Journal of Solar Energy Research (JSER)

Journal homepage: www.jser.ut.ac.ir

Enhancing the Productivity of Agricultural Supply Chains with Solar Tunnel Dryers

T Devaraju[a], K Leleedhar Rao[a], G Hari Krishnan[a], E Parimalasundar[a*]

[a]*Department of Electrical and Electronics Engineering, Mohan Babu University (Erst while Sree Vidyanikethan Engineering College), Tirupati, India.*

ARTICLE INFO

Article Type:

Research Article

Received:19.05.2023
Accepted:21.07.2023

Keywords:
Convection from nature
Rate of drying
Quantity of moisture
Solar cell
Heat efficiency

A B S T R A C T

Solar tunnel dryers are innovative technologies that utilize solar energy to efficiently and cost-effectively dry agricultural products. By harnessing renewable energy, these dryers provide a sustainable alternative to conventional drying methods. The aim of this article is to examine a solar tunnel dryer that is employed to dry a variety of agricultural goods in Chandragiri Mandal, Tirupati (Andhra Pradesh), India under local weather circumstances. The dryer has a polycarbonate sheet that is 1 mm thick and 30 feet long by 12 feet broad. This sheet is utilized as a collector for material and for direct absorption on the item to be dried. About 300 kg can be loaded into the dryer with vegetables or agricultural products. Vegetables have been dried in a solar tunnel dryer in 1 hours from initial moisture content of roughly 85% to 45% whereas open-air drying takes 18 hours. The temperature within the dryer is considerably higher between 30 and 40 degrees Celsius than the ambient temperature. It has been determined that the typical thermal efficiency is around 53.1%. Solar tunnel dryers, such as reduced drying time, improved product quality, and decreased post-harvest losses.

1. Introduction

Agricultural supply chains play a vital role in the food industry as they ensure the smooth flow of food from the producers to the consumers. However, these supply chains are often plagued with inefficiencies that result in food losses and reduced profitability. One major area where inefficiencies occur is in the drying of agricultural products. In many countries, traditional drying methods such as sun drying and open-air drying are still in use, which are inefficient and result in high food losses. Solar tunnel dryers have emerged as a promising solution for enhancing the productivity of agricultural supply chains.

Solar tunnel dryers are a type of solar dryer that uses a tunnel-shaped structure to trap solar radiation and heat, thereby providing a controlled environment for drying agricultural products. They are particularly useful in regions with high solar

*Corresponding Author Email:parimalpsg@gmail.com

Cite this article: T, D., K, L. R., G, H. K., & E, P. (2023). Enhancing the Productivity of Agricultural Supply Chains with Solar Tunnel Dryers. Journal of Solar Energy Research, 8(3), 1574-1586. doi: 10.22059/jser.2023.359435.1308

DOI: 10.22059/jser.2023.359435.1308 DOR: 20.1001.1.25883097.2023.8.3.1.1

radiation and low humidity, where traditional drying methods are inefficient. The design of solar tunnel dryers can vary depending on the specific application, but they generally consist of a transparent cover that allows solar radiation to enter, an absorber plate that absorbs the solar radiation and converts it into heat, and a drying chamber where the agricultural products are placed for drying.

In recent years, there has been a growing interest in the use of solar tunnel dryers for drying agricultural products. This has led to several developments in the design and construction of solar tunnel dryers, as well as improvements in their efficiency and performance.

In addition to these developments, there have also been several studies that have investigated the use of solar tunnel dryers for drying specific agricultural products. Ridoy et al. [1] investigated atmospheric pressure dry nanotexturing involves the modification of surfaces at the nanoscale using various dry processes, such as plasma etching, ion beam etching, reactive ion etching, and laser ablation, among others. These techniques offer several advantages, including simplicity, scalability, and compatibility with various materials, while a study by Sengupta et al. [2] examined the effect of dust accumulation on the transparent cover of PV modules. As a result of investigations, it has been determined that dust buildup reduces light transmission and results in shading, which lowers module performance. Regular cleaning was suggested to maintain module efficiency. Zhao et al. [3] presented an in-depth analysis of solar drying techniques for agricultural products. It covers different solar dryer configurations, drying kinetics, and thermal performance. The authors discuss the challenges and opportunities for improving solar drying efficiency and maintaining crop quality. Aydin et al. [4] developed a solar tunnel dryer (STD) for drying mint leaves. The dryer had a drying chamber, a blower, and a solar collector. The dryer is found to be efficient in terms of drying rate, colour, and aroma of the dried mint leaves. Arslan et al. [5] proposed an infrared-convective dryer that combines infrared radiation and convective heat transfer to facilitate efficient drying of agricultural products. Infrared radiation provides direct heating to the crop surface, while convective heat transfer removes the moisture-laden air from the drying chamber. The integration of these two modes enhances the drying rate and helps maintain the quality of the dried crops.

Babar et al. [6] developed a flat plate collector solar dryer for drying agricultural products. It consists of a flat plate collector, which absorbs solar radiation and transfers the heat to the drying chamber where the agricultural products were placed. The solar dryer helps in reducing the moisture content of the products, thereby preserving them for longer periods and preventing spoilage. Lingayat et al. [7] developed the design, development, and performance evaluation of an indirect solar dryer for drying agricultural products. The dryer utilizes solar energy to heat the air, which was then passed through the drying chamber, where the agricultural crops are placed. The paper discusses the design considerations, construction details, and performance analysis of the solar dryer.

Hao et al. [8] evaluated the performance of a hybrid solar dryer for lemon slices. The proposed approach evaluates the drying characteristics, energy use, and decrease in moisture content. A mathematical model is developed based on the experimental data to predict the drying kinetics of lemon slices in the hybrid solar dryer.

Sajadipour et al. [9] discussed the thermal behaviour of a flat plate water heater solar collector at different times of the day was assessed using the computational fluid dynamics (CFD) method. The CFD analysis allowed for the investigation of heat transfer, fluid flow patterns, and overall performance of the solar collector under varying daylight conditions.

