Ganesan.V, 2026, 14:5
ISSN (Online): 2348-4098
ISSN (Print): 2395-4752

International Journal of Science, Engineering and Technology
An Open Access Journal

Solar Drying of Agriculture Products: A Critical Review of Hybrid Technologies, Thermal Energy Storage, Performance Evaluation and Future Research Directions

[1]Ganesan.V, [2]Krishnaveni.A

[1]Assistant Professor,Department of Mechanical Engineering, J.P. College of Engineering, Ayikudy,Tenkasi, Tamilnadu,India,
[2]Professor, Department of Mechanical Engineering, Government College of Engineering,
Tirunelveli, Tamilnadu, India

Abstract- Solar drying is a promising renewable-energy technology for preserving agricultural products, reducing post-harvest losses and lowering dependence on conventional fuel-based drying methods. However, the intermittent availability of solar radiation, variations in ambient conditions and non-uniform airflow can affect drying time, product quality and overall system performance. Recent research has therefore focused on improved solar collectors, hybrid heating systems, thermal energy storage, computational modelling and intelligent monitoring. This review critically examines the major types of solar dryers, their construction and operating principles, the integration of sensible and latent heat storage, and the application of supplementary energy sources. It also discusses the drying of fruits, vegetables, grains, spices and other agricultural materials, together with the technical, economic and environmental indicators used to evaluate system performance. The literature indicates that no single dryer configuration is optimal for every product or climatic condition. Appropriate selection depends on product characteristics, required drying temperature, local weather, production capacity, investment cost and quality requirements. Important research needs include improved airflow distribution, cost-effective thermal storage, standardized performance testing, product-specific operating conditions and long-term field validation. Solar dryers integrated with suitable storage and auxiliary heating can provide a practical pathway towards more reliable and sustainable agricultural processing.

Keywords: Solar drying; agricultural products; hybrid solar dryer; thermal energy storage; phase-change materials; drying efficiency; renewable energy; post-harvest preservation.

I. INTRODUCTION

Drying is an important post-harvest operation used to reduce the moisture content of agricultural products and improve their storage stability. High moisture levels can encourage microbial growth, enzymatic activity and deterioration during storage. Conventional drying methods may depend on electricity, firewood, fossil fuels or other energy sources, resulting in operating expenses and environmental impacts. Solar drying offers an alternative by utilizing solar radiation to heat the drying air or product directly.

Solar drying technology has developed from simple sun-drying arrangements to enclosed dryers incorporating air collectors, fans, heat-storage units, auxiliary heaters and automated controls. Earlier reviews established the major classifications of solar dryers and examined their technical and economic performance [12]. Subsequent studies have considered improvements in energy efficiency, system configuration and the suitability of different designs for agricultural and food products [8, 10].
Recent reviews show increasing interest in hybrid systems, thermal storage and advanced monitoring methods [1–3]. Hybrid dryers combine solar energy with another source of heat or electrical energy, while storage systems retain part of the available solar energy for later use. These approaches are particularly relevant when solar radiation changes rapidly or drying must continue after sunset [4, 6, 13].

Despite these developments, practical challenges remain. A dryer that performs well under laboratory conditions may produce different results under field conditions because of changing weather, loading

© 2026 Ganesan.V. his is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly credited.

density, product thickness and airflow distribution. Consequently, solar-dryer development should consider not only the heat collector but also the drying chamber, product characteristics, control strategy, energy consumption, cost and final product quality.

The objective of this review is to examine recent developments in solar drying, critically compare major technologies and identify research directions that can improve reliability, affordability and practical adoption.

II. REVIEW METHODOLOGY

This paper presents a narrative critical review based on selected published literature covering solar-dryer classification, collector design, hybrid configurations, thermal energy storage, agricultural applications, performance assessment and numerical modelling. The selected references include recent reviews published between 2021 and 2026, together with earlier foundational studies on solar drying and heat storage.

The literature was organized into the following themes:

- Classification and operating principles of solar dryers.
- Solar collector and drying-chamber design.
- Thermal energy storage and phase-change materials.
- Hybrid heating and auxiliary energy systems.
- Agricultural applications and product quality.
- 6. Technical, economic and environmental evaluation.
- Numerical modelling, automation and future research needs.

The purpose is to synthesize the principal technical findings and limitations rather than to claim an exhaustive systematic review. No new experimental measurements or independent performance data are presented in this article.

