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Review

Solar drying technologies: Selection criteria, technical feasibility, economic viability, and recent advances for sustainable agricultural practices

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Abstract

Recent advances in solar drying technology have enabled food preservation and agricultural processing of energy-friendly, clean, and sustainable developments in the rural sector of developing countries. The present review highlights the significant contributions of solar dryers in addressing energy supply challenges, and achieving the goal of sustainable development by providing affordable, reliable, sustainable, and modern energy for all. The present review discusses innovative approaches in solar drying techniques, direct, indirect, and hybrid systems with a focus on improving drying rates, efficiency, and overall effectiveness. Additionally, the mechanisms, advantages, and limitations of these technologies are analysed. Furthermore, complementary technologies like thermal energy storage, computational modelling, and smart control systems are developed to enhance the performance and reliability of solar drying methods. Emphasising automation, process optimisation, and environmental sustainability, the findings demonstrate the role of solar drying in reducing emissions. The present review aims to cover breadth and depth, serving as a good source of information for scientists, engineers, and policy makers on maximising the possibility of solar drying in providing a more sustainable and resilient future.

Nomenclature

OSD: open sun drying; SD: solar dryer; PSD: passive solar dryer; ASD: active solar dryer; PCM: phase change material; SDG: Sustainable Development Goal; m: mass of drying product (kg); C_p: specific heat of product (kJ/kg K); T: product temperature (K); T_a: air temperature (K); t: time of drying (s); A_s: surface area of product (m^2); A_p: projected area of product (m^2); ε: emissivity; σ: Stefan-Boltzmann constant; F: radiation view factor; α: absorptivity; τ: latent heat of vaporisation; m_w: mass of moisture in product; h: convective heat transfer coefficient (W/m^2K); $\emptyset(t)$: radiation flux density varying with time; MC: moisture content (kg of water/kg of dry matter, d.b.); D: moisture diffusivity (m^2/s); DR: drying rate; E_f: energy requirement of fan (J); LH: latent heat of vaporisation of water (J/kg); η_{th}: thermal efficiency of solar collector; η_{od}: overall drying efficiency; I_c: quantity of solar energy in collector (W/m^2); A_c: collector area (m^2); AS: accumulated savings; IC: investment capital; AC: accumulated costs; i: inflation rate; r: annual interest rate; n: years; and FPSCs: flat plat solar collectors.

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Introduction

Drying serves as a vital process aimed at reducing moisture levels to inhibit the activity of enzymes, bacteria, yeasts, and moulds, thereby playing a pivotal role in enhancing product quality and minimising losses. To achieve these objectives, the selection of appropriate drying technologies is essential. Historically, drying has been one of the earliest preservation techniques employed for fruits, grains, vegetables, fish, meats, woods, and various agronomic products (Kaimal *et al*., 2022).

Traditional open sun drying

Predominantly practiced in tropical and subtropical regions, open sun drying (OSD) utilises

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renewable energy, offering significant benefits for small-scale farmers who lack access to or cannot afford electricity or conventional fuel sources for drying (Prabhu *et al*., 2023).

OSD techniques involve spreading agricultural produce on surfaces such as beaten earth, mats, concrete, or roads to utilise solar heat. However, these methods are highly susceptible to contamination by dirt, dust, and insect infestations, as well as losses caused by interference from birds and animals. For instance, drying maize on beaten earth can lead to aflatoxin contamination, posing health risks due to prolonged drying periods. Similarly, drying marine products like fish on mats or bamboo structures attracts egg-laying insects, causing larvae contamination and often requiring insecticide use, which in turn introduces additional health hazards (Alimohammadi *et al*., 2020; El-Mesery *et al*., 2022).

Challenges of open sun drying

Moreover, OSD demands substantial labour and time investments, necessitating protection against adverse weather conditions and night-time, as well as safeguarding crops from domestic animal interference. Additionally, uneven drying in OSD increases the risk of insect infestation and the growth of microorganisms, limiting its suitability for large-scale production (Dorouzi *et al*., 2018).

Increasing demand for dried products

However, despite the limitations, the global demand for dried vegetables, fruits, spices, medicinal plants, and fish continues to increase (Othman *et al*., 2006). While OSD remains a cost-effective method, the quality of dried products often fails to meet international standards.

Evolution to solar dryers

In response to these challenges and growing demand, the evolution of OSD has led to the innovation of solar dryer (SD) (Chojnacka *et al*., 2021). These enclosed systems maintain elevated internal temperatures, offering key advantages such as protection from flies, pests, rain, and dust. The SD remains a widely used technique for preserving food globally, especially in India, due to the consistently abundant solar energy available for a substantial portion of the year (Amer *et al*., 2018). It describes flat plate solar collectors (FPSCs) with emphasis placed on how their performance can be enhanced using such methods as turbulence generators, fins, phase change materials (PCMs), nano-fluids, reflectors, and mini- and micro-channels. These advancements improve energy efficiency: turbulators and fins enhance heat transfer; paraffin wax, as a PCM, improves thermal performance; nanofluids increase efficiency more effectively than water; reflectors optimise heating; and mini- and micro-channels improve reliability, heat transfer, cost-effectiveness, and resistance management (El-Sebaey *et al*., 2024).

The recent developments in SD technology have proven to be a promising and environmentally sound means of food preservation and agricultural processing in the less-developed rural areas of developing countries. Although this method enhances product quality and minimises losses, it remains expensive and faces significant adoption challenges. However, there are immense challenges in its adoption. Current studies have predominantly focused on broad-based mechanisms while often overlooking advanced innovations such as thermal energy storage, computational modelling, and smart control systems that could potentially contribute to efficiency and reliability. The present review addresses the gap by researching innovative techniques in SD to enhance performance, increase adoption rate, and support attainment of sustainable energy and food security goals.

Solar dryers and their classification

The primary goal of SD is to generate significant heat levels that exceed ambient temperatures. This is essential for removing moisture from the items being dried. The increased heat elevates the vapour pressure within the material while simultaneously reducing the relative humidity of the drying air (Gupta *et al*., 2022). Consequently, this process enhances the air's capacity to absorb moisture from the products being dried. Compared to traditional OSD methods for crop dehydration, SD creates significantly improved drying conditions. The airflow, whether natural or assisted by fans, plays a pivotal role in this process. It circulates within the SD, warming up in the collector, and extracting moisture from the material. The warmer air, with its heightened moisture-retention capability, substantially increases the efficiency of moisture removal. Key factors influencing this efficiency include the temperature within the collector, and the initial humidity of the incoming air. These factors directly impact the air's capacity to absorb moisture during the entire drying process (Asemu *et al*., 2020; Behera *et al*., 2022; Madhankumar *et al*., 2023; Agrawal *et al*., 2023). Solar dryers fall into two categories: passive and active. Passive dryers use sunlight and natural air circulation, while active ones employ forced convection using ventilators. Passive systems, common in Mediterranean, tropical, and subtropical regions, are straightforward in construction, utilising local materials for drying small fruit and vegetable batches (Chaouch *et al*., 2018). Within both active and passive systems, three distinct subcategories exist based on energy sources: direct-type, indirect-type, and hybrid or mixed-mode type as depicted in Figure 1 (Ekechukwu, 1999).

