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Progressive review of solar drying studies of agricultural products with exergoeconomics and econo-market participation aspect

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ABSTRACT

An analysis of review articles on solar drying of agricultural products is presented. The review also discusses detailed economic evaluation methods and market participation approaches for transitioning solar dryers from the workshop to the market. This study aims to serve as a model for future solar drying reviews. In addition to broad perspective reviews, most reviews focused on using thermal storage, hybrid technologies, solar greenhouses, 4E evaluations, software applications and crop quality. From most of the reviews, solar dryers with thermal storage are now a viable substitute for fossil energy source dryers and can provide the continuous temperature range of 40–60 °C required to dry food crops. When phase change material is deployed, the transition temperature should be at 5 °C above the desired drying temperature. However, all reviews included sections on types, classification, mode of airflow through the collector, and use of thermal storage in solar drying. Hence, the authors review nearly the same research material, but review gaps remain. Thus that aspect was covered by examining the economic and exergoeconomic analysis methods used in solar dryer evaluations. Again agribusiness inter-phasing between researchers and users, which will spore market participation of solar dryer fabricators lacking in the literature were presented. Therefore, for a more market-oriented development of solar thermal technologies, solar dryer producers must engage in market-oriented production. The nature of markets located at different places calls for better strategies to improve market orientation and access to solar dryers and fabricators.

1. Introduction

Drying is one of the first unit operations farmers perform in the chain of processing steps to either extend the shelf life of their products for storage or prepare them for secondary processing (Ndukwu et al., 2022; Ihediwa et al., 2022). However, research has shown that drying is a significant energy consumer in many countries, accounting for 12–15% of total global agricultural energy consumption (Samimi-Akhijahani and Arabhosseini 2018); (Ihediwa et al., 2022); (Catorze et al., 2022). Furthermore, it has been reported that drying consumes 6 to 30 times more energy than cooling and freezing (Machala et al., 2022). As a result, relying on fossil energy for heat demand in drying will result in significant carbon emissions into the atmosphere (Ndukwu et al., 2023). Thus it is critical to transition from fossil energy-sourced dryers to clean energy sources (Chowdhury et al., 2020). Most countries now advocate for transitioning from fossil energy-based dryers to renewable energy sources to protect the environment (Kumar et al., 2023). Clean

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Nomenclature

A_C	Area of the collector (m^2)
A	The initial investment, ($)
AM_{yr}	The amount of money($)
C_p	Specific heat (kJ/kg.K)
CFs	The cash flow in savings ($)
C_e	The cost of electricity($)
$\dot{C}_d$	The cost flow rate of exergy ($/GJ)Ci The cost flow rate of exergy ($/GJ)CiThe investment cost ($)
C_{rm}	The raw material cost ($)
C_{lb}	Labour cost ($)
C_{da}	The annual cost of the solar dryer per kg of dried product ($)
$C_{m,k}$	The maintenance cost at a given year, ($)
$C_{op,k}$	The operational cost at a particular year ($)
c_f	The unit cost rate of exergy ($/GJ)
C_{fre}	The cost of fresh produce. ($)
C_d	The initial cost per kg of the product purchased for drying in the solar ($)
C_{skg}	The selling price of a kg of dried product, ($)
C_{dskg}	The cost of drying a kg of the product in the solar dryer($)
D_R	The rate of usage per year (days)
D_b	The number of days to dry a batch (days)
$\dot{E}_{x_d}$	The exergy destructionE_{day} The exergy destructionE_{day}The energy consumed per day (J/day)
E_{yr}	The yearly energy consumption (J/year)
H	The absolute humidity of the air (kg $_{water}$ kg d$_{ry\ air}$)
I	The intensity of the radiation (W/m^2)
k_d	The heating value of diesel (kwh/l)
k	Emission rate
l	Latent heat of vaporisation (J/kg)
i	The interest rate (%), or discount
L_d	The service life of the solar dryer
m	Mass (kg)
M_b	The mass dried per batch (kg)
M_{fre}	The mass of fresh products
M_{py}	The mass of product dried per year
n	Average sunshine hours per day (h) or n life span(yrs) or number of periods
P_i	The initial capital cost($)
P_e	The price of energy per kWh
P_d	Price per kg of dried product($)
P_f	Price per kg of the fresh product($)
Q_d	The quantity of dried product (kg)
Q_f	The quantity of the fresh product,(kg)
R_p	The cost of replacement($)
R	Universal gas constant (kJ/kg.K)
R_{mo}	The cost of maintenance($)
R	The fan running time (h)
SFF	The sinking fund factor (−)
S_{kg}	The savings made per kg of product dried ($)
S_p	The selling price of the solar-dried product per kg ($)
S_{ds}	The cost per kg determined for the solar-dried product($)
S_{fp}	The cost per kg of fresh product($)
S_s	The total cost of drying ($)
S_v	The salvage value ($)
T	Temperature (°c)
t	Time (h)
v_d	Volumes of diesel (L)
W	The power consumption rate (W)
$\dot{Z}_{ic}$	Total investment a cost($)
$\dot{Z}_{oc}$	Operational cost ($)

Greek Symbols

τ	Transmittance(−)
α	The absorbance of the plate (−)
$\dot{m}$	Mass flow rate (kg/s)
λ	Latent heat of evaporation of water (J/kg)
β	the fund factor
η	The efficiency (%)

Subscripts

a	Air or ambient
c	Collector
v	Vapour
0	Initial or reference state
s	Sun
w	Water
R	Radiation
m	melting
p	product
d	drying

Abbreviations

HHV	Heating value
SI	Sustainability index
E.I.F.	Environmental impact factor
L.O.P.	Lack of productivity
IP	Improvement potential
WER	Waste exergy ratio
E.D.C.	Environmental destruction coefficient
BCR	Benefit-cost ratio
CFR	Capital recovery cost
PVC	Present value cost
IRR	Internal rate of return
CF	Cash flow
NPV	Net present value
NPW	Net present worth
PBP	Payback period
AC	Annualized cost
PCM	Phase change materials

technologies are being adopted across energy sectors because they are important for addressing and achieving the sustainable development goal, particularly in rural farm communities (Messina et al., 2022). These include those goals that involve air pollution, resource conservation, and climate change. Currently, the available renewable sources are as follows (Rahman et al. 2022).

- Solar thermal
- Solar photovoltaic
- Wind energy
- Geothermal
- Tidal and wave energies

Among all these alternative energy sources, solar energy is the most widely available and uniformly distributed alternative energy source (Xiong et al., 2021). Moreover, the technologies are cost-effective and environmentally friendly (Bala and Debnath 2012). Because of its affordability and the advancement of technologies for more efficient solar energy harvesting, the use of solar thermal energy for heating in diverse applications is a promising technology accepted globally (Simo-Tagne et al., 2020); Hasanuzzaman, 2022). When integrated with Photovoltaic or used in hybrid mode, the systems combine other energy sources with the capture of solar energy, which converts to added heat for various heating processes (Schoeneberger et al., 2020). Therefore, solar thermal heating technologies have penetrated the world with the highest total installed capacity among renewable energy systems (International Energy Agency IEA, 2018). In 2020, the installed capacity was 6479 MW globally (Mordor Intelligence 2023). Solar thermal systems capture solar energy with the help of a collector, which transfers its heat to various types of fluids (Olfian et al. 2020) and (Hasanuzzaman 2022), which can also be used for drying. Hence, the performance of solar systems is heavily reliant on thermal collectors. A thermal solar collector is a device that absorbs heat from the sun and stores it for later use in any system (Olfian et al. 2020). The geometry of the solar thermal collector, as well as its design considerations, plays an essential role in solar-to-thermal energy conversion. Flat plate solar collectors and evacuated tube collectors can raise heat transfer fluid temperatures to 120–400 °C. However, the temperature required for dehydrating most crops is important in determining heat demand and selecting appropriate drier techniques (Ihediwa et al., 2022; Ihediwa et al., 2022). Many crops dry well at 40–60 °C (Kant et al., 2016). As a result, solar thermal collectors can produce heat in this temperature range and above using a simple flat plate collector to dry a variety of crops (Kant et al., 2016). Thus, several studies have been conducted to answer critical questions regarding using solar drying technology compared to open sun drying to dry crops using different solar dryer designs (Simo-Tagne and MacmanusNdukwu, 2021). For instance, the natural sun drying time of potato slices was reduced by 6–12 h using a mix-mode solar dryer at a 34% solar collector efficiency (Onyenwigwe et al., 2023; Doris Ijeoma et al., 2023). Using a hybrid solar dryer, Nwakuba et al. (2020) achieved a drying time of 1.15–3h in the drying of paper with a solar energy contribution of 39.4–48.5%. Furthermore, (Ndukwu et al., 2020), achieved a time reduction of 28–58% using both indirect and hybrid biomass dryers in drying plantain slices at collector efficiency of 21–22%. Analysis of the drying kinetics showed that the Verma model is the best in predicting the moisture ratio. In the same vein, (Atalay and Cankurtaran, 2021) achieved a time reduction of 16 h from open sun drying in India using a standalone hybrid PVT solar dryer for drying chilli at a thermal efficiency of 31.37%. The process consumed about 4.90 kWh/kg of energy to conclude the drying process. Also using the same hybrid PVT dryer to dry tomatoes (Gupta et al., 2022) concluded that the thermal efficiency achieved using the hybrid PVT dryer was higher by 34.98% compared to other indirect solar dryers used in the same location.

From the above studies and other available research in literature, the primary focus of research questions to encourage the adoption of these solar dryer designs has been on how quickly they can dry compared to open sun drying, the quality of dried product, energy consumption and techno-economic factors (Ndukwu et al. 2018). Numerous studies carried out have determined technical and avoidable carbon emission potential in various countries and regions. As a result, these research questions have served as the theme for several review papers in this area, primarily focusing on a narrow range of questions answered in this research area or technical aspects of design. Thus, several researchers have presented excellent review literature on solar drying of crops of various types and designs over the last 30 years. These review articles on solar drying have accumulated over time. A closer examination of these reviews reveals that the same literature is reviewed repeatedly with overlapping deductions while reaching the same conclusions on the same subject theme in solar drying. Furthermore, these reviews have the same theme, with the same group of papers reviewed repeatedly in different reviewed articles. Consequently, this survey aims to conduct a critical appraisal of the reviews presented in the literature for solar drying of agricultural products, to collate and summarize each of them with the same subject theme for each section and harmonise the overlapping deductions to present a clear literature perspective for future solar drying research reviews. In the end, gaps in the literature review will be elucidated and filled, especially in economic analysis methods and market participation by the fabricators. The goal is to provide a framework for future review of research in solar drying of agricultural products. This is the first review to combine an evaluation of the reviewed literature with fabricators' market participation considerations in deploying solar dryer technology.

2. Assessment of recent reviews in solar drying

The various reviews presented on solar drying fall into the following categories: broad perspective reviews in which all aspects of solar drying research are reviewed, reviews based on thermal storage theme to aid in the drying process, hybrid technologies, solar greenhouse, energy, exergy, economic, and environmental (4E) evaluations, software applications, crop quality attributes, and solar biomass drying. Following that, a critical assessment of the findings of these reviews is presented as illustrated in Fig. 1.

2.1. *Article with broad perspective on solar dryer research*

Table 1 listed review studies with a broader perspective on solar drying. These collections of review papers did not confine the review based on a single subject linked with solar drying rather they used a holistic approach and included studies in every area of solar drying. However, what varied is the method of approach as their assessments are focused on a particular solar dryer design or regional concentrations. In general, they discussed solar dryer classifications, design concepts, thermal storage, assessment approaches, performance evaluations, energy and exergy analyses, and so on. Previously (Sharma et al. 2009), and (Belessiotis and Delyannis 2011) offered wide overviews of solar drying studies. Whereas Sharma et al. (2009) began with the working principles of solar dryers and offered a review of the various designs available in the literature, Belessiotis and Delyannis (2011) presented a historical overview of solar dryers and solar drying processes. According to the assessments, solar dryers are utilized for their energy savings, the lack of conventional dryers in rural areas, and the high cost of transporting fossil fuel to power conventional artificial dryers in remote places, in addition to the environmental advantages. They investigated several types of solar dryers, classifications, and thermal performance when drying numerous crops. The dryers presented varied from very simple designs to hybrid solar dryers, assisted with various supplementary heat-producing technologies. According to the assessment, various criteria determine the choice of a specific kind of design, including low initial capital, low operational expenses, a high load ratio, the availability of components and technology for manufacturing, uniform drying, high throughput of dried products, and a simple material handling arrangement. The drying temperature of the crops, as well as the first pre-treatment procedures employed before drying, are important concerns when it comes to drying parameters. Patil and Gawande (2016) offered another extensive review of solar dryers with an emphasis on tunnel design in another broad assessment. According to them, an economic feasibility analysis of solar tunnel greenhouses proved that it is the greatest drying solution for rural farmers. The high initial capital input, which leads to very long payback periods, is, nevertheless, the biggest hurdle to farmers building confidence in its adoption. It was suggested that in solar tunnel dryers, forced convection drying mode should be used for the best results. This is due to a significant accumulation of humid air along the tunnel trunk, which must be promptly evacuated to make way for entering drier air. Murthy (2009) has also sought to give a thorough assessment of solar driers that tackles essential topics of technology breakthroughs, model developments, and broad outcomes acquired in solar drying research. Since the assessment was brief owing to the limited available literature at the time, it proposed employing evaporative capacity in performance evaluation rather than depending exclusively on the drying properties of the dried product. Several reviewers have also focused on geographical concentration while addressing their solar drying review investigations. While

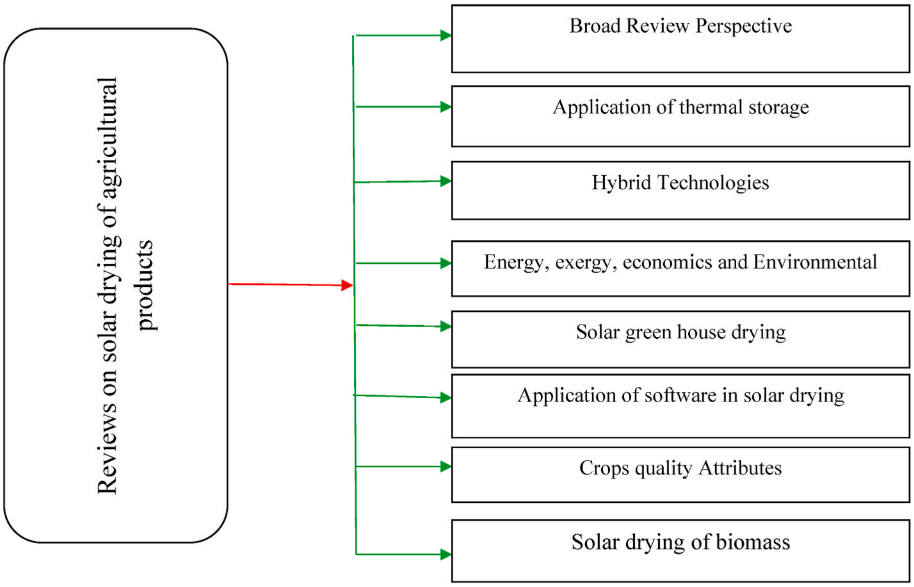

Fig. 1. Classifications of review thematic in solar drying of agricultural products.

