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Solar Tunnel Drying System: A Literature Review

Sistem Pengeringan Terowongan Surya: Sebuah Kajian Pustaka

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Abstract

Production, productivity, and area under production from fruits and spices are gradually increasing. Improper processes of freshly harvested spice and fruit products will make them undergo qualitative deterioration with each passing hour. This deterioration is more pronounced in high humid areas. Drying process in one or the other form is essential. Freshly harvested spices and fruit products in average contain more than 80% moisture. The commodities need to be dried to have a moisture content below 10% in the shortest possible time for safe storage. Drying process in most cases are accomplished by the open sun. Meanwhile, the environmental condition in solar tunnel drying is enclosure type and the product is protected from rains, dust, insects, and rodents. Solar tunnel drying, a widely used bulk dryer, facilitates faster drying than open drying by virtue of the greenhouse effect. Commercial cultivators by and large choose faster drying methods using wood and fossil fuel-fired heating sources. This study attempts to review recent advances of various designs and working of the greenhouse drying system in totality, like auxiliary drying during off-sun hours, bulk drying feasibility, ease in loading and unloading along with an analysis of key features and economics involved.
Keywords: auxiliary drying, greenhouse drying system, processing

Abstrak

Produksi, produktivitas dan luas areal produksi buah-buahan dan rempah-rempah meningkat secara bertahap. Produk rempah dan buah yang baru dipanen akan mengalami penurunan kualitas seiring waktu berjalan jika tidak diproses dengan benar. Kerusakan ini lebih terlihat di daerah dengan kelembaban tinggi. Pengeringan dalam satu atau bentuk lain penting dalam pemrosesan. Rempah-rempah dan produk buah yang baru dipanen rata-rata mengandung lebih dari 80% kelembaban dan perlu dikeringkan hingga kelembabannya di bawah 10% dalam waktu sesingkat mungkin untuk penyimpanan yang aman. Pengeringan ini dalam kebanyakan kasus dilakukan dengan sinar matahari terbuka, sedangkan kondisi lingkungan pengeringan terowongan surya adalah tipe tertutup dan produk terlindungi dari hujan, debu, serangga dan hewan pengerat. Pengeringan terowongan surya merupakan pengering kapasitas besar yang banyak digunaka. Pengeringan dengan alat ini lebih cepat daripada pengeringan terbuka berdasarkan efek rumah kaca. Pembudidaya komersial pada umumnya memilih metode pengeringan yang lebih cepat yang menggunakan kayu dan sumber pemanas berbahan bakar fosil. Studi ini bertujuan untuk meninjau kemajuan terkini dari berbagai desain dan cara kerja sistem pengeringan rumah kaca secara keseluruhan, seperti, pengeringan tambahan di malam hari, kelayakan pengeringan kapasitas besar, kemudahan dalam bongkar muat, serta analisis fitur utama dan ekonomi.
Kata kunci: *pengeringan bantu, pengolahan, sistem pengeringan rumah kaca*

INTRODUCTION

In the rural landscape of a third world country like India, the production catchment of all field and horticultural crops has virtually no or very erratic power supply scenario; hence use of electrical heating, and motorized fans are not possible for agricultural drying activities. In general, farmers are reluctant to use expensive fossil fuel dryers for minimal processing of their produce. In most cases, farmers resort to open sun drying, which is virtually dependent on a bright sunny day and labor. Open sun drying is generally accompanied by some limitations like inadequate drying, over-drying, fungal infestation, loss due to rodents, loss due to unexpected sudden rains, to name a few. The most important two limitations are the long time required for drying to bring the moisture content to the desired level and the second is the labor required on a daily basis to spread and gather the drying commodity.

The problem of drying high-value spice crops like ginger, turmeric, and black pepper is even more. These products are subjected to blanching, followed by dehydration or drying to ensure protection from fungal and bacterial growth. After proper drying at a temperature below 600 °C, essential oil and other essential ingredients of the spices are retained and results in fetching a higher price for that commodity. Moreover, properly dried products are suitable for storage, transportation, and remain tradable for a longer duration. Open sun drying of these products is associated with problems like reducing essential oil compounds due to direct exposure to sunlight, long drying period, and contamination by animals, rats, insects, and miscellaneous materials like dust. Direct exposure to solar radiation damages the preferred combination of color, texture, aroma, and degenerates the ability to rehydration dried products (Gallali, Abujnah, & Bannani, 2000; Murthy, 2009).

North-East India has large production areas of quality ginger, turmeric, black pepper, and numerous minor fruits possessing health benefits. The climatic conditions of these areas are highly humid, thereby influences the process of drying. Moreover, harvested products must be dried to their moisture balance for safe storage. In such climates, deterioration of freshly harvested spices is highest, as both warmth and high moisture content are accompanied by fungi, bacteria, mites, and insects. So proper drying is difficult to accomplish (Jha & Deka, 2012).