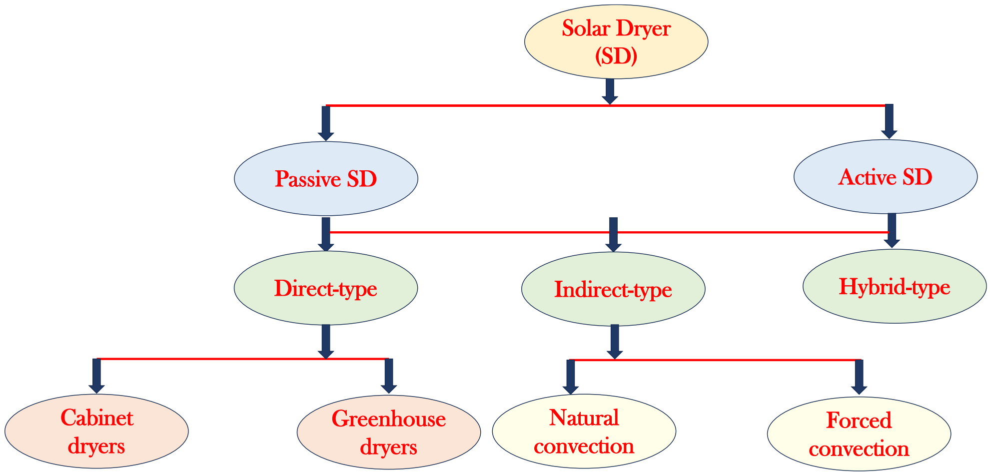

Figure 1. Categorisation of solar dryers.

Solar dryers consist of a collector, absorber, drying chamber, and insulation. They use various collector types like flat-plate, parabolic, and double-pass to harness solar energy efficiently. Absorbers, typically made from materials like galvanised iron or aluminium plates, capture and emit heat. Reflectors focus solar radiation on the collector. Insulation using materials like carton, glass wool, or agro-based products, minimises thermal losses (Jha and Tripathy, 2021). Drying chambers, in direct or indirect types, hold products for drying, employ trays made of bamboo, aluminium, or stainless steel. Ventilation systems remove moist air, and improve drying efficiency. Fans aid in active mode drying. Auxiliary heat sources, including biomass burners or electrical heaters, ensure efficient drying in varied conditions (Sharma *et al*., 2021). Energy storage methods like sensible heat (rock beds) or latent heat (phase change materials) supply energy in the absence of solar energy (Atalay, 2020). Desiccant materials assist in dehumidifying air, further improving drying efficiency. Researchers evaluate and refine these components to enhance SD performance across different applications and settings. Understanding these fundamental principles allows for thematic exploration of the engineering and technological aspects of SD (El Khadraoui *et al*., 2019). This includes optimising collector design, heat storage, and control systems to enhance energy usage and operational efficiency. Such insights are valuable tools for engineers and researchers aiming to enhance SD systems.

Passive solar dryers

Passive solar dryers (PSD), such as the normal and reverse absorber cabinet dryers and greenhouse dryers, harness the sun's radiation to aid crop drying, employing natural air movement and heat circulation mechanisms. These dryers utilise direct exposure to the sun, and employ either natural heating coupled with air circulation through buoyancy or wind pressure, or a combination of both methodologies (Kamarulzaman *et al*., 2021). These PSD are prevalent in various Mediterranean, tropical, and subtropical regions, notably in Africa and Asia, and are commonly adopted by small agricultural communities. Characterised by their primitive yet cost-effective construction, PSDs are built using locally available materials, and simple to install and operate, especially in remote areas lacking access to the electrical grid. Specifically designed for drying small batches of fruits and vegetables such as bananas, pineapples, mangoes, potatoes, and carrots, PSD offers a practical and accessible solution (Azaizia *et al*., 2020).

The direct-type PSD, illustrated in Figure 2a, involves moisture removal by air entering from below, and exiting at the top. Sunlight that enters through the glass cover reflects partially back into the atmosphere, and the remaining portion enters the cabinet. A part of this transmitted sunlight reflects from the surface of the crop, while the remainder is absorbed, consequently increasing the temperature of the crop (Deng *et al*., 2021). As a result, the crop emits long-wavelength radiation, trapped within the cabinet by the glass cover, further elevating the temperature inside. This setup reduces direct convective losses to the surroundings, crucial in maintaining higher temperatures for both the crop and the cabinet (Nukulwar and Tungikar, 2021).

Indirect-type PSD differ from direct ones in their approach to heat transfer and moisture extraction. These dryers feature crops situated on trays or shelves within an opaque drying cabinet as indicated in Figure 2b (Ekechukwu, 1999). A separate unit, known as a solar collector, heats the incoming air directed into the cabinet. The heated air circulates through or over the damp crop, transferring heat to aid moisture evaporation through convective heat exchange. The drying process relies on the moisture content gradient between the drying air and the air surrounding the crop surface (Badaoui *et al*., 2019). An indirect PSD with flat baffles was tested on grapes, and drying correlations for both fan-assisted and chimney-type dryers were developed. Moisture decreased from 79.80 to 14.04% in the chimney dryer, and 15.83% in the fan type dryer within three days. Average thermal efficiency was 27.02% for the fan type dryer, and 29.18% for the chimney dryer. Drying costs were \$4.65/kg for the fan type dryer, and \$4.50/kg for the chimney dryer. Both showed noticeable savings and CO_2 reductions, 286.25 and 337.18 kg/year, respectively (El-Sebaey, 2024). The author evaluated the thermal performance of both chimney-type and fan-type indirect solar dryers with respect to the drying of bananas, addressing concerns about fossil fuel limitations, rising energy costs, and global warming. The experiments conducted using the chimney-type dryer showed a final moisture content at 10.59%, improving efficiency on drying by 81% over open sun drying. It also performed better under the aspect of thermal performance, with average collector efficiency and overall thermal efficiency recorded at 34.14 and 14.45%, respectively, against 29.54 and 12.76% for the fan-type dryer, respectively. These data point to the chimney-type dryer as the more efficient alternative in achieving sustainable drying (El-Sebaey *et al*., 2023b).

Mixed-mode or hybrid-type PSD merge attributes from both direct and indirect solar-energy dryers as depicted in Figure 2c. They operate by harnessing direct solar radiation on the drying product while simultaneously utilising pre-heated air from a solar collector heater. This dual approach provides the necessary heat for the drying process (Mohana *et al*., 2020). The heat transfer in two configurations of flat-plate solar air heaters, under Egyptian climate, was simulated using ANSYS R15.0 and the RNG k-ε turbulence model. Case B outperformed Case A, exhibiting a 31.6% reduction in relative humidity. Thermal efficiencies were recorded at 28.7% by computational fluid dynamics (CFD) simulations, and 26.4% through experimental measurements, with deviations of 7 and 7.8%, respectively, from the CFD predictions. This model demonstrated the applicability for designing other solar air heaters (El-Sebaey *et al*., 2023a).