Rajaee et al. [10] investigated the construction and analysis of smart solar benches with the optimal angle will be conducted in four central cities of Iran. The presented system aims to maximize solar energy generation and provide convenient seating with integrated charging stations. The results will contribute to sustainable urban development and enhance public amenities.

Patel et al. [11] investigated low voltage ride-through (LVRT) capability of photovoltaic (PV) systems connected to an unbalanced main grid is an important area of research in the field of renewable energy. Low voltage ride-through refers to the ability of a power generation system to maintain its operation during and after a voltage dip or disturbance in the grid. An unbalanced main grid refers to a scenario where the voltage and/or phase angles of the three phases are unequal, which can occur due to various factors such as unbalanced loads or faults.

Rakshamuthu et al. [12] investigated solar dryers are devices that use solar energy to remove moisture from agricultural products, thereby extending their shelf life. The integration of phase change materials (PCMs) in solar dryers is aimed at improving their thermal performance by storing and releasing energy during the drying process.

Mirzakhani et al. [13] investigated the optimal configuration for an off-grid PV-wind-fuel cell system with battery and generator backup for a remote house in Iran would involve a combination of solar panels, wind turbines, fuel cells, and a battery bank. The system should be designed to efficiently harness renewable energy sources while ensuring reliable power supply in all weather conditions.

Mohana et al. [14] discussed solar dryers for food applications have gained significant attention due to their potential for sustainable and energy-efficient food preservation.

Battocchio et al. [15] investigated solar cookers and dryers are innovative devices that utilize solar energy for cooking and drying purposes, offering numerous benefits such as reduced fuel consumption, lower emissions, and improved food preservation. Additionally, research investigates the socio-economic impacts of solar cooking and drying, highlighting their potential to address energy poverty and promote sustainable development.

Swami et al. [16] discussed solar fish dryers using phase change material as an innovative technology that combines solar energy and the heat storage capabilities of PCM to effectively dry fish. The PCM absorbs and stores thermal energy during the day when solar radiation is abundant and releases it during the night or when solar radiation is insufficient, providing a consistent and controlled drying environment.

A. Mathew et al. [17] presented thermal energy storage (TES) systems are essential for enhancing the performance and usability of solar dryers, especially in the agricultural sector. This investigation to provides an overview of existing research and developments in the field of a novel thermal energy storage-integrated evacuated tube heat pipe solar dryer for drying agricultural products.

Cetina-Quiñones et al. [18] discussed indirect-type solar dryers for agricultural use in rural communities are an effective and sustainable solution for preserving crops and reducing post-harvest losses. These dryers utilize solar energy to remove moisture from agricultural products, thereby extending their shelf life and maintaining their nutritional value.

Tarigan et al. [19] investigated the use of a solar tunnel dryer for drying whey protein concentrate. The objectives of their study were to determine the effect of various parameters, such as air velocity and temperature, on the drying kinetics and quality of the whey protein concentrate. The results showed that the drying rate increased with increasing air velocity and temperature, and that the quality of the whey protein concentrate was not significantly affected by the drying process. The authors concluded that a solar tunnel dryer could be a viable option for drying whey protein concentrate.

Goud et al. [20] focused on the drying of skim milk using a solar tunnel dryer. The objectives of their study were to investigate the effect of various parameters, such as air temperature and humidity, on the drying kinetics and quality of the skim milk powder. The results showed that the drying rate increased with increasing air temperature and decreasing humidity, and that the quality of the skim milk powder was not significantly affected by the drying process. The authors concluded that a solar tunnel dryer could be a cost-effective and environmentally friendly option for drying skim milk.

Azam et al. [21] investigated a solar collector integrated with a greenhouse dryer can be an efficient and sustainable solution for drying tomatoes. The combination of solar energy and greenhouse technology can provide an optimal environment for drying tomatoes while reducing energy consumption and environmental impact.

Moravej et al. [22] analysed the impact of utilizing Ag-water nanofluid at various concentrations on the performance of circular collectors. The study aims to evaluate how different nanofluid concentrations affect the efficiency and heat transfer characteristics of the collectors.

Murali et al. [23] developed the solar tunnel dryer is a structure designed to harness solar energy to dry shrimp efficiently. It consists of a long, transparent tunnel made of materials that allow sunlight to enter and trap heat inside. The tunnel is equipped with a series of trays or racks where the shrimp are placed for drying.

Eltawil et al. [24] directed a solar photovoltaic powered mixed-mode tunnel dryer is an innovative solution for drying potato chips. This dryer combines the benefits of solar energy and a conventional tunnel drying system. The solar PV panels harness sunlight and convert it into electricity, which powers the dryer's components. The mixed-mode design incorporates both solar heating and forced air circulation for optimal drying efficiency. This sustainable approach reduces reliance on fossil fuels and decreases carbon emissions. The dryer's precise control mechanisms maintain consistent temperatures and airflow, ensuring high-quality, evenly dried potato chips. This technology promotes energy efficiency and environmental sustainability in the potato chip production process.

Aydin et al. [25] investigated the performance of a solar tunnel dryer was evaluated for drying coconut coir. The objective of the study was to investigate the effect of different drying temperatures on the quality of the dried coconut coir. The results showed that the optimal drying temperature was 50°C, which resulted in the lowest drying time and the highest quality of the dried coconut coir.

Ezhilvannan et al. [26] examined the effectiveness of a two-stage three-phase grid-connected inverter for photovoltaic applications indicates promising results. The inverter demonstrates efficient power conversion, high grid synchronization, and effective power control. Its performance ensures optimal utilization of solar energy and seamless integration with the electrical grid, making it a viable solution for photovoltaic systems.

Elahi et al. [27] implemented precision agriculture techniques to optimize the use of fertilizers and pesticides, reducing waste and runoff. Additionally, promoting organic farming methods can minimize the use of synthetic chemicals, protecting soil health and reducing pollution. Integrating agroforestry systems, such as planting trees on farms, helps sequester carbon dioxide and improve biodiversity. Implementing efficient irrigation systems and utilizing water-saving technologies can also minimize water usage and associated energy consumption. Lastly, encouraging the adoption of renewable energy sources in agricultural operations can further reduce emissions and promote a greener farming industry.

