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Design and Analysis of Simple, Low-Cost Solar Dryers for Rural Applications: An Integrated Review

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ABSTRACT

Simple, low-cost solar dryers can reduce post-harvest losses, improving product quality and increasing rural incomes by using locally available materials and renewable solar energy. This paper synthesises the experimental, numerical, and techno-economic literature on solar drying technologies, with a special focus on rural applications and simple constructions. The review includes optimised collector geometries, such as V-groove and V-corrugated collectors, double-pass systems, and finned absorbers, as well as natural and forced convection systems, sensible and latent thermal storage (phase change materials, PCMs), and protection and usability features. Reported results show high thermal efficiencies for advanced solar air collectors, significant reductions in drying time when PCMs or conduction enhancement are used, and favourable energy and economic performance for well-designed systems. The discussion relates such technical findings to implementation realities using design-oriented guidelines for the utilisation of solar thermal energy in rural areas.

Keywords: Rural agricultural processing, Solar drying, Solar air collector, Thermal energy storage.

1. INTRODUCTION

In most low-income rural areas, post-harvest losses of perishable agricultural products often range from tens to very high levels, which can be mainly attributed to the lack of proper drying and storage systems. Solar drying is a favourable solution to this problem, as it can utilise free solar radiation and inexpensive materials to provide a controlled, hygienic drying process that does not depend on unreliable grid power.

Recent experimental studies of solar air collectors and dryers have demonstrated that relatively simple design improvements can lead to significant performance enhancements. An example is a series of research studies on V-groove, double-pass solar air collection and dryer technologies, which have demonstrated high thermal performance, positive exergetic values, and promising techno-economic aspects [1]. Some related studies on recycling of V-corrugated solar air collectors (by using doubling the passes) [2] and V-corrugated absorbers optimised with jet impingement [3] support the possibility of simple geometric adjustments to maximise useful heat gain. At the system level, the development and experimental evaluation of low-cost solar grain dryers and food dryers have been conducted, designed to fit the rural setting and offering obvious benefits in terms of drying time and product quality compared to open-sun drying [4], [5].

The early rural designs of solar agricultural dryers laid the groundwork for many basic design principles, such as mixed-mode designs, natural-convection designs with uniform airflow, and the use of locally available materials, which remain useful benchmarks for today's low-budget

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designs [5]. Newer reviews of domestic solar dryers can be found alongside these developments [6], along with reviews of thermal energy storage (TES) in solar drying systems [7], which focus on both the technical maturity of the technology and the potential for enhancing simple dryer designs.

The paper presented here focuses to the design and analysis of simple, low-cost solar dryers suitable for rural areas. The objectives are to: (i) summarise the main principles of technical design as observed in the literature, (ii) evaluate the role played by collector geometry, convection mode, and thermal storage in performance, (iii) comment on the issue of materials, durability, and costs, (iv) synthesise the performance metrics and optimisation strategies, and (v) transfer these results into practical design guidelines consistent with the current knowledge of the rural adoption of solar-technology.

2. METHODOLOGICAL SCOPE

The review published in this paper is solely based on published works found in the reference section. Such works include experimental, numerical and review studies on:

- Solar air collectors and integrated solar dryers [1-4], [6], [7]
- Thermal and flow simulation of dryers using CFD applied to layers with phase change materials [8]
- Forced-convection solar dryers using PCM-based storage [9]
- Horticultural products: natural convection greenhouse dryers [10]
- Comparative energy, exergy and economic evaluation of forced and natural convection indirect dryers [11]
- Fruits and vegetables: solar conduction dryers [12].

Secondly, the review also includes the literature on advanced collector geometry and fins [13], [14], exergo-environmental evaluations of forced-convection dryers [15], mixed-mode dryers with sensible storage [16], forced-convection dryers with built-in thermal storage in the drying system [17], [18].

Relevant literature on socioeconomic and policy implications of solar dryers and other solar technology applications in rural areas is also used to guide the implementation-focused discussion, such as systematic reviews on solar dryer adoption [19], case study of obstacles and multi-seasonal use [20], and general literature on solar finance, subsidies and community-based energy access [21-25].