Bennamoun (2011) focused on the research output of solar dryer design in Algeria, (Ndukwu et al., 2018) expanded the study to cover solar dryer performance across Africa. Udomkun et al. (2020), on the other hand, combined solar dryer design and performance across Africa and Asia. It is worth mentioning that the three assessments above focused mostly on the technical parameters of the solar dryers, which were determined to be identical to solar dryer designs offered in other nations. Nevertheless, the given results were environmentally specific and the models produced were based on the mode of energy transmission. According to Udomkun et al. (2020) assessment, the review did not show the economic aspect that would give investors confidence in the adoption of the dryers, and optimization studies that can aid the industrial scaling up of these dryers were absent.

Several authors presented an updated overview of solar dryer performance, with a special focus on the technical specifications and concept of existing solar dryers, as well as dryer performance in terms of drying rate for different crops and thermal storage integration. As a consequence, several types, classifications, and applications were offered. The reviewers also identified other crops dried with solar dryers, materials for solar dryer design, and quality results. Yet, the assessment lacked an energetic and techno-economic analytical component. Wood, aluminium, cast iron sheets, polycarbonate sheets, and composite sheets are among the materials used to make solar dryer skeletons, according to Nukulwar and Tungikar (2021). Moreover, Mohana et al. (2020) investigated the material specifications of the different components employed in the design of solar dryers. They offered a thorough examination of the materials and concepts used in the collector cover, absorber, fans, reflector, insulators, drying chamber, exhausts, and auxiliary heater. Additional components examined as means to increase drying included a solar-assisted heat pump, solar-assisted fluidized bed, infrared coupled with solar drying, solar combined with microwave drying, solar-assisted sprout bed, and the use of a sun tracking device (concentrating and non-concentrators). Additionally, Yao et al. (2022) explore solar dryers from a material and a technological viewpoint, with an emphasis on component conceptions, improvements, and material use. Chauhan and Rathod (2020) also provided a complete review analysis on crop drying using solar energy. The review's content is split into two parts: types of dryers and strategies for increasing the performance of solar dryers. Based on their evaluation of several studies and their technical potentials, they determined that using reflective mirrors, improved geometry of the flat plate collector to increase heat transfer area, and selective coatings on absorber plates can significantly improve the dryer's thermal performance. In his review of solar dryer research, Balasuadhakar (2021) concentrated on passive solar dryers. The review addressed the building materials as well as the overall performance of mix-mode passive solar dryers. The ability of the solar collector materials and the drying chamber of a mix-mode solar dryer to absorb solar heat is the most important issue to consider, according to the assessment. Modifying the material used to fabricate the collector and drying chamber can therefore increase the performance of a mix-mode passive solar drier. (Sankat C et al., 2010) reviewed solar drying from the viewpoint of the Caribbean. The purpose was to demonstrate several designs of solar dryers accessible in the Caribbean for drying diverse crops. They detailed different dryer types accessible to farmers, such as wire basket dryers (capable of drying at 5–7 °C above ambient with high airflow), solar cabinet dryers in a variety of design configurations, mix-mode solar dryers, tunnel dryers, solar homes, and hybrid solar dryers with thermal storage. They encouraged small-scale farmers in the Caribbean to utilize wire baskets and cabinet dryers. In contrast, companies can employ a mix-mode solar dryer. Yet, it was suggested in this evaluation that solar drying should create an integrated three-way nexus in food processing, including solar dryer manufacture and entrepreneurship. This is to develop an exotic solar-dried Caribbean product with distinct colour, quality, texture, scent, and flavour. According to them, the design of a solar dryer should involve product creativity that incorporates technological innovation, processes, distinctive product development, and marketing to create an ecologically sustainable product. Pirasteh et al. (2014) examined the evolution of solar dryers in a larger framework. Although solar drying was the topic of this assessment, the focus was on the general drying of products ranging from industrial drying to agricultural drying. Nevertheless, while the study aimed to investigate the benefits of solar drying to these two industries, critical evaluation of process implementation in this sector to minimize the usage of ecologically unsustainable energy sources received little attention. The, earned carbon credit which is the industry's highest carbon emission mark has been approved by several nations, including the United States. The consequence is that with low carbon credits, firms may utilize the balance to cancel other high-emission activities. As a result, highlighting areas, capacity ranges, or product volumes in the drying process chain, as well as emphasizing solar drying design technology to be deployed to achieve measurable efficiency in the processing chain when compared to other high energy-consuming dryers, will be an important component of the review. In their extensive study, Kumar et al. (2016) found that indirect

Table 1
Review studies with broad themes and key research areas discussed

Authors	Research area discussed	Major conclusions
(Lamrani et al., 2022a)	Solar dryer classifications for woods, thermal energy storage, numerical studies, experimental investigations, patents and commercial companies in solar dryer design	The review concluded that most available models in wood drying are simplified lump model techniques. Additionally, most studies on solar drying of wood are lacking on economic and environmental impact assessments
(Patil and Gawande 2016)	Wholesome review of previous work in solar tunnel dryers including classifications, types, performance, economic analysis and numerical models	Technical evaluations showed that solar tunnel dryers are the best to be adopted in rural areas but they are faced with the challenge of high initial capital cost and a long period of investment returns
Murthy, 2009	Types of driers, experimental investigation and performances, models,	Although different solar driers designs are available they lack standard parameters for efficiency evaluation. Thus the review suggested a so-called evaporative capacity concept as an acceptable evaluation parameter
(Bennamoun 2011)	Types of dryers, different modes of operation, performances and numerical models	Algeria has made progress in solar dryer design but lacking is mix-mode solar dryer. However, evaluation periods are confined to the summer season while other periods were neglected. Thus moving forward other seasons should be tested and the drying layer should be expanded to deep bed drying
(Mustayen et al. 2014)	Different types of dryers, different modes of operation, and applications	Different types of solar dryers were identified and the environmental influence highlighted
(Balasuadhakar 2021)	Wholesome review of previous work in different designs of the mix-mode passive solar dryers including classifications, types, performance and materials specifications	Collector performance of passive or mix-mode solar dryers can be improved by the appropriate choice of the construction material
(Chauhan and Rathod 2020)	Different Types of Dryers, Thermal Energy Storage Materials and Performance Enhancement Techniques	The use of PCM is promising in solar drying systems. It is possible to enhance the thermal performance of a dryer by using reflecting mirrors, changing flat plate collector designs to increase heat transfer area, and applying selective coatings to absorber plates to increase solar radiation collection.
(Sankat C et al., 2010)	Drying theory, processing considerations, types of solar dryers design, specifications and performance, quality analysis, the possibility of marketing	Solar drying of various designs has been deployed extensively in the Caribbean to dry several crops. However simple solar cabinet dryers might be adequate for small-scale farmers while mix-mode dryers are recommended for industries. However, combining solar drying with entrepreneurship to create a special Caribbean product was advocated
(Pirasteh et al. 2014)	Performances of solar drying of industrial and agricultural materials, economic, political and environmental role of solar drying	Solar dryers can reduce the energy burden of enterprise with a positive influence on the environmental and economic well-being of the human race
(Kumar and Singh 2020)	Classification of solar dryers, review of previous works in solar drying, thermal storage in solar drying	Different solar dryers exist with mix-mode solar dryers integrated with thermal storage PCM suggesting having better drying efficiency and quicker drying time. However other thermal storage materials exist which has been used by researchers
(Prakash et al. 2016)	Working principles, types of solar dryers, Recent developments of solar dryers in India	The solar drying system is generally simple to build, easy to use and can be used for a wide range of small-scale industrial and agricultural applications. active solar dryers were suggested as the best for the rural area if powered by PV panels
(Singh and Kumar Gaur, 2020)	Classifications of solar dryers advances in solar dryer design, Applications of solar dryers	Solar dryers for different economic sectors were covered. Direct solar dryers are found to be cheaper and easily deployed but indirect solar dryers gave better control of the drying process. However mix-mode solar dryers are quicker but the general drying process depends on heat and mass transfer coefficient which depends on crop parameters
(Sharma et al. 2009)	Working principles, classifications and types of solar dryers, review of previous work of different types of solar dryers	Several designs of solar dryers have been presented but they can broadly be classified as natural or passive convection solar dryers and forced convection solar dryers. Most of these dryers are cheap to construct and can improve agricultural returns to farmers.
(Kumar et al. 2016)	Previous studies on direct, indirect and hybrid solar dryers	Indirect solar dryers present dried crops of higher quality and are suitable for solar drying in low solar radiation intensity areas. Solar collector improvement will improve the performance of the solar dryer. This can be done through the incorporation of v-corrugation, double pass, heated air recirculation, and finned plate on the collector unit. Additionally, the Integration of PCM with the solar drying system will aid performance.
(Mohana et al. 2020)	Classification of the solar dryer, design and construction concept, component design and consideration, techniques to enhance solar drying, system analysis, modelling and cost analysis, quality of solar dried products,	The use of solar dryers to dry food products is an attractive venture. Thus many designs and concepts have been undertaken and operational analysis presented. Yet advances still remain in the area of integration of different kinds of thermal storage, use of PV modules and artificial intelligence.
(Lingayat et al. 2020)	Classification of solar dryers, working principles of indirect solar dryers,	Indirect solar dryer selections are a function of ambient conditions and crop

(*continued on next page*)

Table 1 (*continued*)

Authors	Research area discussed	Major conclusions
	review of previous studies in indirect solar drying, indirect solar drying with thermal storage, indirect solar drying with a corrugated collector, advantages and disadvantages, the effect of pre-treatments and economic analysis	parameters. Available indirect solar dryers are passive and forced convection types but the passive type is easy to fabricate and cheaper. However, with forced convection drying rate could be controlled and when equipped with a reflector produces better performance. Additional integration of the collector with thermal storage reduces drying time.
(Devan et al. 2020)	Types of solar drying forced convection and natural convection solar dryers, solar tunnel dryers, components specifications for the design of solar dryer, solar panels types and classifications,	Forced convection solar dryers are more efficient than natural convection solar dryers. However, performance is affected by environmental and crop parameters. Quality analysis is majorly by colour and textural analysis and modification of collector for improved performance is a future research perspective.
(Kamarulzaman et al. 2021)	Classification and types of solar dryers, design components and specifications, research on flat and evacuated tube collectors, concentrators, parabolic troughs, thermal performance of solar dryers, quality assessments and environmental assessments	Forced convection dryers are better for drying high-moisture crops (40–70 °C) while natural conventions are for low moisture (40–50 °C). For high temperatures, 50–250 °C evacuated tube collectors and parabolic trough-equipped solar dryers are recommended. Modification of the collector design and integration with thermal storage can improve efficiency.
(Lingayat et al. 2022)	Drying and energy consumption, industrial drying application of solar drying of industrial materials, drying application of solar drying of agricultural products, the environmental and economic aspect	Solar dryers have high potential in industrial applications for both low and high-temperature applications. Integration of supplementary heating sources is available but the studies lack control over the drying condition at high temperatures using solar water heating technology can solve this problem. Studies on hybridized solar drying with thermal storage of novel improved characteristic performance are areas of interest
(Udomkun et al. 2020)	Classifications of solar dryers, benefits of solar drying, case studies in Asian and African countries	The design material and choice of solar dry depends on the location, level of resources and the size of the enterprise. Thus thorough cost analysis is required before scaling up. Adoption of the technology requires all the key players in the agricultural production chain.
(Yao et al. 2022)	Basic drying principles, non-concentrating solar dryers, concentrating solar dryers, thermal energy storage assisted dryers	Different concepts and designs of solar dryers are available in the literature. Emphasis is on the improvement of performance. This research has advanced by using nanofluids and smart membranes to increase the heat transfer area of the heat transfer surfaces.
(Nukulwar and Tungikar 2021)	Solar dryer performance for different products, material specifications for design	Solar dryer performance is a function of crop and ambient condition parameters. Forced convection dryers are better for drying high-moisture crops while the natural convention is for low moisture. Integration of thermal storage will allow solar dryers to function during off-sunshine periods
(Messina et al. 2022)	Solar drying of farm produce, sustainable rural development with the use of solar dryers, Solar resources and photovoltaic systems. Performance predictions, energy analysis, achieving net zero emission	Encouraging farmers to adopt solar drying will limit food losses. Solar dryer adoption by farmers requires effective communication and knowledge of the quantity of produce by farmers is very important for effective design. Proper market strategy using innovative net zero packaging scheme of the solar dried products is enhance successful adoption of solar dryers
(Ortiz-Rodríguez et al. 2022)	Principle of thermal drying, industrial drying technologies and classifications, types of industrial dryers, classification of solar dryers, solar dryer components specifications, evaluation parameters, economic analysis, review of previous work on large and medium scale solar drying, solar assisted solar dryers, integral greenhouse solar dryers	Solar energy application has a positive economic and environmental outlook for agro-processing. Forced convection solar dryers have a higher drying capacity than natural convection solar dryers and are ripe for industrial deployment. However, a multi-functional solar dryer is needed for effective utilization. Increased research on economic, environmental and social feasibility is much needed in solar drying research.
(EL-Mesery et al. 2022)	Open sun drying, different types of solar dryers and working principles. Review of previous works on solar dryers based on classifications, hybrid and greenhouse solar dryers, quality of dried products and mathematical modelling	Interest in a quality product that meets up all the sustainable environmental conditions during processing is the major driver currently for drying innovation. Techniques like co-processing technology by combining solar dryers and heat pumps are part of the research methods. Crop pre-treatment can improve the final quality of the dried product. Mix mode solar dryer with PCM yields optimum product at the highest drying rate. Optimum operating parameters can be established using numerical simulation before dryer design and operation.
(Kale and Havaldar 2023)	Classification of solar dryers, review of previous work on indirect solar dryers	Operations of solar dryers are affected by both crop and ambient parameters. However, the use of PCM was encouraged and research into uniform air and temperature distribution in the drying chamber should be studied.
(Belessiotis and Delyannis 2011)	Description of drying principles, thin layer and deep bed drying, different methods of solar drying,	Various solar dryers were classified and their advantages and disadvantages were

(*continued on next page*)

Table 1 (*continued*)

Authors	Research area discussed	Major conclusions
	techniques of solar drying and classifications, mathematical models, heat storage medium, review of recent works in solar drying	presented. However, it was observed that solar dryers are yet to be fully commercialized.
(Ndukwu et al. 2018)	Classification of solar dryers, presentations of previous works, models and dryer performance for different African regions	Designs of solar dryers in the African continent have gone through a series of evolution and improved over the years. Several crops ranging from fruits, vegetables, medicinal and aromatic plants, fishes, tubers etc have been dried with solar dryers in Africa. Virtually all possible design of solar dryer is available in Africa yet sun drying is still dominant among farmers. Most studies lack product quality analysis. Lacking in most research is the energy, exergy and economic analysis.

mode forced convection dryers have been reported to be superior to other types of solar dryers in terms of drying speed and quality. They are suited for low solar radiation and high humidity environments due to their high drying rates and energy consumption effectiveness. The analysis concluded that because the solar air collector unit was identified to be the most critical component of indirect solar dryers, considerable solar air collector unit enhancements might result in better system drying performance. Improvements to collector units can include double or triple-pass heat recirculation.