1. Direct Solar Dryers

In a direct solar dryer, solar radiation passes through a transparent cover and is absorbed by the product or an internal absorbing surface. The resulting heat raises the temperature inside the drying chamber and promotes moisture removal.

Direct dryers are relatively simple to construct and can be suitable for small-scale agricultural applications. However, direct exposure to radiation may cause uneven heating, colour changes or deterioration of heat-sensitive compounds. The extent of these effects depends on product characteristics, temperature and exposure time. The general advantages and limitations of different solar-dryer configurations have been discussed in earlier and recent reviews [8, 12].

2. Indirect Solar Dryers

An indirect solar dryer separates the solar collector from the drying chamber. Solar radiation heats air in the collector, and the heated air then passes through the product bed. This arrangement enables better control over direct radiation exposure and provides opportunities to regulate the drying temperature.

The performance of an indirect dryer depends on collector efficiency, airflow rate, chamber geometry, insulation and the arrangement of product trays. Uneven airflow can cause different drying rates across the chamber. Consequently, appropriate air distribution and collector–chamber matching are essential design considerations [1, 5].

3. Mixed-mode solar dryers

Mixed-mode dryers combine direct solar exposure with heated air supplied by a solar collector. They can use both mechanisms to increase the heat available for drying.

Their performance depends on the relative contribution of direct radiation and heated air. Although mixed-mode designs can provide effective heating, excessive temperature or radiation exposure may be unsuitable for some products. The design should therefore be selected according to the required product quality and operating temperature rather than drying speed alone [8, 12].

Hybrid solar dryers

Hybrid solar dryers combine solar energy with an auxiliary heat source, such as electrical resistance heating, biomass heating or another suitable thermal system. Some designs also include thermal storage or heat pumps.

Hybridization can reduce interruptions caused by low solar radiation and help maintain the required drying conditions. Kong et al. [6] reviewed hybrid solar dryers integrated with auxiliary energy sources and equipment, while recent studies have emphasized the need to balance reliability with energy consumption and system complexity [1, 2].

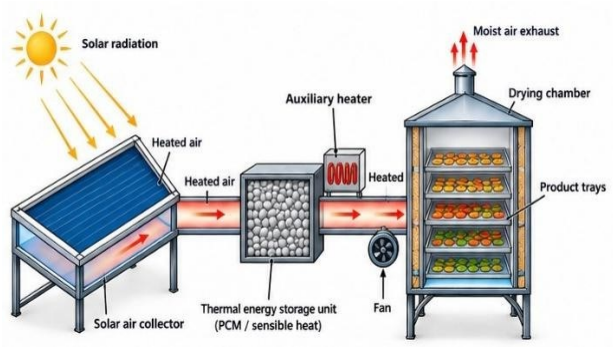


Figure 1. Schematic representation of an indirect solar dryer incorporating a solar air collector, thermal energy storage unit, auxiliary heater, fan and drying chamber

4. Natural and forced convection

Natural-convection dryers depend on buoyancy-driven airflow created by temperature and density differences. They generally require fewer electrical components and can be useful where electricity is limited. However, airflow may be relatively weak and strongly affected by ambient conditions.Recent Development in Solar Collector and Drying-Chamber Design

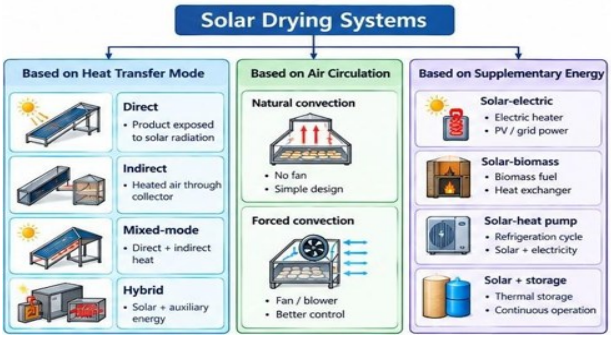


Figure 2. Classification of solar drying systems according to heat-transfer mode, air circulation and supplementary energy source

The solar air collector is a central component of an indirect solar dryer because it converts incident solar radiation into useful heat for the drying process. Collector performance depends on the absorber material, surface properties, insulation, transparent cover, air-channel dimensions and mass flow rate.
Traditional flat-plate air collectors are widely considered because of their relatively simple construction. Design improvements can include extended absorber surfaces, fins, suitable air-channel arrangements and selective absorber coatings. These modifications aim to improve heat transfer between the absorber and the flowing air. However, increasing heat-transfer area may also increase pressure drop and fan power. Collector design should therefore consider both thermal gain and the energy required to circulate air [1, 12].