Shoeibi et al. [28] finned photovoltaic/thermal (PV/T) solar air dryer combines the benefits of solar photovoltaic and thermal technologies to enhance drying processes. Its performance analysis involves evaluating various parameters. The electrical efficiency of the PV module is assessed by measuring the power output under varying solar radiation levels. The thermal efficiency is determined by analysing the temperature rise and heat transfer rates in the air-drying chamber. The drying performance is assessed by measuring the moisture content reduction and drying time for different loads. Overall, the performance analysis of the finned PV/T solar air dryer aims to optimize energy conversion and drying efficiency while considering factors such as solar radiation, air flow, and temperature distribution.

The concept of enhancing the productivity of agricultural supply chains with solar tunnel dryers represents a novel approach to addressing the challenges faced by the agricultural industry. While the use of solar energy in drying agricultural products is not new, the specific application of solar tunnel dryers in supply chains introduces a unique and innovative solution. By harnessing solar power to dry crops efficiently and sustainably, these tunnel dryers offer significant advantages, such as reduced reliance on fossil fuels, decreased post-harvest losses, improved product quality, and increased overall productivity. This integration of solar technology into agricultural supply chains showcases a fresh perspective on optimizing processes and promoting sustainable practices in the agricultural sector. The main difference in work on enhancing the productivity of agricultural supply chains with solar tunnel dryers lies in its operational approach and the novelty it brings to the existing literature. Unlike other works that focus on traditional drying methods, this research explores the use of solar tunnel dryers specifically. The novelty lies in the innovative design, utilization of renewable energy, and its potential to improve the efficiency and sustainability of agricultural supply chains.

The major objectives of the solar tunnel dryers are mentioned below:

- Introduce the concept of solar tunnel dryers and their potential to enhance the productivity of agricultural supply chains.
- Highlight case studies or examples of successful implementation of solar tunnel dryers in agricultural supply chains.
- Address potential barriers to adoption, such as lack of awareness or financing options, and propose solutions.
- Evaluate the impact of solar tunnel dryers on smallholder farmers and their ability to access markets and increase their income.
- Explore opportunities for scaling up the use of solar tunnel dryers in other regions and crops.
- Recommend policy and investment strategies to promote the adoption of solar tunnel dryers in agricultural supply chains.
- The potential impact of solar tunnel dryers on enhancing the productivity of agricultural supply chains and contributing to sustainable development goals.

2. Testing Setup of Solar Dryer

An organic convection sun dryer was developed to dried onions are easier to handle and obtainable in Tirupati, Andhra Pradesh, India. The dryer's main component is a semi-cylindrical collector with a 2.78 m^2 surface area and a maximum height of 2 ft in the centre. Solar energy is transferred across the product using this collector. A sheet of 1 mm polycarbonate is used as a coating.

In order to prevent the dryer's heat loss on the bottom side, the solar tunnel dryer also employs glass wool with a thermal conductivity of 0.04 W/m-K as insulation and stainless-steel wire mesh to load the material. The absorber is 6 feet long and 3 feet wide and is made of a 1 mm black-painted aluminum plate with a thermal conductivity value of 204 W/m-K. The complete device is placed 2 feet above the ground horizontally. A solar dryer typically consists of the following schematic structure to harness solar energy for drying purposes. The operation begins with the sun as the primary source of energy. The sun's rays are captured by a collector, usually made of a dark material that efficiently absorbs solar radiation. The collector is designed to maximize the absorption of solar energy. The absorbed energy is then transferred to the drying chamber through an insulation absorber, which helps in maintaining a suitable temperature within the dryer. The insulation prevents heat loss, ensuring efficient drying. Inside the drying chamber, a wire mesh or racks are used to hold the items to be dried, such as fruits, vegetables, or herbs. The wire mesh allows for proper airflow and prevents the items from falling through. The dryer also includes air inlets and outlets to facilitate the circulation of air. Warm air enters the dryer through the air inlets, flows over the items to be dried, and exits through the outlets. This airflow promotes the evaporation of moisture from the items, facilitating the drying process. Figure 1 illustrates the schematic structure of a solar dryer.

Through the intake aperture, air from the surroundings is drawn in, passed over the product, and then absorbed moisture. Throughout this experiment, no trees or additional structures ever provided shade for the dryer, which is conducted in the months of March and April 2023. A solar meter (WACO 206) is used to measure the sun’s radiation with an accuracy of 0.1 W/m^2. A K-type thermocouple is also used to measure the ambient temperature of air that was moving toward the absorber plate of the dryer. The air flow rate at the intake and the surrounding humidity are measured using digital hygrometers and hot wire anemometers, respectively.