Prakash et al. (2016) focused on solar dryers accessible in India for drying diverse crops. They detailed these dryers and how they performed in India. The majority of the solar dryers shown are simple to construct and employ a direct, indirect, or mix-mode design. The active solar dryers were entirely self-sufficient in terms of fossil fuels because they were powered primarily by photovoltaic cells. Including PV cells, on the other hand, might increase expenses, making it too expensive for rural farmers. This problem can be solved by using low-cost frictionless wind generators driven by a wind-powered fan, as some researchers have done with solar drying solutions ((Ndukwu et al., 2020; Ndukwu et al., 2023; Chinenye et al., 2022). The performances of several solar dryers accessible in the literature were reviewed based on crop performance (Kumar and Singh 2020). They claimed that heat storage might boost performance. In their critical review, Pathak et al. (2023) indicated that numerous adjustments have been made to the collector design to improve the performance of the flat plate collector. This includes metal fins, roughening of the absorber surface, and corrugated baffles. Yet, many study reports showed that evacuated tubes produced more heat than flat plate collectors due to decreased heat losses. As a consequence, they produce greater outlet temperatures while using less energy. However, Devan et al. (2020) concluded in their review that compact collector configurations, flexible thermal storage systems, and long-lasting solar drying systems that can withstand environmental degradation are the key technological directions for designing solar-assisted systems agricultural drying systems. Sharma et al. (2021) and Mekhilef et al. (2011) focused on industrial thermal applications. However, a section on solar thermal uses in solar drying was included. They also investigated different collector integration strategies to aid in the drying process. As a result, adequate additional heat application improves drying efficiency. Lingayat et al. (2020) provided a thorough analysis of the solar drying of crops, with a focus on performance and energy storage integration. The review focused on the operation of indirect-type solar dryers. According to the article, indirect solar dryers have two successful design methods: natural or passive convection and forced convection. The review indicated that single-pass and multiple solar air collectors are provided in the literature for forced convection. The solar air collectors re-circulate air from the absorber many times before it enters the drying chamber. Solar air collectors with single, double, and triple passes have been created, according to the assessment. Corrugated and roughened absorbers have also been proposed as collectors. They further claimed that natural convection is inefficient and can only be utilized to dry low-temperature crops. Forced convection, on the other hand, is more efficient and better for crops with high moisture content. It can also be used to regulate drying times. Thermal storage material has traditionally been used to aid crop drying. When employing indirect solar dryers, the design has been recommended for greater overall efficiency and crop quality. Nevertheless, according to the literature, the efforts lack the modelling and simulation features of multi-pass solar air collectors. Singh and Kumar Gaur (2020) highlighted a variety of solar dryer applications as well as design enhancements made to solar dryer designs from their perspective. The review discussed many types of dryers that work in active and passive modes, such as direct, indirect, and mixed-mode dryers. Several improvements have also been made to the dryers to increase their efficiency. In addition to agriculture, the review looks at other industries too. Direct solar dryers, according to the review, are less expensive, easier to install in rural areas, and can be a useful drying alternative. In comparison to direct solar drying, indirect solar drying allows greater control over the drying rate of their crops and enhances their texture. A mixed-mode dryer can speed up the drying process, while hybrid dryers allow the drying process to continue even during the off-season. The review revealed the importance of heat storage in solar drying, as well as its acceptance as a preferred alternative for industrial applications. Nonetheless, there has lately been an emphasis on the use of PCM as thermal storage materials.

Lamrani et al. (2022) focused on the solar drying of wood in their ten-year update review. This review addressed several techniques of solar drying of wood without or with thermal energy storage devices. According to an overview of models deployed in predicting the drying process in wood, most simulations employed lumped modelling, which overlooked some physical phenomena. Due to the complexities of wood drying, a multi-physical method outperforms a basic lumped model. Thus, they urged greater research into the environmental effect and economic sustainability of solar systems. Additionally, the review assessed the reported research on wood drying during the previous ten years and revealed that the majority of the studies and patents originated in China, France, India and Canada in that order. Ortiz-Rodríguez et al. (2022) gave a future viewpoint in their assessment, concentrating on the deployment of solar dryers for medium and large-scale industrial applications. Although the majority of the studied literature focused on broad industrial drying applications, solar dryer classifications, and component specifications, they narrowed it down to research on semi-industrial solar drying. Yet, the studied literature is not distinct from previously evaluated literature in comparable reviews; rather, the reviewed study was analyzed based on the dry mass of the product. Solar drying on a semi-industrial scale was defined as items weighing between 62.25 kg and 1000 kg. The feedback prompted a scaled-up industrial design for drying solar products. They determined that one of the biggest issues confronting enterprises in solar drying applications is a shortage of space for solar collectors to provide the necessary thermal energy on an industrial scale. They proposed an industrial distributed solar drying system as a method for addressing the space issue in industrial applications.

2.2. *Thermal storage review thematic in solar drying*

One of the challenges of solar drying has been the intermittent nature of solar radiation, which has limited farmers' acceptance of solar dryers (Ndukwu et al. 2018). As a result, thermal storage materials have been used to supplement drying during periods of low sunlight (Srinivasan et al. 2021). These materials range from solid to liquid to phase change materials (Bal et al. 2010). According to the review, thermal storage can be classified into sensible, chemical, and latent heat materials (Sharma et al., 2021) and (Pathak et al., 2023). Furthermore, heat-sensitive material can be liquid (water, thermal oil, paraffin liquid, waste crankcase oil, premium sunflower oil) or solid (aluminium fillings, sand bed, rock bed, NaCl, gravel, Iron scrap, pebble, demolition waste materials) or solid-liquid (paraffin wax, Glycerin wax), liquid-gas, and solid-solid (desiccants). Based on the above theme, several reviews have been conducted on the solar drying performance of dryers integrated with several of these thermal storage materials shown in Fig. 2.

(Mugi et al., 2022) concentrated their review on researchers who used natural sensible heat storage material to help with solar drying. Sand, soil, bricks, charcoal, limestone, gravel, rock pebbles, granite, dry clay, water, and quartz were among the natural sensible heat storage materials observed in the literature. The review lists several advantages, including lower chlorofluorocarbon and CO_2 emissions when compared to thermo-chemical heat energy storage materials. Furthermore, they are less expensive and more thermally stable over time. Mugi et al. (2022) provided three layouts for using these thermal storage materials in their review. The first and most common method is to load the materials under the absorber, while the second method involves placing the materials as a single unit and transferring heat to the drying chamber via a heat exchanger. The third layout keeps the storage material inside the drying chamber, beneath the drying trays, forming a single unit. However, Ref (Yao et al., 2022) stated that the porosity (for solids) and fluctuation in solar radiation due to its intermittent nature are the major factors affecting the performance of sensible heat storage materials. As a result, increasing the thickness of the bed can compensate. Bal et al. (2010) and Yao et al. (2022) summarized studies in this research area. According to their review, water tanks, thermo-cline beds, molten rock beds, and rock beds are the most common structures for sensible heat storage integration in solar drying; however, rock storage beds are the most common sensible heat storage formation found in literature among them. Additionally, researchers have advocated the use of, phase change material (PCM) as one of the most efficient means of storing thermal energy in solar drying (NdukwuChinenye et al., 2021). This aspect and its application in solar drying was the focus of some reviews in solar drying (Shalaby et al. 2014) and (NdukwuChinenye et al., 2021). According to the reviews, this method offers significantly higher storage density than conventional sensible heat storage, with a smaller temperature difference between storing and releasing the heat. Furthermore, phase change materials are said to provide a consistent and moderate temperature, which is important for drying most agricultural materials. PCM can be organic (paraffin, fatty acid) or inorganic (salt hydrates, eutectic, or metallic). Hydrated salts were discovered to be less expensive than waxes, with a higher latent heat of fusion and a smaller volume change after melting. They are super saturated after melting because it was super cool, so the salts settle down and solidify due to their higher density. As a result, they cannot recombine with water during the de-freezing process to become hydrated again. That is, they cannot be reused after being discharged, although some remedies, such as encapsulation, using a large amount of water, and adding thickening agents have been preferred (Bal et al. 2010; Yao et al., 2022) discovered from a review of numerous studies integrating PCM that the methods of PCM integration into the solar system affect performance. As a result, they demonstrated that a different method was used in this regard. These methods include incorporation into the collector or drying chamber, placement on the collector, integration into shell and tube heat exchanger parts, and integration with metallic fins (Yao et al., 2022). Bal et al. (2010) and Shalaby et al. (2014) established from various reviewed literature that the use of paraffin wax as a storage medium among PCM in solar drying systems has long been a common practice. The main disadvantage is the low thermal conductivity of paraffin wax. As a result, various methods in the literature used to improve the energy storage capacity of paraffin wax in solar dryers include the use of metal fines and metal fibres, carbon fibres, expanded graphite, graphite foam, and high thermal conductive particles. Jahromi et al. (2022)also demonstrated from their review that paraffin wax is the most commonly used PCM in solar dryers of various types and produces a better quality product with the shortest payback period. Nonetheless, in their review of sustainable drying systems (Lamidi et al., 2019), recommended hydrated salts as a good prospect for thermal energy storage in the solar drying of food products. Kant et al. (2016) demonstrated from their review that solar dryers with thermal storage are now a viable substitute for fossil energy source dryers and can provide the continuous temperature range of 40–60 °C required to dry food crops. As a result, the global energy demand gap between renewable and non-renewable energy sources is closing. The use of PCM was suggested as a potential untapped area in thermal storage research (Srinivasan et al. 2021). However, the reviews revealed that, despite the high latent heat of fusion and energy density of PCM, many PCM require improved thermal conductivity between it and the heat transfer fluids. As a result, the incorporation of nanoparticles, metallic fins, and encapsulation of the PCM can be explored.

Dake et al. (2021) examined the use of sorption materials in solar dryers. These materials were mentioned as silica gel bed, Zeolite X, calcium chloride solution bed, and so on. Sorbents, also known as sorption materials, are materials or mixtures of materials used to recover liquids from products via sorption without the material dissolving in the liquids. When used in a solar dryer, they can act as a dehumidifier or

Fig. 2. Images of sensible heat storage materials.

thermal storage material, assisting in the drying process during times when the sun is not shining. However, adsorption/desorption methods can also be used to store energy. The review theme can be broadly divided into two categories: using sorption materials as a dehumidifier and as thermal storage. In both cases, the review concluded that its use in solar drying can help achieve better results and reduce drying time, but that the regeneration time, thermal stability, energy storage density, cost, water uptake, and toxicity should be important considerations in the selection of sorbents. Patel et al. (2020) present a review similar to the one above on the use of thermal energy accumulators in the solar drying of agricultural products. They did, however, broaden their review to include both sensible and latent heat storage materials. The most important takeaways from this review are the need to select thermal energy accumulators that can keep the drying temperature at least 10 °C above ambient to prevent product re-wetting and if phase change material is used, the transition temperature should be 5 °C higher than the desired drying temperature. Additional system insulation is required, and micro-encapsulation of the energy accumulator, if possible, can result in greater heat transfer. The second law can be used to better extract thermodynamic information to improve system performance, while metal lamellae structures can improve the thermal conductivity of energy accumulators. Mourad et al. (2022) reviewed recent advances in the integration of PCM in solar dryers. Organic, inorganic, and Eutectic PCM were all available. Due to their high heat density, they can be combined with solar collectors to conserve excess solar energy and control the temperature of photovoltaic solar collectors. Nonetheless, they discovered that the PCM's actual use is restricted due to its poor thermal conductivity, lack of availability, and high cost as well as other issues. The review, along with that of Nukulwar and Tungikar (2021), presented a diverse set of approaches and modifications developed to improve the efficacy of PCMs integrated into solar collectors. Loading the PCM into a honey-comb or metallic mesh structure filled with PCM, using PCM slurry, encapsulation and loading the PCM directly on the collector or embedding it on evacuated tube headers, or using fins attached to the collector are some of these approaches. However, the problem of PCM decomposition persists, despite research into the use of nano-enhancement. Nukulwar and Tungikar (2022) investigated solar dryers with thermal storage and auxiliary heaters for crop drying. According to the above assessment of review papers focusing on thermal storage, the volume of common thermal storage materials required to support the solar drying of crops on an industrial scale is enormous, and industrial dryers will face space constraints. These could be the reasons for Lingayat et al. (2022) observation when they reviewed the integration of solar air heating in drying various industrial materials, including agricultural products. This is a huge setback for solar drying research because drying is one of the most common unit operations observed in the conversion process in most industrial processes. As a result, research into low-volume high-energy density heat storage materials should be pursued for the future of solar dryers and other similar technologies that require them. The summary of the review studies in this study is presented in Table 2.