The drying chamber must distribute heated air evenly across the product. Poorly designed chambers may create stagnant zones, bypass flow or uneven product temperatures. Tray spacing, perforation size, inlet and outlet positioning, insulation and loading density can all affect the drying process.

Computational fluid dynamics (CFD) can help predict airflow patterns and temperature distributions before a prototype is manufactured. Nevertheless, numerical predictions should be validated against experimental measurements. Nnamchi et al. [5] emphasized the importance of understanding the coupled heat-transfer, moisture-transfer and airflow mechanisms in solar drying. More broadly, computational modelling can support the design and optimization of complex drying processes [17].

Recent review literature also identifies improved system integration, hybridization and application-specific design as important development directions [1, 3]. A successful design should not maximize collector temperature in isolation; it should provide an appropriate and sufficiently uniform temperature and airflow throughout the product bed.

Forced-convection dryers use fans or blowers to move air through the collector and drying chamber. They provide greater control over airflow and can improve temperature distribution, but the electricity consumed by fans must be included in the overall energy assessment. The most suitable configuration depends on the scale of operation, the available energy sources, the product and the required level of process control.

III. THERMAL ENERGY STORAGE IN SOLAR DRYERS

1. Need for thermal energy storage

Solar radiation is variable, and its availability does not always coincide with the drying demand. Clouds, seasonal changes and sunset can reduce the heat supplied to a dryer. Thermal energy storage helps address this mismatch by storing energy when solar heat is available and releasing it when solar input decreases.

Bal et al. [13] reviewed thermal energy storage in solar dryers and described the potential for continued drying when direct solar input is unavailable. More recent reviews have examined the integration of latent heat storage into different dryer configurations [4, 11].

2. Sensible heat storage

Sensible heat storage uses a material whose temperature rises when energy is supplied and falls when energy is released. Common examples include stones, sand, water and other suitable solid or liquid materials. The principal advantages are simplicity, relatively low cost and ease of integration. However, useful storage capacity depends on the material mass, specific heat capacity and allowable temperature change. A sufficiently insulated storage unit is necessary to reduce heat loss.

The storage material must also be compatible with the operating temperature and airflow arrangement. For example, a solid storage bed placed in the air path may improve heat retention but can increase pressure drop if the flow passages are not designed appropriately.

3. Latent heat storage and phase-change materials

Latent heat storage uses a phase-change material (PCM) that absorbs or releases energy during a phase transition, generally melting and solidification. The material can store useful thermal energy over a relatively narrow temperature range, depending on its properties.Organic PCMs, inorganic PCMs and selected eutectic mixtures have been investigated for thermal applications. Their suitability for solar drying depends on melting temperature, latent heat capacity, thermal conductivity, cycling stability, compatibility, cost and safety. The selected phase-change temperature should correspond to the desired drying-air temperature.

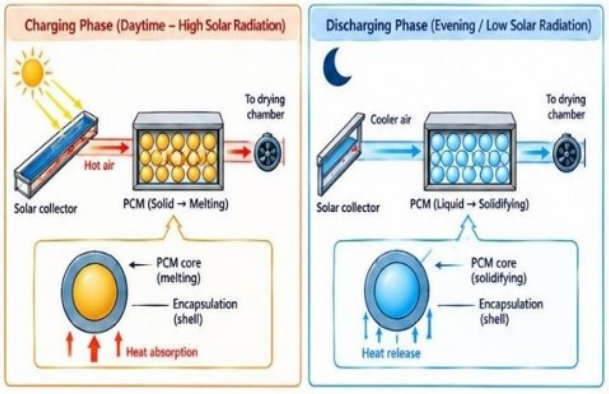


Figure 3. Conceptual charging and discharging cycle of a PCM-based thermal energy-storage unit integrated with a solar dryer

Recent studies have specifically examined PCM-integrated solar dryers and their potential to extend useful heating periods [4, 7, 11]. Ranasingha et al. [7] reviewed PCM applications in solar drying, while Abueluor et al. [11] considered PCM integration as a means of improving drying performance.

A PCM cannot automatically guarantee better overall efficiency. If its melting temperature is unsuitable, heat transfer is poor or the storage mass is incorrectly sized, the system may not deliver useful heat when required.

