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Cost analysis of effective drying of onions using hybrid solar drying solution

Anand P. Chavan[1]*, Pradeep Kumar Ramteke[1] & Bhaskar N. Thorat[2]

[1]Department of Chemical Engineering, Shri Guru Gobind Singh ji Institute of Engineering and Technology, Nanded-431606, Maharashtra, India

[2]Department of Chemical Engineering, Institute of Chemical Technology, Mumbai-400019, Maharashtra, India

*E-mail id: apchavan@sggs.ac.in

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The utilization of staple food items such as onions, whether fresh or dehydrated, is influenced by various factors beyond just their price point. Nowadays, the feasibility of obtaining dehydrated onions at a reasonable cost has become plausible, thanks to the emergence of new, sustainable solar drying technologies. This research focused on onion dehydration utilizing the Solar Conduction Dryer and its variations. Through this drying process, the initial moisture content of 86% was reduced to 7%, resulting in the extraction of 84.95 kg of water from 100 kg of fresh onions to attain the desired moisture level. Economic evaluations were conducted, considering parameters such as life cycle cost, capital investment, variable expenses, internal rate of return, and payback period, among others. The findings revealed that daily savings for onion dehydration using conduction dryers were $41.61, $42.87, and $35.16 for the Solar Conduction Dryer (SCD), Corrugated Solar Conduction Dryer (CSCD), and Corrugated Solar Conduction Dryer with Electric Backup (CESCD), respectively. The capital costs and dryer efficiencies for SCD, CSCD, and CESCD were as follows: $6015 and 50.62%; $3760 and 84.37%; and $5640 and 84.37%, respectively. Notably, the CSCD exhibited superior performance in terms of dryer efficiency and capital investment compared to other conduction dryers. Moreover, the utilization of solar conduction dryers facilitated an annual reduction of approximately 120 tons of CO_2 emissions, making a significant contribution towards greenhouse gas mitigation.

Keywords*:* Internal rate of return, Payback period, Reduced inequality Solar Dryer, Sustainable development goals

Introduction

Onion (*Allium cepa*), as an all-season vegetable and condiment, are desirous of imparting the delicious taste and flavour to food products besides it offering medicinal benefits as an immune booster (quercetin). Onion is one of the vegetables produced on a humongous scale and is consumed not only in India but also in the whole world[1]. The gradually increasing production of the onion itself speaks of its high demand[2]. Food and Agriculture data indicate that global onion production has been consistently high, with total output around 110–117 million tonnes and several million hectares under cultivation[3]. In India, onion production in 2025-26 is estimated to be 26.92 million tons.

Onion serves as a good medicinal compound for cataracts, cardiovascular disease, and cancer due to its hypocholesterolemia, thrombolytic, antimicrobial, anti-inflammatory, and antioxidant properties[4]. In addition, onions contain a variety of other naturally occurring flavanols and organosulfur compounds that have been associated with the lowering of blood pressure and cholesterol[5,6]. In India, onion production has been surplus every year despite its large-scale consumption, making it crucial to preserve this agri-produce. Food processing for its value addition is one of the better available options. It facilitates to store them and sell them during the off-season period at a reasonably higher price. Food processing not only provides the option of availability of onion during the off-season but also several value-added products can be manufactured out of it through secondary or tertiary agri-processing technologies. Additionally, in countries like India, changing lifestyles and improving the standard of living creates scope for more processed food products[7]. According to Gulati *et al*. (2022), about 480 thousand hectares of land in India are dedicated to onion production, accounting for approximately 14% of the total global area under onion cultivation[8]. Having such a significant area for onion production, India is only the second-largest producer after China, with 14%. However, India's share in dehydrated onions is only 7%, thus with further scope to improve upon the secondary farm processing for both domestic as well as export market.

Among the common food processing techniques, drying is one of the preferred methods of food preservation. The dehydrated products also serve as raw materials for many food processing industries. Dehydration also increases the concentration of phytochemicals by decreasing the moisture content within the onion. The moisture content of fresh onions varies between 84% to 86%, while the dehydrated onions have a moisture content of about 4% to 8%[9]. Common dehydrated product of onion includes shreds, powders, and dried slices.

Traditional sun-drying is still the most common preservation method used by food processors and small farmers, who process more than 80% of the total food[10] . The technology used in developed countries or by big industries in developing countries is techno-economically not feasible for small holding farmers. In order to ensure continuous food supply to the growing population and to enable small farmers to produce high-quality, marketable dried products, the main emphasis must be given to the development of efficient drying methods suitable for small farmers and processors. The major role of a dryer is to accelerate the drying and to produce a better-quality product. To overcome the existing issues related to post-harvest processing of onion and other perishable food material in developing countries[11], solar drying seems to be a promising alternative[12]. A popular and economical drying method is open sun drying, which comes with limitations of environmental factors such as air contamination, rain, dust, infestation, affecting the quality of the product. Additionally, the key parameters, the heat input, product moisture content, temperature, drying air flow rate, are not controllable and provide variable drying rates and longer drying periods[13]. Solar dryers are developed with considerations including preferred airflow, dimensions, configuration, and placement of solar collectors, the nature of the product being dried, and the incorporation of insulation during assembly[14]. There are two types of solar dryers classified by air movement modes: forced and natural. In forced-type dryers, drying air is propelled into the dryer chamber through the solar collector using a blower. Conversely, natural-type solar dryers rely on the natural convection of air for airflow and can also be referred to as natural convection and direct solar-type (NCDT) dryers[15]. Natural dryers can be further categorized into Integral (Direct) type solar dryers, distributed (Indirect) type solar dryers, and Mixed-mode (Hybrid) solar dryers based on the specific design of system components and the utilization of solar heat.