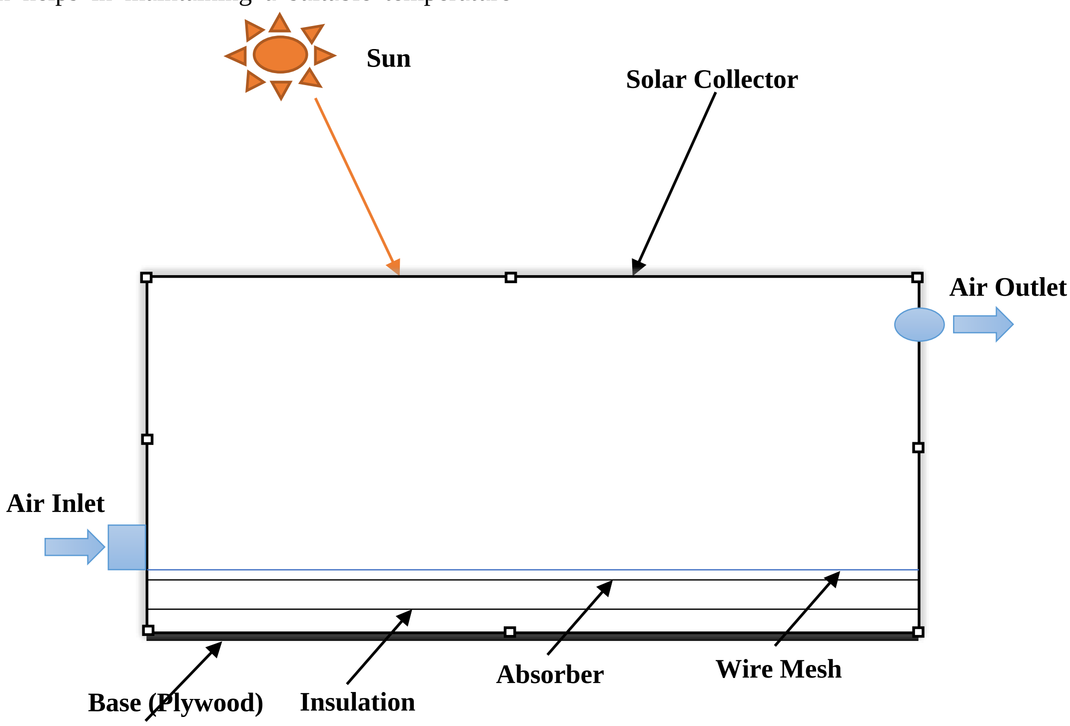

Figure 1. Schematic structure of a solar dryer

Figure 2. Schematic arrangement of a solar dryer – outer view

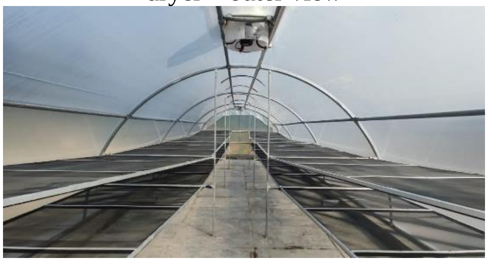

Figure 3. Schematic arrangement of a solar dryer – inner view

The major points to be considered in solar tunnel dryer are as follows:

- A collector and an absorber are being tested.
- drying rate of various collector and absorber combinations.
- Effect of loading and unloading.
- Efficiency of traying.

A solar dryer is a device that utilizes the power of the sun to dry various agricultural products, food items, or other materials. The outer view of a solar dryer typically consists of a sturdy frame made of metal or wood, supporting a transparent cover made of glass or plastic. This cover allows sunlight to enter while preventing dust and insects from entering the drying chamber. The inner view of a solar dryer includes shelves or trays where the materials to be dried are placed. These trays are designed to maximize air circulation and promote efficient drying. Ventilation openings are strategically placed to ensure proper airflow and moisture escape, facilitating the drying process. Figure 2 illustrates the schematic diagram of solar dryer's inner view. Figure 3 illustrates the schematic diagram of solar dryer outer view. Experimental methodology of the solar dryer is illustrated in Figure 4. Table 1 illustrates the major materials used in solar tunnel dryer.

Table 1. Major materials used in solar tunnel dryer

Materials	Type/Quantity
Gathering materials	Sheets of polycarbonate
Sorbent substance	Aluminium sheet
Onion's original weight	1600 gm
Onion final weight	1200 gm

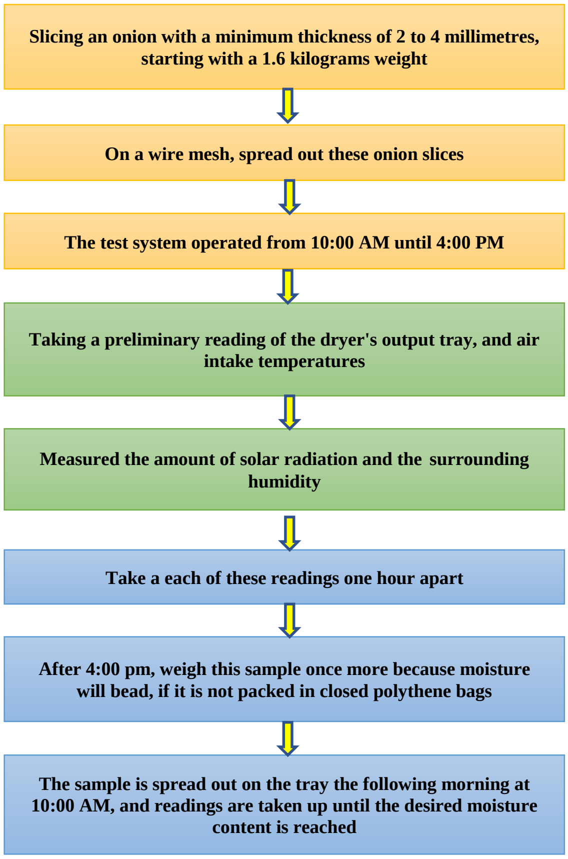

Figure 4. Experimental methodology of the solar dryer

3. Result and analysis with Different Agricultural Products

Solar tunnel dryers can significantly enhance the productivity of agricultural supply chains, particularly in the case of tomatoes. By utilizing solar energy to dry tomatoes, these innovative systems provide numerous benefits. Firstly, solar tunnel dryers ensure efficient and consistent drying, reducing spoilage and post-harvest losses. This technology also enables farmers to extend the shelf life of tomatoes, preserving their quality and nutritional value. Moreover, solar tunnel dryers contribute to energy savings, reducing dependence on fossil fuels and lowering operating costs. Additionally, these dryers offer a sustainable solution, reducing greenhouse gas emissions and promoting environmentally-friendly agricultural practices.