4. Improving thermal storage performance

The relatively low thermal conductivity of some PCMs can limit charging and discharging rates. Possible improvement strategies include incorporating conductive fins, increasing heat-

transfer surface area, using suitable encapsulation and improving the arrangement of air passages. These changes must be evaluated against additional cost, weight, manufacturing complexity and pressure drop. A storage system should be assessed using measurements of charging time, discharge duration, useful heat delivered, thermal losses and its effect on drying time and product quality. The objective is to deliver useful heat at the required time, rather than merely to maximize the amount of storage material. The choice between sensible and latent heat storage should be based on the drying temperature, required storage duration, cost and practical maintenance requirements [4, 13, 14].

Table 1. Comparison of thermal energy storage approaches

Feature	Sensible heat storage	Latent heat storage
Storage mechanism	Temperature change	Phase transition
Typical materials	Water, stones, sand and solids	Organic or inorganic PCMs
System complexity	Generally low	Moderate, depending on containment
Operating temperature	Changes as energy is stored or released	Can remain near the phase-change temperature
Design considerations	Heat capacity, insulation and storage volume	Phase-change temperature, latent heat, conductivity and cycling stability
Main limitation	May require substantial storage mass or volume	Material cost, heat-transfer limitations and containment requirements

5. Hybrid Solar Drying Systems

Hybrid solar dryers seek to maintain acceptable drying conditions when solar energy alone is insufficient. They are particularly relevant when a product requires controlled processing or when delays can reduce product quality.

6. Solar-Electric Hybrid Systems

Biomass heating can provide supplementary heat in locations where suitable biomass residues are readily available. Such systems may reduce dependence on grid electricity or fossil fuels.

However, combustion systems require appropriate heat exchangers and controls to prevent smoke, combustion gases or contaminants from contacting food products. Fuel moisture, combustion efficiency, emissions and maintenance also affect practical performance. The environmental benefit depends on the biomass source and how it is collected, processed and used.

7. Solar drying with heat pumps

Heat-pump-assisted systems can recover heat from moist exhaust air or use a refrigeration cycle to provide controlled heating and dehumidification. Their effectiveness depends on the temperature level, humidity conditions, heat-pump coefficient of performance and electrical input.

Although heat pumps can improve control and reduce some energy losses, they add capital cost and system complexity. Their suitability should be evaluated against the scale of production and local energy prices.

8. Hybridization combined with thermal storage

Combining solar collectors, thermal storage and auxiliary heating can improve continuity of operation. Solar energy may serve as the primary source, storage can buffer short-term fluctuations, and the auxiliary heater can provide additional heat when the stored energy is insufficient.

Hybrid configurations and auxiliary energy integration have been examined in recent reviews [1, 2, 6]. The design objective should be to minimize unnecessary auxiliary energy while maintaining safe drying conditions. A more complicated system is not necessarily better if its additional investment, maintenance and control requirements outweigh the practical benefits.

9. Application of Solar Drying

Fruits and Vegetables

Fruits and vegetables often have high initial moisture contents and may be sensitive to temperature,

oxidation and prolonged exposure to light. Solar drying can be used for products such as mango, banana, tomato, onion and leafy vegetables. The optimum conditions vary with the product, cut size, pretreatment and desired final quality. Excessively high temperatures may cause colour changes, texture damage or loss of heat-sensitive compounds. Drying should therefore be optimized using both moisture-removal measurements and product-quality tests.

Recent reviews of solar dryers for perishable agricultural products emphasize the importance of assessing technological performance alongside food quality, economics and environmental impacts [15].
Grains and seeds

Grains and seeds require suitable moisture reduction before storage. Drying conditions should be selected to prevent excessive heating, cracking or loss of viability when seeds are intended for planting.

The design must account for the depth of the product bed, airflow resistance and moisture variation within the load. Large beds may experience non-uniform drying if airflow is insufficient or bypasses parts of the material. These issues make air distribution and loading density important design parameters.

10. Spices and medicinal plants

Spices and medicinal plants may contain valuable volatile compounds, pigments and other heat-sensitive constituents. Their drying conditions should be selected to preserve the required aroma, colour and chemical quality.

Indirect solar dryers can be useful when direct solar exposure is undesirable. Temperature, air velocity, product layer thickness and drying duration should be adjusted according to the material. Product-specific testing is needed because conditions suitable for one spice or plant cannot automatically be applied to another.