The NCDT dryers are popular among farmers in temperate countries of the world as these provide desired quality product avoiding the environmental issues[16]. Generally, these cater to 10-15 kg of raw materials at household level. NCDT dryers are reported to use convection and radiation as the main heat transfer mechanism. While reports on the use of conductive mode in such dryers are scant. The authors have investigated the utilization of all three heat transfer mechanisms in the solar conduction dryer. It has proposed that incorporating the conduction mechanism alongside the other two mechanisms yields higher thermal efficiency compared to earlier prototypes of NCDT dryers[17]. The study investigated the impact of individual heat transfer modes in solar crop dryers (SCD) on the drying of agricultural products through the utilization of drying kinetics and fundamental heat transfer calculations. The observation revealed that the predominant order of influence of heat transfer mechanisms is primarily conduction, followed by radiation, and then convection[17]. The convection contribution is a bare minimum to the overall heat transfer.

This study undertook a techno-economic analysis of the Solar Conduction Dryer (SCD) alongside its derivatives, the Corrugated Solar Conduction Dryer (CSCD) and Corrugated Solar Conduction Dryer with Electric Backup (CESCD), focusing on onion dehydration. Additionally, an evaluation of greenhouse gas (GHG) emissions was performed to measure the prospective decrease in CO_2 emissions facilitated by the dryers utilized in this research.The document is organized into three distinct sections. The initial section underscores the imperative for the development of exceptionally efficient solar drying systems. Subsequently, the second section scrutinizes the engineering intricacies of solar conduction dryers alongside two alternative iterations. Lastly, the third section offers a thorough economic evaluation and comparative analysis of the aforementioned solar drying technologies.

Experimental Section

Solar Conduction Dryer (SCD)

The Solar Conduction Dryer (SCD), illustrated in Fig. 1, was developed through collaborative efforts between the Advanced Drying Laboratory at ICT, Mumbai, and M/s. S4S Techno Services Pvt. Ltd.

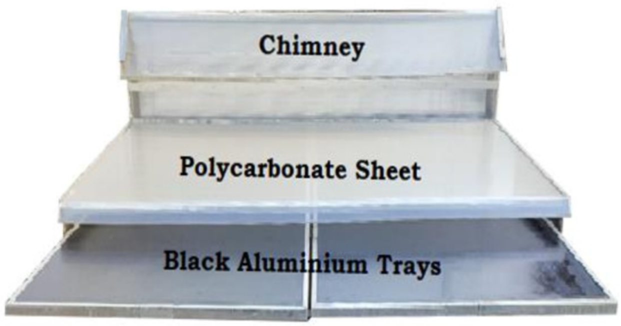

Fig. 1 — Solar conduction dryer

This dryer distinguishes itself by effectively harnessing all three modes of heat transfer: conduction, convection and radiation. While conduction and radiative heat transfer play significant roles, convective heat transfer through natural draft, though minor, remains integral for moisture extraction within the dryer.

An air velocity of 0.1 m/s has been observed as sufficient for surface moisture removal. The SCD comprises four drying chambers constructed from hollow stainless steel sections, each boasting a surface area of 1 m^2, allowing for a total loading capacity of approximately 15 kg across the 4 m^2 dryer. Transparent polycarbonate multiwall sheets cover the trays, which are coated with food-grade black coloring and adequately insulated to minimize heat dissipation. A low-height air vent is integrated to promote horizontal air currents within the dryer, facilitating the natural convective flow of atmospheric air to aid in moisture elimination. Tray movement is facilitated through sliding them in and out via a specially designed channel for material loading.

Corrugated Solar Conduction Dryer (CSCD) and Corrugated Electric Solar Conduction Dryer (CESCD)

The CSCD introduces a novel tray design as a refinement of the SCD concept, offering two distinct variants: one equipped with electrical backup and another without, as depicted in Figs 2 and 3, respectively. Notably, the corrugated trays present a significant enhancement in loading capacity, ranging from 20% to 50% compared to conventional flat trays, owing to their raised surfaces and indentations. Particularly in applications involving grains, legumes, and pulses, the loading capacity can even triple that of standard SCD setups. The corrugated structure, characterized by its crests and troughs, further augments mass and heat transfer within the dryer. In the case of the electrical backup system, uninterrupted operation, regardless of weather conditions, is achievable. With a heating capacity of 500 Watts derived from electrical energy, the dryer maintains a surface temperature ranging between 65-70 °C, ensuring optimal drying conditions.