The main aim of drying is to reduce the moisture content of the product to a degree that prevents degradation within a specific time period, usually called the "safe storage period”. Drying comprises two processes. First, heat transfer from the heat source to the product. Second, mass transfers from the inside to the product surface and from the surface to the surrounding air in the form of a moisture transfer. The transfer of moisture from the product to the encompassing is affected by heating and the discharged vapor was carried away by the sectioning of the air mass around it. This process is repeated until the moisture vapor pressure in the product reaches the environmental pressure. The rates of moisture removal from the product to the environment and ingestion from the environment are in equilibrium. At this point, the content of crop moisture is known as the equilibrium moisture content. The drying process is moderate under atmospheric conditions in northeast India and the equilibrium moisture content for safe storage is higher in environments with high relative humidity (Ekechukwu, 1987; McLean, 1989). Tropics or subtropics, such as North East India, are characterized by hot and humid climates. Ambient air relative humidity is too high for drying, and the need for more efficient commercial drying methods is practically determined.

METHODS

In view of the above factors, a protected type of drying is required where expedited moisture removal can be achieved by virtue of solar energy without being directly exposed to direct sunlight and safe from untimely rains, animals, rodents, flies, and dust. Solar tunnel dryer, a type of greenhouse dryer, is one such type of dryer. Different researchers have contributed to the development of different dryers. This type of dryer is based on the concept of the greenhouse effect of heating the microenvironment.

The method of study adopted is a meta-analysis of a journal published data by various researchers in the field of greenhouse energy drying systems under different agro-climatic situations drying various agricultural produce. The analysis is mainly focused on drying parameters and mass flow rate. In addition, economic analysis, quality of dried products, and ease of loading and unloading, if reported by the author, are also analyzed.

Solar dryers are capable of overcoming most of the shortcomings of the usual drying system by capitalizing on the thermal component of solar energy. The purpose of the dryer is to provide the product with more heat than is available under atmospheric circumstances, thus significantly increasing the vapor pressure of the moisture found inside the crop and significantly reducing the relative humidity of the drying air and thereby improving its carrying ability for moisture. Different researchers have contributed to the development of various solar dryers. Most published greenhouse dryers are of a batch type, and the suitability of these dryers for commercial bulk drying needs to be analyzed. On the one hand, greenhouse drying systems can circumvent the shortcoming of usual solar dryers; however, its applicability in achieving the drying needs in high humid production catchment of northeast India will be one of the objectives of this study. This paper is an endeavor to review the work done specifically on greenhouse drying system in removing shortcomings like the difficulty of bulk drying in high humid regions, sluggish rate of drying and energy efficiency in accomplishing improved quality of dried products, difficulty in product loading and unloading and uninterrupted minimum drying during non-sunny hours.

RESULTS AND DISCUSSION

Earliest Greenhouse Dryers

The earliest concept of a practical non-dryer greenhouse was done by the Brace Research Institute (Lawand, 1977). The greenhouse (Figure 1) was oriented east-west with a transparent slanting roof (5.49 m) and a vertical wall (1.53 m) on the southern side. The northern wall was slanting and insulated to prevent heat loss. This greenhouse was designed to have the highest transmittance of solar radiation and maximum reflection of radiation on the crop canopy. These practical greenhouses laid the foundation of the modern-day greenhouse dryer.

In the initial years, passive greenhouse dryers were polythene-tent type dryer (Doe, Muslemuddin, & Sachithananthan, 1977). The solar tent dryer developed was initially tested in Bangladesh for drying fish. Later on, this dryer was tested in Africa, SE Asia, and Latin America to produce various dried fish products with considerable good performance. The drier (Figure 2) was constructed of a ridged bamboo frame covered on the sun-facing side and at the ends with a transparent polyethylene sheet. The rear surface was clad with a black polyethylene sheet, which was also spread across the floor to enhance solar radiation absorption. The cladding at one-end was arranged to provide entry to the drying chamber. The transparent plastic cladding at the bottom edge of the front was rolled around a bamboo pole, which could be adjusted to regulate the passage of air into the chamber, whilst the vents at the top of the ends were used as an outlet for the moist exhaust air.

Exell (1980) designed a mixed-mode natural-circulation tray type, bulk rice solar dryer (capacity 0.5 ton) at the Asian Institute of Technology, Bangkok. The dryer (Figure 3) was a mix of the direct and indirect types. The device consists of a solar-powered air heater, a rice bed, and a reasonably high chimney, which gives a higher buoyancy and better performance. The air radiator's absorber is comprised of a thick layer of rice husks secured by a transparent plastic sheet on a slanted structure.

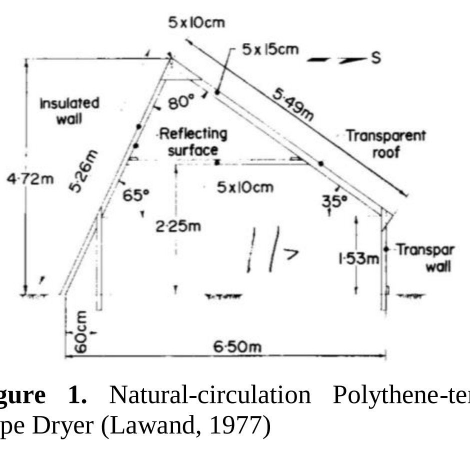

Figure 1. Natural-circulation Polythene-tent Type Dryer (Lawand, 1977)