11. Other agricultural products

Solar drying can also be applied to selected fishery products, herbs, agricultural residues and other materials for which the drying temperature and final moisture requirements are compatible with solar heat. The suitability of a design depends on hygiene requirements, product geometry, local climate and the need for consistent production. The literature indicates that the broad classification of solar dryers remains useful, but practical selection must be based on the specific product and operating conditions [8, 10, 12].

12. Performance Evaluation of Solar Dryers

A meaningful comparison between solar dryers requires consistent definitions, measurement methods and operating conditions. Reporting only the maximum drying temperature or total drying time is insufficient.

13. Moisture content and drying rate

Moisture content indicates the amount of water present in a product. It can be reported on a wet basis or a dry basis, and the chosen basis must be clearly stated. Drying rate describes the reduction in moisture over time.

A fair comparison should include the initial and final moisture contents, sample mass, sample dimensions, loading density, drying duration and measurement method. The moisture content at which a product becomes suitable for storage depends on the product and the intended use.

14. Drying time and temperature distribution

Drying time is affected by solar radiation, ambient temperature, relative humidity, airflow rate, product thickness and the initial moisture content. A shorter drying time is useful, but it should not be interpreted as proof of better performance unless product quality and energy consumption are also considered. Temperature should be measured at several relevant locations, including the collector outlet, drying-chamber inlet and different tray levels. This helps identify non-uniform heating and determine whether all product portions experience suitable conditions.

16.Thermal efficiency and energy consumption

Thermal efficiency relates useful energy used for moisture removal to the energy supplied to the

system, according to the selected evaluation boundary. Researchers should state whether the calculation includes collector losses, fan electricity, auxiliary heating and thermal-storage losses.

A solar dryer with a high collector temperature may still have poor overall performance if airflow is inadequate or a substantial fraction of the collected heat is lost before reaching the product. For this reason, system-level evaluation is more useful than isolated component measurements [2, 9].

Exergy analysis

- Exergy analysis considers the ability of energy to
- Product-quality indicators
- Cost and environmental indicators
- to energy consumption Evaluates suitability of the dried product
- Assesses practical sustainability

perform useful work and identifies sources of irreversibility. It can help distinguish energy quantity from energy quality and identify components where improvements may be most beneficial.

Ahmadi et al. [9] reviewed energy, exergy and techno-economic evaluation of solar dryers. Such analyses can support design decisions, but comparisons are meaningful only when the system boundary, environmental reference conditions and calculation assumptions are clearly reported.

17. Specific moisture extraction and product quality

Specific moisture extraction rate (SMER) relates the amount of moisture removed to the energy consumed, using a clearly defined energy boundary. It can be useful for comparing systems that employ fans, auxiliary heaters or heat pumps.

Product-quality measurements may include colour, texture, rehydration behaviour, nutrient retention, microbial quality and sensory properties, depending on the application. A technically effective dryer should achieve the target moisture content while preserving the qualities required for storage, sale or further processing.

18. Economic and environmental assessment

Table 2. Recommended parameters for evaluating solar-dryer performance

Parameter	Purpose
Initial and final moisture content	Confirms the extent of moisture removal
Drying time	Measures process duration
Solar radiation and ambient conditions	Provides the weather context
Air temperature and relative humidity	Describes drying conditions
Airflow rate and pressure drop	Evaluates air distribution and fan requirements
Thermal efficiency	Assesses useful thermal-energy utilization
Electricity and auxiliary-fuel consumption	Quantifies supplementary energy demand
SMER	Relates moisture removed to energy consumption
Product-quality indicators	Evaluates suitability of the dried product
Cost and environmental indicators	Assesses practical sustainability

Economic assessment may include initial investment, installation, maintenance, electricity or fuel use, labour, product losses and equipment lifetime. Indicators such as payback period and benefit–cost ratio are useful only when assumptions are stated transparently.

Environmental assessment should consider the energy source, material use, operational emissions, product losses and expected service life. Recent reviews have highlighted the importance of considering both techno-economic performance and environmental effects when evaluating solar dryers [9, 15].

19. Numerical Modelling, Automation and Intelligent Control

Numerical modelling can reduce the number of physical prototypes required during the early stages of dryer development. CFD simulations can predict air velocity, temperature distribution, pressure drop and possible stagnant zones within collectors and drying chambers.

Drying is a coupled process involving heat transfer, moisture movement within the material and mass transfer from the product surface to the surrounding air. Models that consider only the air temperature may not accurately predict the drying behaviour different agricultural products. Nnamchi et al. [5]

20. content Drying time

Solar radiation and ambient conditions Air temperature and relative humidity Airflow rate and pressure drop Thermal efficiency

Electricity and auxiliary-fuel consumption SMER Experimental validation remains essential. Model predictions should be compared with measured temperatures, airflow data and product moisture changes. Validation should cover more than a single operating point where practical, because a model calibrated under one weather condition may not remain accurate under another.