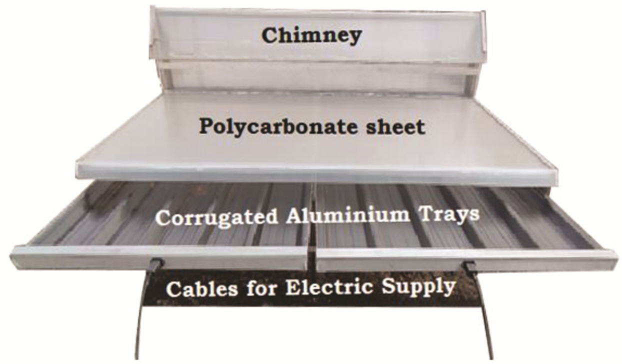

Fig. 2 — Corrugated Electric Solar Conduction Dryer

Fig. 3 — Corrugated solar conduction dryer

The corrugated tray design offers significant advantages over flat trays in terms of heat and mass transfer performance. The corrugated surface increases the effective heat transfer area, thereby enhancing both conductive and convective heat transfer; similar improvements have been reported for corrugated absorber plates due to increased surface exposure and induced turbulence[18]. In addition, the corrugated geometry promotes airflow turbulence and disrupts boundary layers, resulting in improved mixing and more uniform air distribution within the drying chamber[19]. The tray configuration also influences product exposure, where optimized geometries reduce overlapping and enhance spatial distribution, leading to more efficient moisture removal[20]. Consequently, the combined effects of enhanced heat transfer and improved airflow distribution significantly increase the drying rate and uniformity, ultimately reducing drying time and improving overall dryer performance[21].

Measurements and instrumentation

K-type thermocouples, paired with a data logger (IM 2000 N, Ajinkya Electronic Systems, Mumbai, India), were utilized to gauge the temperature of both the polycarbonate multiwall sheet and the black-coated aluminium trays. Measurement of air velocity at the inlet and outlet was conducted using a vane anemometer (VT100, Kimo Instruments, France). Within the tray section, monitoring of air temperature and humidity was facilitated by instruments sourced from Vaisala (HMD82D, Finland), calibrated across a range of 0 to 100% for humidity and -40 to 100 °C for temperature. Furthermore, a pyranometer (DAM 8101, Dynalab Weathertech Pvt. Ltd., Pune, India) was employed for the measurement of solar radiation flux.

Experimentation

Fresh Nashik red onions were sourced from the local market immediately before the commencement of experiments. They underwent a thorough cleaning process to eliminate any traces of dirt or dust before peeling. Subsequently, the cleaned onions were sorted and diced using an industrial cutter (Robot-Coupe CL-50), employing various blade configurations. The resulting shreds measured 1 mm in thickness and ranged from 3 to 10 mm in length, suitable for drying purposes. The drying experiments were conducted using the SCD, CSCD, and CESCD systems. In all three cases, efforts were made to maintain consistent initial conditions, with the samples possessing an initial moisture content of 86% and weights of 50 kg for both SCD and CSCD, and 33 kg for CESCD. The experiments were scheduled on days with a minimum of 8 h of available sunlight, with solar radiation intensity being monitored throughout the process, as depicted in Fig. 4. The sample weights were recorded at regular 10 min intervals using a weighing balance. Notably, experiments involving the CESCD were carried out during night-time, as its operation did not rely on solar energy.

Analysis

Design of solar conduction dryers

Design calculations and determination of dryer dimensions relied on the following equations. The weight of water to be evaporated during drying, denoted as M_w (kg),[22]

$$M_w = \left(\frac{m_i - m_f}{100 - m_f}\right) \times W \qquad \ldots(1)$$

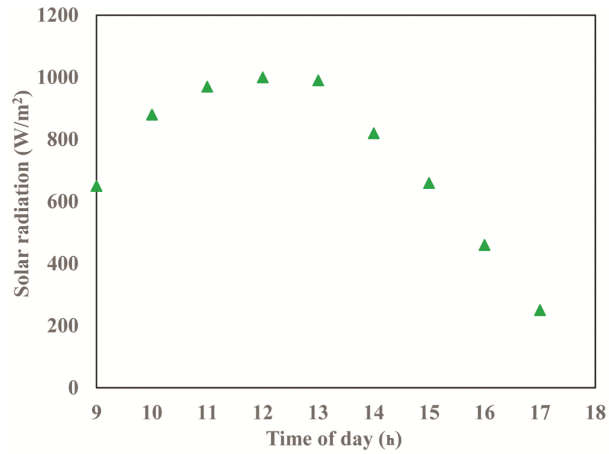

Fig. 4 — Variation of solar radiation

Where, W, m_i, and m_f represent the weight of product at the start of the drying process (kg), initial moisture content (%) and final moisture content (%), respectively.

The overall required energy is calculated as follows, Q (kJ),

$$Q = WC_p(T_d - T_a) + M_w\lambda \qquad \ldots(2)$$

Where C_p denotes the specific heat (kJ kg^{-1} °C^{-1}), T_d represents the drying temperature (K), T_a signifies the ambient temperature (K) and λ is the latent heat of vaporization (kJ kg^{-1}).

The efficiency of the dryer, denoted as η, is determined by the following equation

$$\eta = \frac{Q}{IA} \qquad \ldots(3)$$

Where, A represents the area of the solar collector (m^2), and I denotes the incident solar radiation (MJ m^{-2}).

