large hybrid dryers are discussed here. The solar heat pump system has been developed to dry maize [53]. The main components were the solar collector, heat pump and grain drum, and four modes of operation were performed. The energy required for drying was fully provided when a sufficient amount of solar radiation was available and the heat pump was used when solar radiation was not available. A combination of solar collector and heat pump was used when sunlight was less available and during high humidity conditions, dehumidification of the heat pump was used. The qualities of the dried product such as taste, color, odour and nutrients are significantly affected by the temperature of the drying air. They can be improved by supplying air at a steady temperature. A similar type of hybrid dryer for was developed for timber drying [54]. A hybrid drying system with heat pump and solar heat collectors has been developed at the National University of Malaysia [55].

The purpose of the solar thermal collector was to supply the energy necessary for the operation of the system and to collect heat during the hours of sunshine. The heat collected in the collector was provided at night or when the available sunlight is insufficient. The aluminium rods and fins were inserted into the vaporizer and condenser to increase the rate of heat transfer to the airflow. Similar type solar–assisted chemical heat pump dryer was developed [56]. The system mainly consists of three interconnected circuits; a solar energy collection and storage circuit, a solid gas circuit to transfer the stored energy, and a drying air circuit to remove the moisture from the products to be dried. If the required temperature value is not reached during cloudy conditions, the auxiliary heating supplies the energy to the drying air flow.

A solar–powered biomass dryer with fluidised bed was developed for rice drying [57]. The main parts are: solar collector, biomass oven, fluidized bed. An air distribution system was used at the base of the fluidized bed to provide uniform distribution.

An attempt was made to incorporate the geothermal system with the dryer [58]. The dryer receives energy in the form of incident light during sunny hours. To extract geothermal heat, a heat exchanger is provided in the drying chamber.

For the drying of a large number of commodities, solar greenhouse dryers are used. These dryers consist of a concrete floor or shelves coated in polycarbonate sheets. A solar greenhouse PV ventilation dryer has been developed for drying peppers [59]. The system consisted of a 5.5×8.0 m^2 concrete floor covered with polycarbonate sheet and three fans were used for the air circulation. The PV panels provide the power needed by the fans. The loading capacity for the system was between 100 and 150 kg per lot. Results showed that the higher drying temperature was achieved throughout the drying periods with low relative humidity and the heat absorbed by the concrete floor was emitted during the night time [49]. Figure 3 shows a tunnel type of dryer dryers.

A numerical investigation was conducted on the solar greenhouse dryer for the drying copra [53] and the model used during the analysis. Compaq Visual FORTRAN version 6.5 software was used for the analysis. It was observed that the air temperature inside the greenhouse was higher than the ambient temperature throughout the drying periods. A similar type of experimental, simulation and thermal analysis was conducted on the greenhouse dryer by using banana, peeled Logan, and copra as the test samples [60, 61].

Figure 3. Tunnel type dryer

Selection of solar dryers

It is a well–known fact that the properties of food crops vary significantly from one crop to another and the selection of solar dryers for the drying of a specific product depends on many factors. Visavale [62] recommended the parameters given in Table 1 for the selection of dryers.

CONCLUSIONS

In this review, a comprehensive study of various solar dryer designs has been carried out. The main operational challenges associated with conventional solar dryers are the intermittent nature of solar energy and the lack of uninterrupted energy supply. The operational time of the solar dryer can be improved by incorporating the sensible and latent heat storage materials. The use of a backup facility for the combustion of biogas allows the dryer to function during rainy days. Hybrid systems such as chemical heat storage and heat pump–assisted solar dryer are able to deliver uninterrupted energy without large fluctuations in air temperature.

Practical challenges associated with solar dryer are; uninterrupted operation is difficult due to intermittent sunlight, blanketing of glass cover due to evaporated moisture, shading effect of upper trays on lower trays, difficult to maintain constant temperature. Further research work is necessary to address these issues. Solar

Table 1. Dryer selection parameters

Sl. No.	Parameters	Features
1	Physical features of the dryer	Type, size, and shape Collector area Drying capacity
2	Thermal performance	Solar insolation Drying time/drying rate Dryer/drying efficiency Drying air temperature and relative humidity Airflow rate
3	Properties of the material being handled	Physical characteristics Acidity Corrosiveness Toxicity Flammability Particle size
4	Recovery problems	Dust recovery Solvent recovery
5	Facilities available at the site of the proposed installation	Temperature, humidity, and cleanliness of the air Available fuels Permissible noise, vibration, dust, or heat losses Source of wet feed Exhaust–gas outlets
6	Drying characteristics of the material	Type of moisture Initial moisture content Final moisture content Probable drying time for different dryers
7	The flow of material to and from the dryer	Quantity to be handled per hour Continuous or batch operation Process before drying Process after drying
8	Product qualities	Shrinkage Contamination Uniformity of final moisture content Decomposition of product Flavour Bulk density
9	Economics	Cost of dryer Cost of drying Payback
10	Other parameters	Operator requirements Safety Reliability

dryer would be made smart by embedding sensors and Internet of Things (IoT).

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Persian Abstract

چکیده

در خشک کردن خورشیدی، رطوبت یک محصول با استفاده از نور خورشید کاهش می‌یابد. خشک کردن خورشیدی از زمان تمدن برای خشک کردن محصولات انجام می‌شود. محصول خشک شده ماندگاری بیشتری دارد و به فضای ذخیره سازی کمتری نیاز دارد. برای خشک کردن محصول، هوای گرم در محدوده دمایی متوسط ۴۰ تا ۷۵۰ درجه سانتی‌گراد مورد نیاز است. خشک کن خورشیدی به دست آوردن کیفیت بهتر محصول را ممکن می‌سازد. در طول ۲۰ سال گذشته، پروژه‌های آزمایشی متعددی در زمینه خشک‌کن های خورشیدی انجام شده است. اکثر خشک‌کن های معمولی قادر به کار مداوم در زمان خاموش بودن آفتاب نیستند. با این حال، تلاش‌هایی برای توسعه سیستم‌های خشک‌کن خورشیدی بدون وقفه با ترکیب یک تأسیسات ذخیره‌سازی انرژی و یک حالت عملکرد ترکیبی انجام شد. روش‌های ذخیره‌سازی گرمای محسوس و نهان به طور گسترده‌ای برای ذخیره انرژی خورشیدی استفاده می‌شود. مواد ذخیره‌سازی گرما انرژی را به صورت گرما در هنگام تابش خورشید ذخیره می‌کنند و هر زمان که نیاز باشد آن را آزاد می‌کنند. روش‌های مکمل و پشتیبان بیوگاز، پمپ حرارتی شیمیایی، فتوولتائیک و بستر سیال با خشک‌کن‌های خورشیدی برای عملکرد بی‌وقفه ادغام شدند. در این مقاله در مورد خشک‌کن های مختلف بحث شده است. همچنین، چالش‌ها و دامنه در ناحیه خشک‌کن خورشیدی برجسته شده است.