2.3. Hybrid technologies in solar dryer design

A summary of reviews based on hybrid technologies is presented in Table 3. Mishra et al. (2021) critically assessed recent trends in greenhouse solar drying technology and their impact on various obtained parameters. The trend is to incorporate technologies into the design such as inclined, reflective north walls, thermal storage materials, opaque insulated north walls, solar air heaters, and PV and PV/T technology, to maximize the use of available solar energy. They recommended forced convection for crops with high moisture content and natural convection for crops with low moisture content for improved performance. The review focused on the performance, environmental, and economic impact of solar dryers in general. Gorjian et al. (2021) focused their reviews on the incorporation of other supplementary technologies as

Table 2
Review studies with thermal storage as a focused theme and key research area discussed

Authors	The area of research discussed	Major conclusions
(Dake et al. 2021)	Typology of solar dryers, principles of heat storage with sorption materials, Application of sorption materials as a dehumidifier and thermal storage in solar dryers, previous works of sorption materials as a humidifier and thermal storage in solar drying	Sorption materials as dehumidifiers are promising in solar drying and can reduce considerably the drying time in solar drying of products. Placing the materials at the top or at the inlet has various performance implications. However, lacking in the literature is the cost implication of using these materials
(Patel et al. 2020)	Types of thermal storage, the use of paraffin, methods of thermal storage integration, theoretical evaluation processes, energy and exergy analysis, CFD predictions	PCM is promising as an energy storage material, though its application is still at the laboratory stage while the industrial application is yet to be fully developed. How important in its application is keeping the transition temperature of the PCM at 5–10 °C above the drying air temperature
(Shalaby et al. 2014)	Wholesome review of previous work in solar dryers with thermal storage, methods of enhancements of performance of Paraffin wax as thermal storage in solar drying,	PCM with high energy storage density is the current focus of research in thermal storage. To improve performance, The use of carbon fibres, graphite foams, expanded graphite, and high thermal conductivity particles is found to be beneficial in the performance enhancement of PCM.
(Mourad et al. 2022)	Overview of PCM and classifications, properties and standards for selections, integrations of PCM in a flat plate and evacuated tube collectors, photovoltaic modules, challenges and prospects.	Several researchers have integrated PCM in solar heating systems with different strategies adopted in its integration into the drying unit. While drawbacks have been observed especially incongruent melting of some PCM, toxicity, destructive capability etc. but they have significantly enhanced performance. However, lacking in literature are studies on their thermal properties behaviour.
(Nukulwar and Tungikar 2022)	Thermal storage systems, sensible, latent, chemical	Latent heat storage material produces drying chamber temperatures high than sensible heat storage material in solar drain applications, though both integrations in solar drying are still evolving. Integration of auxiliary units will assist performance.
Bal et al. (2010)	Thermal energy storage systems and classifications, storage of latent heat in PCM materials, thermo-physical, kinetic and chemical properties of PCM, economic criteria for selections, classifications of PCM, review of previous works in the solar dryer with thermal energy storage	PCM provides a good alternative to heat storage in solar drying. However, the application of thermal storage is limited by space constraints in most solar dryers. However, research in this area needs consolidation. Research should look for better alternatives besides paraffin due to its low thermal conductivity.
(Mugi et al. 2022)	Overview of natural thermal storage materials, available natural thermal storage materials for solar dryers, thermo-physical properties, befits of natural thermal storage materials, review of previous works in natural	Most of the studies in the literature use sand, water and rock as natural sensible heat storage materials and the prospect is good. Thus by performance, the decreasing order of natural sensible heat storage material was listed as

(continued on next page)

Table 2 (*continued*)

Authors	The area of research discussed	Major conclusions
	thermal storage materials under different solar dryer classifications	quartz, sand and gravel, soil minerals, sandstone, rocks, limestone, granite stone, soil, clay, waste concrete, fire bricks and water. They can be integrated into an absorber unit or into a heat exchanger
(Barghi Jahromi et al., 2022)	Benefits of solar dryers, different types of solar dryers, parameters affecting solar drying, design and thermal equations, thermal storage materials, phase change materials, review of previous studies in solar cabinet dryers assisted with phase change materials, quality aspect and simulation results	The deployment of PCM to assist in solar drying improved the quality attributes of dried products due to the drying homogeneity generated by continuous drying using PCM. Commonly in literature paraffin wax is used as PCM and can improve collector and drying efficiency up to 62 and 39% respectively. The effect of using PCM has been studied with CFD and good results were obtained between the experimental data and simulated data
(Srinivasan et al. 2021)	Types of solar dryers, thermal energy storage systems and classifications, review of previous work integrated with sensible energy storage for different types of the solar dryer, latent energy storage for different types of solar dryers and air conveyance modes	The use of thermal storage material improved the drying process by providing heat for continuous drying. Methods of integrating PCM into the solar drying unit vary from placement in a plat and microencapsulation. Paraffin is the common PCM used but the challenge is the low heat transfer rate and improvements made to overcome this added to the cost of the initial investment
(Kant et al. 2016)	Classification of thermal storage systems, phase change materials, review of solar dryer studies with thermal storage for different types of solar dryers, use of software in solar drying	Due to continuous experimental and theoretical research, improved designs of solar dryers are now available. However, the focus should be on the use of thermal storage especially in drying medicinal plants which is an area yet to be consolidated. The challenge of poor thermal conductivity of PCM is an area needed to be addressed. Thus the addition of nanoparticles to PCM and the use of commercial software is a promising research area in thermal storage applications in solar drying.
(M. Sharma et al. 2021)	Types of solar dryers, Review of research on PCM-based indirect solar dryers	Indirect solar dryer assisted with PCM provides a better drying quality and efficiency and among the PCM available, paraffin wax is the most commonly used in the literature

schematically shown in Fig. 3 into the solar dryer to achieve the goal to improve thermal performance.

Singh and Gaur (2022) also reviewed the theoretical analysis of modified hybrid dryers. They discussed the recent advances in the use of PV and PV/T cells, improved collectors, opaque north wall integration, heat pumps, thermal storage material, and biogas to improve performance. The reviews noted the difficulties faced by food processors in selecting the right technology from among the various available technologies to augment the thermal energy required for drying in greenhouses. This includes several competing factors such as climatic and operational parameters. Though they noted that incorporating assisted technology into solar dryers can increase drying rate and improve dried product quality in some cases, it also comes at an additional cost, which may discourage poor farmers from adopting it. While hybrid solar dryers are more expensive than conventional ones, their shorter payback times more than makeup for the difference. As a result of their higher drying capacity and ease of design, hybrid solar dryers are likely to be the future of solar drying systems. Furthermore, due to low electricity penetration densities in rural areas, where the majority of crop processing occurs, solar-hybrid dryers with thermal storage will be the best option for rural farmers.

Table 3
Review studies focusing on using auxiliary units and key research are discussed

Authors	The area of research discussed	Major conclusions
Fadhel et al., 2011	Heat pump dryers, solar assisted heat pump dryers, chemical heat pump dryers, Advances in chemical heat pump assisted solar dryer	Conventional chemical heat pumps are energy-consuming and the use of solar energy to assist will reduce energy consumption and enhance efficiency. Thus, will make it has wide utilization
Daghigh et al. (2010)	Basics of heat pumps, heat pump drying, classification of heat pumps, review of heat pump assisted dryers, review, description and description of solar assisted heat pump dryers	Solar-assisted heat pump dryer is promising in drying sensitive products. The advantage of drying at low temperatures and independent of ambient air is an advantage coupled with a high coefficient of performance which results in lower energy consumption making it a better alternative to other conventional artificial dryers. However lacking is studies on exergy, energy and economic analysis. Collector modification studies are another area of research focus.
(Nukulwar and Tungikar 2022)	Solar dryers with supplementary heating systems, biomass heaters, LPG, electric heating, geothermal or wastewater, photovoltaic, heat pump and wind power	Solar dryers with auxiliary units reduce the drying time and offer a good prospect for large drying capacity. To improve performance there is a need to control the airflow rate. However, optimum space management and thorough economical benefit need to be analyzed. The major challenge is adapting the dryers to work all year round.
(Singh and Gaur 2022)	Wholesome review of a hybrid greenhouse, integrated with PV/T, collector, heat and mass transfer analysis	Hybrid solar dryers are the most suitable dryers to dry high-moisture crops. The challenge is the high initial cost which could be compensated by a low payback period.
Lamidi et al., 2019	Physics of renewable energy drying, hybrid drying, the use of phase change materials, effects of methods of drying on the dried crop quality, modelling results, exergy and economic analysis, and life cycle assessments.	Integration of biomass is most promising in hybrid technology due to the possibility of operational control and biomass availability. Meanwhile, it produces better-dried quality crops compared to other artificial drying sources studied

According to Singh and Gaur (2022), the major heat transfer parameters that influence the drying rate and time of hybrid solar greenhouses are the convectional heat transfer coefficient and air flow rate. Kumar and Singh (2020) and Kale and Havaldar (2023) reviewed the technological advancements in solar dryer performance. The results were presented following various classifications of solar dryers available in the literature based solely on crop characteristics. However, they stated that regardless of the type of solar dryer, solar radiation, type of product, initial moisture content of the product and total mass of the product determine the efficiency and drying rate of the solar dryer. The

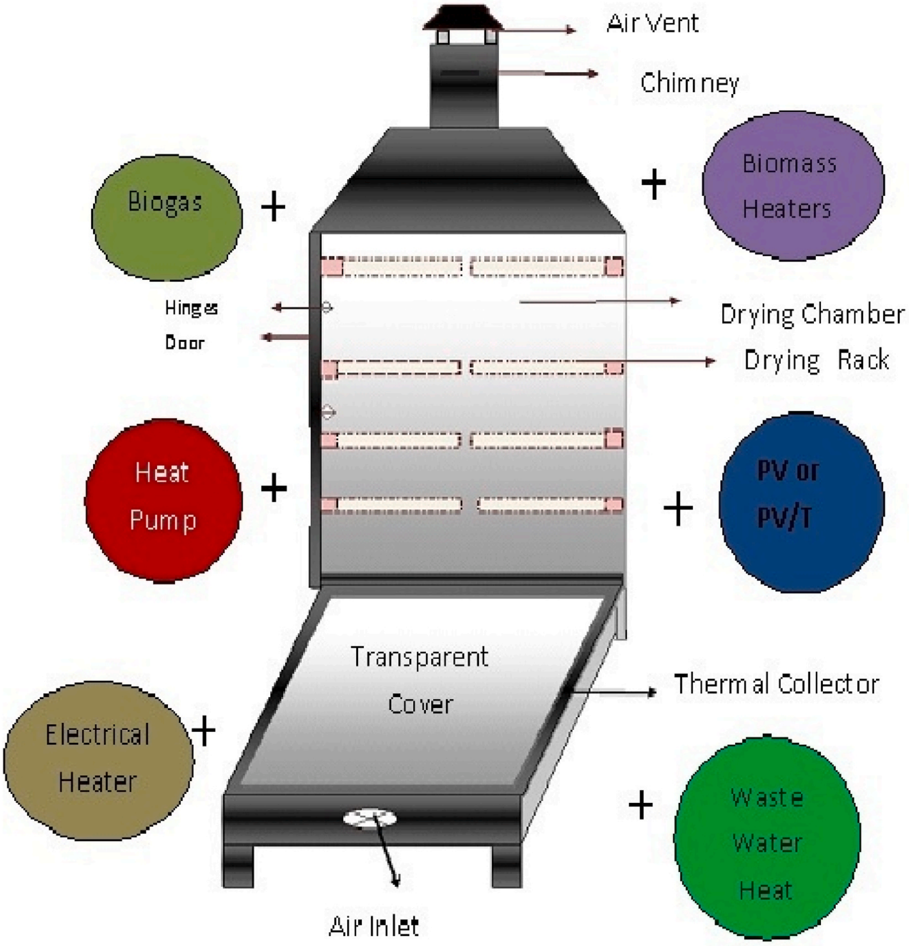

Fig. 3. Solar dryer-assisted supplementary heat technologies reviewed in most literature presented ("+" sign indicated incorporation to the solar dryer).

best-performing solar dryer, according to the review, is a mix-mode solar dryer equipped with phase change energy storage material. HS-58 is one of the thermal storage materials used in the literature that they reviewed. Inorganic salt, Capric acid, Lauric acid, and Palmitic acid, they concluded that paraffin wax is the most efficient, which supports the review of Ref (Shalaby et al. 2014). However, it is important to note that thermal storage materials will play a significant role in solar dryer design in the future, so efforts should be directed toward identifying and developing new materials in this regard. According to Kale and Havaldar (2023), there is a need to investigate the temperature and air velocity uniformity in the drying chamber for various hybrid drying modules. Daghigh et al. (2010) reviewed the use of heat pumps to assist solar dryers in detail, while Fadhel et al. (2011) focused on chemical heat pump-assisted solar dryers. The systems work in both heat pump and solar drying modes. In general, heat pumps are a reversal of the refrigeration process. The energy obtained from the refrigerant medium is raised to a higher temperature with the help of external energy sources and transferred to another energy transfer fluid. As the product moves through the drying chamber, the inlet drying air absorbs moisture from it. The evaporator of the heat pump, which acts as a dehumidifier, is exposed to the humid air from the dryer. Before being desiccated, the damp air is appropriately cooled to its dew point. Water vapour in the air condenses as the temperature drops further. The evaporator's absorption of both sensible and latent temperatures then brings the refrigerant to a boil. The recovered working fluid is heated in the condenser. Solar radiation is converted into sensible heat by the solar collector. The air passing through the collector is then heated.

Daghigh et al. (2010) distinguished between conventional solar-assisted heat pumps and direct expansion heat pumps. Air, ground and chemical heat pumps are the most common types of heat pumps. The chemical heat pump produces heat by absorbing and releasing heat generated by chemical reactions. The two processes that comprise the overall operation of the chemical heat pump are adsorption and desorption. The cold production adsorption phase is followed by the breakdown regeneration phase. In the manufacturing phase, the conversion of solid or liquid gas produces low-temperature cold gas in the evaporator. The chemical reaction between the gas and the solid or liquid medium at a high temperature would simultaneously release reaction heat. Because the condensing refrigerant warms the incoming air, it reaches the proper drying temperature before entering the dryer and continuing the drying process. After drying, a portion of the moist airstream exiting the drying chamber is directed into the evaporator to be cooled and dehumidified. The operating medium can be liquid (isopropanol-acetone-hydrogen) or solid (methane) (metallic hydrides or metallic ammonia systems). Depending on the operating conditions, a liquid-gas chemical heat pump with an 80 °C heat source and a 30 °C coolant can provide 200 °C heat (Hiyashi et al., 1995). To maintain maximum efficiency, the concentration of the operating medium must be high in this process, and a catalyst is essential. A liquid-phase exothermic reactor, a vapour-phase exothermic reactor, and a distillation tower are included in the heat pump. The liquid-phase reactor also serves as a heat transfer device in addition to being a reboiler. As a result of the various studies reviewed, Daghigh et al. (2010) and Fadhel et al. (2011) concluded that combining solar and a heat pump improves energy utilization efficiency. It allows for greater flexibility in quality control and energy utilization while minimizing environmental impact.

However, the amount of literature presented indicated that research in this area is still ongoing and needs to be expanded. The use of auxiliary heaters to support solar dryers can also help to extend drying times during times when the sun is not shining. The risk of using auxiliary heaters is over-drying if the dryer does not have a temperature regulator (Mugi et al., 2022). In their review, Nukulwar and Tungikar (2022) also demonstrated that auxiliary dryers available as supplementary heaters in solar drying can be biomass heaters, liquefied natural or petroleum gas, heat pumps, wind power, electrical heating, wastewater heat, or photovoltaic modules. The performance of several crops (for example, Musa nendra, Momordica charantia, Sliced Black Turmeric, Potato, Apple slices, Red chilli, plum, Wood, Garlic clove,) under the various heat modules described above for natural or forced convection were presented in the review. The review concluded that the problem of the non-commercialization of these dryers, as with other designs of solar dryers, persists. Farmers are excluded from the benefits of solar dryers, but the intermittent nature of solar radiation poses a problem that auxiliary heaters can solve. However, the designs of solar dryers with supplementary heaters should be such that the dryers can continue to dry efficiently even in extreme weather conditions. As a result, farmers will not have to look for alternatives that may increase the cost of the enterprise due to the addition of an additional dryer to assist in extreme conditions.

2.4. Energy, exergy, economics, and the environment theme

Various review studies focusing on energy and exergo-environmental analysis are presented in Table 4. Desa et al. (2020) presented a brief overview of the economic, environmental, and energy evaluation approach for solar dryers. Specific energy consumption, specific moisture extraction rate, and thermal and pick-up efficiency were all energy parameters. The solar fraction that contributed to the heat input was also calculated if the solar drier is of a hybrid design. The review used carbon emissions and earned carbon credits to assess environmental impact, while the payback period and energy savings potential were used to assess economic impact. El Hage et al. (2018) conducted economic and environmental impact assessments of solar dryers using a case scenario of Lebanon after reviewing different types of solar dryers and their classifications with performance parameters.