Economic evaluation

One notable advantage of utilizing SCD for dehydrating food and agricultural products is the assurance of producing contamination-free final goods with superior quality in terms of both appearance and retained nutrition. The resulting dried products from SCD tend to command higher prices in both local and international markets. This suggests the potential for establishing a distinct brand and generating added value, consequently bolstering the income of small and medium enterprises specializing in agricultural products. The economic examination undertaken here involves comparing the selling price of solar-dried products with that of branded alternatives available in the market.

In this research, the economic analysis employs five distinct methodologies. The annualized cost approach juxtaposes the drying cost per unit weight of product in SCD against that of electric dryers. However, this method fails to comprehensively encapsulate the economic dynamics of solar dryers as it disregards fluctuations in drying costs throughout the dryer's lifespan, particularly in response to changes in conventional energy expenses. Hence, the life cycle savings method is employed to assess the cumulative savings over the system's lifespan, thereby providing a more holistic perspective on economic benefits. If the payback period of the system is short, economic considerations are likely to drive buyers towards adopting solar dryers for processing. Conversely, a protracted payback period may deter commercial adoption despite potential long-term savings. It has previously outlined pertinent equations for economic analysis applicable to domestic solar dryer usage[23].

Annualized cost method

To assess the cost of drying, an analysis was conducted using the annualized cost method, comparing it against alternative drying systems. This method entails computing the drying cost per unit weight of the dried product, achieved by dividing the annualized cost of the dryer by the quantity of product dried annually. Further details regarding this methodology can be found in a prior publication authored by in this study[23].

Life-cycle savings

The life cycle savings method was employed to evaluate the economic performance of the solar dryer. Initially, the daily savings were calculated as the difference between the operating cost of the conventional drying method and that of the solar dryer. These daily savings were then used to estimate the annual savings based on the number of drying days per year. Subsequently, the present worth of annual savings was determined by discounting the annual savings over the system lifespan using an appropriate discount rate. Further, the present worth of cumulative savings was calculated by summing the discounted savings over the entire life cycle of the system. A detailed methodology and equations for these calculations are available in previous studies[7,23].

Payback period

The payback period denotes the duration necessary to recoup the total investment cost, serving as the timeframe to achieve the break-even point. Another perspective on the payback period emerges from cumulative fuel savings equating to the initial investment outlay. This period is delineated in the latter section. The calculation of the payback period (N) employs an equation provided by in this study[23], utilized herein to compare the techno-economic aspects of SCDs.

$$N = \frac{\ln\left(1 - \frac{C_{cc}}{S_1}(d - i)\right)}{\ln\left(\frac{1+i}{1+d}\right)} \quad \ldots(4)$$

Where, C_{cc} represents the capital cost of the dryer (USD), S_1 denotes the saving during the first year of the solar dryer (USD), d is the rate of interest (%) and ignifies the rate of inflation (%).

Internal rate of return (IRR)

The Internal Rate of Return (IRR) was used as a key indicator to evaluate the economic feasibility of the solar drying system. IRR is defined as the discount rate at which the net present value (NPV) of all cash flows becomes zero. In this study, the cash flow series included the initial capital investment (outflow) and the annual net savings (inflows) obtained from reduced operating costs.

The annual cash inflows were assumed to be uniform over the system lifespan, considering 250 operating days per year and a project life of 20 years, while operation and maintenance costs were accounted for in the net savings. The IRR was calculated using the built-in IRR function in Microsoft Excel by inputting the complete cash flow sequence.

This approach is consistent with standard techno-economic evaluation methods reported in the literature[30].

Life cycle cost (LCC)

The life cycle cost of a system can be defined as the total sum of all expenses accrued throughout its lifespan. To conduct life cycle cost studies, several types of information are necessary, such as the acquisition cost of the item, the useful operational life of the drying system in years, the annual operating and maintenance costs of the dryer, transportation expenses, salvage value, and installation costs.

In this study, the life cycle cost of the dryers was determined by the following formula[24].

$$LCC_a = PC_a + PV_{af} + PV_{ao} \quad \ldots(5)$$

Where, PC_a is the procurement cost of the dryer, PV_{af} is the present value of the life cycle failure cost of a dryer, and PV_{ao} is the present value of the life cycle operating cost of the dryer.

Results and Discussion

Temporal profiles of temperature and relative humidity during drying

Experimental procedures were undertaken to evaluate the temperature profiles of plates across different iterations of the SCD under varying weather conditions, ensuring daylight hours from 9 am to 5 pm. Monitoring of solar radiation intensity was conducted, as illustrated in Fig. 4. Air velocities at inlet and outlet points of the dryer were also measured. Temperature assessments utilized K-type thermocouples, with multiple readings taken to gauge the bottom aluminium plate's temperature. Results indicated an average chamber temperature exceeding ambient levels by 30-32 °C. Temperature fluctuations during full-load testing of the SCD variants are graphically depicted in Fig. 5.

Observations from Fig. 5 highlights maximum plate temperatures of 58, 59, and 66 for SCD, CSCD, and CESCD, respectively, with corresponding minimum temperatures of 50, 51, and 48. Recent studies report that onion drying is typically performed within 50–70 °C, where moderate temperatures (~65 °C) provide an optimal compromise between drying rate and retention of physicochemical and antioxidant properties[25]. Higher temperatures (>70 °C) may lead to degradation of heat-sensitive compounds, colour deterioration, and quality loss[26].