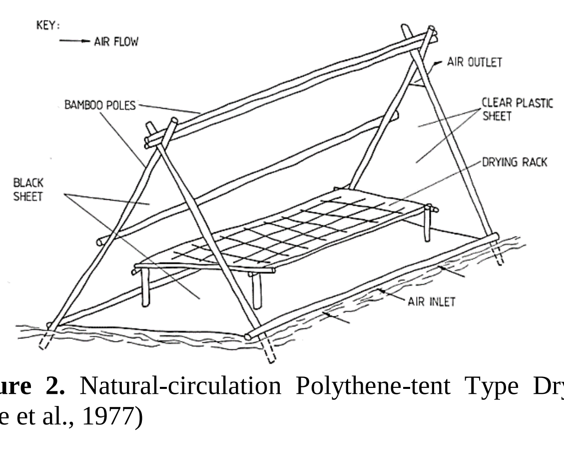

Figure 2. Natural-circulation Polythene-tent Type Dryer (Doe et al., 1977)

Some practical innovation of natural-circulation solar-energy based greenhouse dryers have been reported by Sadykov & Khairiddinov (1982), Shaw (1981), Muthuveerappan et al. (1985), and Yang (1980). Yang's design was a passive solar kiln for timber drying. The drying rate was reported to be faster twice times in winter and nine times in summer than in the open-air. The average daily maximum temperature of the kiln in July (tests performed in Ontario Canada) was 49.40 °C relative to the average temperature of the ambient air of 20.30 °C. (Figure 4).

The solar dome dryer (Figure 5) reported by (Sachithananthan, Trim, & Speirs, 1983) was another fish-drying greenhouse of a transparent plastic sheet over a dome-shaped metal frame. The black galvanized sheet of iron was used as a floor absorber. Inlet vents were mounted along the entire length of both sides at the base and the outlet vents at the top of the dome. In order to prevent insects and dust, outlet vents were attached with fine plastic netting. The plan by Ayensu & Asiedu-Bondzie (1986) consists of a mixed mode of natural-circulation air heater with a heap of stone as an absorber cum thermal storage in plate solar dryer, protected from the ground by an approximately 5 cm thick straw layer.

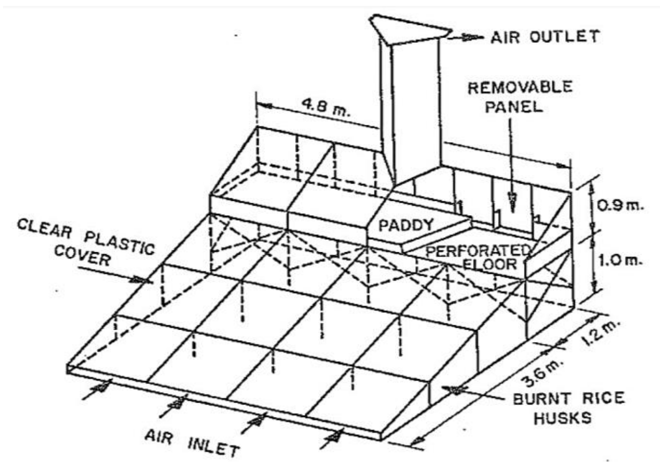

Figure 3. Mixed Mode Half Ton Rice Dryer at Asian Institute of Technology, Bangkok (Exell, 1980).

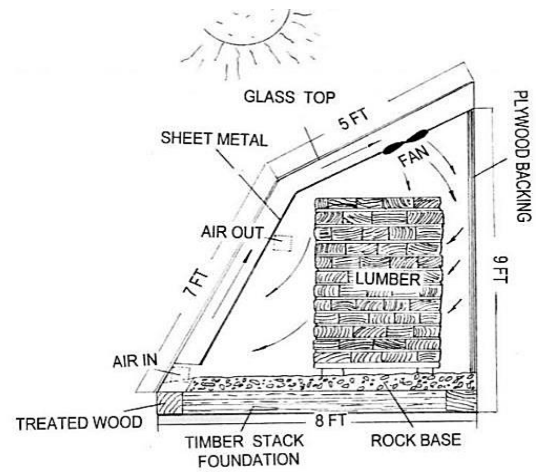

Figure 4. Greenhouse Type Solar Kiln for Lumber Drying (Yang, 1980).

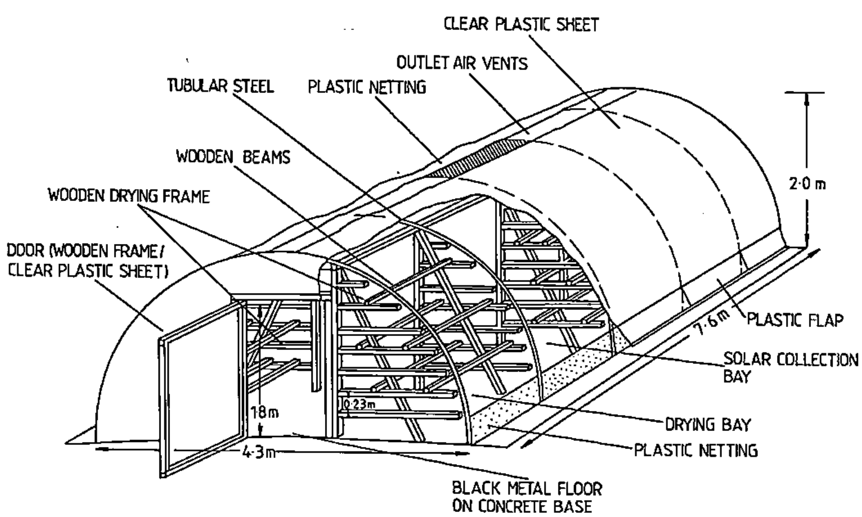

Figure 5. Natural Circulation Solar Dome Dryer (Sachithananthan, Trim, & Speirs, 1983)