Table 4
Review studies focusing on energy, exergy environmental and economic studies

Authors	The area of research discussed	Major conclusions
(Desa et al. 2020)	Solar drying principles, energy analysis, economic and environmental impact analysis	The overall benefit of solar drying systems can be deduced by carrying out thermo-economic and environmental analysis and this can be done through the concept of energy analysis
(El Hage et al. 2018)	Principles of solar drying, classifications, components, Types of air movements, design specifications of drying chamber and collectors, parameters affecting performances, benefits, drawbacks, barriers and environmental and economic concerns	Several solar dryer designs have been presented in literature but lacking is the economic analysis which is country-specific and the gap is needed to be filled on a country basis.
(Pathak et al. 2023)	Solar thermal collectors, solar air heating systems, Energy, exergy, economic and environmental analyses of solar air heating systems, exergoeconomic analysis, performance improvements, use of PCM and its classifications, properties of PCM, comparison of current studies on exergy, energy and environmental analysis of the integration of PCM in different types of solar dryers, PV/T and hybrid collectors	Several studies with or without PCM or PVT abound in the literature on solar drying and their uses have improved its performance and helped to limit the greenhouse gas effect. The deployment of energy, exergy, environmental and economic analysis has deepened the study of solar drying systems. However, the exergy efficiency depends on the air velocity, temperature increase and solar radiation intensity.
(Ahmadi et al. 2021)	Drying of agricultural products, drying technologies, solar greenhouse, classification of solar dryers, types of solar dryers hybrid dryers, solar assisted dehumidification systems, PV/T systems, different drying methods, energy, exergy, environmental and economic analysis	Solar energy is good for drying agricultural products however using a parabolic reflector will reduce the drying time and improve efficiency. Energy, exergy and economic analysis can deepen the understanding of the energy usage in solar drying systems

The review also discussed the disadvantages and advantages of using solar dryers. The payback periods and CO_2 mitigation potentials are economic and environmental indicators. CO_2 reduction is one method of achieving sustainable agro-food production (Gorjian et al., 2022). The review identified the number of dried products, sample pre-treatments, temperature, and airflow rate as key performance indicators affecting drying rates and product quality of solar drying. They acknowledged the benefits of solar dryers but stated that more work is needed before farmers, industries, and other food processors adopt them. According to the reviews, encouraging the use of solar dryers is extremely beneficial, particularly in areas with high solar energy potential. Solar dryer research and development must be financially and technically supported to achieve this goal. Scientific marketing techniques such as outreach, exploration, lectures, and commercials are required to draw attention to this field. Several reviews revealed that, in addition to energy analysis, exergy analysis based on the second law of thermodynamics has been widely used in solar drying energy analysis (Pathak et al., 2023; Balasuadhakar, 2021). Exergy is defined as the amount of work done to bring a thermodynamic system closer to its reference state (Ndukwu et al., 2022; NdukwuChinenye et al., 2021). The goal is to determine the state point at which maximum exergy destruction occurs, which necessitates further development (Fudholi et al., 2013). The methods used in the study can be divided into two categories. The first step which is commonly used is determining the exergy flow based solely on the exergy stream of air (X_a), as shown in Table 5 (Rao et al., 2021). However, based on other reviews, it is believed that the exergy analysis should include the exergy of solar radiation (X_R) and the exergy exchange of the material (X_w). The procedure and man equations for exergy calculations and sustainability indices used depending on the configurations of the solar dryer as enumerated in various review studies are summarized in Table 5 (NdukwuChinenye et al., 2021; NdukwuChinenye et al., 2022). To use these equations, the researchers ignored kinetic and potential energy, as well as variations in the chemical process. Furthermore, it is assumed that the experiment was carried out under steady-state conditions, with air serving as the ideal gas (Pathak et al., 2023).

Most of these studies, with energy, exergy, and economic or techno-economic analysis as the review theme, examine the design, concepts, classifications, models, transportation phenomena, and quality attributes of dried products (Ahmadi et al., 2021). This always leads to the same conclusion in the majority of the reviews. Another aspect that was studied was the environmental impact of using solar dyers. The majority of research is focused on how solar dryers reduce the entry of greenhouse gases, particularly CO_2, into the atmosphere if used instead of other energy sources. The world is going green in the sense that green energy is being used to replace fossil fuels. The impact of using a solar thermal system can be evaluated in solar system analysis by comparing the solar dryer energy output to the equivalent energy output to perform similar function using alternative energy sources such as diesel, coal, electricity, etc (Merlin et al., 2022). This is accomplished by equating the total useful energy consumed by the solar system to the energy consumed by the other energy systems and calculating the mass of carbon that would have been produced by using alternative energy sources. The various equations used for these calculations as summarized in the various review literature are presented in Table 6.

Table 5
Equations used in Exergy analysis

Equation	Description/ name	reference
$X_a = \dot{m}_a\left\{C_{p,a}\left(T - T_0 - T_0 In\frac{T}{T_0}\right) + R_a T_0 \times \left[\left(1 + \frac{M_a}{M_v}H\right) In\frac{1+\frac{M_a}{M_v}H_0}{1+\frac{M_a}{M_v}H} + 1 + \frac{M_a}{M_v}H In\frac{H}{H_0}\right]\right\}$	Exergy stream of air	(NdukwuChinenye et al., 2021)
$X_R = I\tau\alpha_p A_c\left(1 - \frac{T_a}{T_s}\right)$	Exergy of solar radiation	(NdukwuChinenye et al., 2021)
$X_w = \dot{m}_w\left[(h_f(T) - h_f(T_0)) + v_f(P - P_g(T)) - T_0(S_f(T) - S_g(T_0)) + T_0 R_w In\left(\frac{P_g(T_0)}{P_0 X_v^0}\right)\right]$	Exergy exchange of the material	(Ahmadi et al., 2021e 2021)
$X_{PCM} = T_e\left[\frac{m_p\lambda_p}{T_m}\right]$	Exergy stream of the PCM	(Macm Ndukwu, Bennamoun, and Simo-Tagne 2021)
$X_b = \dot{m}(X_{ch}X_{fg})$	Exergy of the biomass	(NdukwuChinenye et al., 2021)
$X_{ch} = 1.047 \times \mathrm{HHV}$	Exergy of burnt charcoal	(NdukwuChinenye et al., 2021)
$X_{ch} = RT_o\frac{y_i}{y_o}$	Exergy of flue gas	(Manos and Vincent, 2012)
$\eta_{ex} = \frac{X_o}{X_i} = 1 - \frac{X_{loss}}{X_i}$	Exergy efficiency	(Ahmadi et al., 2021)
$IP = (1 - \eta_{ex}) \times \mathrm{Ex}_{loss}$	Improvement potential	(Ahmadi et al., 2021)
$SI = \frac{1}{(1-\eta_{ex})}$	Sustainability index	(Ahmadi et al., 2021)
$WER = \frac{\mathrm{Ex}_{loss}}{\mathrm{Ex}_{in}}$	Wes exergy ratio	(Ahmadi et al., 2021)
$LOP = \frac{\mathrm{Ex}_{loss}}{\mathrm{Ex}_o}$	Lack of productivity	(Ahmadi et al., 2021)
$EIF = WER\, x\, \frac{1}{\eta_{ex}}$	Environmental effect facto	(Ahmadi et al., 2021)

Table 6
Equations used for determining the mass of CO_2 mitigated

Equation	Description	reference
$m_C = v_d k_f$	Mass of CO_2 produced by a given litre of diesel	(Ndukwu et al., 2017)
$E = v_d k_d \eta_d$ $k_{f,} = 2.63$ kg/l, $k_d = 10.08$ kWh/l, $\eta_d = 30\%$	The energy utilized by a diesel system	(Ndukwu et al., 2017)
$M_{CO_2} = EF_{CO_2} x\, Q_e$	Mass of CO_2 mitigated by grid-based electricity source	(Simo-Tagne et al., 2020)
$M_{CO_2} = \sum_i f_i\left(\frac{f_{es}Q_d Q_u}{\eta_i}\right) EFCO2.FCO_2\left(\frac{44}{12}\right)$ $FCO_2 = 0.9$; $EFCO_2 = 0.0258$ kg/ MJ; $f_i = 1$; $f_{es} = 1$.	Mass of CO_2 mitigated based on disaggregation of equivalent fossil fuel (coal)	(Simo-Tagne et al., 2020)

2.5. *Solar greenhouse dryers*

Drying crops in greenhouses has proven to be an extremely effective method of incorporating solar energy. Substituting renewable energy for traditional energy sources through energy-saving strategies is a viable energy solution for reducing greenhouse gas emissions. As a result, some research has been conducted in this area for drying various types of crops. Some authors have reviewed this research. Sahdev et al. (2016) and Safri et al. (2021) concentrated on solar greenhouses for drying a variety of commodities. In their reviews the drying performance of several greenhouses solar dryer in drying fruitsand vegetables like cabbage, pea, onion flakes, Rose, Java tea, Jaggery, Tomato, bitter guard, red pepper, garlic, longan, banana, groundnut, papad, date, peppermint, cayenne pepper, gooseberry, medicinal plants and herbs, food products, fish, and pork was highlighted. Passive, active, and hybrid greenhouses are commonly found in the reviewed literature. They reviews concluded that the main issue with passive solar greenhouse dryers is moisture build-up caused by slowly evaporated moisture evacuation, resulting in higher relative humidity, which may cause product rewetting. The reviews highlighted various parameters in solar greenhouse evaluation, such as crop characteristics, thermal performance, energy and exergy analysis, economic analysis, and theoretical heat and mass transfer analysis. According to the review, researchers presented different values for convectional heat transfer coefficient, drying efficiency, payback period, exergy, and energy efficiency, and thus it can be concluded that these values are based on the technical specifications of the dryer, type of crop and external environment. Modification of existing greenhouses for improved performance is critical for future adoption, as is the introduction of PV/T and high energy density storage materials for increased efficiency. According to Sahdev et al. (2016), affordable greenhouse dryer designs that are cost-effective will be required in rural communities for farmers to dry their crops and increase their return on investment. Tiwari et al. (2018) reviewed the integration of PV/T in solar greenhouses. The review presented the technical specifications, thermal performance, and thermal modelling approach for the greenhouse dryers under consideration. In a solar greenhouse, forced convection was recommended for high-moisture crops, while natural convection was recommended for low-moisture crops. According to the review, PVT collector's integrated solar greenhouses have better temperature control, which can be achieved by varying the solar packing module, thereby varying the air flow rate. As a result, a single PVT system can be used to dry different crops that require different drying temperatures. However, increasing the cell temperature reduces the PVT module's electrical efficiency. The review suggested integrating a desiccant wheel and a PCM with PVT modules to help during the off-season.

The technical specifications, modelling techniques, and eco-thermal and environmental aspects of solar greenhouse dryers have been discussed by some researchers (Tiwari et al. 2016; Srinivasan and Muthukumar 2021). Furthermore Ahmad et al. (2022) reviewed various thermal performance results for crops such as red chilli, turmeric, copra, grapes, peanuts, and fish. Even span, Quonset, parabolic, tunnel, vertical cylindrical tower, rack type, sandwich greenhouse, and chapel shapes are among the various greenhouse shapes presented in various reviews (Gorjian et al., 2021; Safri et al., 2021). Transparent materials such as poly cabinet, polyethene, or Perspex were used to cover these shapes. According to the various reviews, the even span and Quonset design are popular among solar greenhouses for drying agricultural products, but the even span is preferred because it is more effective in solar radiation received during the winter and summer. However, Prakash and Kumar (2014) stated that for maximizing global solar radiation, a dome shape solar greenhouse is preferable, while an even span is preferable for air mixing. Furthermore, bulk-level drying in solar greenhouse dryers is simple to control. The floors can be concrete, rock bed, PVC, or left unfinished, and the north walls can be inclined, insulated, or reflective (Singh et al. 2018). The reviews revealed that improving drying efficiency with PCM and PV modules is possible. The air from the greenhouse cools and heats the PV modules while increasing the electrical performance of the PV module, which is used to power the fans in active mode. Greenhouse shape and orientation, greenhouse room condition, moisture accumulation and evaporation, wind speed, solar and transpiration flux, and turbulent kinetic energy can all be predicted using computational fluid dynamics tools. Mishra et al. (2021) examined recent advances in solar greenhouse drying. They concentrated on the economic, performance, and environmental advantages. The reviewed solar greenhouse was classified based on its structure, type of floor, air flow, heating, thermal storage material, covering material, and use of the north wall. According to Mishra et al. (2021), recent technological advancements in the solar greenhouse include the use of PV/T and PV modules, inclined reflective north wall, thermal storage materials, and opaque insulated north wall. All of the reviews agree that crops dried in a solar greenhouse have superior quality when compared to open sun drying. Furthermore, forced convection is best for drying crops with high initial moisture contents in the greenhouse, and natural convection is best for drying crops with low initial moisture contents. Table 7 gave a summary of research reviews based on greenhouse design.

2.6. Modelling and software applications in solar drying

Table 8 gave a summary of review studies focusing on software applications in solar drying. Prakash et al. (2016a,b) and Chauhan et al. (2015) examined different models and software used in parametric predictions in solar drying systems. These models and software were used to predict the drying rate, crop quality, moisture content, temperature, and other product attributes. It concentrated on various techniques used in the modelling of drying behaviours, such as mathematical modelling of drying kinetics and mechanistic thermal modelling based on experimental moisture ratio and energy balancing on different dryer components. According to the review, network-based simulation software such as artificial neural networks (ANN) and adaptive network-based fuzzy inference systems (ANFIS) have been used to predict drying characteristics, particularly for data sets with non-linear interactions. This is common in solar dryers, particularly when airflow is provided by natural convection. This is due to weather fluctuations, which cause solar radiation and airflow to be intermittent. Furthermore, as shown in the review, predictions based on computational fluid dynamics (CFD) with the assistance of FLUENT, ANSYS, COMSOL, and Fuzzy logic have been used to predict temperature distribution and airflow. For practical purposes, this software employs digital twins, which are digital representations of physical products, processes, and systems that are indistinguishable digital counterparts of the physical product. According to Prakash et al. (2016a,b), problems can be solved with fuzzy logic using open, imprecise data and heuristics, resulting in an array of accurate conclusions. CFD is used to investigate the various fluid interactions at the boundary conditions. The interaction of airflow dynamics within the drying chamber is predicted by FLUENT. Prakash et al. (2016a,b) presented the methodology, simulation techniques, equations involved, and a review of work done using each reviewed modelling technique. Chauhan et al. (2015) presented a similar review based on results from various classifications of solar dryers. The reviews also revealed that FORTRAN and MATLAB can be used to develop mathematical models to predict crop moisture loss rate, air temperature, and crop temperature, while statistical analysis software such as SPSS, Statistica, and Sigma Plot V are used. Furthermore, Kant et al. (2016) included CFX and Open FOAM in their software review use in solar dryers. Getahun et al. (2021) presented a review of solar dryers in which they discussed the importance of incorporating product quality into the modelling and optimization of solar drying of fruits and vegetables. According to the review, most CFD studies do not consider quality when evaluating or optimizing dryer performance. CFD-based performance evaluations or optimization studies yield the most reliable results. Solar dryers should be able to predict quality attributes in addition to airflow, heat, and moisture transfer characteristics, which CFD can help achieve. The above review's themes can be divided into opportunities and challenges in solar drying, classification of solar dryers, performance factors, modelling techniques and developed mathematical models, governing equations, and the prospect of using CFD in the modelling of solar drying of fruits and vegetables quality attributes.