Additionally, Fig. 6 illustrates the variation of relative humidity inside the dryer under full-load conditions. Initially, the presence of high moisture content in the product (≈86%) leads to evaporation, increasing the water vapour concentration in the air and resulting in a rise in relative humidity, reaching peak values of approximately 55%, 55%, and 58% for SCD, CSCD, and CESCD, respectively.

As drying progresses, the rate of moisture evaporation decreases due to reduced free moisture in the product. Consequently, the vapour pressure of water in the drying air declines, leads to a gradual reduction in relative humidity. This behaviour is consistent with the principles of heat and mass transfer, where relative humidity is governed by the ratio of partial vapor pressure to saturation vapour pressure.

Furthermore, relative humidity plays a significant role in drying performance. Lower relative humidity enhances the moisture-carrying capacity of air, thereby increasing the drying rate. It also facilitates higher air temperature within the dryer due to reduced evaporative cooling effects, improving overall thermal efficiency. Similar trends have been reported in solar drying studies[22,27,28].

Drying characteristics

Onion shreds were dried in SCD, CSCD, and CESCD, reducing the moisture content from 6.14 to 0.08 kg water per kg dry matter. The variation of moisture content with time is presented in Fig. 7,

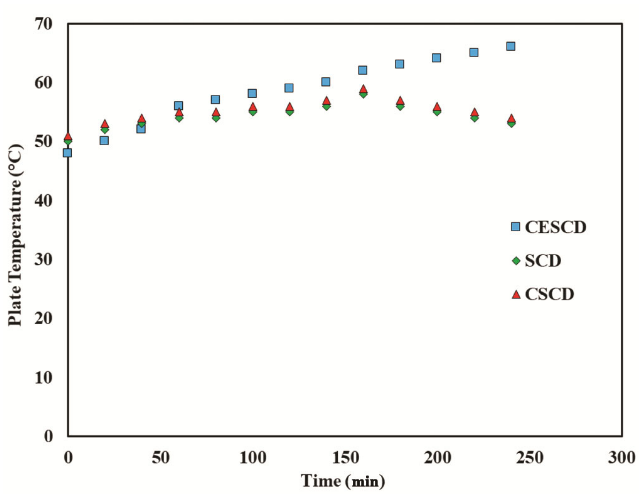

Fig. 5 — Temperature variation during the drying

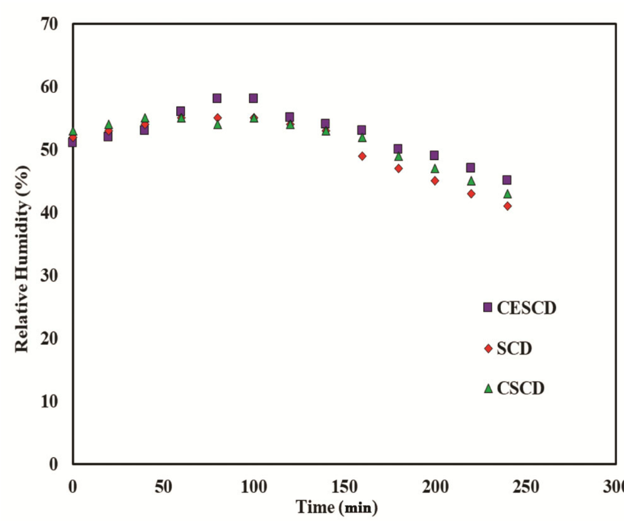

Fig. 6 — Variation of relative humidity with time

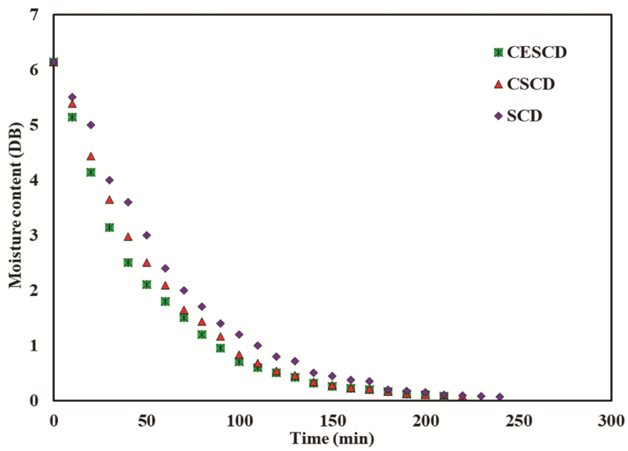

Fig. 7 — Moisture reduction with respect to time

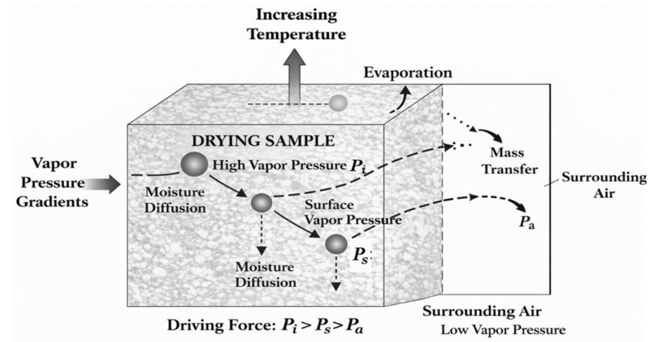

Fig. 8 — Schematic representation of moisture diffusion and vapour pressure

where the drying curve of CESCD exhibits a steeper slope compared to CSCD and SCD, indicating a higher drying rate.