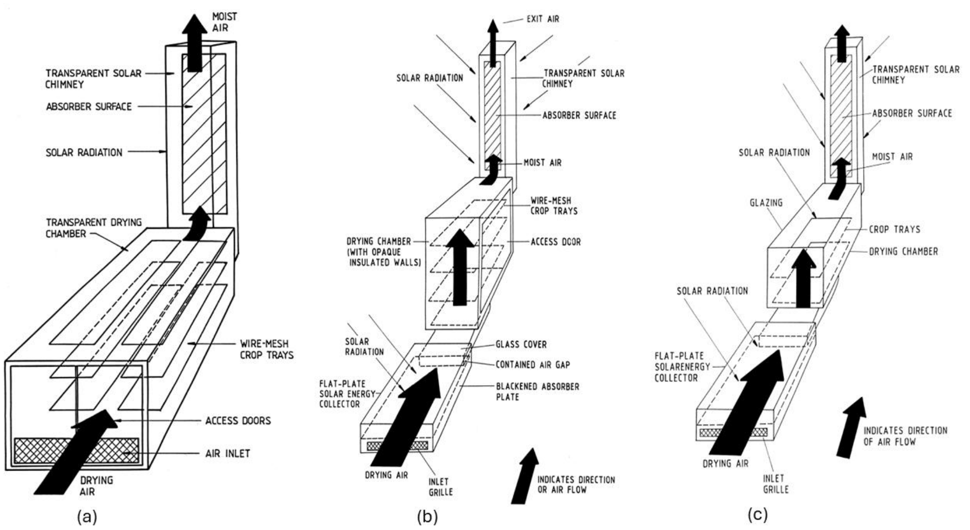

Figure 2. (a) Direct-type PSD, **(b)** indirect-type PSD, and **(c)** hybrid-type PSD (Ekechukwu, 1999).

Active solar dryers

Active solar dryers (ASD) employ external mechanisms like fans or pumps to transfer solar energy, specifically heated air, from the collector area to the drying beds. Consequently, all ASD operate as forced convection dryers. Typically relying solely on solar energy as their heat source, these dryers incorporate motorised fans or ventilators for efficient air circulation. They find significant use in large-scale commercial drying setups, often combined with conventional fossil fuels to ensure better control over the drying process, particularly when managing fluctuations in solar radiation that impact the drying air temperature (Ahmadi *et al*., 2021). ASD are preferred for drying food items with higher moisture content, such as papayas, kiwi fruits, brinjals, cabbages, and cauliflower slices (Kumar and Singh, 2020; Srinivasan *et al*., 2021; Jangde *et al*., 2022). ASD include various types broadly classified as direct-type, indirect-type, or hybrid-type dryers.

Direct-type ASD incorporate a solar energy collection mechanism within their structure, as illustrated in Figure 3a. These dryers operate by allowing crops to directly absorb solar radiation. Certain ASD designs resemble solar kilns, while others adopt practical implementations such as transparent roof solar barns. Additionally, smaller-scale ASD are equipped with auxiliary heating systems to enhance their functionality (Barrientos *et al*., 2019).

Indirect-type ASD consist of several components: a solar air heater, a drying chamber, an air circulation fan, a solar energy collector, and ducting. The distinct air heating element allows for achieving higher temperatures while regulating airflow. However, achieving an optimal balance between temperature and airflow rates is vital for economical design due to the reduced efficiency of the collector at higher temperatures. Most collectors use metal or wood absorbers coated appropriately, although materials such as black polythene serve as economical alternatives. Figure 3b illustrates a typical indirect-type ASD (Koşan *et al*., 2020; Menon *et al*., 2020; Rakshamuthu *et al*., 2021). Some designs incorporate the recirculation of drying air, enhancing energy efficiency by maintaining lower exhaust air temperatures. The effectiveness of the indirect-type ASD depends significantly on the placement of the fan, especially in larger setups. The fan serves a dual purpose: ensuring a consistent flow rate within the drying cabinet for uniform moisture evaporation from the wet material, and aiding heat collection in the collector by maintaining negative pressure to minimise heat losses (Devan *et al*., 2020; Madhankumar *et al*., 2021).

Hybrid-type ASD combine solar energy aspects with traditional or supplementary energy sources, providing the flexibility to utilise either or both energy sources. Usually, these dryers are medium to large-scale setups, operating at approximately 50 - 60% capacity. This operational mode effectively reduces temperature variations induced by unpredictable weather conditions. Figure 3c outlines the components typically found in a standard hybrid-type ASD (Visavale, 2012; Basumatary *et al*., 2013; Chauhan and Kumar, 2018; Ghosal, 2019; Lingayat *et al*., 2020).

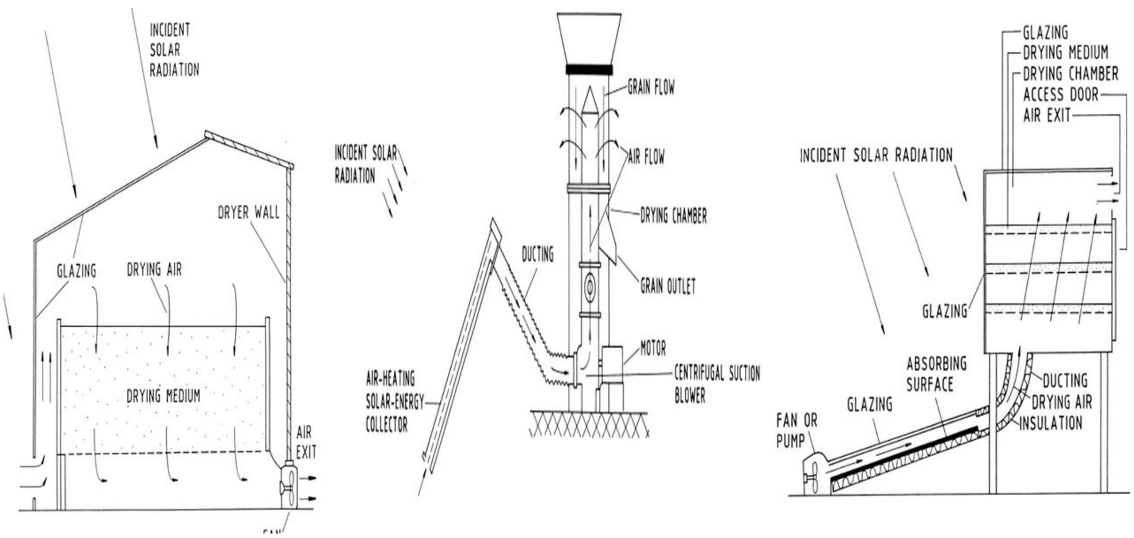

Figure 3. (a) Direct-type ASD, **(b)** indirect-type ASD, and **(c)** hybrid-type ASD (Ekechukwu, 1999).