The tomato is both a fruit and a vegetable that has been widely used for industrial and domestic purposes due to its numerous benefits. It can spoil easily if not handled properly because it contains a lot of moisture. Tomato slices were dried using a newly developed sun drying as a control in the development of a solar drier with a data monitoring system in this study. Following that, the solar dryer's performance was evaluated using quality studies and profile analyses of the temperature at which it dried, sunlight intensity, humidity level, relative amount of moisture, and drying rate. Tomato slices began with a moisture content of 90% wet basis and were dried until they reached a moisture content of 25-50% wet basis. According to the trial results, the solar drier dried things significantly faster than the sun. The final moisture content after 4 days of solar drying was determined by changes in the weight of STD and DSR that met the specified value. The tray exposed to sunlight was the only one that showed signs of tomato slices drying faster. Dried tomato slices have less vitamin C than fresh ones, according to quality studies. The cell walls of dried tomato slices were more delicate, but tomato slices were brighter when dried using a sun drier. These findings demonstrated the viability of a solar dryer for drying tomato slices, but they also revealed a number of issues that must be addressed in the future by improving the dryer or the drying process. You can use the dried tomato without seasoning. Figure 6 depicts before using a solar dryer to dry tomatoes. Table 2 depicts the observation of tomato parameters with respect to relative humidity (RH) and STD relative performance in percentage.

Solar tunnel dryers are a technology that can greatly enhance the productivity of agricultural supply chains, particularly in the case of bitter guard. These dryers utilize solar energy to dry crops efficiently and effectively. By harnessing the power of the sun, they eliminate the need for traditional, fuel-based drying methods, reducing costs and environmental impact. Solar tunnel dryers provide consistent and controlled drying conditions, ensuring optimal quality and reducing post-harvest losses. This technology improves the shelf life of bitter guard, increases its market value, and allows farmers to access better markets, thereby enhancing the overall productivity of agricultural supply chains.

The water content, drying rate, drying duration, and moisture ratio of bitter gourd were investigated to better understand its drying properties. The bitter gourd was flown directly through an evacuated tube solar dryer, and the moisture content change over time is shown below. The bitter guard had an average weight by weight (wb) of 91.85%, which dropped to 6-7% wb. The moisture content of the bitter gourd decreased as the drying process progressed until it reached a final moisture content value. The bitter gourd was dried for 12 hours in total, with a final moisture level of 6-7%. The moisture content first decreased gradually due to the drying chamber's low intake temperature and low sun intensity. However, as the drying process progressed, the solar intensity increased until 1 PM, quickly reducing the moisture before it began to decline as the day ended (sunset). The non-dried product from the first drying day was stored in desiccators for the night. The drying process began at 9 AM on the second day and continued until the desired final moisture content was reached. The brightness, greenness, and yellowness of dried bitter gourd were significantly reduced.

Solar tunnel dryers are an innovative technology that can significantly enhance the productivity of agricultural supply chains, particularly for crops like onions and chilies. These dryers utilize solar energy to efficiently dry and preserve the harvested produce. By harnessing the power of the sun, they eliminate the need for traditional fuel sources, reducing operating costs and carbon emissions. Solar tunnel dryers also provide a controlled environment, protecting the crops from pests, diseases, and adverse weather conditions. With faster and more consistent drying, farmers can increase their production capacity and minimize post-harvest losses. Ultimately, this technology improves the quality, shelf life, and market value of onions and chilies, benefiting both farmers and consumers.

The onion slices had an initial moisture content of 87.10% wb and an ultimate moisture content of 9.1% wb after drying. Onion slices dried in direct sunlight versus slices dried in a solar dryer with a natural convection current. Both onion slices dried in the open air and those placed in a single tray in a solar drier exhibited the same patterns of rapidly dropping moisture content. The first slice, however, showed the greatest moisture loss, indicating a rapid decline in moisture content. On day 2, the moisture content of the slices dropped dramatically, reaching its lowest point after 12 hours. Figure 7 shows the results of using a solar dryer to dry bitter guard and onion. Table 4 shows the correlation of chili parameters with RH and the percentage performance of STD. Table 5 depicts the observation of onion parameters with RH and the percentage performance of STD.

The drying chamber, gathering area, and chimney are all components of the solar tunnel dryer. A market is covered with a sheet of UV-stabilized polythene that is easily accessible in the vicinity of the drying chamber. The semi-cylindrical shape of the solar tunnel drier increases solar light absorption. The dryer is designed to be simple to open and close in order to distribute the drying substance and clean the tray and absorber surface at the start of the day. To prevent heat leakage, one inch of thermal insulation is installed at the tunnel dryer's base. According to research, red chilies have a 75% initial moisture content. An experiment on drying cold is run in the solar tunnel dryer to evaluate the dryer's performance when loaded. At 9 AM, 1.5 kg of chilies are spread out in a single layer inside the dryer. The process is repeated once the desired moisture content is reached. During the drying process, the ambient temperature ranged from 230°C to 270°C at its lowest and highest points. The interior temperature of the solar tunnel dryer ranges from 47.46°C to 56.9°C. The efficiency calculation for solar collector and dryer are represented in following equations (1) [5] and (2) [5] respectively,

$$N_c = \frac{mcp_a(T_a - T_L)}{A_c I} \quad (1)$$

$$N_d = \frac{m_w h_l}{A_c I} \quad (2)$$

Water evaporated in volume of solar dryer is mentioned the following equation (3) [5],

$$m_w = \frac{InitialValue - FinalMass}{InitialMass} \quad (3)$$

A variation of a solar tunnel dryer is a modified design that incorporates additional features to enhance its performance and efficiency. These variations may include improved insulation, adjustable airflow control mechanisms, and automatic temperature and humidity regulation systems. By integrating these enhancements, the dryer can optimize the drying process by maintaining ideal conditions for moisture removal while minimizing energy consumption. Figure 8 illustrates the variation of solar tunnel dryer and diffused solar radiation in one month period of STD and DSR with different values, STD has given better results than DSR.