Automated monitoring can use temperature, humidity, solar-radiation and airflow sensors connected to a microcontroller or data-logging system. Such monitoring allows operating conditions to be recorded continuously and can support automatic fan or auxiliary-heater control.

Recent reviews identify smart control as a promising direction for improving the reliability and consistency of solar drying [3, 15].

Artificial-intelligence methods may also assist with drying-time prediction, process optimization and adaptive control. Their usefulness depends on the quality and diversity of the training data.

Models developed from limited laboratory datasets should not be assumed to generalize to different products, climates or dryer geometries without validation.

21. Critical Comparison of Solar-Dryer Technologies

Table 3. Qualitative comparison of solar-dryer configurations

Dryer configuration	Main advantages	Main limitations	Potential applications
Direct solar dryer	Simple construction and low component count	Direct radiation exposure and potentially uneven heating	Small-scale drying where product quality permits
Indirect solar dryer	Better separation of product from direct radiation; controllable heated-air supply	Requires collector and appropriate airflow design	Fruits, vegetables, herbs and selected sensitive products
Mixed-mode dryer	Combines direct radiation and heated air	Temperature and exposure may be difficult to balance	Products compatible with mixed heating
Forced-convection dryer	Better airflow control and potential for more uniform drying	Fan electricity and maintenance requirements	Applications needing controlled airflow
Hybrid solar dryer	Improved continuity when solar input is insufficient	Higher cost and more complex operation	Production requiring more reliable drying conditions
Solar dryer with thermal storage	Can extend useful heating beyond peak sunshine	Storage losses, additional material and design requirements	Applications affected by intermittent solar radiation
Hybrid dryer	Combines solar	Greater	Larger or

with storage heat, stored heat and supplementary energy control, cost and maintenance requirements quality-sensitive

21. operations requiring reliable

conditions

Recent reviews of hybrid systems and storage technologies suggest that combining complementary components can address some

limitations of conventional solar drying [1, 4, 6]. Nevertheless, the best option should be identified through product-specific testing and a transparent assessment of total energy use and cost.

The major solar-dryer configurations offer different balances of cost, control, complexity and operating reliability. Their suitability depends on the product and local production requirements.

Research Gaps and Future Directions

Although solar drying has advanced considerably, several research gaps remain.

22. Standardized performance testing

Different studies use different operating conditions, product loads, efficiency definitions and system boundaries. This makes direct comparison difficult. Future studies should report weather conditions, moisture basis, loading density, airflow, auxiliary-energy use and product-quality indicators in a consistent format.

23.Long-term field validation

Many designs are evaluated over limited experimental periods. Longer field trials are needed to assess performance under seasonal weather variation, repeated thermal-storage cycles, equipment ageing and changing product loads.

24. Affordable thermal storage

Thermal storage can improve continuity, but the cost and durability of storage materials and containment systems may restrict adoption. Research should focus on locally available materials, practical charging and discharging arrangements, reduced heat losses and manageable maintenance requirements [4, 7, 11, 13].

25 .Improved airflow distribution

Non-uniform airflow can lead to uneven moisture removal and inconsistent product quality. Future designs should combine experimental measurements and CFD to optimize tray spacing, plenum geometry, inlet and outlet positions, and fan selection. Pressure drop and fan electricity should be considered alongside heat-transfer improvement [5, 17].

26. Product-specific quality optimization

Drying conditions should be optimized for the product rather than for maximum temperature or minimum drying time alone. Research should examine the relationship between drying conditions and quality parameters, including colour, texture, rehydration properties and relevant nutritional or chemical characteristics.

27.Techno-economic and environmental evaluation

Future studies should use transparent assumptions for investment cost, maintenance, equipment lifetime, energy prices and product losses. Life-cycle environmental assessment can help determine whether a proposed improvement delivers meaningful benefits beyond the immediate drying operation [9, 15].

28. Intelligent and adaptive control

Sensor-based monitoring and data-driven control may improve reliability. Future research should investigate robust control strategies that respond to changing solar radiation, product moisture and chamber temperature. Such systems should be affordable, maintainable and suitable for the intended operating environment [3, 15].