Solar energy harness for sustainable development

In recent years, significant efforts have been directed towards leveraging solar energy for drying purposes, notably in developing nations such as India, aimed at preserving agricultural products by harnessing the sun's energy (Bhaskara Rao and Murugan, 2021). This initiative is fuelled by the persistent challenge of accessing reliable and affordable energy sources in rural regions of these countries. The absence, unreliability, or high costs of grid-connected electricity and conventional non-renewable energy sources present obstacles, hindering communities from meeting their fundamental energy needs necessary for socio-economic progress (Amer *et al*., 2010).

Understanding the nuances of global radiation variations, geographical positioning, and climatic influences unveils the immense potential of solar energy, particularly in areas with high solar insolation levels. Sunlight duration and intensity fluctuate based on seasonal variations, weather patterns, and geographic locations. Regions such as the Sun Belt exhibit annual global radiation on horizontal surfaces exceeding 2,200 kWh/m^2. Consequently, these countries have shifted their energy policies away from heavy reliance on petroleum imports and non-renewable energy sources, aiming for a more sustainable approach centred on renewable energies (Singh and Gaur, 2020). The geographical positioning of the developing nations in climatic zones boasting significantly higher insolation levels than the global mean of 3.82 kWh/m^2 day offers an opportunity to utilise solar energy as a pivotal resource for sustainable development. This foundational knowledge forms the basis for implementing innovative solutions like SD, tapping into the abundant solar resource to confront energy challenges, foster sustainable practices, and promote socio-economic development (Ameri *et al*., 2018). Vertical farming offers a sustainable 21st-century agricultural approach, maximising area and improving crop yields compared to all other production methods. Controlled environment agriculture uses 70 - 95% less freshwater compared with all other production methods, hence the perfect solution for arid lands. Its very high energy input remains its greatest challenge, and triggers further research in developing more environmentally friendly energy sources (Khalaf *et al*., 2023). Solar food drying provides a low-cost solution for processing food with medium- and large-capacity systems, with particular attention to the challenges of potential industrial applications in the agro-industrial sector. Energy consumption from food industries amounts to 30% of all energy globally, and 26% of greenhouse gas emissions, with dehydration among the major energy users. Over 50 papers and four reviews of solar technologies for loads exceeding 90 kg or collector areas of more than 30 m^2 since 1991 are reviewed. Mature solar thermal convection systems provide opportunities for small to medium producers to increase production sustainably (Ortiz-Rodríguez *et al*., 2022).

This paradigm shift brings to the forefront the innovation of SD as a pragmatic and commercially viable solution to circumvent the challenges associated with traditional drying methods. By harnessing ample solar energy available in these regions, SD present a promising avenue to overcome the limitations of commonly used OSD techniques in agricultural practices. Beyond their environmental benefits, the operational, marketing, and economic aspects of SD highlight their potential not only to just bolster sustainable energy practices, but also spur economic growth within these communities.

However, the performance of these dryers heavily relies on weather conditions, as solar energy powers both the heat required for moisture removal, and the electricity needed for fan operation (Battocchio *et al*., 2021). Weather variations, alongside proper product pre-treatment, significantly influence drying capacity, resulting in shorter drying times under sunny conditions, and longer periods during adverse weather. For small-scale dryers, relying solely on solar power is recommended to minimise spoilage risks during unfavourable weather (Arun *et al*., 2019; Ananno *et al*., 2020; Bhatia *et al*., 2023). However, larger commercial dryers are advised to incorporate backup heaters to manage inclement weather periods effectively (Sekyere *et al*., 2016).

SD offer multifaceted advantages, efficiently drying a variety of fruits and vegetables while maintaining product quality. They ensure superior product quality due to reduced exposure to direct sunlight, shorter drying durations (up to one-third compared to traditional sun drying), and preservation of nutritional value. Successful drying operations extend beyond mere moisture removal; they encompass various quality factors influenced by drying conditions and equipment choices. Desired qualities in dried products include uniform moisture content, minimal damage, high viability, low susceptibility to breakage, low mould counts, and favourable taste and appearance (Agrawal and Sarviya, 2016; Gorjian *et al*., 2021).

Despite the technical advantages, farmers encounter challenges in adopting recommended SD technologies due to economic constraints, labour issues, or shortages of materials. In countries like India, the government's support in promoting SD by providing financial and technical aid to emerging entrepreneurs acknowledges its significant potential in fostering sustainable development through efficient energy use and food preservation. This adoption aligns with SDG by enhancing energy efficiency, reducing waste, ensuring food security, and supporting local economies (Arabhosseini *et al*., 2019).

Selection of solar dryer

Solar drying, compared to conventional methods, presents a cost-effective and environmentally friendly approach. Choosing the right SD involves an initial assessment focused on aligning the dryer type with material handling requirements, process continuity, and desired product characteristics. This assessment entails evaluating different dryers based on cost and performance, and eliminating those that do not meet the specified criteria (Bhardwaj *et al*., 2019; Erick César *et al*., 2020; Pagukuman and Wan Ibrahim, 2022). Subsequently, conducting small-scale drying tests using selected dryers helps determine their operational conditions, material handling capabilities, and resulting product quality. These test results guide the procurement of formal quotations and guarantees from manufacturers (Böer, 1978; van Hung *et al*., 2020). Final selection considerations encompass initial and operating costs, product quality, ease of operation, and adaptability to various material types (*e.g*., coarse solids, slurries, sheets). Additional analysis optimises the chosen dryer's size and cost-effectiveness, factoring in various influencing elements. This inclusive evaluation examines related processes like sorting, conveying, or packaging that may impact drying, ensuring a well-informed selection of SD (Chauhan *et al*., 2018; Kalbande *et al*., 2018).

Effective SD incorporate techniques for enhanced performance, such as utilising corrugated and roughened collectors to improve heat and mass transfer. Employing photovoltaic-thermal fans and ventilators reduces operational costs while sustaining efficiency. Integrating double or triple pass solar air collectors and thermal storage systems accelerate drying rates and ensures continuous operations (Pirasteh *et al*., 2014; Ceylan and Gürel, 2016; Kumar *et al*., 2016; Chabane *et al*., 2023). Component selection is critical for optimal performance, considering both feasibility and applicability. Diverse configurations of SD cater to varying material quantities, natures, intended uses, and energy sources (Kant *et al*., 2016; Djebli *et al*., 2020). This diversity results in different SD types, each meeting specific drying needs and energy considerations. Variations in heat supply, moisture transport, and product handling distinguish these types, and Table 1 provides a comprehensive checklist for selecting an appropriate solar dryer based on specific criteria.