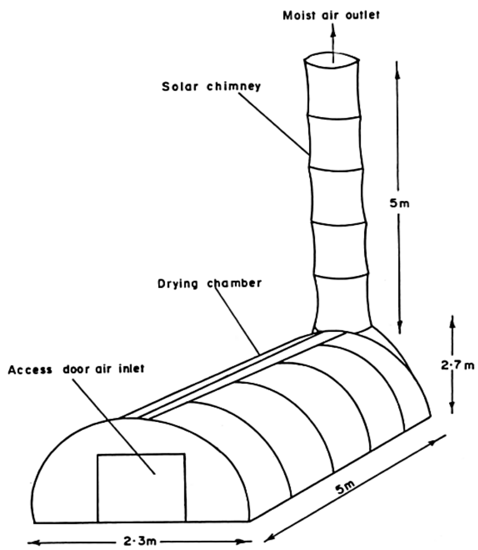

Figure 6. Greenhouse Natural Convection Solar Energy Dryer (Ekechukwu & Norton, 1997)

An improved greenhouse-type naturally ventilated sun-powered dryer explored by Ekechukwu & Norton (1997) consists of a semi-round drying compartment made of polythene attached to a round shaped chimney rising vertically to one end, while the opposite end is equipped with an entrance passage to load drying load and fresh air (Figure 6). Measurement of the drying chamber quantifies roughly 6.67 m long, 3.0 m wide, and 2.3 m high. The round air outlet, built from steel, contains a vertically hung, dark engrossing curtain inside the dryer. The dryer operates through the sun's heat dropping on the product within the dryer, and no extra power source is required to run it. The product and the vertically hung curtain inside the round air outlet take up solar radiation and heat up. The encompassing inside air is warmed up too. The warm air is lighter, rises and moves up the round outlet to the outside of the dryer. Fresh renewing air is drawn from the opposite end of the dryer, which is also the gateway.

For a rural farm located in a country like ours, passive solar-energy dryers are more preferred over the active ones because of their simplified built up and operation, low cost and plausibility of mass drying. Its significant disadvantage is its susceptibility to damage under extremely high wind speeds.

Solar Tunnel Drying Systems: A Review

Seveda (2012) reported the performance of solar tunnel dryer for bulk drying of dibasic calcium phosphate for industrial use in summer and winter months in the state of Rajasthan. The drying results were shown in terms of the variation of ambient air temperature, solar radiation, relative humidity, and airflow rate. The economics of using a solar tunnel dryer compared to the diesel-run mechanical dryer was worked out. The benefit-cost ratio was found to be 3.06, and the payback period was two years and five months.

Saravanapriya & Mahendiran (2017) reported about the bulk drying of coconut in a solar tunnel drier at Coimbatore in Tamilnadu. The designed capacity of heat required for drying coconut in this dryer was the summation of the sensible heat of product, the sensible heat of the water in the product, and latent heat of vaporization of water. Gross heat required is calculated considering heat loss. Gross heat Q of air is a product of airflow rate G in kg/hr, humid heat of the ambient air inside the tunnel, temperature difference (between air inlet and outlet), and drying time. Humidity sensors inside the dryer regulate the fan below the chimney for the forced evacuation of hot, humid air. These dryers are basically natural convection type but become forced convection with the triggering of the humidity sensors.

Bhardwaj, Kumar, & Chauhan (2019) reported the result of an indirect type of solar dryer with an integrated mechanism of sensible heat storage in the air inlet and phase conversion material (PCM) in the drying chamber. Iron scrap combined with gravel is mounted on the absorber plate, and copper tubes made up of engine oil have been used as SHSM (Sensible Heat Storage Media) in the solar collector. Collector air temperature was found to be 27.66 °C more than the ambient temperature. Paraffin used as phase conversion material in the drying chamber absorbs the excess heat during daytime and continues drying up to 6 hours after sunset. The use of these materials also increases the drying rate.

A systematic review of greenhouse solar tunnel drying systems, tested and as reported by different researcher have been analyzed and presented in Table 1, as mentioned in materials and methods. A tabular representation compares different parameters of various dryers with mentionable unique features grouped under column “others”.