2.7. Crop quality attributes in solar drying

One of the benefits of using solar dryers to dry food is the better quality of the product when compared to open sun drying. Hii et al. (2019) provided a critical assessment of the qualities of solar-dried food

Table 7
Review studies with solar greenhouse dryers as subject them and research are discussed

Authors	Area discussed	Major conclusions
(Mishra et al. 2021)	Classifications, performances, economic analysis and environmental impact analysis	The integration of solar air collectors with thermal storage material, opaque insulated north wall, inclined reflecting north wall, PV and PVT systems is a new trend in solar greenhouse design for enhanced performance. Automation is available but with added initial cost
(Sahdev et al. 2016)	Previous research works and results in solar drying of vegetables, fruits, food products, medicinal and aromatic plants, fish/pork; theoretical analysis and models, energy and exergy analysis and economic aspect	Greenhouse solar dryers produce a dried product of superior quality compared to open sun drying and can operate in natural and active mode
(Singh et al. 2018)	Wholesome review of research in solar greenhouse drying, dryer types, specifications, experimental results and overall performance	Forced convection, indirect solar dryers produced dried crops with better quality in greenhouse dryers. The integration of solar air collectors with thermal storage material, opaque insulated north wall, and PV and PVT systems is a new trend in solar greenhouse design for enhanced performance. For better choice location data can be used to simulate for best performance
Safri et al., 2021	Classifications of the solar greenhouse, passive, active and hybrid solar greenhouse	The most important in solar greenhouse design is the design concept, the cost of building and the heating dynamics of the system. However, forced convection solar greenhouse produces dried products of superior quality. Hybrid technology can improve the performance of solar greenhouse
(Tiwari et al. 2018)	PVT collectors and solar dryers integrated with PVT, Thermal analysis, Thermal models, experimental procedures,	PVT collector has better energy storage and temperature control than PV modules and one system can be adapted to dry multiple crops. Forced convention for high moisture crops and natural convention for low moisture including the use of the insulated north wall for better performance in the greenhouse are major deductions from research on greenhouses equipped with PVT collector
(Tiwari et al. 2016)	Types of solar drying methods, types of solar dryer designs, thermal modelling and performance evaluation	Forced convection, indirect solar dryers and thin-layer drying produced dried crops with better performance. The density of crops influenced their drying kinetics
(Srinivasan and Muthukumar 2021)	Material selection, application of solar thermal storage units, application of solar PV modules in solar greenhouse dryers, energy, economic and environmental studies, different modelling techniques and application	The location of solar greenhouse dryers is environmentally specific, however, Quonset design with low-density polythene and east-west orientation has better performance. Forced convection solar greenhouse

(continued on next page)

Table 7 (*continued*)

Authors	Area discussed	Major conclusions
	of CFD in solar drying modelling.	with thermal storage and integration of PV modules enhanced performance. However, they increase the embodiment energy and CO_2 mitigation. General the product geometry influenced the energy consumption and payback time.
(Gorjian et al. 2021)	Solar-Assisted Dryers for Agricultural and Marine Products based on different classifications of solar dryers Solar-Assisted green house Dryers for Agricultural and Marine Products for different classifications, solar greenhouse with PV modules, thermal collectors, thermal storage and heat pumps, hybrid solar greenhouse dryers, economic analysis	The solar greenhouse has a large capacity for drying agricultural products and Heat pumps and different kinds of thermal storage materials have been used to support solar greenhouse drying.
(Ahmad et al. 2022)	Drying methods, greenhouse drying of different products, classifications of greenhouse dryers, performance analysis under load and no-load conditions with different evaluation parameters, thermal modelling, environmental analysis, cost analysis and review of recent trends in greenhouse research for different types of greenhouse	The location of solar greenhouse dryers is environmentally specific, however, Quonset design with low-density polythene and east-west orientation has better performance. The addition of paraffin wax and heat pumps can assist in drying. However in terms of drying kinetics, it is impossible to generalize the thin layer model for crops in the solar greenhouse, thus each must be personally validated for the best model.
(Prakash and Kumar 2014)	Classification of greenhouse dryers, Review of previous research under passive and active greenhouse dryers	Forced convection solar greenhouses are better for drying high-moisture crops while natural conventions are for low moisture. Generally, solar greenhouse dryer produces crops with good quality and the integrated ion of PVT in a solar greenhouse is widely used in South East Asia and therefore recommended for rural areas.

crops in several countries for various types of products. Documentation from various studies in this area conducted in over 20 countries revealed that solar dryer utilization has a higher drying quality potential than open sun drying. Thus, industrial solar dryers have been used to dry crops in countries such as Tanzania, Senegal, and Zimbabwe (Hii et al., 2019). While some countries, such as India, Iran, and Malaysia, have integrated solar dryers into their energy demand chains, others lag. The reviewers cite a lack of government intervention, poor extension service, farmer apathy toward technology, and poor pricing as barriers to technological transfer. However, based on the review findings, it is critical to charge a premium for solar-dried products as a healthy product due to their superior qualities and environmentally friendly processing conditions when compared to other products. This can be accomplished comprehensively if farmers are innovative in adopting or developing environmentally sustainable crops from planting to processing with solar dryers as part of the value chain. Creating this awareness necessitates the involvement of agribusiness executives, which will result in a value chain that integrates all aspects of raising agricultural products in an environmentally sustainable manner. As a result, agribusiness executives will devise more creative methods of presenting solar-dried products to consumers, as well as marketing solar dryers to end users. A couple of researchers have examined the use of solar dryers to dry medicinal and aromatic plants. While Chauhan et al. (2022) concentrated on its applications in the Himalayas (Ndukwu et al., 2020), examined the African experience critically. Bhaskara Reddy Mugi and Chandramohan (2021) also presented a broader review of the same topic. According to the reviews, various types of solar dryer designs have been used to dry medicinal and aromatic plants. These dryers were evaluated based on their effect on active ingredients, colour, essential oil, microbial load, and dried product quality, as well as economic policy indicators. Chauhan et al. (2022) concluded that forced mode indirect solar drying at 30–40 °C can preserve medicinal and aromatic plants close to their natural state, whereas (Ndukwu et al., 2020) discovered that the amount of energy cost savings that can be made by using solar dryers to dry medicinal and aromatic plants varied by country. Furthermore, Bhaskara Reddy Mugi and Chandramohan (2021) found that direct solar drying of medicinal plants can increase internal heat capable of reducing dried product quality. However, Kant et al. (2016) suggested in their review that using PCM to dry medicinal plants could improve product quality. Some of the solar-dried medicinal plants whose solar drying parameters were presented in Bhaskara Reddy Mugi and Chandramohan (2021) review studies are Moringa, Bay leaves, Valeriana Jatamansi, Mint, olive, Fenugreek-Coriander, thymus, Curry leaves, Stevia leaves, Rupturewort, Sweet basil leaves, Lemon verbena leaves, Horehound, Marrubium vulgare leaves, Roselle, Rosemary leaves, Sweet basil and Motherwort. In their review of solar dryers, Bala and Debnath (2012) discussed the development and potential of solar drying technologies for drying fruits, spices, vegetables, fish, and medicinal plants. They also drew on previous efforts in solar drying as well as recent developments in various types of solar dryers for drying cereal grains, vegetables, and fruits. They stated that a critical examination of the drying performance and product quality of these products in rural areas of the tropics and subtropics had been conducted. Several types of

Table 8
Review studies focusing on software applications and key areas discussed

Authors	Area discussed	Major conclusions
(Getahun et al. 2021)	Product quality, types of the solar dryer, drying kinetics and CFD modelling, simulation, governing equations, continuity equations, energy equations, heat transfer equations, modelling radiation, turbulence, porous media, quality attributes and CFD solution procedures	The use of CFD to predict the optimum performance of solar dryers is promising but lacking is the integration of quality attributes in most works outside the current focus on air flow rate and heat and moisture transport
(Prakash et al. 2016)	reviews of different modelling techniques in solar drying, CFD modelling, ANFIS modelling, ANN modelling, FUZZY modelling, Thermal and mathematical modelling, thin layer and energy modelling	Various packages like Fuzzy, ANN, and ANFIS have assisted solar dryer designers in material selection and also resolve other complex problems in solar drying. Additionally, they have helped to save time and resources
(Singh and Kumar Gaur, 2020)	Simulation methodologies, reviews on solar drying studies simulations using CFD, FORTRAN, SPSS, TRNSYS, MATLA, and ANN for different classifications of solar dryers	Models in solar drying of crops are broadly based on the application of energy balancing using partial differential equations and model simulations using established commercial software. The choice and design optimization of solar dryers for a particular crop can heavily be influenced using these two broad approaches. However, the complexity of using this software has been a limitation in its adoption.

solar dryers were tested to demonstrate their potential for agricultural use, with energy and exergy analysis, modelling and simulation results presented. The summary of reviews with crop performance attributes as its key area of focus is presented in Table 9.

2.8. *Solar drying of biomass*

The agricultural process generates a large amount of biomass in the form of sludge, fibrous waste, and waste from spoilt fruits and vegetables (Lingayat et al., 2022). These by-products are dewatered and dried in solar dryers for other uses. Some reviews have concentrated on this aspect of solar drying research. In their review, Gomes et al. (2023) and Lingayet et al. (2022) observed the effectiveness and higher drying rate of mix-mode solar dryers over chapel-green house dryers in drying sewage sludge. The review, however, focused on the solar dryers used in wastewater treatment plants and their suitability. Sludge disposal from wastewater presents numerous challenges to industries. As a result, they are dewatered and dried to reduce their mass and volume for ease of transportation, storage, or further energy-intensive conversion (Lingayat et al., 2022). Sludge drying is therefore part of its management, regardless of its usage or destination. As a result, the review divided the solar drying research in sewage sludge drying into commercial solar dryers and alternative solar dryers. Commercial solar dryers have installed collectors, whereas alternative solar dryers have solar dryer geometry covered in transparent materials. In this field of study, theoretical and semi-theoretical models were also presented. However, the review mentions that sludge thickness is a key determinant in the drying kinetics of solar sludge drying because of the possibility of the upper layer acting as an insulator to the lower. This information should be included in the modelling information along with other parameters. Researchers are concerned about the possibility of pathogen development due to the drying temperature range of solar dryers, which may not be sufficient to inactivate them. Available reviews in the above area are presented in Table 10.

Table 9
Review studies focusing on crop attributes after drying and key area discussed

Authors	Area discussed	Major conclusion
(Hii et al. 2019)	Classification of solar dryers, quality attributes of solar-dried products,	Solar drying is advantageous in drying agricultural products and has been used to dry fruits, vegetables, grains, seeds, beans, herbs, spices and medicinal plants. However, adoption is still low but has been commercialized in some countries
(Balasuadhakar, 2021)	Medicinal herbs, drying methods, solar dryer classifications, drying leaves, experimental results, and assessments, exergy analysis, thin layers and simulation studies, pre and post-processing, the integration of thermal storage materials, solar drying and cost analysis	Drying medicinal plants in solar dryers needs temperature control to retain the essential oil and other biochemical constituents. Thus indirect solar drying mode is recommended in most literature. The use of artificial intelligence can also assist to maintain quality and commercial software can help to simulate designs for optimum operational performance.
(M C Ndukwu et al. 2020)	Overviewing designs of solar dryers used in Africa, drying kinetics of medicinal and aromatic plants, the influence of solar drying on essential oil and active ingredients, microbial load and appearance, factors affecting solar dryer performance, energy and economic analysis	Solar dryers can provide temperature thresholds to effectively dry medicinal plants. The performance indicators for medicinal plants in the solar dryer should include the drying kinetics, preservation of essential oil and useful bio-chemicals and reduction of the microbial load on dried product. Research should focus more on colour appreciation and biochemical retention in solar drying analysis of medicinal and aromatic plants
(P. Chauhan et al. 2022)	Basic solar drying principles, review of solar dryer performance and results for different types and classification under natural and forced convection mode, thin layer and deep bed models, factors influencing performance, review of results of solar drying of herbs	Solar dryers are environmentally friendly drying systems and can replace sun drying methods. However, forced convection indirect solar dryers are better at preserving the natural quality of medicinal plants

3. Economic analysis methods of solar dryers

The benefit of individual smallholder ownership of solar driers considering the capital investment has been questioned in some economic analyses (Machala et al., 2022). The reason is simple due to the economics of scale where the capital investment does not vary linearly with capacity. Thus the installation cost, cost of manufacturing, operational cost and efficiency of the solar dryer become major constraints for farmers in solar dryer ownerships in several countries (Machala et al., 2022). Thus the farmer has to consider the following.

- The capacity of the fresh product to dry
- Drying duration
- Because solar radiation is intermittent, the usage rate in a year is very important
- The size of the enterprise
- The revenue variable between solar-dried products and open sun-dried product
- Operational, maintenance and the cost of fabrication of the solar dryer
- The energy efficiency of the solar dryer

Table 10
Review studies focusing on solar drying of biomass and key research area discussed

Authors	Area discussed	Major conclusions
(Gomes et al. 2023)	Performances of commercial solar dryers, Alternate solar dryers, review of solar drying modelling, software applications	Using solar dryers reduces energy consumption in sludge drying and the cost of the dried sludge. However, lacking in the literature is the drying kinetics and optimal sludge thickness in solar drying application due to surface insulation. The operational and initial investment cost is still a grey area that needed to be tackled in solar industrial drying of sludge
(Lingayat et al. 2022)	Drying and energy consumption, industrial drying application of solar drying of industrial materials, drying application of solar drying of agricultural products, drying of sewage sludge and wastewater environmental and economic aspect	Solar dryers have high potential in industrial applications for both low and high-temperature applications. Integration of supplementary heating sources is available but the studies lack control over the drying condition at high temperatures using solar water heating technology can solve this problem. Studies on hybridized solar drying with thermal storage of novel improved characteristic performance are an area of interest

Thus these factors are integrated into establishing the feasibility of solar dryer designs in different localities when direct cash benefit is needed. Thus the following sections look at how this method has been used in solar drying follows.