Technical feasibility of solar dryer

The effective operation of SD hinges upon a comprehensive understanding and mathematical representation of diverse factors such as transport phenomena, drying kinetics, thermal efficiency, and the overall system dynamics. In SD, heat is transferred through conduction, convection, or radiation. The overall energy balance in solar drying is described by Eq. 1 (Mohana *et al*., 2020). It evaluates the thermal energy gained by the product against absorbed solar radiation, convective heat loss, moisture evaporation, and radiation heat loss (Ahmad, 2001; Lahnine *et al*., 2016; Chavan *et al*., 2021).

$$\frac{\mathrm{d}(\mathrm{m}C_pT)}{\mathrm{dt}} + A_s\varepsilon\sigma F(T^4 - T_a^4) + \frac{\mathrm{d}(\tau m_w)}{\mathrm{dt}} + hA_s(T - T_a) = \alpha A_p \emptyset(t) \quad \text{(Eq. 1)}$$

where, $\frac{\mathrm{d}(\mathrm{m}C_pT)}{\mathrm{dt}}$ = rate of change of thermal energy within system; M = mass; C_p = specific heat capacity; T = temperature; $A_s\varepsilon\sigma F(T^4 - T_a^4)$ = heat transfer by radiation from surface of material to surrounding environment; A_s = surface area; ε = emissivity; σ = Stefan Boltzmann constant; F = configuration factor; T_a = ambient temperature; $\frac{\mathrm{d}(\tau m_w)}{\mathrm{dt}}$ = rate of change of moisture content in system; m_w rate of change of water mass; τ = drying time; $hA_s(T - T_a)$ = heat transfer by convection from surface of material to

Table 1. Common criteria for initial assessment and choosing solar dryers (Visavale, 2012).

Parameter	Feature
Physical dryer characteristic	- Dryer type, dimension, and shape - Collector area - Drying capacity (kg per unit tray area) - Tray quantity and dimension - Loading and unloading convenience
Thermal performance	- Solar radiation intake - Drying duration and rate - Dryer and drying efficiency - Air temperature and humidity - Airflow volume
Material handling property	- Material attribute (wet and dry) - Acidity - Corrosiveness - Toxicity - Flammability - Particle size and abrasiveness
Material drying characteristic	- Moisture type (bound, unbound, or both) - Initial moisture content - Maximum final moisture content - Safe drying temperature - Estimated drying time for various dryers
Material flow in and out of dryer	- Processing capacity per hour - Continuous or batch operation - Pre- and post-drying processes
Product quality	- Shrinkage - Contamination risk - Consistency in moisture content - Product decomposition potential - Avoiding over-drying - Material state - Appearance, flavour, and density
Recovery challenge	- Dust and solvent retrieval issues
Site facility available	- Space availability - Air quality (temperature, humidity, cleanliness) - Fuel and power sources - Noise, vibration, dust, and heat control - Source of wet material - Exhaust outlet
Economic consideration	- Dryer cost - Drying cost - Return on investment (payback)
Additional parameter	- Requirement for skilled personnel - Emphasising safety, reliability - Maintenance requirement

surrounding air; h = heat transfer coefficient; $\alpha A_p \emptyset(t)$ = solar energy absorbed by material; α = absorptivity; A_p = projected area; and $\emptyset(t)$ = solar radiation.

Similarly, the equation governing mass transfer in solar drying, incorporating Fick's second law, can be expressed in Eq. 2 (Mohana *et al.*, 2020).

$$\frac{\partial MC_{r,t}}{\partial t} = \frac{\partial}{\partial r}\left(D\frac{\partial MC}{\partial r}\right) \quad \text{(Eq. 2)}$$

where, $\frac{\partial MC_{r,t}}{\partial t}$ = rate of change of moisture content in material over time; $MC_{r,t}$ = moisture content as a function of position r and time *t*; $\frac{\partial}{\partial r}$ = spatial derivative with respect to radial position *r*, represents change in moisture content across distance inside material; *D* = diffusion coefficient, which is a measure of how easily moisture diffuses through the material; $\frac{\partial MC}{\partial r}$ = spatial gradient of moisture content.

Eq. 3 (Mohana *et al.*, 2020) is used to evaluate the moisture content of the samples throughout the drying process. Eq. 4 (Mohana *et al.*, 2020) describes the moisture ratio (MR) of the sample, while Eq. 5 (Mohana *et al.*, 2020) expresses the drying rate as a function of the variation in moisture content over time change (Maundu *et al.*, 2017; Dhalsamant *et al.*, 2018; Kuttybay *et al.*, 2019; Hidalgo *et al.*, 2021).

$$MC = \frac{m_t - m_d}{m_d} \quad \text{(Eq. 3)}$$

where, *MC* = moisture content which is amount of water present in sample relative to dry mass; m_t = total mass of material which includes both mass of dry matter and moisture within sample; m_d = dry mass of material which is constant mass of sample once it is completely dried, and serves as reference for determining moisture content.

$$MR = \frac{MC_t - MC_e}{MC_0 - MC_e} \quad \text{(Eq. 4)}$$

where, *MR* = moisture ratio which is a dimensionless value representing relative amount of moisture remaining in sample at a given time compared to its initial moisture content; MC_t = moisture content at time *t* which is moisture content of sample at any particular time during drying process; MC_e = equilibrium moisture content which is moisture content at which sample reaches equilibrium with its surroundings, meaning no further moisture loss or gain occurs; and MC_o = initial moisture content which is moisture content of sample at beginning of drying process.

Understanding drying kinetics is crucial for optimising the drying process. Various thin layer drying models, such as the Newton-Lewis model, are widely used to describe the moisture removal process in agricultural products. These models provide a simplified representation of the drying behaviour, linking product dehydration to the airflow in the dryer.

$$DR = \frac{d(MC)}{dt} \quad \text{(Eq. 5)}$$

where, *DR* = drying rate which represents rate at which moisture is being removed from material over time; *t* = time; and *MC* = moisture content which is amount of moisture present in sample at a given time, typically expressed as a fraction or percentage of the samples mass.

The Newton-Lewis model Eqs. 6 - 7 (Mota *et al.*, 2010; Dasore *et al.*, 2019a), for instance, assumes a constant drying rate at the start, and follows a first-order exponential decay in the moisture ratio over time. This basic model is particularly effective in capturing the general trend of moisture loss during drying, and offers practical insights into the airflow management needed to enhance drying rates.

$$MR = \exp(-kt) \quad \text{(Eq. 6)}$$

where, *MR* = moisture ratio which is ratio of current moisture content to initial moisture content; *k* = drying constant which depends on factors such as temperature, humidity, and airflow; *t* = drying time; and exp(−*kt*) = exponential decay in moisture over time.

$$M^* = e^{(-kt)} \quad \text{(Eq. 7)}$$

where, M^* (or sometimes represented as *MR*) = dimensionless moisture ratio which is ratio of moisture content at any time *t* to initial moisture content; *k* = drying constant which depends on drying conditions such as air velocity, temperature, and humidity; *t* = drying time; and exp(−*kt*) = exponential decay of moisture content over time, assuming a constant rate drying process.

While Eq. 8 represents the Root Mean Square Error (RMSE), it is a measure used to evaluate the differences between predicted values and observed values (Wan Nadhari *et al*., 2014).