Table 1. Systematic review of solar energy drying systems with more on the functioning of greenhouse energy dryers

Author(s) and *Place of Experiment*	**(Pawar, Takwale, & Bhide, 1995)** ***Pune, Maharashtra, India***	**(Abdullah & Mursalim, 1997)** ***Bogor, Indonesia***
Drying Time/Rate	There are three drying cabinets, each has 30 trays. One tray can hold 2.75 kg of custard powder. 225 kg of custard dough with a thickness of 3 cm. The moisture content of dough was 35% which was to be reduced to 10.55% by solar heated air blown through the drying cabinet in 4 hours.	Average time for drying curved cylindrical shaped vanilla pods (average diameter was 5 cm and the length was 16 cm - 17 cm) with an initial moisture content of 82.6% wb was brought down to 37.9% wb in 49 to 53.5 hours.
Drying Temperature	Air was heated in a solar array comprising of glazed top insulated bottom and an absorber plate in middle. The temperature of the drying air on average was 20 °C more than the ambient.	Drying air temperature 33 °C – 65 °C.
Air Flow Rate	Airflow was 0.533 m/s, and mass flow was 0.57 kg/s. Using a 2500 -3000 kg/h blower capacity. From the solar collector array, the blower takes in the hot air through the air ducts.	0.6 kg/s. Air handling system consisted of a 740 W, 1420 RPM axial blower connected to a Pressure Differential Inducer (PDID) exhaust pipe system. Specified primary airflow rate was maintained throughout the experiment.
Drying Capacity (kg)	225 kg x 2 starch rich custard dough per batch.	46.5 kg fresh vanilla in the first experiment & 52.4 kg in the second experiment
Test Quality of Dried Product	After colouring and flavouring, custard powder was dried at to a moisture content of 10.55% at 25 °C (i.e. equilibrium moisture content)	Dry products were grade 1A of export quality level
Parameters of Energy Consumption for Drying	Around 62.5 kg of water from 225 kg of custard dough should be evaporated by solar drying. The heat transfer to the dough was 51.25 kWh (assuming the vaporization water was 0.82 kWh/kg).	The average solar radiation was 516 w/m^2 for the first and 444 w/m^2 for the second test. Four coal stoves with an average combustion rate of 0.3 kg/h (6.l kW) were installed within the chamber. Coal consumption for the experiment was 58 kg.
Benefit Cost Ratio / Payback Period	Not available	Not available
Temperature and RH Air (Inside and Outside)	The ambient temperature was 30 °C and the average temperature increase inside the dryer was 22 °C. The exit air has low relative humidity and high temperatures during the important part of bright sun shine hours, indicating low drying efficiency. Low drying efficiency may be due to high airflow.	Average inside temperature was -43.3 °C. Average inside RH was -34.9%
Loading and Unloading Convenience	After the blower was turned off, the custard dough was filled and custard powder was discharged from the drying cabinet trays.	Vanilla pod was) was loaded into 7 trays (0.9 m x 1 m) within the cabinet
Others	Thermal efficiency of performance test data was 40%. The incident power must be 100 kWh to extract 40 kWh of energy. In order to supply 12.81 kWh, 32.02 kWh of energy should have an incident on the collector. The data for solar radiation at Pune was 0.63 kWh/m^2. The total area required for 32.02 kWh of solar energy was therefore 50.8 m^2. The area of one single module was 1.5 m^2, so there will be 34 total collectors. Taking heat loss into account, the total collector was 40.	Laboratory greenhouse type solar dryer (3.5 m x 3.5 m) was evaluated to dry vanilla pods. Auxiliary heating during the night and cloudy day was with coal stoves done inside the chamber. Aside from the sensible heating of the stoves all the combustion heat was transmitted to the drying air

Table 1. Systematic review of solar energy drying systems with more on the functioning of greenhouse energy dryers (Continue)