3. LOW-COST SOLAR DRYERS TECHNICAL DESIGN PRINCIPLES

3.1 Optimised Collector Geometries

The essence of most solar dryers, whether operating in indirect or mixed mode, lies in the solar air collector. The absorber geometry, flow configuration, and operating conditions determine their performance.

V-groove, two-pass solar air collectors integrating dryers are reported to operate at high thermal and acceptable exergy efficiencies over a range of mass flow rates, with the two-pass system maximising the effective heat transfer area and air residence time [1]. Analogous benefits are realised by recycling the double-pass V-corrugated collectors, which increase the outlet air temperature and maintain the system's simplicity [2]. V-corrugated collector plates, which are further enhanced by jet impingement, increase the level of turbulence and heat transfer, but at the expense of a high pressure drop [3].

In addition to these configurations, recent studies have examined the application of V-angled perforated fins on solar air collectors with a two-pass configuration [13]. The perforations and V-shaped configuration of the fins interfere with the thermal boundary layer, providing superior intensified mixing of air near the absorber and resulting in higher overall thermal efficiency compared to similar collectors without fins or with plain fins, especially at moderate to high mass flow rates.

Experimental comparisons between V-groove and cross-corrugated collectors also show that V-groove absorbers can provide excellent thermal performance under comparable operating conditions, which can be mainly attributed to favourable flow patterns and increased convective heat transfer on the air side [14]. These results indicate that, even for low-cost rural dryers, switching to V-groove or V-corrugated geometries in single- or multi-pass formats is a potentially viable route to optimise collector and dryer performance, while remaining amenable to manufacturability.

3.2 Natural and Forced Convection Systems

Solar dryers can be generally divided into two types: natural convection and forced convection. Greenhouse dryers, based on the principle of natural convection, utilise the natural movement of air due to buoyancy, often with the aid of a vertical chimney. The geometry of a greenhouse dryer used to dry grapes was optimised, with inlet and outlet geometries to achieve satisfactory drying rates under normal domestic conditions [10]. These systems eliminate the need for electrical fans, making them appealing in areas where electricity is unavailable or the cost of photovoltaic (PV) modules is prohibitive.

In contrast, forced-convection dryers utilise fans to circulate air actively through the collector and drying chamber. The performance of an indirect solar dryer for green chilli was considered in both forced and natural convection modes. The forced-convection condition resulted in shorter drying times, higher thermal and exergy efficiencies, and improved economic performance, albeit at the cost of increased fan power consumption [11]. Similarly, a combination of PCM and a forced-convection dryer achieved more uniform temperatures and halved the drying time compared to a similar system without PCM [9].

Exergo-environmental analysis of an indirect forced-convection dryer for bitter gourd slices also shows that better thermodynamic performance can be translated into environmental benefits, primarily when the fans are powered by PV or other low-carbon sources [15]. In rural applications, this highlights a profound design trade-off: forced convection presents a clear performance/product quality trade-off that the increased complexity and power requirements may justify.

3.3 Thermal Storage and Phase Change Material

Solar thermal systems are intermittent and typically operate only during the daytime, which is why thermal storage, whether sensible or latent, is essential for reducing solar energy intermittency and enabling continued drying in the late afternoons and evenings.

In recent literature, thermal energy storage (TES) is emphasised as a key to the development of both household- and industrial-based solar drying technologies [7]. Moderate storage media, such as rocks, sand, and pebble beds, can be incorporated into the dryer structure. For example, a mixed-mode solar kiln with a black-painted pebble bed beneath the drying chamber was found to offer higher temperature stability and longer timber seasoning times in tropical climates, utilising only inexpensive, locally available materials [16].

Latent storage, commonly based on the use of phase change materials (PCMs), offers a higher energy density and nearly isothermal heat release during solidification. A computational fluid dynamics simulation of a solar dryer with different PCMs has shown how the PCM type, amount, and position affect the temperature distribution and airflow in the drying chamber [8]. An investigation of a forced-convection solar dryer with the addition of a PCM storage device revealed that the PCM addition reduced the drying period and ensured more stable air temperatures compared to the dryer without PCM addition [9].