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2\right]^{½} \quad \text{(Eq. 8)}$$

where, N = number of observations or data points; $MR_{pre,I}$ = predicted moisture ratio at i-th observation; and $MR_{exp,I}$ = experimental (or actual) moisture ratio at i-th observation.

The coefficient of determination in Eq. 9 (Dasore *et al*., 2019b) measures how well the predicted values match the actual values in a regression model. It indicates the proportion of the variance in the dependent variable that is predictable from the independent variable.

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(M^*_{pre,i} - M^*_{\exp,i}\right)^2}{\sum_{i=1}^{N}\left(M^*_{\exp,i} - M^*_{avg}\right)^2} \quad \text{(Eq. 9)}$$

where, $M^*_{pre,i}$ = predicted value at i-th observation; $M^*_{exp,i}$ = experimental (actual) value at i-th observation; M^*_{avg} = average of experimental values; and N = number of observations.

The solar collector's thermal efficiency (η_{th}) denotes the proportion of energy utilised compared to the entire incident energy on the collector plate, as shown in Eq. 10 (Mohana *et al*., 2020):

$$\eta_{th} = \frac{m_a c_p (T_{co} - T_{ci})}{I_c A_c} \quad \text{(Eq. 10)}$$

where, η_{th} = thermal efficiency which denotes proportion of energy absorbed by solar collector that is effectively for heating, compared to the total incident solar energy; m_a = mass flow rate of air which is the air flowing through collector in kg/s, also called mass flow rate which determines how much heat is being absorbed by air; c_p = specific heat which is the thermal energy required to raise temperature of air by one degree Celsius for each kilogram of air in volume (J/kg·°C), which also represents amount of heat carried by air; T_{co} = outlet temperature which is temperature of air that leaves solar collector after being heated, and shows at what extent energy has been absorbed by air; T_{ci} = inlet temperature which is temperature of air entering solar collector before heating– difference between T_{co} and T_{ci} indicates amount of heat air has gained; I_c = incident solar radiation which refers to quantity of solar energy incident on collector surface per unit area, expressed watts per square meter (W/m^2); A_c = area of solar collector which is defined as area solar collector receives sunlight from, in m², which also affects net quantity of solar energy that collector can collect.

The overall drying efficiency (η_{od}) signifies the energy used in evaporating moisture, as elucidated in Eq. 11 (Mohana *et al*., 2020):

$$\eta_{od} = \frac{m_w LH}{\emptyset A_c t + \emptyset A_g t + E_f} \quad \text{(Eq. 11)}$$

where, η_{od} = overall drying efficiency which indicates ratio of total energy provided to drying system that is effectively utilised for evaporating moisture from material undergoing drying; m_w = mass of water which is total amount of moisture removed from material throughout drying process, and measured in kilograms (kg); LH = latent heat of vaporisation which refers to energy necessary to transform one kilogram of water into vapour at constant temperature, quantified in joules per kilogram (J/kg); ϕ = solar radiation intensity which is amount of solar energy per unit area, measured in watts per square meter (W/m²), that is available for drying; A_c = area of solar collector which is surface area of solar collector that receives solar energy, and measured in square meters (m²); A_g = area of drying chamber which is surface area of drying chamber or enclosure where drying takes place, and measured in square meters (m²); t = duration of drying process which is duration over which drying process occurs, and measured in seconds or hours; and E_f = additional energy input from non-solar sources used to aid drying process, and measured in joules (J).

Calculating the Nusselt number for both the air-product interface and the air-shelf interface is necessary to explain a system of mass and heat transfer in the dryer. The temperature of the shelves and the structure made of stainless steel varies due to exchange with dry air; so, the heat exchanged between air and shelves, as well as the structure is calculated. The coefficient for the heat transfer is derived using an empirical correlation for forced convection along a flat plate. That is crucial in the correct modelling of the thermal interactions along the drying process. Those equations and correlations are covered in detail in Eqs. 12 - 14 (González-Bravo *et al*., 2024):

$$\frac{dT_{shelf}}{dT} = \frac{\hat{Q}_{air-shelf}}{m_{shelf}\, C_{shelf}} \quad \text{(Eq. 12)}$$

where, $\hat{Q}_{air-shelf}$ = heat exchanged between air and shelf; m_{shelf} = mass of shelf; and C_{shelf} = specific heat capacity of shelf material.

The heat exchanged between the air and the shelves and structure ($Q_{air-shelf}$) is calculated using Eq. 13:

$$\hat{Q}_{air-shelf} = h_{air-shelf} A_{eff-shelf} \left(T_{air} - T_{shelf}\right) \quad \text{(Eq.13)}$$

where, $\hat{Q}_{air-shelf}$ = heat transfer rate between air and shelf; $h_{air-shelf}$= heat transfer coefficient between air and shelf; $A_{eff-shelf}$= effective surface area of shelf for heat exchange; T_{air}= temperature of air, and T_{shelf} = temperature of shelf.

The heat transfer coefficient is determined using an empirical correlation for forced convection in a flat plate, which is essential for accurately modelling the thermal interactions in the drying process.

$$Nu_{shelf} = 0.023 \cdot \mathrm{Re}_{shelf}^{0.8} \cdot \mathrm{Pr}^{0.4} \quad \text{(Eq. 14)}$$

where, Nu_{shelf}= Nusselt number which represents ratio of convective to conductive heat transfer; R_{shelf}= Reynolds number which indicates flow regime (laminar or turbulent); and Pr = Prandtl number which relates viscosity to thermal diffusivity of air.

Economic aspects of solar dryer

Solar dryers require financial viability for competitiveness against other methods. Financial analysis assesses dryer costs (fixed, operating) and payback. Feasibility relies on balancing annual investment costs with fuel savings, or reducing equipment expenses (Hughes and Oates, 2011; Dhanushkodi *et al*., 2014; Davidson *et al*., 2020). The payback period measures the time needed to recover the initial investment without accounting for profitability or the dryer's lifespan. Economic analysis should consider benefits like improved quality, higher yields, space efficiency, and quicker drying (Babar *et al*., 2020).

The economic assessment of solar dryers aims to establish the payback period. Calculating the payback period using the dynamic method incorporates the impact of inflation. This method considers payback as the point where the accumulated savings (AS) equal the total of investment cost (IC), annual interest, and accumulated costs (AC) as shown in Eq. 15 (Böer, 1978; van Hung *et al*., 2020):

$$AS = IC + AC \quad \text{(Eq. 15)}$$

where, AS = accumulated savings which represents total amount of savings accumulated over time, typically from reduced operational costs or energy savings, up to payback point; IC = investment cost which is initial capital expenditure required to implement system or project, such as cost of installing equipment or infrastructure; and AC = accumulated costs which are ongoing operational and maintenance costs incurred over time, and accumulate along with interest or other financial charges.