Author(s) and ***Place of Experiment***	**(Condorí, Echazú, & Saravia, 2001)** ***Buenos Aires, Argentina***	**Hosain and Bala (2007).** ***Mymensingh, Bangladesh***	**(Ayyappan & Mayilsamy, 2010)** ***Coimbatore, Tamil Nadu, India***
Drying Time/Rate	Longitudinally sliced sweet pepper, 80% of the weight was lost within the first day. The mean drying period for garlic to reach moisture content less than 10% was three days with good radiation.	Red chili moisture content decreased from 2.85 to 0.05 kg/kg db in 20 hours of sunshine in solar tunnel drier.	Copra's moisture content decreased from 52.2% to 8% in 57 hours under maximum load and 52 hours in half load.
Drying Temperature	Without load during sunny days. Maximum temperature was near 60 °C and Relative Humidity (RH) was 15%. Drying air temperature was 25 °C more than ambient (mid-day). Difference of a few degrees during night	Average air temperature increase over ambient air temperature at the outlet of the collector was found to be 21.62 °C during solar chill drying.	Max temp in top tray – 67 °C (during peak sunshine hours) Lowest temperature – 35 °C (off sunshine hours and nights)
Air Flow Rate	The drying chamber is divided into 2 compartments. The product in one and the fresh product in the other was partly dried. The air is circulated from the first to the second chamber by two fans.	A 40 W solar module is installed to power the fan in the inlet that supplies the product with air.	0.3 m/s – 1 m/s
Drying Capacity (kg)	300 kg of fresh sweet pepper	80 kg of red and green chilies	5000 kg of coconut dried per batch
Test Quality of Dried Product	Moisture content was obtained less than 10%	The average colour value of the open sun dried chili is significantly lower than that of the solar tunnel.	Dryer produced high quality copra (Milling grade was 1, 85%)
Parameters of Energy Consumption for Drying	When the product is dried in the first chamber, the air circulation is reversed and the new fresh product is loaded in the second chamber. Better energy efficiency was obtained.	Drier consists of a plastic sheet covered with a flat plate solar air heating collector (20 m x 1.80 m), a single DC fan (40 W). It is independent of the electrical grid.	Not available
Benefit Cost Ratio / Payback Period	Not available	Not available	Average thermal efficiency was found to be 20% and the payback period was 2 years.
Temperature and RH Air (Inside and Outside)	Not available	The temperature of the ambient air during the drying time (February–April) ranged from 20 °C to 35 °C while the temperature of the air inside the dryer varied from 40 °C to 66 °C.	Average humidity inside dryer was 30% compared to 60% under ambient condition.
Loading and Unloading Convenience	Wheeled carts system, with continuous product loading and discharge facility, improves its handling and reduce labour requirement.	One end of the plastic sheet was fixed to a metal tube in the drying machine, allowing the plastic sheet to be rolled up and down to load and unload the dryer.	By the door in the east of the tunnel
Others	An auxiliary heating system was introduced. The ambient air was drawn directly from the outside and forced into an un-finned tubular heat exchanger by the fans, where the combustion gas circulating within the tubes indirectly heats it. Hot gas was produced by a forced-flow stove, fed with firewood or Agricola surplus.	This dryer has shortened drying time considerably compared with conventional sun drying. Products that were dried in this drier were of higher quality than sun-dried conventionally. The dryer can be installed using locally - sourced materials.	Inside dryer cement flooring was painted black. Two exhaust fans, front and back. Three exhaust vents with butterfly at the top. Drying rate in lower tray was 2% lesser than upper tray.

Table 1. Systematic review of solar energy drying systems with more on the functioning of greenhouse energy dryers (Continue)

Author(s) and *Place of Experiment*	**(Rathore & Panwar, 2010)** ***Udaipur, Rajasthan, India***	**(Dulawat & Rathore, 2012)** ***Nathdwara, Rajasthan, India***	**(Seveda, 2012)** ***Udaipur, Rajasthan, India***
Drying Time/Rate	In a solar tunnel dryer, 320kg of grapes were dried from 84.4% to 16.2% wb in seven days.	500 kg tobacco requires 8 hours of drying using forced convection mode of drying.	Drying rate 0.035 kg/hr. Drying time 2 days.
Drying Temperature	Inside air temperature varied from 45 °C - 50 °C at 9:30 a.m. to 55 °C -60 °C at 2:30 p.m. against solar insolation of 400 W/m^2 to 950 W/m^2 respectively.	Temperatures inside the dryer were around 18 °C - 20 °C higher than the ambient temperature during no-load, without flat plate collectors, meanwhile, the temperature was 28 °C higher with flat plate	Temperature goes up to 63 °C
Air Flow Rate	Chimneys were provided on the top of the dryer to produce natural draft within the dryer, which works by increasing the buoyancy force to support airflow in the natural draft.	Incoming air through 12 flat plate collectors 2 m × 1 m. The air was pushed over the products by two exhaust fans with a capacity of 1 kW of duct size of 450 mm at either end of the tunnel.	A 2%-3% slope along the tunnel length and a 0.75kW exhaust fan of 1.500 m^3/h flow rate given for maintaining preset level humidity.
Drying Capacity (kg)	The system consists of a 10 x 3.75 m^2 system with rotating level trays that can hold 320 kg of grapes.	500 kg of tobacco	1,500 kg Dibasic calcium
Test Quality of Dried Product	Good quality raisins with a moisture content of 16% were obtained.	Tobacco was dried to 8.7% with an initial moisture content of 138% db.	Dibasic calcium phosphate for industrial use, initial moisture content of 62.87% db to a final moisture content of 10.62% db
Parameters of Energy Consumption for Drying	Incident solar radiation was trapped inside a transparent ultraviolet stabilized sheet. Grapes absorbed heat from heated air and direct solar radiation. The heat evaporated grape moisture.	Tunnel dryer using greenhouse type solar heating system and air inlet through 12 flat plates.	Solar collector area of 134.74 m^2. Global solar radiation I = 5.5 kWh/m^2
Benefit Cost Ratio / Payback Period	Not available	Not available	With dibasic calcium B.C ratio was 3.06 and the payback period was found to be 29 months
Temperature and RH Air (Inside and Outside)	The temperature difference between the ambient and the dryer from 9:30 a.m. to 15:30 p.m. ranges from 12.2 °C –27.5 °C.	The maximum temperature inside the tunnel was 60 °C at 1:00 p.m. while the minimum temperature inside the tunnel was 26.3 °C at 8:00 a.m. in April. This is the natural convection mode under no load.	The temperature of the air inside the solar tunnel dryer was 18 °C –21 °C higher than outside.
Loading and Unloading Convenience	Loading and unloading was carried out through the door on the east side of the tunnel dryer. It is a walk through type of dryer.	The door of 1.60 m to 0.75 m was provided at the upper end of the tunnel for loading and unloading.	The upper end of the tunnel was equipped with 1.6 m x 0.75 m door to load and unload the material.
Others	It took more than 11 days to dry in the open sun drying. Whereas, it was in tunnel dryer for about 7 days. Applying suitable pre-treatment will further reduce the period.	Air inlet was through the flat plates. Thus there was an increase in inlet air temperature. No load forced convection mode was marked by flat plate as inlets and exhaust fans as outlets with no loading.	Walk-in type hemi cylindrical solar tunnel dryer with northern wall glass wool sandwich cover to avoid heat loss. The number and size of the chimney was determined by the amount of moisture removed on a day and requirement of the drying rate