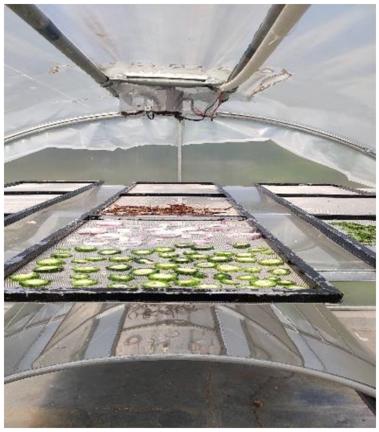

Figure 5. Before using a solar dryer to dry - Bitter Guard

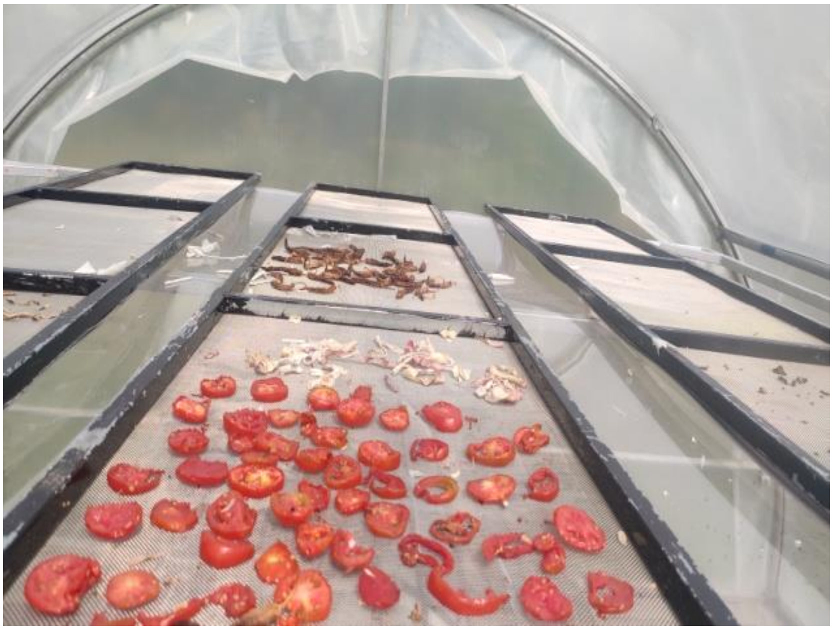

Figure 6. Before using a solar dryer to dry – Tomato

Figure 7. After using a solar dryer to dry – Bitter Guard and Onion

Table 2. Observation Table of Tomato

Test Day Count	Time of the Day	Recorded Temperature (°C)		RH (%)	Weight (gm)		Relative Performance of STD %
		Ambient	Internal		STD	DSR	
Day-1	12:00	25℃	53.5℃	34.2	500	500	0
Day-1	14:00	26℃	50℃	36.4	440	420	4.5
Day-1	16:00	23℃	30.6℃	64	350.01	311.5	11
Day-2	11:00	26℃	56℃	32.4	327.76	236.95	27.7
Day-2	14:00	25℃	49℃	35	272.05	179.56	34
Day-2	16:00	23℃	47.7℃	33.7	219.85	124.72	43.3
Day-3	11:00	28℃	57℃	31.4	120.36	90.25	25
Day-3	14:00	29℃	49℃	35	89.32	66.32	25.8
Day-3	16:00	25℃	47.7℃	33.7	44.3	30.31	31.6
Day-4	11:00	29℃	56℃	32.4	21.75	10.68	50.9
Day-4	14:00	27℃	49℃	35	16.12	5.26	67.4
Day-4	16:00	24℃	47.7℃	33.7	16.13	5.26	67.4
						Average	**32.38**

Table 3. Observation Table of Bitter Guard

Test Day Count	Time of The Day	Recorded Temperature (°C)		RH (%)	Weight (gm)		Relative Performance of STD %
		Ambient	Internal		STD	DSR	
Day-1	12:00	25℃	53.5℃	34.2	14.2	14.2	0
Day-1	14:00	26℃	50℃	36.4	14.2	14	1.4
Day-1	16:00	23℃	30.6℃	64	14.19	13.65	3.8
Day-2	11:00	26℃	56℃	32.4	14.09	13.5	4.2
Day-2	14:00	25℃	49℃	35	14.09	13.5	4.2
Day-2	16:00	23℃	47.7℃	33.7	14.09	13.5	4.2
						Average	**2.96**

Table 4. Observation Table of Chilli

Test Day Count	Time of the Day	Recorded Temperature (°C)		RH (%)	Weight (gm)		Relative Performance of STD %
		Ambient	Internal		STD	DSR	
Day-1	12:00	25°C	53.5°C	34.2	15.13	15.13	0.0
Day-1	14:00	26°C	50°C	36.4	14.62	13.09	10.5
Day-1	16:00	23°C	30.6°C	64	13.76	12.53	8.9
Day-2	11:00	26°C	56°C	32.4	13.13	11.86	9.7
Day-2	14:00	25°C	49°C	35	12.65	11.77	7.0
Day-2	16:00	23°C	47.7°C	33.7	12.48	11.72	6.1
						Average	**7.03**

Table 5. Observation Table of Onion

Test Day Count	Time of the Day	Recorded Temperature (°C)		RH (%)	Weight(gm)		Relative Performance of STD %
		Ambient	Internal		STD	DSR	
Day-1	12:00	25°C	53.5°C	34.2	16.44	16.44	0.0
Day-1	14:00	26°C	50°C	36.4	15.75	15.25	3.2
Day-1	16:00	23°C	30.6°C	64	14.7	14.25	3.1
Day-2	11:00	26°C	56°C	32.4	13.87	13.7	1.2
Day-2	14:00	25°C	49°C	35	13.76	13.65	0.8
Day-2	16:00	23°C	47.7°C	33.7	13.42	12.89	3.9
Day-3	11:00	28°C	57°C	31.4	13.31	12.72	4.4
Day-3	14:00	29°C	49°C	35	13.2	12.65	4.2
Day-3	16:00	25°C	47.7°C	33.7	13	12.35	5.0
Day-4	11:00	29°C	56°C	32.4	12.99	12.35	4.9
Day-4	14:00	27°C	49°C	35	12.99	12.35	4.9
Day-4	16:00	24°C	47.7°C	33.7	12.99	12.35	4.9
						Average	**3.37**