The yearly accrued savings can be computed from the net income (D), mitigating mass and quality losses, potentially raising the product's market price in natural solar dryers. In PSD, savings are derived from the cost of replaced conventional energy (D) (Dissa *et al*., 2011). By factoring in the annual interest rate (r) and yearly inflation rate (e) for energy prices over n years, the annual accumulated savings can be calculated as in Eq. 16:

$$AS = \frac{(1+r)^n - (1+e)^n}{r-e} D \quad \text{(Eq. 16)}$$

where, AS = annual accumulated savings which represents total savings accumulated annually over a period of time, factoring in both interest rate and inflation rate; r = annual investment rate at which investment grows due to interest, typically expressed as decimal (*e.g.*, 0.05 for 5%); e = annual escalation rate of costs at which value of money decreases over time due to inflation, and expressed as decimal; n = number of years which is period over which savings accumulate; and D = revenue from investment which represents amount of savings or cash flow generated annually, before adjusting for interest and inflation.

The total sum of the initial investment cost (IC) with interest over n years will be as in Eq. 17 (Böer, 1978):

$$IC = C(1+r)^n \quad \text{(Eq. 17)}$$

where, IC = investment cost which is final amount that initial investment will grow to after accounting for interest over n years; C = initial investment cost which is original amount of money invested at start of project; r = annual interest rate at which investment grows annually, and expressed as decimal; and n = number of years which is length of time, in years, over which investment grows with interest.

The cumulative annual expenses, considering the annual fixed charge rate (mC) and inflation rate (i) for equipment, can be expressed as in Eq. 18 (Böer, 1978):

$$E = \frac{mC(1+r)^n - mC(1+i)^n}{r-i} D \quad \text{(Eq. 18)}$$

where, E = cumulative annual expenses over n year which represents total accumulated annual costs for equipment over a period of time, factoring in both interest and inflation rates; mC = annual fixed charge rate which is annual cost associated with equipment, such as maintenance or operating costs, which is constant over the years; r = annual interest rate at which costs increase due to accrual of interest over time, and expressed as decimal; i = operational cost rate at which value of money decreases over time, causing costs to increase, and expressed as decimal; n = number of years over which expenses are calculated; and D = revenue which represents starting amount of annual expense or cost associated with equipment, before adjusting for interest and inflation.

Utilising the values of C and D, graphical representations can aid in determining the payback time (n), considering the variables r, m, i, and e. Figure 4, illustrates the relationship between payback time and D/C ratio for different values of r, m, i, and e. This graph allows easy identification of the required D/C values to achieve the desired payback period when other parameters are fixed. When parameters differ, calculations need to be separately executed using Eqs. 6 through 9 (Djebli *et al*., 2019; Veeramanipriya and Umayal Sundari, 2019; Sandali *et al*., 2019). Comparing curves 1 and 2 reveals the impact of the interest rate (r) in scenarios without inflation, while curves 3 and 6 highlight the influence of energy prices when compared. Achieving a 10-year payback time requires a D/C ratio ranging between 0.12 and 0.23 (Böer, 1978). As payback time relies on the D/C ratio, it is apparent that cost-effective (lower C) and less efficient (lower D) setups are justifiable, as long as cost reduction does not significantly compromise system durability. Payback computations encompass the entire solar energy drying system (Hossain *et al*., 2008; Borah *et al*., 2015; Geete *et al*., 2021).

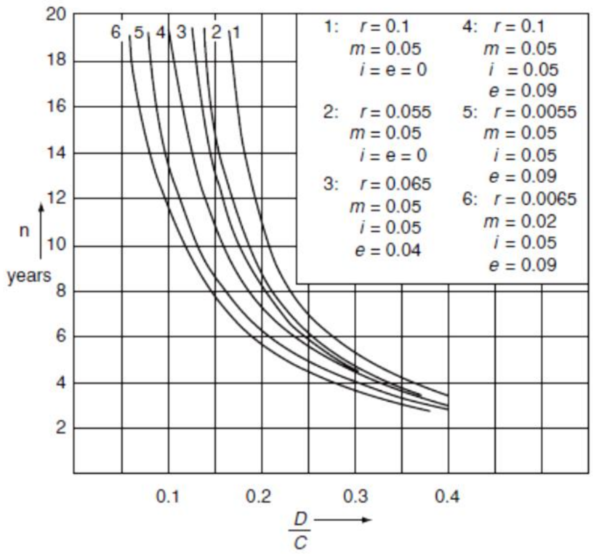

Figure 4. Payback time in years (Böer, 1978).

Recent advances of solar dryer

The evolution of SD technologies in various sectors, emphasises their substantial impact on agriculture, food preservation, and industrial applications. Initially, extensive research studies focused on comparing SD techniques with traditional dehydration methods, stressing the need for efficient drying without excessive heat, and to economically maintain the quality of dried products (Komilov *et al*., 2009; Parikh and Agrawal, 2011; Ghatrehsamani and Zomorodian, 2012). Subsequently, researchers delved into numerous facets of SD, exploring fundamental construction principles of solar dryers, their usability, performance, energy storage, and diverse pretreatment techniques (Srittipokakun and Kirdsiri, 2014). They experimented with various tools such as parabolic reflectors and innovative models like inflated PE tubes to expedite the dehydration process. Some researchers specifically focused on designing and evaluating SD setups tailored for specific products, including red chili and various fish types, addressing distinct challenges posed by diverse environmental conditions (Tripathy and Kumar, 2009a; Prakash and Kumar, 2013; Ziaforoughi and Esfahani, 2016).

However, despite the extensive earlier research, SD encountered limitations. Managing heat levels to prevent over-drying or under-drying remained challenging, particularly in fluctuating environmental conditions (Stiling *et al*., 2012; Eltawil *et al*., 2018; Zoukit *et al*., 2019). Consistency in drying rates across diverse products and environments posed hurdles, impacting product quality. Adapting existing techniques to accommodate various products or settings constrained designs optimised for specific items. Challenges persisted in ensuring continuous operation during limited sunlight and effectively storing energy. Scaling up SD while maintaining efficiency proved complex, requiring uniformity in product quality throughout the drying process—a crucial yet difficult achievement. Balancing technological sophistication with usability, especially in rural or small-scale settings, added to these challenges (Yahya *et al*., 2016; Chaudhari *et al*., 2018).

Nonetheless, recent research has significantly addressed these limitations, marking substantial advancements in SD technology. These innovations have led to improved efficiency, increased automation, and the integration of renewable energy sources (Yoha *et al*., 2020; Clauser *et al*., 2021; Hasan *et al*., 2023). For instance, novel materials like nanomaterials and selective coatings have enhanced solar collector efficiency. Advanced tracking systems and intelligent control algorithms enable solar dryers to optimise sunlight exposure, and adapt to changing weather conditions (Yassen and Al-Kayiem, 2016). Notably, an intelligent automated solar tracking control system dynamically adjusts panel angles, showing a remarkable 18% energy generation increase during cloudy weather as (Kuttybay *et al*., 2019). Moreover, the integration of phase change materials (PCMs) and energy storage systems ensures uninterrupted drying processes. A solar-powered heat sink unit, coupled with a PCM, demonstrated continuous and consistent drying, even during periods of limited sunlight, exemplified by drying potato chips (Vithu and Moses, 2016; Eltawil *et al*., 2018; Yahya *et al*., 2018). These recent advancements mark a significant leap in overcoming earlier limitations observed in SD research studies.