Table 1. Systematic review of solar energy drying systems with more on the functioning of greenhouse energy dryers (Continue)

Author(s) and ***Place of Experiment***	**(Kaewkiew, Nabnean, & Janjai, 2012)** ***Nakhon Pathom, Thailand***	**(Saravanapriya & Mahendiran, 2017)** ***Coimbatore Tamil Nadu India***	**(University of Hohenheim and the company Innotech (Hoedt, n.d.))** ***Stuttgart Germany***
Drying Time/Rate	500 kg of chili with an initial moisture content of 74% wb were dried to 9% wb in 3 days	0.042 g of moisture per g of dry matter. Drying time is 49.5 hours compared to 80 hours in open drying	7 mm thick product requires 7 sunny hours
Drying Temperature	Maximum temperature inside the dryer is 55 °C - 60 °C against an ambient temperature of around 30%	Temperature goes up to 65 °C. Maintained at 55 °C.	56 °C
Air Flow Rate	The air speed at the dryer inlet and outlet was recorded during the drying experiments.	23.3 m^3/min	40 to 50 m^3/h for every m^2 of absorber area
Drying Capacity	500 kg	1000 kg	300-500 kg
Test Quality of Dried Product	The colour of dried chilies in the solar dryer was better than sun-dried samples.	Coconuts dried from moisture content of 110.5% db to 7.36% db	Solar panel to run inlet fan
Parameters of Energy Consumption for Drying	Solar radiation ranges from 400 W/m^2 at 8:00 a.m. to 820 W/m^2 at 12:00 p.m.	Solar intensity 33W/m^2 to 993W/m^2	Not available
Benefit Cost Ratio / Payback Period	The dryer's construction and installation cost was estimated at USD 25,900. Payback period is 2 years.	Not available	Not available
Temperature and RH Air (Inside and Outside)	Temperature in 41 different positions were collected. At 5 locations temperature vary within a narrow band were considered.	Ambient temperature 23.8- 30.7 °C and RH 50-90%. Inside temperature 31 - 65 °C, RH 40% lesser.	Not available
Loading and Unloading Convenience	Door located in one end of the dryer (near the base inlet slots) is used for loading and unloading.	By door in the East. Using trolley with wheels.	By unfolding the transparent cover. Easy attachment of transparent cladding material by plastic screws.
Others	The dryer consists of a polycarbonate sheet shaped parabola roof structure on a concrete floor. The dryer has 9 DC fans powered by three 50 W solar cell modules in the wall opposite the 2 air inlets.	Semi-cylindrical solar tunnel dryer covered with a UV-stabilized polyethylene sheet. The dryer relative humidity was controlled using exhaust fans in the chimneys with control system	Solar dryer platform at waist height. Half covered portion is absorber and other half drying chamber.

CONCLUSIONS

A comprehensive review has been carried out of the different designs of greenhouse energy dryers appropriate for drying horticultural products and spices. Evaluations were carried out on specifics of construction and operating concepts of a broad range of technically realized designs directly tailored to tunnel dryers of the greenhouse energy type. Each dryer reviewed has a unique characteristic in one or more of the selected tabular parameters.

The study of different aspects of greenhouse energy drying systems was shown in a tabular form. Operational principles, operating temperature ranges, heating sources and modes, operating modes, or structural modes were systematically represented in the table. Furthermore, direct or integral solar dryers, indirect or distributed mode, and mixed-mode dryers were studied respectively for natural circulating passive dryers and forced active convection dryers.

It can be inferred from this analysis that a load of 1000 kg of fresh produce can be dried to the equivalent moisture content in a greenhouse drying system with inside moisture regulation by an exhaust fan at chimneys. The number and size of a chimney in natural convection can be estimated according to the amount of moisture to be removed on a day. In case of forced convection, 9 DC exhaust fans installed in the western wall across two air inlets (in the eastern wall) in a tunnel-shaped, concrete-floored structure can dry 500 kg fresh produce. In order to improve drying in high humid areas of North-East India, either incoming air by flat-plate collectors can be driven over the products by exhaust fans or ambient air pushed by fans through an unfinished tubular heat exchanger, where it is indirectly heated by biomass combustion gas flowing within tubes.

References

Abdullah, K., & Mursalim. (1997). Drying of vanilla pods using a greenhouse effect solar dryer. *Drying Technology*, *15*(2), 685–698. https://doi.org/10.1080/07373939708917254

Ayyappan, S., & Mayilsamy, K. (2010). Solar tunnel dryer with thermal storage for drying of copra. *Proceedings of the 37th National & 4th International Conference on Fluid Mechanics and Fluid Power*. Chennai: Indian Institute of Technology Madras.