The drying behaviour is strongly influenced by the temperature of the drying plate. An increase in temperature enhances the drying rate and reduces the overall drying time. This can be explained based on heat and mass transfer principles: as temperature increases, the saturation vapour pressure of moisture within the product rises, which increases the vapour pressure gradient between the interior and surface of the sample as well as between the product surface and surrounding air. This gradient acts as the driving force for moisture diffusion and evaporation.

Consequently, higher temperature accelerates internal moisture diffusion and surface evaporation, leading to faster drying. This phenomenon is widely reported for various agricultural products, including onion slices and other food materials[9,27,29].

To further clarify this mechanism, a schematic diagram illustrating vapour pressure gradients, internal moisture diffusion, and mass transfer during drying has been added as Fig. 8.

Comparison of various solar conduction dryers for 100 kg/day capacity

SCD, CSCD, and CESCD are equipped with 4 m^2 modules (projected area) and have loading capacities of 15 kg, 25 kg, and 25 kg, respectively. To dehydrate 100 kg/day of onion, dryer areas of 13.33, 8, and 5.33 m^2 were necessary for SCD, CSCD, and CESCD, respectively. The drying process aimed to reduce the initial moisture content from 86% to approximately 7%, necessitating the removal of 84.95 kg of water from 100 kg by mass. The total energy (sensible and latent) required for evaporating 84.95 kg of water amounted to 1.94×10^5 kJ. Energy received during sunshine hours were calculated as 3.84×10^5, 2.3×10^5, and 2.3×10^5 kJ for SCD, CSCD, and CESCD, respectively. The overall efficiencies of the dryers (SCD, CSCD, and CESCD) were determined to be 50.62%, 84.37%, and 84.37%, respectively. Construction and installation costs per m^2 absorbing surface, along with accompanying accessories, were estimated at 376, 470, and 705 USD for SCD, CSCD, and CESCD, respectively. Capital investments for SCD, CSCD, and CESCD were 6015, 3760, and 5640 USD, respectively. A study conducted by in the study on bottle gourd drying using tunnel and cabinet dryers revealed lower efficiencies of 29% and 30.93%, respectively[7]. Tunnel and cabinet dryers incurred higher capital costs (10025 USD and 22560 USD, respectively) due to larger dryer areas, fewer batches per day, and higher electricity costs. In contrast, conduction dryers demonstrated higher efficiencies attributed to the conduction mode of heat transfer. Among conduction dryers, CSCD required lower capital costs due to its smaller area and higher efficiency. These design parameters for solar conduction dryers are presented in Table 1 for ease of understanding and comparison.

Economic evaluation of the dryer

The economic parameters are based on the prevailing conditions in India, as outlined in Table 2. A comprehensive summary of the economic analysis, conducted utilizing the five methods described earlier, is methodically presented here.

Annualized cost method

The initial phase involved calculating the annual capital expenditure, with a presumed salvage value set at 10% of the annual capital cost, as delineated in

Table 1 for all three dryers under scrutiny. For ease of computation, it was assumed that the solar dryer could function for 250 solar days per year. The total volume of dried product processed annually in the solar dryer was standardized to 3763.44 kg for comparative purposes. The drying cost per kilogram of dried onion was computed as 0.22 USD for SCD, 0.14 USD for CSCD, and 0.65 USD for CESCD. In similar studies, the drying expenses for 1 kg of pineapple and bitter gourd in roof-integrated solar collectors and cabinet dryers were documented at 0.52 USD and 0.82 USD, respectively[23]. The per-kilogram drying cost of dried product is indirectly impacted by the dryer's capital outlay; a higher capital investment in the dryer corresponds to an increased drying cost per kilogram of product.

Table 1 — Design parameters of solar dryers

Parameter	Solar conduction dryer	Corrugated SCD	Corrugated electrical SCD
Capacity of dryer (kg/day)	100	100	100
Number of batches in a day	2	2	3
Dryer area (m^2)	13.33	8	5.33
Energy received by the dryer (kJ)	3.84×10^5	2.3×10^5	2.3×10^5
Dryer efficiency (%)	50.62	84.37	84.37
Average temperature of drying plate (°C)	54	55	57
Average relative humidity of drying section (%)	50.39	51.63	57.53
Solar radiation values (W/m^2)	791	810	-
Moisture removed (kg)	84.94	84.5	84.7
Installation cost per m^2 (USD)	376	470	705
Capital cost (USD)	6015	3760	5640

Table 2 — Cost and economic parameters of various solar dryers

Parameters	Cost
Interest rate	11 %
Rate of inflation	5 %
The life span of the dryer	20
Cost of onion	0.47 USD/kg
The selling price of onion	6.10 USD/kg