Forced convection and indirect arrangements can also be used in combination with sensible and latent storage. Thermal storage increased the exergy efficiency and economic viability because, in an indirect dryer for green chilli, the air temperature remained closer to the optimal temperature due to the presence of thermal storage [11]. The results of experiments on guava slabs dried using a forced-convection indirect solar dryer with thermal storage also emphasise the advantages of using the storage: the system with storage had higher average drying air temperatures and a shorter total drying time [17].

Another method of combining thermal and electrical subsystems is the use of PV-assisted dryers. A new PV-assisted solar dryer was tested with and without a modified absorber, using energy and exergy indicators, showing better performance and greater flexibility, allowing operation under changing solar and load conditions [18]. In rural areas, PV-assisted forced-convection TES-based dryers can potentially offer high performance, especially when PV modules are already in place or can be funded collectively.

3.4 Protection, Hygiene and Usability

Protection from sun exposure, dust, insects, and animals is a key benefit of solar dryers compared to open-sun drying. Economic solar grain dryers and small-scale agricultural dryers used in rural settings typically feature enclosed drying chambers, mesh screens, and durable glazing to prevent contamination while ensuring sufficient solar transmittance and airflow [4], [5].

Dryers relying on solar conduction, where products are deposited on metal or other conductive plates heated by absorbed solar radiation, would be another focus of protection, along with enclosed and insulated buildings and tray designs [12]. Studies of local solar dryers [6] emphasise that user-friendly design characteristics, including readily available trays, easy loading and unloading systems, and easy maintenance, are key determinants of long-term utilisation, particularly compared to thermal performance.

4. MATERIALS, DURABILITY AND COST CONSIDERATION

In low-cost, simple solar dryers used in rural locations, the materials should be cheap, locally sourced and within the local fabrication capability. Most designs are based on a structural frame made of plywood or other timber, absorbers and internal walls made of thin galvanised or painted metal sheets, glazing made of transparent glass or plastic, and trays made of wire mesh or perforated sheets [4], [5], [12].

The mixed-mode solar kiln, featuring a black-painted pebble bed, demonstrates an efficient utilisation of affordable stones, locally sourced timber, and basic glazing materials to achieve solid thermal efficiency in timber drying [16]. In the same way, several grain and crop dryers combine absorber plates made of metals generally available, painted black to be highly absorptive, with internal baffles or partitions made of wood or sheet metal [4], [11], [12].

One of the main concerns is durability under humid and high-temperature conditions. Although the durability of plywood, low-cost metals, and glazing materials in tropical conditions is not well documented, individual experimental studies typically span only days to months. However, it is widely agreed that careful detailing, including sealing joints against moisture entry, applying weather-resistant finishes, and ensuring sufficient ventilation to prevent condensation, can significantly increase service life [6], [7].

Cost surveys of economic solar grain dryers and conduction dryers indicate that the domestic solar dryer system can be manufactured at a relatively low capital cost, especially when labour is locally available. Some materials can be recycled [4], [12]. Reviews of domestic solar dryers highlight that payback periods of a few seasons are common when dryers are operated at full capacity and integrated into existing value chains [6], [7].

5. PERFORMANCE MEASUREMENTS AND OPTIMISATION

5.1 Drying Performance, Energy, and Exergy

The performance of dryers is commonly measured in terms of drying time, end moisture content, energy efficiency and, in various studies, exergy and exergo-environmental ratios. Empirical research on forced convection PCM-aided dryers has shown faster drying and a more homogeneous drying regulation than similar non-PCM systems, which is attributed to the buffering effect of latent heat storage on air temperature changes [9]. The induced dryers used in green chilli forced convection have better thermal and exergy efficiency compared to natural convection modes, with lower drying times [11]. Similar findings are reported for bitter gourd slices, where an exergo-environmental analysis of a forced-convection solar dryer indicates both positive thermodynamic and environmental performance [15].