Moreover, specialised mixed-flow rice dryer was designed to utilise rice husk energy and solar power as depicted in Figure 5. This dryer presented a practical and cost-effective solution for small-scale rice producers, offering significantly lower operating costs compared to conventional alternatives (Wilkins *et al*., 2018; Buisman *et al*., 2019; Holka *et al*., 2022). Additionally, a newly designed air collection system with a solar dryer to dry peanuts at three different modes: forced convection, natural convection, and open-sun drying was evaluated. The key parameters evaluated included solar radiation, moisture extraction, and air temperature. The system using energy from the sun used for drying peanuts reduced peanut moisture from 72 to 18%. The results indicated that forced convection proved quite effective with higher electrical and thermal efficiencies. These findings are useful for developing advanced solar dryer technology (Amirtharajan *et al*., 2024). These advancements not only improve product quality and reduce energy consumption, but also advocate for sustainable practices. Hybrid systems that combine solar energy with wind and biomass sources are highlighted as promising approaches to addressing energy sustainability and reduce environmental impact (Udomkun *et al*., 2020; Dwivedi *et al*., 2023). However, there is a need for further research to address regulatory constraints, economic feasibility, and optimisation of these hybrid systems (Tripathy and Kumar, 2009b; Tripathy *et al*., 2014; Singh and Sethi, 2018; Borode *et al*., 2019; Wikström *et al*., 2023).

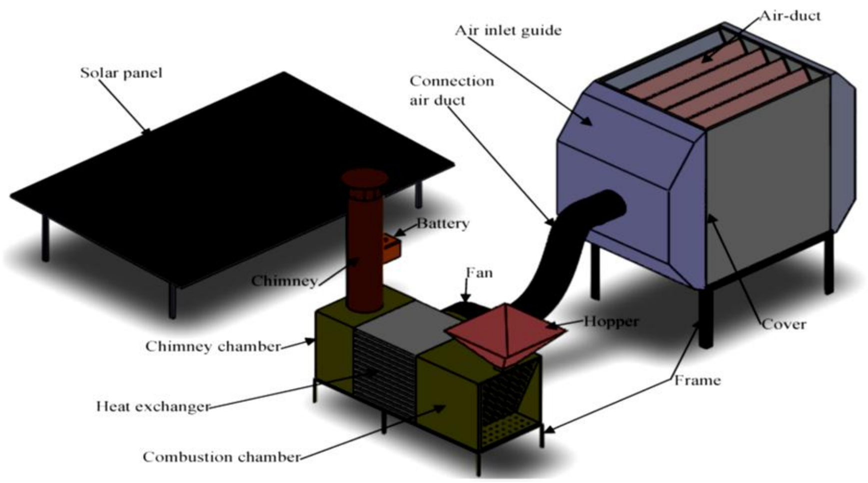

Figure 5. Novel mixed-flow rice dryer powered by rice husk energy (Mihret *et al*., 2023).

Few studies have explored computational simulations of biomass drying chamber performance emphasising heat transfer and tray configurations as illustrated in Figure 6a. However, these studies lacked detailed experimental specifics and discussions on the limitations of their approaches (Tunde-Akintunde, 2011; de Andrade Santos *et al*., 2020; López-Castrillón *et al*., 2021; Divyangkumar *et al*., 2022). Additionally, research on the sensory evaluation of dried food products has highlighted the importance of exploring diverse drying methods and parameters for optimal preservation of aroma, taste, and texture as depicted through Figure 6b (Petikirige *et al*., 2022). Overall, these advancements in SD technologies have played a pivotal role in enhancing product quality, reducing energy consumption, and advocating sustainable practices across industries, contributing significantly to global food security and environmental conservation.

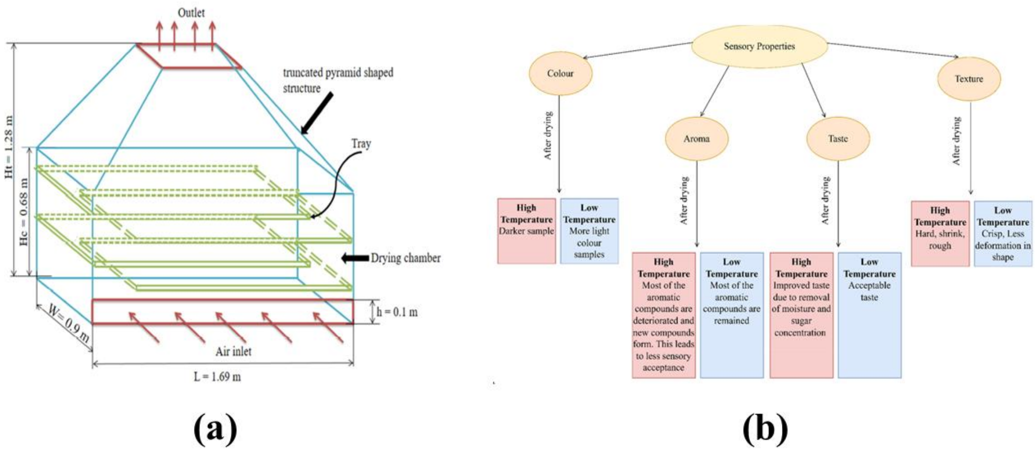

Figure 6. (a) Numerical modelling of drying chamber with solid trays affixed to chamber walls (Petikirige *et al*., 2022), and **(b)** influence of sensory attributes under varying temperature conditions (Anand *et al*., 2020).

Conclusion

The study on solar drying technologies began with their primary functions in agriculture, food preservation, and industrial sectors, from the simple traditional open sun drying technique toward more advanced developments through various solar dryers. Despite this development, there were still challenges in managing heat, achieving uniform drying rates, and achieving flexibility in various conditions. The current studies could better deal with such problems through improvements in efficiency of solar collectors using advanced materials, intelligent tracking systems, phase-change materials to dry continuously, and specific mixed-flow rice dryers. Such improvement will give a higher quality product, reduced energy consumption, and promote sustainability, while further research is necessary to improve hybrid systems, computational simulation techniques, as well as sensory evaluation in order to focus on the critical role of solar drying in the achievement of global food security and environmental conservation.

The present review comprehensively discusses how solar dryers have developed over the last two decades, with special attention to what has happened in the last five years and more specifically in tropical regions of developing countries. It is relevant to SDG 7, Clean Energy for All, and underlines the contribution that solar drying technologies make to sustainable ways of life. The present review further provides extensive literature on recent literature surveyed in the area, including conventional solar drying systems, an appropriate selection of solar dryers, existing challenges, technical feasibility, economic viability, and research needs that are urgent in this area.

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