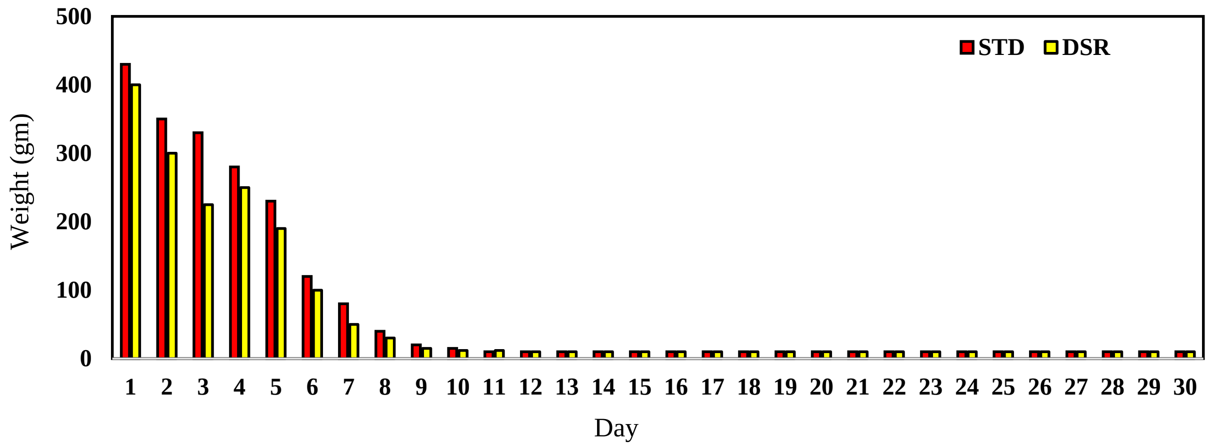

Figure 8. Variation of solar tunnel dryer and diffused solar radiation

4. Conclusions

The implementation of solar tunnel dryers holds significant potential for enhancing the productivity of agricultural supply chains. By harnessing solar energy to efficiently and sustainably dry crops, these innovative systems can reduce post-harvest losses, improve product quality, and increase overall productivity. Additionally, these dryers can be easily adopted by small-scale farmers, empowering them with a technology that improves their economic opportunities. In these experiments, an onion weighing 1650 gm was dried down to 250 g in 11 hours as opposed to 18 hours in the open sun, resulting in a 15% moisture content reduction. The table observations also show that as the temperature changes and rises, the outlet temperature and tray temperature rise as well, reducing the time it takes to dry the goods. The intensity of the sun's radiation increases until picking hours, then gradually decreases. Finally, the refined material can be stored and used for a few months. The color of bitter guard, tomato, and onion changed, but chili remained the same. Using solar tunnel dryers can help to create a more efficient and resilient agricultural supply chain, which benefits both farmers and consumers. Future directions for enhancing the productivity of agricultural supply chains with solar tunnel dryers include optimizing drying processes through advanced automation and sensor technologies, integrating machine learning algorithms for real-time data analysis, exploring energy storage solutions to ensure uninterrupted operation, and fostering collaborations between researchers, industry stakeholders, and policymakers. However, some limitations include high initial investment costs, reliance on sunlight availability, and the need for proper maintenance and technical expertise. Overcoming these challenges and addressing scalability issues will be crucial for widespread adoption and maximizing the benefits of solar tunnel dryers in agricultural supply chains.

Acknowledgments

This work was supported by Science Technology and Innovation (STI) hub in Chandragiri Mandal, Chittoor District, Andhra Pradesh, India for the Socioeconomic Development of scheduled caste (SC) and scheduled tribe (ST) communities in collaboration with Mohan Babu University (Erst while Sree Vidyanikethan Engineering College), Tirupati, India.

Nomenclature

m	Mass flow rate of air (m/s)
C_p	A specific heat of air (KJ/kg k Temp)
T_0	At collector outlet Temperature (˚c)
T_i	At collector inlet Temperature (˚c)
A_cI	Area of collector (m^2)
m_w	Average solar radiation ($W/m^{2)}$
h_l	Height of solar dryer (m)

References

[1] Ridoy, A., Khan, N., Kafle, B., Schmidt, S., Clochard, L., Hofmann, M., & Rentsch, J. (2022). Optimizing Emitter Diffusion Process for Atmospheric Pressure Dry Nanotextured Monocrystalline PERC. IEEE Journal of Photovoltaics, 12(1), 244–250. DOI: 10.1109/jphotov.2021.3130007.

[2] Sengupta, S., Sengupta, S., & Saha, H. (2020). Comprehensive Modeling of Dust Accumulation on PV Modules Through Dry Deposition Processes. IEEE Journal of Photovoltaics, 10(4), 1148–1157. DOI: 10.1109/jphotov.2020.2992352

[3] Zhao, W., Lv, Y., Zhou, Q., & Yan, W. (2021). Investigation on particle deposition criterion and dust accumulation impact on solar PV module performance. Energy, 233, 121240. DOI: 10.1016/j.energy.2021.121240.

[4] Aydin, D., Ezenwali, S. E., Alibar, M. Y., & Chen, X. (2019). Novel modular mixed-mode dryer for enhanced solar energy utilization in agricultural crop drying applications. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 43(16), 1958–1974. DOI: 10.1080/15567036.2019.1663306.

[5] Arslan, E., & Aktaş, M. (2020). 4E analysis of infrared-convective dryer powered solar photovoltaic thermal collector. Solar Energy, 208, 46–57. DOI: 10.1016/j.solener.2020.07.071.

[6] Babar, O. A., Tarafdar, A., Malakar, S., Arora, V. K., & Nema, P. K. (2020). Design and performance evaluation of a passive flat plate collector solar dryer for agricultural products. Journal of Food Process Engineering, 43(10). DOI: 10.1111/jfpe.13484.

[7] Lingayat, A. B., Chandramohan, V., Raju, V., & Meda, V. (2020). A review on indirect type solar dryers for agricultural crops – Dryer setup, its performance, energy storage and important highlights. Applied Energy, 258, 114005. DOI: 10.1016/j.apenergy.2019.114005.

[8] Hao, W., Liu, S., Mi, B., & Lai, Y. (2020). Mathematical Modeling and Performance Analysis of a New Hybrid Solar Dryer of Lemon Slices for Controlling Drying Temperature. Energies, 13(2), 350. DOI: 10.3390/en13020350.