3.1. Cash inflow methods

The main challenge in developing solar dryers is getting farmers to accept them because they are an investment though beneficial but still carry risks in terms of capital input and recovery. After all, their use is intermittent or requires the involvement of additional supplementary technology. Farmers' economic capacity and needs change over time, necessitating the use of technology to adapt to these changes. Economic analysis is critical in determining the viability of renewable energy systems. They are widely used in energy system development, construction, and optimization. They serve as a foundation for calculating the energy system's operating costs and the period of investment recovery. It considers the construction and energy output details and provides an estimate of the cost coefficient. The economic analysis models use three methods. The first is based on a simple cash inflow that only includes the solar dryer's financial components. The solar dryer designs are projected in terms of the rate at which the invested capital is recovered and the expected income. In this case, the methods look at the capital (non-recurring cost) and operational (recurring cost) expenses, the risk involved, and the uncertainties surrounding the energy system investment (Hassan et al., 2022). They also use the benefit-cost ratio (BCR) (Kiburi et al., 2020), savings per kg of dried product, Capita recovery factor (CRF), return on investment (ROI) and present value cost (PVC) as economic indicators. Furthermore, the economic viability of solar dryers has also been determined using net present values (NPV), internal rate of returns (IRR), and pay-back period (PBP) (Aravindh and Sreekumar 2015; Onyenwigwe et al., 2023). The second method is more detailed and involves a life cycle analysis of the entire solar dryer during its operation, whereas the third method is energy payback time, which is the period during which the solar dryer can produce the required amount of energy it uses for drying the product during its life cycle. These economic indicators are widely used to assess the economic potential of solar dryers. These energy system indicators can be further classified into dynamic and static evaluation indicators based on the inclusion of time duration impact on the system. Annualized costs, static payback periods, and return on investment are static evaluation indicators because they consider only the cash flow before the payback periods and not the equipment's lifetime. Furthermore, the dynamic evaluation indicators, which include the BCR, PVC, IRR, and NPV, among others, consider the design lifetime in their cost analysis. In some studies, the authors based their economic evaluation solely on the amount of money saved per kilogram of the dried product (Ekka and Palanisamy 2021).In this review, the common indicators are compiled and analyzed.

The benefit-cost ratio (BCR) is used by solar dryer researchers to relate the overall benefit of the solar dryer to the relative cost of the project in monetary or qualitative terms (Kiburi et al., 2020). The closer the BCR is to 1.0, the more likely the solar dryer will deliver positive returns; otherwise, if the BCR is less than 1.0, the capital investment outweighs the benefits. The BCR does not provide the actual economic value of the solar dryer, but it does provide a rough estimate of project viability by indicating the degree to which the IRR exceeds the rate of discount. It is expressed generically as follows:

$$BCR = \frac{\sum_{t=0}^{n} \frac{CF_t[Benefits]}{(1+i)^t}}{\sum_{t=0}^{n} \frac{CF_t[Costs]}{(1+i)^t}} \tag{1}$$

In the case of solar dryer Kaburi et al. (2020) simplified the BCR as follows

$$BCR = \frac{Benefit\ received\ per\ year}{total\ cost\ of\ the\ dryer} \tag{2}$$

Where the total cost of the dryer is the sum of the material costs and labour costs for the fabrication of the solar dryer. Ekka and Palanisamy (2021) investigated the economics of solar dryers using CFR, NPW, IRR, annualized uniform cost, and payback periods. The CRF reflects the ratio of a constant annuity to the value of that annuity delivered over time. CRF is the inverse of NPW, and the product of CFR and NPW has been used to calculate the annualized uniform cost of a solar-dried product (Ekka and Palanisamy 2021). Thus, to calculate savings per kg of dried product, use equation (20) as follows (Ekka and Palanisamy 2021).

$$S = S_p - S_{ds} \tag{3}$$

$$S_{ds} = S_{fp} - S_s \tag{4}$$

$$S_s = \frac{Annualized\ uniform\ cost}{dried\ product\ output/kg} \tag{5}$$

$$Annualized\ uniform\ cost = NPW \times CRF \tag{6}$$

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{7}$$

$$NPW = \left[p_i R_{mo} \left(\frac{(1+i)^n - 1}{i(1+i)^n} \right) + R_P \left\{ \frac{1}{(1+i)^3} + \frac{1}{(1+i)^6} + \frac{1}{(1+i)^9} + \frac{1}{(1+i)^{12}} \right\} - S_v \left(\frac{1}{(1+i)^n} \right) \right] \tag{8}$$

Thus the net present worth was used to deduce the payback period for the solar dryer as follows

$$PBP = \frac{In\left(\frac{CFs}{CFs - NPW}\right)}{In(1+i)} \tag{9}$$

In calculating the above payback periods, the researchers assume that the utilization of solar dryers is intermittent; therefore the cash inflow generation is not consistent.

Hadibi et al. (2021) and Kumar et al. (2023)used three key methods that include the payback periods, life cycle savings and annualized cost methods in their economic analysis. When a cost component is annualized, its net present cost is the same as its actual cash flow sequence given its occurrence equally during a project's lifetime. Thus, Hadibi et al. (2021) and Singh and Gaur (2021) determined the cost of drying a kilogram of the product using the annualized cost as follows

$$C_{dry} = \frac{AC}{M_p} \tag{10}$$

Where the mass of dried product per annum (M_p) is determined as follows (Sethi et al., 2021)

$$M_p = \frac{M_b D_R}{D_b} \tag{11}$$

The annualized cost (AC) for a solar dryer where given by (Hadibi et al., 2021; Madhankumar et al., 2023; Philip et al. 2022) as follows

$$Annualized\ cost = C_{acc} + \mathrm{C_{mc}} - \mathrm{S_a} + \mathrm{C_{rfc}} + \mathrm{C_{rec}} \tag{12}$$

C_{mc} is the annual maintenance cost usually taken as a percentage of the capital cost, C_{rfc} is the annual fuel given as zero for solar dryers, and C_{acc} is the annualized capital cost given as follows

$$C_{acc} = C_{ccd} \times CRF \tag{13}$$

Where C_{ccd} is the capital cost of the dryer

$$\mathrm{S_a} = \mathrm{S} \times \mathrm{SFF} \tag{14}$$

$$\mathrm{SFF} = \frac{\mathrm{i}}{(\mathrm{i}+1)^{\mathrm{n}} - 1} \tag{15}$$

The fan running cost for a forced convection solar dryer powered with supplementary energy is given as follows

$$C_{rec} = R \times W \times C_e \tag{16}$$

This cost is excluded if the dryer operates in natural convection mode or if the fan is powered by a wind generator as observed in some research (Ndukwu et al., 2022; Ndukwu et al., 2020b).

The second method proposed to determine the cost of dried products per year is using the life cycle saving methods. Using the life-cycle hypothesis, a solar dryer keeps the same level of operation over time by saving energy costs that would have been expanded in sourcing fuel to run a typical artificial dryer. Over the lifetime of the solar dryer, annual savings are estimated using the reference first-year savings as a base saving. Thus savings per kg of dried product in the solar dryer per annum is determined as follows (Mishra et al. 2021)

$$S_{py} = S_{kg} \times M_{py} \tag{17}$$

Where the savings made per kg of product dried is given as follows

$$S_{kg} = C_{skg} - C_{dskg} \tag{18}$$

$$C_{dskg} = C_d + C_{dry} \tag{19}$$

$$C_d = C_{fre} \times \frac{M_{fre}}{M_p} \tag{20}$$

Thus savings per day is given (Hadibi et al., 2022)

$$S_d = \frac{S_{py}}{D_R} \tag{21}$$

Therefore to obtain the amount of savings in a particular year (j) of the lifetime of the solar dryer is calculated as follows

$$S_j = S_d \times D_{year} \times (\mathrm{i}+1)^{\mathrm{j}-1} \tag{22}$$

Thus the present worth savings can be determined as follows

$$P_w = P_{wf} + S_j \tag{23}$$

Where P_{wf} is the present worth factor given as follows

$$P_{wf} = \frac{1}{(\mathrm{i}+1)^{\mathrm{j}}} \tag{24}$$

It's of note that the annualized present worth cost of the solar dryer is the life cycle savings throughout the lifetime.

Using the life-saving method (Philip et al. 2022), determine the payback period of the solar dryer as follows

$$PBP = \frac{In\left(1 - \frac{C_{cc}}{S_1}(i-d)\right)}{ln\left(\frac{1+d}{1+i}\right)} \tag{25}$$

Where d is the inflation rate and S_1 is the first-year annual savings.

For Mugi and Chandramohan (2021) they did not annualize the cost of the solar dryer which should be the expected cost of the dryer over a lifetime, however, they used the annual cost which is the gross yearly cost of the dryer when they are in actual operation. Thus the annual cost is determined for a particular year as follows

$$Annual\ cost\ (C_a) = \left[C_T + \sum_{k=1}^{L_d}\left(C_{m,k} + C_{op,k}\right)\beta^k\right]\left[\frac{\beta - 1}{\beta\left(\beta^{L_d} - 1\right)}\right] \tag{26}$$

$$\beta = \frac{100 + i_d}{100 + i_f} \tag{27}$$

Where i_f and i_d are the percentage inflation rate and interest rate respectively.

The capital cost is given as the labour cost and the raw material is determined as follows

$$C_T = C_{rm} + C_{lb} \tag{28}$$

Thus the annual saving was deduced as

$$S = Q_d P_d - Q_f p_f - Q_d c_{da} \tag{29}$$

$$C_{da} = \frac{C_a}{Q_d} \tag{30}$$

(Lamrani, et al. 2022; Lamrani et al., 2021) assumed that the solar dryer generates a constant cash inflow, thus they simply divided the total investment with the national cash inflow as follows

$$PBP = \frac{C_i}{NCF} \tag{31}$$

$$NCF = AR - (F_C + V_C + I_{TX}) \tag{32}$$

Where F_C, V_C and I_{TX} are the fixed cost, variable cost and income tax respectively.

Simo-Tagne et al. (2020) replaced net cash inflow with the amount of money saved from operational energy consumption when calculating the payback period of a solar dryer assuming even energy consumption in the period of the lifetime. Thus the payback period was given as follows

$$PBP = \frac{|A|}{AM_{yr}} \tag{33}$$

$$AM_{yr} = E_{yr} P_e \tag{34}$$

$$E_{yr} = \sum_{j=1}^{12}\left[\sum_{i=1}^{20} E_{day_i}\right]_j \tag{35}$$

3.2. Application of exergoeconomics model in cost analysis

Exergoeconomics is an economic analysis model that combines thermodynamic evaluations based on exergy analysis and economic principles at the system and component levels. It provides information useful for the design and operation of cost-effective systems that cannot easily be obtained by conventional energy and exergy analyses or cash inflow economic analyses. It s referred to energy consumption cost and provides an overview of the cost due to exergy destruction in the system. It tends to evaluate the values of exergy destroyed in the system and use it to estimate the overall cost of the inefficiencies in the system. It has been shown that as the exergy destruction increases, the unit cost decreases. It is carried out at different levels of components which reveal the cost relatively in terms of importance for an energy system. Thus the exergoeconimc analysis can be done for these few components. Since the exergy stream flows through the system, the cost rate is deduced with equations in Table 11 (Atalay and Cankurtaran 2021).

This method has been adopted in solar dyer economic evaluations by some other researchers (Atalay 2019; Singh et al. 2020). While the cash inflow cost analysis discussed above uses only the cost of the

Table 11
Equations used for determining exergy cost

Equation	Description	reference
$\dot{C}_{total} = \dot{C}_d + \dot{Z}_{total}$	Cost Rate	(Atalay and Cankurtaran 2021)
$\dot{C}_d = c_f \dot{E}_{x_d}$	Cost flow rate of exergy	(Atalay and Cankurtaran 2021)
$\dot{Z}_{total} = \dot{Z}_{ic} + \dot{Z}_{oc}$	Total cost	(Atalay and Cankurtaran 2021)

components and operational cost. Exergoeconomics analysis considers this cost in addition to exergy destruction cost and exergy loss amount ratio to the cost of components used in the fabrication of the solar dryers. Thus using the exergoeconomic investigation a solar drying system's cost can be estimated by examining its basic purchase cost, its exergy destruction ratio, its overall cost, its system recovery factor, and its exergoeconomic factor. Higher exergy cost indicates more exergy destruction from those components and to improve the system and reduce the cost of the system, the components have to be improved. Solar dryers have very few components, which include the collector drying chamber and fan for active systems or supplementary heating device for hybrid systems. Following the exergoeconomics method some researchers have proposed the cost of exergy destruction of various components in a solar-assisted hybrid dryer. Analysing the cost implication of exergy dynamics of a solar-assisted heat pump dryer (Singh et al. 2020), concluded that the exergy destruction cost was lowest for the drying chamber but peaked for the compressor. In terms of overall exergy cost, they found out that it was highest for the compressor and lowest in the expansion system of the solar-assisted heat pump dryer. The reason is that the total exergy cost is a combination of the purchasing cost and the exergy destruction rate. It was observed from their analysis that the higher the number of system components, the more exergy destruction increases which increases the overall exergy cost for the drying system. Thus in terms of overall exergy destruction to component purchase cost, the expansion device which had to lowest purchasing cost had the highest cost ratio of 10.2 W/$ while the drying chamber had the lowest cost ratio of 0.4312 W/$. However, by determining the various individual exergy economic factor and exergy destruction costs for each system component, it is possible to determine the component that requires improvement to reduce cost. Hence a component with the lowest exergoeconmic factor and highest exergy destruction cost is the one that requires the most thermodynamic improvement. For the hybrid solar dryer presented by Ref (Singh et al. 2020), the compressor had the highest exergy destruction cost while the expansion device had the lowest exergoeconomic factor. The same observation was made by (Hussain and Lee 2023) that the circulating pump of the solar dryer with concentrator produced the lowest exergoeconomc factor of 0.442 and highest exergy destruction cost of 0.268 $/h due to high energy consumption. In addition, the thermal storage unit also increased the total exergy cost thus the pump and the thermal storage unit must be improved. In a similar vein (Atalay and Cankurtaran 2021), found out that the fan and thermal storage unit is the major contributor to exergy destruction cost in an active solar dying system with thermal storage despite the integration of heat exchanger in the system while the collector had the lowest exergy destruction cost of $0.0044/h. Thus to improve the design and reduce energy consumption costs these two components needed to be improved which could be done by simulating the operating conditions of the system for optimum performance (Agrawal and Tiwari 2012). found that the overall exergy destruction rate to component purchase cost for solar air collector integrated with glazed PVT module is lower compared to that with PV module by 35.56%, thus offering a better potential n solar thermal application. A similar observation was made by (Atalay 2022) in the exergoeconomic analysis of a hybrid solar dryer powered by the wind. The fan unit had an overall exergy destruction rate to component purchase cost and exergy destruction cost for both conventional and hybrid systems while the wind generator maintained the lowest value exergy destruction cost. Thus from exergoeconomc analysis, it was found that the comparatively lower energy consumption cost of the wind-powered dryer can compensate for the higher initial purchase cost compared to the conventional solar dryers.