29.Scale-up and technology transfer

A dryer that performs effectively at laboratory scale may encounter different airflow, loading and heat-loss conditions at commercial scale. Research should address modular construction, ease of cleaning, material availability, operator training and local repair capability. These factors are important for the adoption of solar drying by small-scale processors and agricultural enterprises.

IV. PRACTICAL RECOMMENDATIONS FOR SOLAR-DRYER DEVELOPMENT

Based on the reviewed literature, the following recommendations can guide future design and experimental work:

- Select the dryer configuration according to product sensitivity, required temperature, production scale and local climate.
- Optimize the collector and chamber as one integrated system rather than as independent components.
- Use thermal storage when the expected benefit from extended operation justifies the added cost and complexity.
- Consider auxiliary heating where uninterrupted operation is important, but record its energy consumption separately.
- Measure airflow and temperature at multiple locations to identify non-uniform drying conditions.
- Report moisture content on a clearly specified basis and document the initial and final product conditions.
- Evaluate product quality alongside drying time and energy performance.
- Validate numerical models with experimental data before using them to recommend design changes.
- Include maintenance, investment, operating costs and environmental considerations in the final assessment.
- Test the system under realistic weather and loading conditions before recommending large-scale deployment.

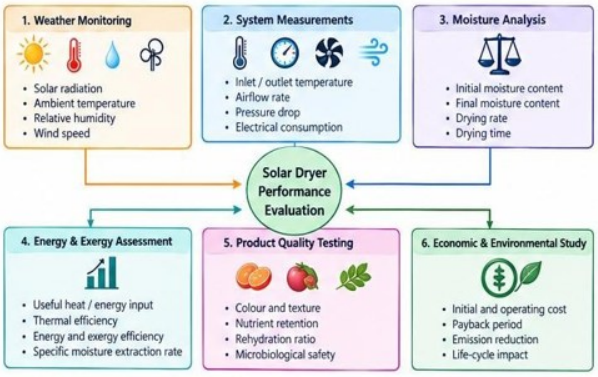


Figure 4. Proposed workflow for solar-dryer performance evaluation, including weather monitoring, airflow measurements, moisture analysis, energy assessment and product-quality testing

These recommendations reflect the broader direction of the literature towards integrated, reliable and application-specific solar drying [1–3, 5, 9, 15].

V. CONCLUSION

Solar drying provides a practical opportunity to reduce post-harvest losses and use renewable energy in agricultural processing. Direct, indirect, mixed-mode and hybrid dryers each have advantages and limitations, and their performance depends on product characteristics, weather conditions, collector design, airflow distribution and operating strategy.

Thermal energy storage can help reduce the mismatch between solar-energy availability and drying demand. Sensible heat storage offers a relatively simple approach, whereas phase-change materials can provide latent heat storage over a selected temperature range. Hybrid systems incorporating electrical, biomass or heat-pump assistance may improve operating continuity but introduce additional costs and complexity.

Performance evaluation should extend beyond drying time or maximum temperature to include moisture reduction, energy consumption, product quality, economics and environmental impacts. Numerical modelling, sensor-based monitoring and intelligent control offer further opportunities, provided that their results are experimentally validated and appropriate for the intended application.

Future development should prioritize affordable storage, uniform airflow, standardized testing, product-specific quality control and long-term field validation. With these improvements, solar dryers can contribute to more energy-efficient, reliable and sustainable agricultural preservation.

Acknowledgements

The author would like to express sincere gratitude to the management and Principal of J. P. College of Engineering (JPCOE), Ayikudy, Tenkasi, Tamil Nadu, India, for their encouragement and support in academic and research activities. The author also acknowledges the contributions of researchers

whose published works on solar drying technologies, thermal energy storage, hybrid systems and renewable energy provided valuable background for this review article. No external funding was received for the preparation of this review.