[9] Sajadipour, F., Kheiralipour, K., Mirzaee-Ghaleh, E., & Rabani, H. (2022). Assessment of Thermal Behavior of a Flat Plate Water Heater Solar Collector at Different Day Times by Computational Fluid Dynamics Method. Journal of Solar Energy Research, 7(4), 1134-1142. DOI: 10.22059/jser.2022.333698.1227.

[10] Rajaee, M., & Jalali, M. (2023). Construction and Analysis of Smart Solar Bench with the Optimal Angle in Four Central Cities of Iran. Journal of Solar Energy Research, 8(1), 1345-1356. DOI: 10.22059/jser.2023.349600.1261.

[11] Patel, H., & Mishra, N. (2019). Modelling and Analysis of Grid Connected Three-Phase Photovoltaic Inverter. SSRN Electronic Journal. DOI: 10.2139/ssrn.3442520.

[12] Rakshamuthu, S., Jegan, S., Joel Benyameen, J., Selvakumar, V., Anandeeswaran, K., & Iyahraja, S. (2021). Experimental analysis of small size solar dryer with phase change materials for food preservation. Journal of Energy Storage, 33, 102095. DOI: 10.1016/j.est.2020.102095.

[13] Mirzakhani, A., & Pishkar, I. (2023). Finding The Best Configuration of an Off-Grid PV-Wind-Fuel Cell System with Battery and Generator Backup: A Remote House in Iran. Journal of Solar Energy Research, 8(2), 1380-1392. DOI: 10.22059/jser.2023.349781.1259.

[14] Mohana, Y., Mohanapriya, R., Anukiruthika, T., Yoha, K., Moses, J., & Anandharamakrishnan, C. (2020). Solar dryers for food applications: Concepts, designs, and recent advances. Solar Energy, 208, 321–344. DOI: 10.1016/j.solener.2020.07.098

[15] Battocchio, C., Bruni, F., Di Nicola, G., Gasperi, T., Iucci, G., Tofani, D., . . . Venditti, I. (2021). Solar Cookers and Dryers: Environmental Sustainability and Nutraceutical Content in Food Processing. Foods, 10(10), 2326. DOI: 10.3390/foods10102326.

[16] Swami, V. M., Autee, A. T., & T R, A. (2018). Experimental analysis of solar fish dryer using phase change material. Journal of Energy Storage, 20, 310–315. DOI: 10.1016/j.est.2018.09.016.

[17] Mathew, A. A., & Thangavel, V. (2021). A novel thermal energy storage integrated evacuated tube heat pipe solar dryer for agricultural products: Performance and economic evaluation. Renewable Energy, 179, 1674–1693. DOI: 10.1016/j.renene.2021.07.029.

[18] Cetina-Quiñones, A., López López, J., Ricalde-Cab, L., El Mekaoui, A., San-Pedro, L., & Bassam, A. (2021). Experimental evaluation of an indirect type solar dryer for agricultural use in rural communities: Relative humidity comparative study under winter season in tropical climate with sensible heat storage material. Solar Energy, 224, 58–75. DOI: 10.1016/j.solener.2021.05.040

[19] Tarigan, E. (2018). Mathematical modeling and simulation of a solar agricultural dryer with back-up biomass burner and thermal storage. Case Studies in Thermal Engineering, 12, 149–165. DOI: 10.1016/j.csite.2018.04.012.

[20] Goud, M., Reddy, M. V. V., V.P., C., & S., S. (2019). A novel indirect solar dryer with inlet fans powered by solar PV panels: Drying kinetics of Capsicum Annum and Abelmoschus esculentus with dryer performance. Solar Energy, 194, 871–885. DOI: 10.1016/j.solener.2019.11.031.

[21] Azam, M. M., Eltawil, M. A., & Amer, B. M. (2020). Thermal analysis of PV system and solar collector integrated with greenhouse dryer for drying tomatoes. Energy, 212, 118764. DOI: 10.1016/j.energy.2020.118764.

[22] Moravej, M., Namdarnia, F., & Partabian, L. (2022). An experimental study of the effect of using Ag-water nanofluid in different concentrations on the performance of circular collectors. Journal of Solar Energy Research, 7(2), 1016-1026. DOI: 10.22059/jser.2022.336571.1236.

[23] Murali, S., Alfiya, P., Aniesrani Delfiya, D., Harikrishnan, S., Kunjulakshmi, S., & Samuel, M. P. (2022). Performance evaluation of PV powered solar tunnel dryer integrated with a mobile alert system for shrimp drying. Solar Energy, 240, 246–257. DOI: j.solener.2022.05.028.

[24] Eltawil, M. A., Azam, M. M., & Alghannam, A. O. (2018). Solar PV powered mixed-mode tunnel dryer for drying potato chips. Renewable Energy, 116, 594–605. DOI: 10.1016/j.renene.2017.10.007.

[25] Aydin, D., Ezenwali, S. E., Alibar, M. Y., & Chen, X. (2019). Novel modular mixed-mode dryer for enhanced solar energy utilization in agricultural crop drying applications. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 43(16), 1958–1974. DOI: 10.1080/15567036.2019.1663306.

[26] Ezhilvannan, P., Krishnan, S., Hemanth Kumar, B., Janardhan, K., & Ramachandran, S. (2023). Analysis of the Effectiveness of a Two-Stage Three-Phase Grid-Connected Inverter for Photovoltaic Applications. Journal of Solar Energy Research, 8(2), 1471-1483. DOI: 10.22059/jser.2023.357025.1285.

[27] Elahi, E., Khalid, Z., & Zhang, Z. (2022). Understanding farmers' intention and willingness to install renewable energy technology: A solution to reduce the environmental emissions of agriculture. Applied Energy, 309, 118459. DOI: 10.1016/j.apenergy.2021.118459

[28] Shoeibi, S., Kargarsharifabad, H., Mirjalily, S. A. A., & Zargarazad, M. (2021). Performance analysis of finned photovoltaic/thermal solar air dryer with using a compound parabolic concentrator. Applied Energy, 304, 117778. DOI: 10.1016/j.apenergy.2021.117778.