Life-cycle savings

The analysis began with assessing the cost to dry 1 kg of onion in SCD, CSCD, and CESCD, as detailed previously. Following this, the daily savings were computed, yielding USD 41.60, 42.87, and 35.17 for SCD, CSCD, and CESCD, respectively. Tables 3, 4, and 5 present the present value of annual savings, calculated annual savings, and present cumulative value of annual savings for each year throughout the lifespan of SCD, CSCD, and CESCD. Furthermore, Figs 9, 10, and 11 provide a comparative view of life-cycle savings parameters across the solar dryers. Figs 9, 10, and 11 illustrate that both the annual and cumulative savings increase with prolonged dryer usage. However, the present value of annual savings diminishes over time due to the declining present value factor with each year of usage. Consequently, the resulting cumulative present value stood at USD 26,286, USD 27,082, and USD 22,215 for SCD, CSCD, and CESCD, respectively, based on an investment of USD 6,015 for SCD, USD 3,760 for CSCD, and USD 5,640 for CESCD, assuming a dryer lifespan of 20 years. Comparable computations were

Table 3 — Life-cycle savings of the SCD

Year	The annualized cost of the dryer (USD)	Annual savings (USD)	The present worth of annual savings (USD)	The present worth of cumulative savings (USD)
1	841	10402	9355	9355
5	841	12644	7436	41840
10	841	16137	5582	73246
15	841	20596	4190	96819
20	841	26286	3145	114515

Table 4 — Life-cycle savings of the CSCD

Year	The annualized cost of the dryer (USD)	Annual savings (USD)	The present worth of annual saving (USD)	The present worth of cumulative saving (USD)
1	525	10717	9638	9638
5	525	13027	7662	43108
10	525	16626	5751	75465
15	525	21220	4317	99754
20	525	27082	3240	117985

conducted for an indirect solar cabinet dryer by this study[2], revealing a cumulative annual saving value of USD 1,488.

Economic evaluation of solar conduction dryers

The economic performance of the solar conduction dryers was evaluated using key indicators, including payback period, Internal Rate of Return (IRR), and Life Cycle Cost (LCC). These parameters provide a comprehensive assessment of financial feasibility and long-term economic benefits.

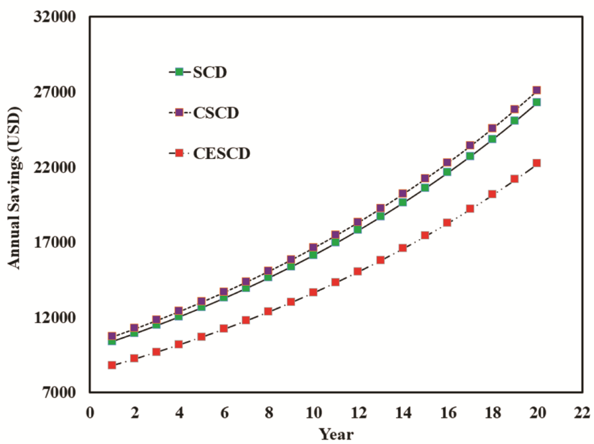

Fig. 9 — Comparison of annual savings (USD) of various solar dryers over the dryer's life span.

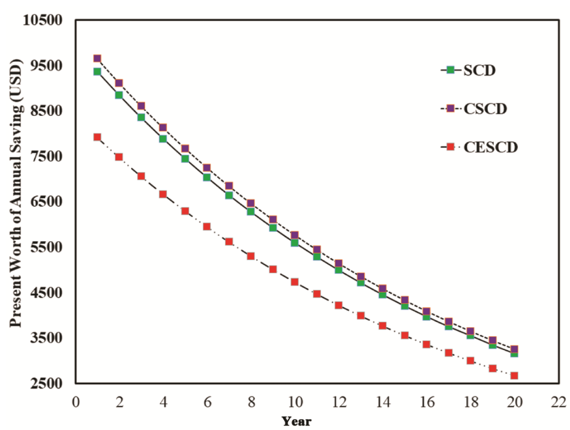

Fig. 10 — Comparison of the present worth of annual savings (USD) of various solar dryers over the dryer's life span

The payback period represents the time required for cumulative savings to recover the initial investment cost. As shown in Table 6, the payback periods for SCD, CSCD, and CESCD were found to be 0.64, 0.38, and 0.71 years (i.e., 160, 96, and 177 drying days), respectively. These values indicate rapid cost recovery compared to conventional dryers, which typically exhibit longer payback periods[7].

The Internal Rate of Return (IRR), defined as the discount rate at which the net present value becomes zero, is a crucial indicator for investment decision-making. The IRR values for SCD, CSCD, and CESCD were determined as 49%, 76%, and 3%, respectively. Among the three systems, CSCD demonstrates the highest IRR, indicating superior profitability. In contrast, the lower IRR of CESCD is