REFERENCES

1. Kherrafi, M. A., Benseddik, A., Saim, R., Bouregueba, A., Badji, A., Nettari, C., & Hasrane, I. (2024). Advancements in solar drying technologies: Design variations, hybrid systems, storage materials and numerical analysis: A review. Solar Energy, 270, 112383. https://doi.org/10.1016/j.solener.2024.112383
2. Venkateswarlu, K., & Reddy, S. V. K. (2024). Recent trends on energy-efficient solar dryers for food and agricultural products drying: A review. Waste Disposal &SustainableEnergy, 6, 335–353. https://doi.org/10.1007/s42768-024-00193-3
3. Villagran, E., Espitia, J. J., Velázquez, F. A., & Rodriguez, J. (2024). Solar dryers: Technical insights and bibliometric trends in energy technologies. AgriEngineering, 6(4), 4041–4063. https://doi.org/10.3390/agriengineering6040228
4. Atia, A., Teggar, M., Laouer, A., et al. (2024). Performance of various solar dryer types integrating latent heat storage for drying agricultural products: An up-to-date review. Journal of Energy Storage, 102, 114048. https://doi.org/10.1016/j.est.2024.114048
5. Nnamchi, O. A., Tom, C. N., Akpan, G., Umunna, M., Ubong, D., Ibeh, M., Adindu, L. C., Akuwueke, L., Nnamchi, S. N., Ben, A. E., & Ndukwu, M. C. (2025). Solar dryers: A review of mechanism, methods and critical analysis of transport models applicable in solar drying of product. Green Energy and Resources, 3(2), 100118. https://doi.org/10.1016/j.gerr.2025.100118
6. Kong, D., Wang, Y., Li, M., & Liang, J. (2024). A comprehensive review of hybrid solar dryers integrated with auxiliary energy and units for agricultural products. Energy, 293, 130640. https://doi.org/10.1016/j.energy.2024.130640
7. Ranasingha, D., Chatterjee, S., & Bandara, P. (2026). Applications of phase-change materials in solar drying technology: A review. Solar Compass, 17, 100155. https://doi.org/10.1016/j.solcom.2025.100155
8. El-Mesery, H. S., El-Seesy, A. I., Hu, Z., & Li, Y. (2022).Recent developments in solar drying technology of food and agricultural products: A review. Renewable and Sustainable Energy Reviews, 157, 112070.https://doi.org/10.1016/j.rser.2021.112070
9. Ahmadi, A., Das, B., Ehyaei, M. A., Esmaeilion, F., El Haj Assad, M., Jamali, D. H., Koohshekan, O., Kumar, R., Rosen, M. A., Negi, S., Bhogilla, S. S., & Safari, S. (2021). Energy, exergy, and techno-economic performance analyses of solar dryers for agro products: A comprehensive review. Solar Energy, 228, 349–373. https://doi.org/10.1016/j.solener.2021.09.060
10. Saini, R. K., Saini, D. K., Gupta, R., Verma, P., Thakur, R., Kumar, S., Verma, A., & Wassouf, A. (2024). A review of agricultural solar dryers for the years 2016–2023. International Journal of Ambient Energy, 45(1). https://doi.org/10.1080/01430750.2024.2352056
11. Abueluor, A. A. A., Amin, M. T., Abuelnour, M. A., & Younis, O. (2023). A comprehensive review of solar dryers incorporated with phase change materials for enhanced drying efficiency. Journal of Energy Storage, 72, 108425. https://doi.org/10.1016/j.est.2023.108425
12. Fudholi, A., Sopian, K., Ruslan, M. H., Alghoul, M. A., & Sulaiman, M. Y. (2010). Review of solar dryers for agricultural and marine products. Renewable and Sustainable Energy Reviews, 14(1), 1–30. https://doi.org/10.1016/j.rser.2009.07.032
13. Bal, L. M., Satya, S., & Naik, S. N. (2010). Solar dryer with thermal energy storage systems for drying agricultural food products: A review. Renewable and Sustainable Energy Reviews,14(8),22982314.https://doi.org/10.1016/j.rser.2010.04.014
14. Bal, L. M., Satya, S., Naik, S. N., & Meda, V. (2011).Review of solar dryers with latent heat storage systems for agricultural products.

Renewable and Sustainable EnergyReviews,15(1), 876–880.https://doi.org/10.1016/j.rser.2010.09.006

15. Roy, N. K., Tasnim, N., Khatun, J., & Saha, C. K. (2025). A comprehensive review on solar dryers for perishable agro-products: Aspects of technological advancements, techno-economic performance, and environmental impacts. Comprehensive Reviews in Food Science and Food Safety, 24(3), e70186. https://doi.org/10.1111/1541-4337.70186
16. Prasad, G., Sarkar, S., & Sethi, L. N. (2024; published online 2025). Solar drying technology for agricultural products: A review. Agricultural Reviews, 45(4), 579–589. https://doi.org/10.18805/ag.R-2457
17. Defraeye, T. (2014). Advanced computational modelling for drying processes—A review. Applied Energy, 131, 323–344.https://doi.org/10.1016/j.apenergy.2014.06.027