Natural convection greenhouse dryers, such as the grape drying system, achieve acceptable moisture removal over multiple-day periods; however, they lack accurate temperature regulation and take longer to dry than forced convection or PCM-based systems [10]. As a result, in situations where capital constraints or an electricity shortage hinder the operation, such designs can offer a significant improvement over open-sun drying.

The use of sensible storage, as in pebble-bed mixed-mode dryers, and latent storage, as in PCM-equipped forced convection dryers, always shortens drying time and improves uniformity, especially in the late afternoon and early evening hours [16], [17]. PV-assisted dryers with modified absorbers are even more effective, as they enable more flexible operation and generally consume a larger amount of overall energy due to extended operation, while improving flexibility [18].

5.2 Optimisation of Flow and Temperature Field

To achieve even drying, a thorough understanding of the airflow and temperatures within the dryer cavity is required. The computational fluid dynamics (CFD) analysis of different PCM-based dryers reveals the presence of hot and cold spots, which help guide design improvements to the ducting, baffles, or PCM positioning [8].

Indirect and greenhouse dryer optimisation programs demonstrate that changes in inlet and outlet sizes, chimney length, and tray layout can significantly enhance airflow distribution and temperature equality [10], [11]. The reviews of domestic solar dryers emphasise the value of straightforward design principles, i.e., the adequacy of interspersions among trays and the absence of flow hindrances, which can be applied without complex instruments [6].

5.3 Hybrid Technologies and System-Level Optimisation

At the system level, hybrid solar dryers combine several elements, including PV modules, thermal collectors, thermal energy storage (TES), and, sometimes, biomass or other auxiliary heat sources, to optimise reliability and performance. The broad review shows that photovoltaic/thermal (PV/T) panels, integrated TES, and auxiliary heating offer extended operating time, higher drying temperatures under weak conditions, and overall system flexibility [26].

Technical, economic, and practical criteria are the factors that determine the selection of a suitable drying technology for a given situation. A recent survey of solar drying technologies describes selection models that consider crop properties, desired product quality, weather conditions, and financial considerations, with low-cost indirect or mixed-mode dryers and simple TES generally offering the most favourable balance for small-holder farmers [27].

6. DESIGN GUIDELINES AND REAL-WORLD IMPLICATIONS

Technical performance is insufficient to ensure the widespread adoption of solar dryers. The socio-economic research and adoption case studies provide the crucial background for translating engineering designs into practical impact.

A systematic analysis of the socio-economic factors influencing the adoption of solar dryers reveals that perceived benefits of adoption, perceived ease of use, initial investment, and access to credit or subsidies play key roles in determining whether solar dryers will be adopted [19]. In India, field research has pinpointed major obstacles to the adoption of solar dryers, such as high start-up cost, poor awareness and the need to make the device usable in many seasons and many crops, which can be overcome by creating designs that can be usable in multiple crops and several seasons and providing suitable financing systems to motivate increased adoption [20].

Financial instruments play a key role. Studies on solar finance and subsidy programmes in Pakistan indicate that appropriately designed financial assistance could significantly reduce the obstacles to installing solar systems in households and small businesses with limited liquidity [21]. The same trends are observed in the utilisation of solar home systems in Ghana, where socio-economic variables such as income, education, and access to information impact adoption, but targeted finance can alleviate most of the limitations [22]. Research on solar PV water pumps in rural Angola also highlights the importance of harmonising technology design with funding plans, cash flows, and farmers' risk perceptions [23].

In addition to funding, institutional arrangements and community dynamics are also necessary. Research on community-based solar energy adoption in rural Zambia suggests that it is influenced by observational learning, the neighbour effect, and local leadership, which can significantly hasten adoption once some systems have succeeded [24]. The critical analysis of solar PV interventions in rural India leads to the conclusion that long-term energy access can be more effective if local communities are involved in the planning, implementation, and maintenance of technology, governance, and maintenance, rather than being passive recipients of externally designed systems [25].