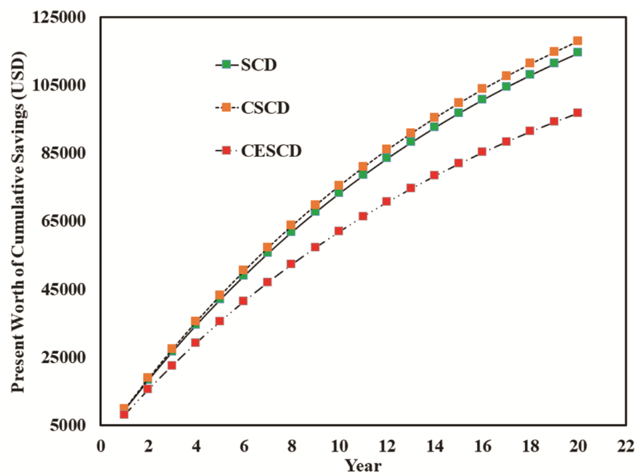

Fig. 11 — Comparison of the present worth of cumulative savings (USD) of various solar dryers over the dryer's life span

Table 6 — Comparative analysis of various solar dryers for onion

Parameters	Value
Moisture removed	85 kg/day
Energy reuired	60 kWh/day
Coal consumption	24 kg/day
CO_2 emission factor	2.4 kg CO_2/kg coal
Annual operation	250 days/year
System lifespan	20 years
Total CO_2 emission reduction	120 tons

Table 5 — Life-cycle savings of the CESCD

Year	The annualized cost of the dryer (USD)	Annual savings (USD)	The present worth of annual savings (USD)	The present worth of cumulative savings (USD)
1	2452	8791	7906	7906
5	2452	10686	6285	35360
10	2452	13638	4717	61902
15	2452	17406	3541	81825
20	2452	22215	2658	96780

Table 7 — Summary of CO_2 Emission Reduction Calculation

Parameter	Conduction dryer (SCD)	Corrugated SCD (CSCD)	Corrugated electrical SCD (CESCD)
Capital cost(USD)	6015	3760	5640
Capacity of dryer (kg/day)	100	100	100
Number of batches in a day	2	2	3
Dryer area (m^2)	13.33	8	5.33
Product quality	Good	Good	Good
Electricity cost (USD/year)	None	None	1664
Savings per day (USD)	41.61	42.87	35.16
Internal rate of return(IRR) (%)	49	76	3
Payback period (days)	160	96	177
Dryer efficiency (%)	50.62	84.37	84.37
Life cycle cost (USD)	6618	4137	6212

attributed to additional electricity consumption, increasing operational costs.

The Life Cycle Cost (LCC) analysis considers the total cost over the system lifespan, including capital, operation, maintenance, and energy costs. The LCC values for SCD, CSCD, and CESCD were calculated as 6618, 4137, and 6212 USD, respectively. The lowest LCC for CSCD confirms its economic advantage over the other configurations.

CO_2 reduction potential in SCD, CSCD, and CESCD

The reduction in CO_2 emissions was estimated based on the equivalent energy savings achieved by replacing conventional fossil-fuel-based drying with solar drying systems[31]. The energy required for moisture removal was calculated assuming 2500 kJ per kg of water evaporated, which is typical for hot air drying processes. In the present study, approximately 85 kg of moisture is removed per day, corresponding to an energy requirement of about 60 kWh/day.

If this energy were supplied using coal-based systems, it would require approximately 24 kg of coal per day. The associated CO_2 emissions were estimated using a standard emission factor of 2.4 kg CO_2 per kg of coal. Considering 250 operating days per year and a system lifespan of 20 years, the cumulative CO_2 emission reduction achieved by the solar dryers (SCD and CSCD) is approximately 120 tons of CO_2. A summary of the calculation procedure and assumptions is presented in Table 7.

Comparative economic and quality performance

In addition to economic evaluation, product quality aspects were also assessed. All dryers utilized polycarbonate multiwall sheets as glazing material, which enhance the greenhouse effect while reducing harmful UV radiation. This contributes to improved product quality in terms of colour, texture, and nutrient retention.

Lower UV exposure minimizes oxidative degradation and discoloration, thereby preserving key quality attributes such as LAB values, hue, and chroma. The predominance of infrared radiation in conduction dryers further supports better retention of sensory and nutritional properties. Similar improvements in microbial and biochemical quality have been reported in solar drying studies[16].

Table 6 summarizes the overall comparison of economic and performance parameters, including capital cost, operating cost, IRR, payback period, efficiency, and LCC. Based on this integrated assessment, CSCD emerges as the most favourable option due to its lower life cycle cost, higher return on investment, and superior product quality.

Conclusion

The solar conduction dryer and its variants were compared on a techno-economic basis for the drying of 100 kg of onion. The examination of economic factors indicates that the collective present value of yearly savings derived from the onion drying process throughout the operational lifespan of the conduction dryers reaches 26,286 USD for SCD, 27,082 USD for CSCD, and 22,215 USD for CESCD. Capital investment, life cycle cost and payback period are 6015 USD, 6618 USD, 160 days (SCD); 3760 USD, 4137 USD, 96 days (CSCD) and 5640 USD, 6212 USD, 177 days (CESCD); respectively. CSCD boasted a lower initial capital investment, along with notably reduced life cycle costs and payback periods in contrast to alternative conduction dryers. Moreover, it showcased superior Internal Rate of Return (IRR) and dryer efficiencies when juxtaposed with its counterparts. Hence, SCD could serve as the preferred decentralized post-harvest technique, emerging as the optimal choice for the dehydration of agricultural products, highly recommended for post-harvest processing of agricultural and food products.

Conflict of Interest

The authors declare no conflict of interest.

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