Bhardwaj, A. K., Kumar, R., & Chauhan, R. (2019). Experimental investigation of the performance of a novel solar dryer for drying medicinal plants in Western Himalayan region. *Solar Energy*, *177*, 395–407. https://doi.org/10.1016/j.solener.2018.11.007

Condorí, M., Echazú, R., & Saravia, L. (2001). Solar drying of sweet pepper and garlic using the tunnel greenhouse drier. *Renewable Energy*, *22*(4), 447–460. https://doi.org/10.1016/S0960-1481(00)00098-7

Doe, P. E., Muslemuddin, M., & Sachithananthan, K. (1977). A polythene tent drier for improved sun drying of fish. *Food Technology in Australia*, *29*(11), 437–441.

Dulawat, M. S., & Rathore, N. S. (2012). Forced convection type solar tunnel dryer for industrial applications. *Agricultural Engineering International: CIGR Journal*, *14*(4), 75–79.

Ekechukwu, O. V., & Norton, B. (1997). Experimental studies of integral-type natural-circulation solar-energy tropical crop dryers. *Energy Conversion and Management*, *38*(14), 1483–1500. https://doi.org/10.1016/S0196-8904(96)00102-1

Ekechukwu, O. V. (1987). *Experimental Studies of Integral-Type Natural-Circulation Solar-Energy Tropical Crop Dryers*. Ph.D Thesis. Cranfield University. United Kingdom.

Exell, R. H. B. (1980). Basic design theory for a simple solar rice dryer. *Renewable Energy Review Journal*, *1*(2), 1–14.

Gallali, Y. M., Abujnah, Y. S., & Bannani, F. K. (2000). Preservation of fruits and vegetables using solar drier: a comparative study of natural and solar drying, III; chemical analysis and sensory evaluation data of the dried samples (grapes, figs, tomatoes and onions). *Renewable Energy*, *19*(1–2), 203–212. https://doi.org/10.1016/S0960-1481(99)00032-4

Hoedt, H. (n.d.). *Small Solar Tunnel Dryer*. Aislingen: Solare Brücke e.V.

Jha, A. K., & Deka, B. C. (2012). *Present Status and Prospects of Ginger and Turmeric in NE States* (pp. 1–5). pp. 1–5. ICAR Research Complex for NEH Region.

Kaewkiew, J., Nabnean, S., & Janjai, S. (2012). Experimental investigation of the performance of a large-scale greenhouse type solar dryer for drying chilli in Thailand. *Procedia Engineering*, *32*, 433–439. https://doi.org/10.1016/j.proeng.2012.01.1290

Lawand, T. A. (1977). The potential of solar agricultural dryers in developing areas. *UNIDO Conf 5, Tech for Solar Energy Utilization*, 125–132.

McLean, K. A. (1989). *Drying and Storing Combinable Crops* (2nd ed.). Ipswich: Farming Press.

Murthy, M. V. R. (2009). A review of new technologies, models and experimental investigations of solar driers. *Renewable and Sustainable Energy Reviews*, *13*(4), 835–844. https://doi.org/10.1016/j.rser.2008.02.010

Muthuveerappan, V. R., Ambalavanan, G., Kunchithapatham, M., Kamaraj, G., & Ananthanatesan, T. (1985). Low costplastic-suction-type-greenhouse grain dr. *ISES Cong INTERSOL 85*, 1077–1081. Montreal: Pergamon Press.

Pawar, R. S., Takwale, M. G., & Bhide, V. G. (1995). Solar drying of custard powder. *Energy Conversion and Management*, *36*(11), 1085–1096. https://doi.org/10.1016/0196-8904(94)00083-C

Rathore, N. S., & Panwar, N. L. (2010). Experimental studies on hemi cylindrical walk-in type solar tunnel dryer for grape drying. *Applied Energy*, *87*(8), 2764–2767. https://doi.org/10.1016/j.apenergy.2010.03.014

Sachithananthan, K., Trim, D., & Speirs, C. I. (1983). *A Solar Dome Dryer for Drying of Fish*. Cairo: Food and Agriculture Organization.

Sadykov, T. A., & Khairiddinov, B. (1982). A year-round double-block greenhouse-dryer. *Applied-Solar-Energy (Geliotekhnika)*, *18*(1), 69–72.

Saravanapriya, G., & Mahendiran, R. (2017). Design and development of solar tunnel dryer with control system for large scale drying of agro products. *International Journal of Agriculture Sciences*, *9*(40), 4626–4631.

Seveda, M. S. (2012). Design and development of walk-in type hemicylindrical solar tunnel dryer for industrial use. *ISRN Renewable Energy*, *2012*, 1–9. https://doi.org/10.5402/2012/890820

Shaw, R. (1981). Solar drying potatoes. *Appropriate Technology*, *7*(4), 26–27.

Yang, K. C. (1980). Solar kiln performance at a high latitude, 48 degrees N [lumber drying rate]. *Forest Products Journal*, *30*(3), 37–40.