These lessons are particularly relevant to low-cost solar dryers. Surveys of hybrid solar dryers also emphasise that the complexity introduced by PV/T, biomass backup, or desalination units should be offset by local technical capacity and apparent economic advantages to users [26]. Similarly, models for selecting the right solar drying technologies emphasise that technical, financial, and practical factors should be considered in a complex manner [27].

By joining these strands, a set of design-oriented rules can be suggested to be used to simple, low-cost solar dryers in rural situations:

a. Collector and Dryer Arrangement:
    - Use V-groove or V-corrugated absorbers in one- or two-pass designs to increase air heating efficiency [1-3], [13], [14].
    - Forced convection drying systems should be considered when photovoltaic power or other reliable energy sources are available, and when improvements in throughput or product quality can economically justify the additional system cost [9] – [11], [15], [17], [18].

b. Thermal Storage:
    - Use cheap but rational storage (stones, sand, pebble beds) wherever possible, especially in mixed-mode dryers [16].
    - PCM modules should be used in forced-convection dryers when the aim is to prolong operation beyond peak sunshine and enhance temperature stability [7-9], [11], [17].

c. Materials and Fabrication:
    - Prefer materials that are of local sources and known to local craftsmen: wood or metal frames, plain metal absorbers, glazing materials that are readily available in the market [4], [5], [12], [16].
    - Design system to be easily maintained and repaired, with replaceable parts, and internal surfaces are easily accessed [6], [7].

d. Protection and Usability:
    - Provide strong durability against rain, dust and pests through a closed drying chamber, mesh screen and correctly closed joints [4], [5], [12].
    - Facilitate easy loading and unloading of products, with ergonomic access to trays and simple, intuitive control of vents or fans to improve usability and operational efficiency [6].

e. Business and Ownership Models:
    - Link deployment of dryers to microfinance, cooperative ownership or pay-per-use service conceptualisations based on experience in solar home systems and PV water pumps [20-23].
    - Support local ownership and involvement in the design and siting decisions by encouraging community-based initiatives, peer learning, and participation in design and siting choices [24], [25].

f. Technology Selection and Size:
    - Select between natural convection, forced convection, mixed-mode dryers and hybrid dryers based on specific conditions using structured selection criteria: technical, economic and social [26], [27].
    - In a small-scale deployment, simple and robust designs should be considered first; more sophisticated hybrid or PV-assisted systems can be added when local capacity and institutional backing have been established.

7. CONCLUSION

Affordable solar dryers can provide a viable solution to reducing post-harvest losses, improving food quality, and enhancing rural livelihoods through easy-to-construct structures that utilise solar energy. As the reviewed literature demonstrates:

a. Optimised solar air collectors, particularly two-pass configurations incorporating V-groove or V-corrugated absorber geometries, demonstrate a significant improvement in air-heating efficiency. This enhancement is primarily attributed to the introduction of fins, which increase the effective heat transfer surface area and promote flow turbulence, thereby improving convective heat transfer with only modest geometric modification.

b. Forced convection dryers, particularly when sensible or latent thermal storage is also used, consistently outperformed natural convection systems in drying time, energy and exergy consumption, and product quality, but at increased capital and power costs.
c. Inexpensive materials, such as wood, plain metals, glass or transparent plastics, and stones available in the local market, can be used to make strong dryers that deliver decent performance when well detailed and maintained.
d. Socio-economic studies on solar dryers and other rural solar technologies indicate that adoption cannot be driven solely by technical performance. Effective uptake requires complementary support mechanisms, including accessible financing, user awareness and training, strong community engagement, and sustained institutional or policy encouragement.

These results collectively suggest a design approach that is integrated, utilising thermally efficient and buildable collectors, selecting suitable convection modes and storage sources, employing long-lasting and inexpensive materials, and making design decisions that address local socio-economic conditions. Subsequent research based on the synthesised studies will be able to optimise such designs with long-term field tests, better integration of storage, and increased integration of models of technical innovation and community-based implementation.

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