4. Market participation and agribusiness of solar dryer fabrication

Although reports on economic analysis and the performance of solar dryers abound in many countries (Mohammed et al. 2020), the status of the fabricator's market orientation is yet to be established. However, this section of the review tends to address these questions: how well are the solar dryer fabricators participate in the market, what are the factors hindering market participation and what are the strategies to gain more market access. Market participation is among the prerequisites of economic development. A market gives producers the prospect of taking comparative advantage of areas of production strength to enable them to enjoy benefits. The efficiency and effectiveness of solar dryers have been well documented by researchers globally (Goel et al., 2023; Pruengam et al. 2021). Its usefulness to Agricultural productivity is also highly acknowledged in the review literature documented in section 2. They are designed to suit farmers' drying needs at low energy cost and environmental sustainability (Eze and Agbo 2011; Manju and Sagar 2017). They are good energy-saving devices, reduce drying time compared to open sun drying, improve the quality of the dried product and also protect the environment (EL-Mesery et al., 2022; Rahman et al., 2022). Notwithstanding, all these clear-cut benefits, the market for designed and fabricated solar dryers is still undeveloped, especially in resource-poor economies in most developing countries (Ozoegwu 2019). The act of firms participating in the market has been considered as the assimilation of resource-poor producers into the value chain activities of products with an increase in income and poverty reduction as an outcome (Holloway and Ehui, 2001 and Reardon and Peter Timmer, 2007). Productivity gains could be achieved if fabricators of solar dryers engage in market-oriented production (Moti et al., 2009) but, most designed and fabricated machines for drying agricultural products are left to lie on the shelves of most workshops (Nwoke et al., 2011). Heltberg and Tarp (2002) reported that active participation in agricultural markets by rural technologies could help improve productivity, alleviate poverty and enhance food security in resource-poor economies. According to Ref (Barrett 2007, 2008), access to productive technologies and sufficient private and public goods is required from smallholder farmers to enable them to produce a marketable surplus. Tung and Costales (2007)affirm that infrastructure and institutional factors are crucial for improving the opportunities for rural farmers to increase market participation. There is a great need to stimulate the participation of these entrepreneurs in the market to help them to enjoy the benefit necessary to boost food security and socio-economic status. Increased returns that will accrue from the sale of locally fabricated solar dryers can be a way in for welfare gain and a way -out of poverty (Boughton et al., 2007). Producers of solar dryers which comparatively has low transaction costs will participate and sell more because of having more likelihood of recovering their production and marketing cost (Fischer and Qaim 2014). However, the lack of economies of scale has resulted in an uncompetitive market price of the solar dryer, increasing transaction costs which often is referred to as an economic barrier that will hinder market participation (Painuly 2001). Unfortunately, most of the local fabricator is constrained by several market barriers that hindered them from participating in the solar dryer market for their goods and services (Ozoegwu, 2019). For example, the adoption of solar dryer technologies among rural farmers in sub–Saharan Africa is challenged by little disposable income, lack of information, risk-averse, technology and financing, and poor institutional and legal framework (Otekunrin et al., 2019 and Mohammed et al., 2020). The study of Onyenwigwe et al. (2023) on the development of a low-cost dryer found that it will cost approximately $ 40 (US Dollar) for a solar dryer fabricated with materials obtained locally. This will be out of reach for rural farmers with little disposable income. Thus, the research of Kumar and Kandpal (2005) also acknowledged that solar dryers are facing the problem of low-capacity utilization in India. Hence producers find it difficult to dispose of their works at attractive prices and in places of their choice due to such perceived weaknesses. This development will dampen any eagerness about raising production and improving supply; this often leads to high rates of food loss, food shortages and low farm income (Munesue et al. 2015). To assist the solar dryer designers some market models can be used to increase the market participation of fabricators.

4.1. Strategies to market participation

Markets for innovative solar applications are still in their early stage in Sub-Saharan Africa (SSA). Therefore, the need for a more market-oriented development of solar thermal technologies. Due to the lack of uniformity in the different markets operating in the location, it is evident that there are strategies required to improve market orientation and access to solar dryer fabricators. These strategies are grouped as follows; use of.

1. Market-led approach to design and fabrication
2. Efficient research -extension – farmer linkage system
3. Application of the LEAN approach to design and Fabrication

4.2. Market-led approach to design and fabrication

In other to improve market participation, smallholder fabricators need to be market-oriented in their production. They need to have proper market intelligence concerning current and future customer needs. The concept of market orientation has been used by manufacturers to refer to the extent to which a producer uses knowledge about the market as a basis to decide on what to produce, how to produce and whom to produce for (Otekunrin et al. 2019; Gebremedhin and Jaleta 2010). This also borders on identifying profitable markets and buyers and connecting producers to buyers, thereby building the marketing capacity of the producer. As fabricators plan to produce for the market, considerations related to the cost of production and competitiveness, quality and handling becomes more important. Producers need a regular supply of market-related information to keep abreast of changing market conditions and consumer preferences (Moti and Berhanu, Gebremedhin Dirk 2009). Issues associated with the cost of production in the fabrication of solar dryers require great attention since the alternative, which is the traditional sun drying will cost little or nothing to dry materials and is the most common preservation method used by smallholder farmers in developing economies (Orsat et al. 2008). Cost of production could be minimized by using locally available materials for the fabrication and gain gotten from economies of scale. The findings of (Chua and Chou 2003) show that for better acceptability of new technology at a small scale and by rural households, the technology must have low initial capital cost, basically be constructed with locally available materials and parts, easy mechanical operations, easy maintenance, and evident benefit in drying such as time or energy saving and improved end-product quality.

4.3. Efficient research -extension – farmer linkage system

Effective collaboration among researchers, extension agents and farmers is required to achieve the common goal of increasing agricultural production and increasing farmers' income (Girma and Kuma 2022). Research outputs that are not properly linked to extension activity could be difficult to get to the farmer as well as know the feedback from farmers (Sewnet et al. 2015) The poor adoption and dissemination of new agricultural technologies is a result of weak linkages existing among the research, extension and farmers (Teklu 2001; Diao and Diao 2010). This aforementioned linkage weakness among the agricultural knowledge system actors will result to poor flow of information either from research to extension or from extension to farmers thereby leading to low productivity and loss of income (Adesoji and Tunde 2012). According to Diao and Diao (2010) the Ethiopia agricultural market problem is greatly caused by institutional failures such as extension services. He also identified the linkage system among the actors as a useful tool required to improve farm technology adoption, farmers' skills and market information for the farmers. In other to properly address the needs of the solar dryer fabricators, an appropriate research approach should be adopted by researchers, extension workers and farmers. They need to work together to identify these problems, adapt practical solutions and provide feedback to researchers on the technology developed (Gershon et al., 2010). The level of interaction and cooperation among researchers, extension agents and farmers could translate into how well the newly developed technology succeeds or fails as a reagent of economic development and as an instrument of eradicating poverty. This interaction is said to be lacking in the value chain. Nwoke et al. (2011) reported that the awareness of the use of solar dryers is very low among local farmers in Nigeria. They want further to say that the practical use of these dryers is completely absent domestically and industrially and also not available in the open market. Developed prototypes are only on display at government-funded research centres and dissemination of these technologies is usually done at workshops and seminars where the potential users who are rural dwellers are absent. An effective functioning market requires that the various stakeholders should be aware of the current technology. Lack of information among the stakeholders has been reported by many researchers as a barrier to the dissemination of improved solar energy technology (Painuly 2001).

4.4. Application of the lean approach to the design and fabrication of solar dryers

Lean philosophy in production is based on what the customer values, with all efforts targeted towards serving the customer as efficiently as possible by eliminating unnecessary waste from production (Manos and Vincent 2012). The major purpose of applying the lean approach is to properly serve customers with the exact product or service demanded that posse higher quality has a low price and is delivered in a shorter timely manner (Modi and Thakkar 2014). Here waste refers to the activities that do not add value to the customer, and value is that which the customer is willing to pay for. Lean stresses the efficient flow of products rather than the maximum utilization of resources. In manufacturing which includes (design and fabrication), lean is built on the following principles which are value, value steam, flow, pull and perfection. In other to effectively access the solar dryers' market, the fabricators need to understand what the customers want and what brings value to them. All the activities are needed to transform a product from an idea to the hands of the customer. This includes the design activities, management of all the information needed from the order to the delivery, and fabrication of raw materials into the finished product (Womack and Jones 2003). The application of the lean principle will help a producer to appraise and re-examine who their real customers are and what those customers regard as value. The principle emphasizes defining value from the customer's perspective because they are the ones that will decide the value of a product or service (Lian and Van Landeghem, 2002). Apte and Kang (2006) described this way of thinking to be different from what is commonly practised by many producers where value is specified from the departmental point of view like research and development, or engineering and finance. Defining value is the means of classifying the form, feature, or function that a customer is willing to purchase in a situation where they can't perform the required task on their own or without investing substantial time or cost (Smith and Thangarajoo, 2015).

4.5. Use of decision-making model for market participation of solar dryer fabricators

Any fabricator of solar dryers should engage in a range of economically significant market activities to sell their products. Small-scale solar dryer fabricators should seek to participate in the commercial market in other to maximize a multi-dimensional objective function, which includes an increase in incomes and food security as well as reducing all forms of risk (Mignouna et al., 2015) and (Strauss et al. 1989). However, the level of market participation or approach adopted should first satisfy certain indices which include the economic benefits and other social satisfaction associated with it. Thus, in examining the satisfaction derived from producers' participation in solar dryer utilization as a decision-making tool, the utility model can be used. The model explained that when there is a change in certain economic parameters related to market participation, the main question is on how much return, whether paid or received, would the decision maker be interested or otherwise about the change. Hence, the change in welfare associated with this development will be used as the basis for the economic evaluation. The theory explained the process. when an individual producer receives a change that is a measurable attribute, for example, higher returns or lower expenditures from participating in the market (q), then q changes from q^0 to q^1 (with $q^1>q^0$). The indirect utility functions U after the change becomes higher than the status quo.

The equation is expressed as:

$$U_{1_m} = U_n\left(y_n z_m q^0 \varepsilon 0\mathrm{m}\right) \tag{56}$$

Where U refers to the utility function, y_n is the producer's income, z_m is a vector of the producer's socio-economic variables and attributes of choice, and ε_m is the stochastic error term representing other unobserved utility components.

On the other hand, the change or final state due to market participation is written as

$$U_{2_m} = U_n\left(y_n z_m q^1 \varepsilon \mathrm{mn}\right) \tag{57}$$

The producer would decide to participate in the markets on the following condition

$$U_n(y_m - q_m z_n \; \varepsilon \mathrm{mn}) > U_n(y_n z_m, \varepsilon 0\mathrm{m}) \tag{58}$$

Where q_m is the monetary investment associated with market participation.

Since the random components of the preferences are not known with certainty; it is likely only to make probabilistic statements about the expected outcomes. Therefore, the decision by the producer to participate is the probability that they will be better off if participation improves their welfare. This is represented as follows:

$$Prob(yes_m) = Prob\left[U_n\left(y_m - p_{m,} z_{n,} \; \varepsilon \mathrm{mn}\right) > U_n\left(y_{i,} z_i, \varepsilon \mathrm{mn}\right)\right] \tag{59}$$

The utility function expressed in equation (4) was done in general terms. In other to specify the function as additively separable in deterministic and stochastic preferences. The function becomes:

$$U_m\left(y_{m,} z_n, \varepsilon \mathrm{nm}\right) > U_n\left(y_{n,} z_m\right) + \varepsilon \mathrm{nm} \tag{60}$$

Where: The first part of the right-hand side is the deterministic part and the second part is the stochastic part. The assumption that ε_{nm} are independently and identically distributed with mean zero describes the most widely used distributions.

5. Concluding remarks and future directions for studies

This review gives a critical appraisal of various review literature on the solar drying of agricultural products and filled the gap observed in review studies of solar drying of agricultural products. Thus studies involving economic and exergoeconomic analysis were reviewed and market participation models to assist solar dryer fabricators to gain access to the market were discussed. Thus the following conclusions were made.

1. Sections dealing with the types of solar dryers, the classification of solar dryers, the mode of airflow through the collector, and the use of thermal storage are common in most reviews. Each of these sections is repeatedly reviewed before narrowing down to the present review's theme. In most cases, they constitute the majority of the review material, regardless of the review's theme. As a result, the authors review nearly identical research material based on these sections, which deal with these classifications and solar dryer types.
2. The application of economic indicators and models in solar dryer selections is one aspect that lacks an in-depth overview of the review literature. While other aspects of solar dryer evaluations have been extensively covered in review literature, there is a lack of an in-depth literature survey on project decision-making techniques in solar dryers, the feasibility of economic influencing factor analysis methods, and risk analysis methods that are common in other energy investment research reviews. Where they are mentioned, it is not in detail but serves as a minor part of the review under the previously appraised 8 categories of existing literature.
3. Exergoeconomic analysis showed that component units with high energy consumption will increase the total exergy cost. Thus increase in the number of system component units, exergy destruction will also increase which will increase the overall exergy cost for the drying system. Therefore active solar dryers with fan and PV modules has higher total exergy cost compared to natural convection solar dryers
4. Agribusiness inter-phasing between researchers and users which will spore market participation of solar dryer fabricators solar dried products is also lacking in the literature reviewed. Market development for solar dryers is still at its early stage in most developing and less developed economies. Fabricated prototypes are left to lie on the shelves of most workshops or displayed at government-funded research centres. Therefore, the need for a more market-oriented development of solar thermal technologies, and solar dryers' producers need to engage in market-oriented production. This review presented methods that can be adopted and models to assess the acceptability of solar dryers to achieve this. An effective functioning market requires that the various stakeholders should be aware of the current technology. The nature of markets located at different places calls for better strategies required to improve market orientation and access to solar dryers and fabricators.

We, therefore, suggest that researchers, industries, and suppliers should collaborate through agribusiness to develop, manufacture, and distribute solar dryers in a common value chain, with the solar dryer as the end product and the solar-dried product that goes on the market as a premium product. Thus, solar dryer research and development can form an integrated tripartite nexus in food processing with solar dryer fabrication and entrepreneurship to create a sustainable marketable product with unique colour, quality, texture, aroma, and taste through agribusiness. Solar dryer design should include targeted product creativity that integrates technology innovation, processes, unique product creation, and marketing to create an environmentally sustainable product. This study is limited to the appraisal of previous collections of reviews studies carried out on solar drying of agricultural products with the intent to determine the gaps in reviews on solar drying of agricultural products due to the enormous review literature that abounds in this area of study. The study did not delve into reviewing already discussed areas of solar dryer classifications, design concepts, thermal storage, assessment approaches, performance evaluations, energy and exergy analyses, and so on. However, it summarizes the conclusions and perspectives of various reviews. Hence, the observed gap in the area of Econo-market participation which will enable solar dryer fabricators to transfer their innovation to consumers through a market decision approach was fully discussed and the needed tools were presented.

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Data availability

Data will be made available on request.

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